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An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef

ANDREW CHIN*, PETER M. KYNE†, TERENCE I. WALKER‡§ and RORY B. McAULEY¶

**Fishing and Fisheries Research Centre, School of Earth and Environmental Sciences, James Cook University, Qld 4812, Australia, †Tropical Rivers and Coastal Knowledge, Charles Darwin University, Darwin, NT 0909, Australia, ‡Marine and Freshwater Fisheries Research Institute, Department of Primary Industries, PO Box 114, Queenscliff, Vic 3225, Australia, §Department of Zoology, The University of Melbourne, Parkville, Vic 3052, Australia, ¶Government of Western Australia, Western Australian Fisheries and Marine Research Laboratories, Department of Fisheries, North Beach, WA 6920, Australia*

Abstract

An Integrated Risk Assessment for Climate Change (IRACC) is developed and applied to assess the vulnerability of sharks and rays on Australia's Great Barrier Reef (GBR) to climate change. The IRACC merges a traditional climate change vulnerability framework with approaches from fisheries ecological risk assessments. This semi-quantitative assessment accommodates uncertainty and can be applied at different spatial and temporal scales to identify exposure factors, at-risk species and their key biological and ecological attributes, critical habitats a'nd ecological processes, and major knowledge gaps. Consequently, the IRACC can provide a foundation upon which to develop climate change response strategies. Here, we describe the assessment process, demonstrate its application to GBR shark and ray species, and explore the issues affecting their vulnerability to climate change. The assessment indicates that for the GBR, freshwater/estuarine and reef associated sharks and rays are most vulnerable to climate change, and that vulnerability is driven by case-specific interactions of multiple factors and species attributes. Changes in temperature, freshwater input and ocean circulation will have the most widespread effects on these species. Although relatively few GBR sharks and rays were assessed as highly vulnerable, their vulnerability increases when synergies with other factors are considered. This is especially true for freshwater/estuarine and coastal/inshore sharks and rays. Reducing the impacts of climate change on the GBR's sharks and rays requires a range of approaches including mitigating climate change and addressing habitat degradation and sustainability issues. Species-specific conservation actions may be required for higher risk species (e.g. the freshwater whipray, porcupine ray, speartooth shark and sawfishes) including reducing mortality, preserving coastal catchments and estuarine habitats, and addressing fisheries sustainability. The assessment identified many knowledge gaps concerning GBR habitats and processes, and highlights the need for improved understanding of the biology and ecology of the sharks and rays of the GBR.

Keywords: adaptive capacity, climate change, exposure, Great Barrier Reef, rays, risk assessment, sensitivity, sharks, vulnerability

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Introduction

When planning climate change response strategies, there is a need to assess and prioritize the risks posed to individual components of socio-ecological systems (AGO, 2005). These efforts are complicated by uncertainty about the rate, magnitude and likelihood of change and their resulting impacts, particularly where the systems assessed are poorly understood (Jones, 2000). Additionally, many climate change risk assessments focus on specific species, habitats, interactions, or spatial and temporal scales (Harley *et al.*, 2006), reducing their applicability to assessments of other species groups and spatial and temporal scales. However, some vulnerability assessment approaches accommodate uncertainty (Füssel & Klein, 2006) and more recent assess-

Correspondence: Andrew Chin, Fishing and Fisheries Research Centre, School of Earth and Environmental Sciences, James Cook University, Townsville, Qld 4811, Australia, tel. + 61 7 4781 6796, e-mail: andrew.chin@jcu.edu.au

ments integrate multiple variables, species and systems (e.g. Hobday *et al*., 2006; Poloczanska *et al*., 2007). This paper presents an Integrated Risk Assessment for Climate Change (IRACC) that builds on these approaches, accommodating uncertainty and data paucity, integrating multiple climate change factors, ecological and habitat processes, and considers the species-specific attributes that confer vulnerability and resilience. Accordingly, the assessment can potentially be applied to a wide range of species across a range of spatial and temporal scales. We applied the assessment to assess a data-poor group of species across an entire ecosystem, namely the chondrichthyan fishes (sharks, rays, skates and chimaeras – henceforth referred to as 'sharks and rays') of Australia's Great Barrier Reef (GBR). This assessment considers *in situ* changes and effects occurring in the region over the next 100 years, and aims to identify the shark and ray species most vulnerable and the factors influencing their vulnerability.

Australia's Great Barrier Reef (GBR) region stretches for 2300 km along the east coast of Queensland, and covers approximately 350 000 km^2. The GBR ecosystem consists of a diverse range of interconnected habitats, of which coral reefs only comprise between 5% and 7% by area (Hutchings *et al*., 2008; GBRMPA, 2009). The coastal environs of the GBR include habitats such as rivers, floodplains, mangroves, salt marshes and seagrass beds. Further offshore, lesser known deepwater sponge and soft coral habitats, algal beds, deep seagrass beds, rocky shoals and seabed habitats of the continental shelf (up to 200 m depth) account for over 60% of the region's area. A further 31% of the area is comprised of continental slope habitats (200–1000 m depth) and deep oceanic waters ($>$1000 m depth) that are mostly unexplored (GBRMPA, 2009). Altogether, some 70 distinct bioregions (areas of relatively uniform habitats, communities and physical characteristics) have been identified and represent great diversity (Hutchings *et al*., 2008; GBRMPA, 2009). This diversity extends to sharks and rays with some 133 species from 41 families recorded from the GBR including a particularly high proportion of Australian endemics (Last & Stevens, 1994; Kyne *et al*., 2005; W.T. White, pers. comm.). Climate change is a priority issue for GBR managers with rising sea levels and temperatures, increases in ocean acidity and extremes in weather predicted to have severe impacts on the GBR system (GBRMPA, 2009).

Both globally and in the GBR, sharks and rays are affected by a variety of pressures including fishing and habitat loss (Chin, 2005; Stevens *et al*., 2005). Sharks and rays are especially vulnerable to such pressures given their life history characteristics (late age at maturity, low fecundity, long lifespan, low natural mortality); traits that also reduce their capacity to recover once populations are depleted (Camhi *et al*., 1998; Cortés, 2000, Simpfendorfer, 2000). Examples of declining shark populations have been well documented (Camhi *et al*., 1998; Dulvy *et al*., 2000, 2008; Simpfendorfer, 2000) and approximately 20% of chondrichthyan species assessed by the World Conservation Union (IUCN) are considered to be threatened (IUCN, 2008). Despite this vulnerability and their ecological significance in marine ecosystems (Stevens *et al*., 2000; Heithaus *et al*., 2008), sharks and rays are poorly understood and basic biological and life history traits for many GBR sharks and rays are unknown (Chin, 2005). Similarly, while the effects of climate change on fishes in the GBR have been considered, (Munday, 2004; Bellwood *et al*., 2006; Wilson *et al*., 2006, 2008; Munday *et al*., 2008), there are no such assessments for GBR sharks and rays, or indeed for sharks and rays elsewhere in the world.

The sharks and rays of the GBR are morphologically and ecologically diverse, occurring in habitats ranging from freshwater river systems to pelagic waters and bathyal (deep-water) habitats of the continental slope. Many sharks and rays use specific habitats at various stages of their life cycle. For example, many species utilize estuaries and seagrass beds as nurseries or foraging grounds (Blaber *et al*., 1989; Simpfendorfer & Milward, 1993; Heithaus *et al*., 2002; Heupel *et al*., 2007). GBR sharks have a wide range of feeding strategies and trophic relationships, ranging from generalist predators such as the tiger shark *Galeocerdo cuvier*, which preys upon reptiles, teleosts and large mammals (Simpfendorfer *et al*., 2001), to specialist feeders such as the whale shark *Rhincodon typus* and manta ray *Manta birostris* that feed exclusively on plankton (Last & Stevens, 1994).

Little is known about the population status of GBR sharks and rays (Chin, 2005). The proportion of threatened sharks and rays in the Australasian region is similar to that of the global situation and the GBR region is home to several internationally threatened species (Cavanagh *et al*., 2003). There is evidence that populations of some reef sharks have declined with significantly fewer sharks found in areas subjected to fishing pressure than areas where fishing pressure is reduced (Robbins *et al*., 2006; Heupel *et al*., 2009), but such data are not available for other species. This has complicated efforts to assess impacts from fishing and habitat loss on GBR shark populations, let alone their vulnerability to emerging pressures such as climate change, but there is increasing concern about their status (GBRMPA, 2009).

Risk and vulnerability assessments are applied in a wide range of forms in the management of human and natural systems. Climate change vulnerability assessment frameworks have progressed from relatively simple 'risk-hazard' models and impact assessments to increasingly complex 'vulnerability assessments' that consider resilience and consequences, and 'adaptation policy assessments' to inform adaptation policy (Turner *et al.*, 2003; Füssel & Klein, 2006). Vulnerability assessments have been used to assess the vulnerability of marine fauna to climate change (Hobday *et al.*, 2006; Poloczanska *et al.*, 2007) and the vulnerability of national economies to climate change impacts on fisheries (Allison *et al.*, 2009). Highly specialized vulnerability assessments have also been applied as detailed ecological risk assessments (ERAs) to assess the vulnerability of habitats and target and bycatch species to fisheries (Milton, 2001; Stobutzki *et al.*, 2001, 2002; Walker, 2005; Griffiths *et al.*, 2006; Hobday *et al.*, 2007; Salini *et al.*, 2007; Walker *et al.*, 2008; Waugh *et al.*, 2008; Zhou & Griffiths, 2008; Zhou *et al.*, 2009). ERAs are especially useful in fisheries management as they are flexible enough to apply to a variety of contexts and can accommodate uncertainty. Consequently, ERAs can be used where there are insufficient data to assess risks by conventional means such as population models and stock assessments (Walker, 2005). Such assessments can be qualitative, semiquantitative or quantitative, or may include a combination of these approaches (Hobday *et al.*, 2007). A variety of ERA tools have been applied such as Productivity-Susceptibility Analysis (Stobutzki *et al.*, 2001; Hobday *et al.*, 2007; Walker *et al.*, 2008) or Recovery-Susceptibility Analysis (Griffiths *et al.*, 2006). A common feature is the ability to identify risk factors, identify attributes of the species that confer susceptibility or resilience to these factors, and then rank and integrate these to derive the vulnerability of each species to risk factors. ERAs often assess and rank variables such as the exposure of species to fishing gear, the selectivity of gear for certain species or size and age classes, species abundance and distribution, biological productivity, and natural and fishing related mortality. These rankings are applied to an assessment framework that has clearly defined mathematical treatments and logic rules. The end result of a qualitative or semi-quantitative ERA is a set of rankings that describe the *relative* vulnerability of each species assessed to that fishery. The assessment process can also identify the main pressures and components that contribute to vulnerability of species, and highlight knowledge gaps. The logical structure and transparency of ERAs facilitates the involvement of stakeholders which in turn, can improve management outcomes (Fletcher, 2005). These features also allow assessments to be regularly updated as more data become available (e.g. Griffiths *et al.*, 2006).

The IRACC presented here combines elements of ERAs developed for Australian fisheries with a climate change vulnerability assessment framework applied to the GBR (Johnson & Marshall, 2007). In doing so, the IRACC provides a simple and transparent mechanism to assess the vulnerability of individual species to climate change even when there are few data available.

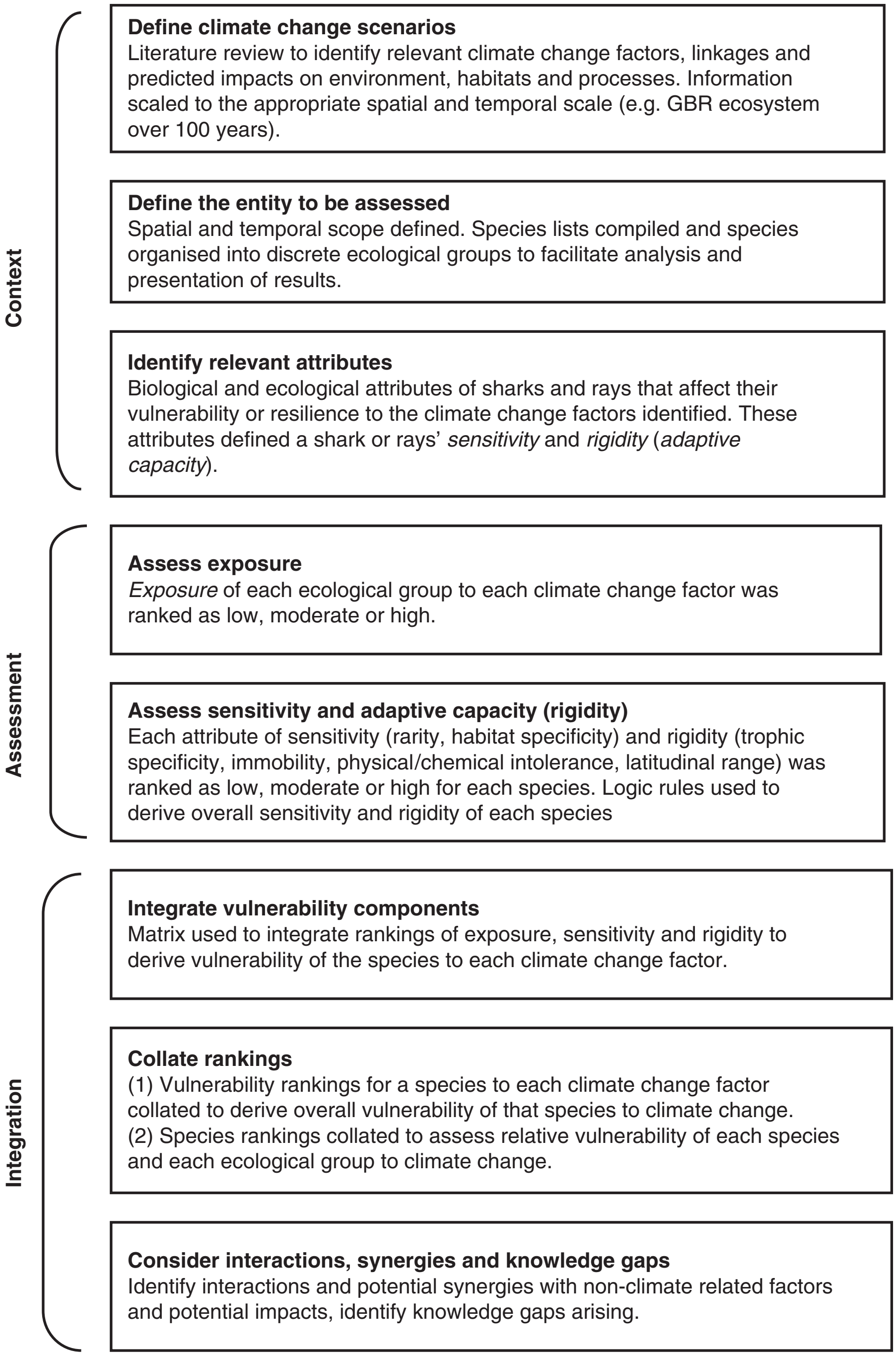
Materials and methods

The assessment involved three steps: defining the assessment context; assessing components of vulnerability; and integrating vulnerability components to derive the predicted vulnerability of each species of shark and ray in the GBR to climate change. An overview of the process is presented in Fig. 1.

Context: climate change factors, ecological groups, vulnerability components and attributes

Johnson & Marshall (2007) provided up-to-date and regionally down-scaled climate change projections for the GBR for the next 100 years. These projections described changes in climate variables based on A1 and B2 emission scenarios from the 2007 IPCC assessment (IPCC, 2007), and rankings of certainty (Lough, 2007). Johnson & Marshall (2007) also described numerous linkages between climate change factors and the species, habitats, physical and ecological processes of the GBR ecosystem, and further information was collated through literature review (see supporting information, Table S1). This information was used here to identify the specific climate change factors (elements of climate such as temperature or rainfall) most relevant to GBR sharks and rays (these factors are outlined in the Results). Uncertainty about climate change predictions was approached according to the IPCC recommendations on working with uncertainty (IPCC, 2005).

For this assessment, the GBR region was considered to encompass the GBR itself, as well as adjacent freshwater, coastal and deep water environments. To manage the analysis and present the data, the 133 species of sharks and rays known from the GBR were assigned to *ecological groups* defined by habitat types and associated biological and physical processes. A species was assigned to an ecological group if it occurs in the habitats found in that ecological group, and is affected by the physical, chemical and ecological processes occurring within those habitats. Highly mobile, widely distributed and ecologically flexible species (e.g. the bull shark *Carcharhinus leucas*) appear in more than one ecological group. The species composition of each ecological group was derived from published information on species distribution, habitat use and ecology (Last & Stevens, 1994; Kyne *et al.*, 2005) and unpublished data provided by chondrichthyan researchers (R.D. Pillans,



Define climate change scenarios
Literature review to identify relevant climate change factors, linkages and predicted impacts on environment, habitats and processes. Information scaled to the appropriate spatial and temporal scale (e.g. GBR ecosystem over 100 years).

Define the entity to be assessed
Spatial and temporal scope defined. Species lists compiled and species organised into discrete ecological groups to facilitate analysis and presentation of results.

Identify relevant attributes
Biological and ecological attributes of sharks and rays that affect their vulnerability or resilience to the climate change factors identified. These attributes defined a shark or rays' *sensitivity* and *rigidity* (*adaptive capacity*).

Assess exposure
Exposure of each ecological group to each climate change factor was ranked as low, moderate or high.

Assess sensitivity and adaptive capacity (rigidity)
Each attribute of sensitivity (rarity, habitat specificity) and rigidity (trophic specificity, immobility, physical/chemical intolerance, latitudinal range) was ranked as low, moderate or high for each species. Logic rules used to derive overall sensitivity and rigidity of each species

Integrate vulnerability components
Matrix used to integrate rankings of exposure, sensitivity and rigidity to derive vulnerability of the species to each climate change factor.

Collate rankings
(1) Vulnerability rankings for a species to each climate change factor collated to derive overall vulnerability of that species to climate change.
(2) Species rankings collated to assess relative vulnerability of each species and each ecological group to climate change.

Consider interactions, synergies and knowledge gaps
Identify interactions and potential synergies with non-climate related factors and potential impacts, identify knowledge gaps arising.

Fig. 1 Overview of the integrated risk assessment for climate change.

J.D. Stevens, W.T. White, pers. comm.). If no data were available, proxy data on con-specifics or closely related taxa from other regions were used.

The IRACC employed three commonly used components of climate change vulnerability: *exposure*, *sensitivity* and *adaptive capacity* as described by Johnson & Marshall (2007). Exposure and sensitivity were 'negative' components that represent the potential impacts of climate change. Adaptive capacity was a 'positive' component that embodied the ability to absorb impacts and accommodate change. These components are conceptually analogous to factors used in fisheries ERAs such as fishing pressure, fishing gear selectivity, fishing mortality rate and biological productivity. Fisheries ERAs were reviewed to identify suitable approaches to assess and combine the three climate change vulnerability components within a robust yet simple and transparent framework.

Exposure was assessed by comparing the extent of overlap between a species' geographic and bathymetric range and habitat use with the predicted footprint of the climate change factor. As a 'negative' component, high exposure represented increased likelihood of impact. The second component of vulnerability, 'sensitivity', was characterized by two attributes; *rarity* and *habitat specificity*. These attributes are inherent traits that individual sharks and rays cannot alter. Rarity encompasses the size and rebound potential of a shark or ray population. Compared with more common species, populations of rare sharks and rays may have reduced phenotypic variation (increased susceptibility to change), lower reproductive capacity, and single mortality events are more significant in terms of loss to the population. Rarity is especially significant for sharks and rays as they are generally slow growing, long lived animals with low reproductive capacity and long recovery times (Cortés, 2000; Simpfendorfer, 2000). These traits are especially true of larger species of sharks and rays (Smith *et al.*, 1998). Habitat specificity describes the extent of dependence on particular habitat types and locations. Sharks and rays that are ecologically dependent on specific habitat types, even if this dependence only exists during one stage of their life cycle, are more susceptible than those sharks and rays that can successfully utilize a number of alternative habitat types. Species with high degrees of rarity and specialization have been widely proposed to have an increased risk of extinction (Davies *et al.*, 2004; Julliard *et al.*, 2004; Munday, 2004; IUCN, 2008; Munday *et al.*, 2008).

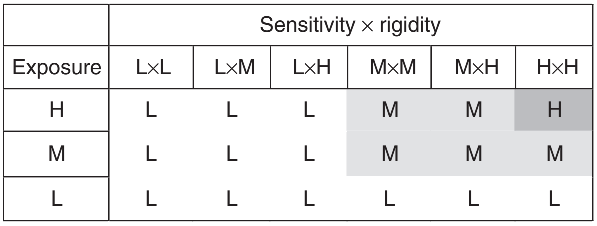
Adaptive capacity is the third vulnerability component and is a 'positive' component. Highly adaptable sharks and rays can alter their behaviour or physical state to accommodate changing conditions and exploit new opportunities. However, to numerically integrate the three vulnerability components, all three components must be expressed as like terms (either positive or negative). Hence, adaptive capacity was expressed as *rigidity* where *low rigidity* indicates that a species had a *high* adaptive capacity. Rigidity of GBR sharks and rays was characterized by four attributes that reflect a species' ability to accommodate change: (1) *Trophic specificity* represented a shark or ray's extent of specialization to certain prey types. Highly specialized sharks and ray species may not be able to exploit alternative prey groups should their preferred prey become unavailable, and thus had high rigidity; (2) *Immobility* represented a shark or ray's ability to successfully locate and physically move to and establish in alternative locations. A species that is unable to travel large distances due to physical limitations or barriers is less adaptable (high rigidity) than more mobile species; (3) *Physical or chemical intolerance* described a shark or ray's capacity to accommodate physiochemical change. A species that can tolerate a wide range of environmental conditions (e.g. salinity or temperature) can acclimate to changing conditions (low rigidity), and; (4) *Latitudinal range* was used as a proxy for temperature intolerance as species-specific data on environmental tolerances were seldom available. A shark or ray population that is widely dispersed over a large latitudinal range inhabits a wide range of temperature regimes, inferring that the species has the capacity to be successful in a wide range of conditions.

Given the slow generation times and rate of genetic change of sharks and rays (Martin *et al.*, 1992) and the scope of this assessment (100 years), adaptation through genetic evolution is not considered here as an attribute of adaptive capacity.

Assessment and integration

The exposure of each ecological group to each climate change factor was ranked as low, moderate or high. The magnitude of expected changes and level of certainty of predicted changes were also considered. Likewise, the attributes of sensitivity and rigidity were ranked as low, moderate or high for each of the 133 GBR shark and ray species using literature, unpublished data and expert knowledge. Once each attribute was ranked, two logic rules were applied to derive overall sensitivity and rigidity. First, the most conservative ranking of the attributes determined the overall rank of that component. For example, if a shark was highly abundant (low rarity = low sensitivity) but was entirely dependent on a specific habitat type (high habitat specificity = high sensitivity), the sensitivity of that shark was ranked as high. Secondly, if there was no information available to rank attributes of sensitivity or rigidity, the attribute was ranked as high. This is consistent with fisheries ERA approaches where the precautionary principle is applied to recognize that lack of information increases risk (Stobutzki *et al.*, 2001, 2002; Hobday *et al.*, 2007). This is especially pertinent for sharks and rays given that they are long-lived, slow-growing animals, with relatively low reproductive outputs and a record of population depletion (Camhi *et al.*, 1998).

Once exposure, sensitivity and rigidity were ranked, the component ranks were integrated using a matrix (Fig. 2) to derive the vulnerability of that shark or ray to that specific climate change factor. The integration matrix describes the outcomes of each combination of component ranks based on two logic rules: (1) if any one component is ranked as low, overall vulnerability must be low; and, (2) a rank of high vulnerability can only



	Sensitivity × rigidity					
Exposure	L×L	L×M	L×H	M×M	M×H	H×H
H	L	L	L	M	M	H
M	L	L	L	M	M	M
L	L	L	L	L	L	L

Fig. 2 Component integration matrix to determine species vulnerability rating from component rankings (L, low; M, moderate; H, high).

arise when all three components of vulnerability are ranked as high. The logic rules and outcomes of different rank combinations in the matrix have a mathematical basis that stems from approaches developed for fisheries ERAs (see Stobutzki *et al*., 2001, 2002; Hobday *et al*., 2007 for review). More information about the basis of the matrix is included in supporting information, Table S2. The process of combining and integrating attribute and component rankings to derive overall vulnerability is illustrated for two very different species in Table 1.

Table 1 demonstrates how attribute rankings determine component rankings, and how vulnerability to a given climate change factor is determined by the interaction of all three components. Even though the bull shark and freshwater sawfish have the same level of exposure to changes in freshwater input (they both occur in the freshwater habitats and are thus in the same ecological group), the sawfish is more vulnerable as it is rarer and more specialized, attributes which increase its sensitivity and rigidity.

Once all species were assessed, the vulnerability rankings of each species in each ecological group were collated to determine the relative vulnerability of each of the six groups. Species-specific attribute rankings and vulnerability rankings were also examined to determine whether any patterns of vulnerability emerged amongst species, their attributes, climate change factors and vulnerability components. Lastly, interactions between climate change factors, vulnerability components and nonclimate related variables were considered. These include information from existing threat and risk assessments for habitats and for sharks and rays taken in fisheries, and conservation listings such as the IUCN *Red List of Threatened Species*™.

Results

The IRACC process identified (1) relevant climate change factors and ecological groups of GBR sharks and rays; (2) the linkages between and relative exposure of these groups to the climate change factors; and

Table 1 Worked examples of the integrated risk assessment for climate change: vulnerability of the freshwater sawfish *Pristis microdon* and the bull shark *Carcharhinus leucas* to the climate change factor 'changes in freshwater input'

	Exposure (*to indirect effects of freshwater input*)	Sensitivity		Rigidity			
	Overlap between distribution and factor's footprint	Rarity	Habitat specificity	Trophic specificity	Physical–chemical intolerance	Immobility	Latitudinal range
Freshwater sawfish							
Attribute rank	High	High	High	Mod	Low	Low	Low
Component rank (as per logic rules)	*High*	*High*		*Moderate*			
Component integration			H × H × M				
Vulnerability rank (from integration matrix)			*Moderate vulnerability*				
Bull shark							
Attribute rank	High	Low	Low	Low	Low	Low	Low
Component rank (as per logic rules)	*High*	*Low*		*Low*			
Component integration			H × L × L				
Vulnerability rank (from integration matrix)			*Low vulnerability*				

(3) the relative vulnerability of each species and ecological group, as well as the factors and attributes contributing to their vulnerability or resilience.

Climate change factors and ecological groups

Ten climate change factors were relevant to sharks and rays of the GBR. Climate change factors affect the physiochemical environment in which species live (direct effects) and affected species will experience altered environmental conditions. Climate change factors will also influence the health and distribution of habitats as well as the geophysical, biological and ecological processes occurring within them (indirect effects). Consequently, climate change factors were classed as *direct* or *indirect* factors. Direct factors include water temperature, ocean acidification and freshwater input – these factors elicit a direct physiological response from GBR sharks and rays. *Indirect factors* include ocean circulation, water and air temperature, sea level rise, severe weather, freshwater input, light and ultra-violet radiation, and ocean acidification – these factors affect habitats and processes upon which sharks and rays depend. The indirect links between ocean acidification and GBR sharks and rays were difficult to identify. While a growing amount of information is available about the effects of ocean acidification on coral reefs, there were insufficient data to even begin to predict how increasing acidity might alter nonreef habitats and ecological processes. Consequently, the indirect affects of ocean acidification were only assessed for coral reef sharks and rays.

Six ecological groups of sharks and rays were identified: freshwater/estuarine, coastal/inshore, reef, shelf, pelagic and bathyal. These groups encompass habitat zones from rivers and estuaries to offshore pelagic habitats and the deep-water bathyal habitats of the continental slope (Table 2). A complete list of the species and their ecological groups is provided in supporting information, Table S3.

Linkages and exposure to climate change factors

The exposure of species in an ecological group to a given climate change factor varies according to the direct and indirect linkages between them. Physiochemical changes will affect shark and ray homeostasis but will also affect habitats and processes. Loss of habitat and altered processes will directly affect some sharks and rays but may also affect prey species, altering prey availability and increasing the exposure of affected sharks and rays. Exposure to climate change factors varied between ecological groups and the most significant factors and linkages are summarized in Fig. 3. More information and references describing these linkages are in supporting information, Table S1, and the complete rankings of the exposure of each ecological group to each climate change factor are available in supporting information, Table S4.

Figure 3 shows that the freshwater/estuarine and coastal/inshore sharks and rays had the highest exposure of the six ecological groups, with high to moderate exposure to most climate change factors. The shallow inshore environments of the GBR region, especially floodplain, riverine and estuarine water bodies, already experience extremes of water quality. Rising temperatures may negatively affect habitats such as mangroves, salt marshes and seagrass meadows and inshore reef habitats. These habitats are also likely to be affected by changing salinity regimes and geophysical processes from rising sea levels and altered rainfall regimes (freshwater input and floods), as well as increased physical disturbance from storms. Nutrient cycling and productivity are closely linked to freshwater input, and increased light and UV radiation coupled with greater extremes of drought and flood are predicted to cause greater extremes of high and low biological productivity, ultimately making prey availability less reliable. Further off the coast, productivity may be somewhat affected by changing currents.

Reef habitats also have high to moderate exposure to several climate change factors (Fig. 3). Rising temperatures, ocean acidity and storm activity are predicted to have serious detrimental effects on coral reefs. Increased light and UV radiation may also affect corals and nutrient cycling and productivity. Changing currents and rainfall/runoff regimes may affect habitat condition, connectivity and biological productivity on some coral reefs.

Shelf and pelagic sharks and rays had low to moderate exposure as relatively few of the climate change factors identified were thought to significantly alter the physiochemical environment or to have large effects on shelf and pelagic habitats and processes. Significant climate change factors include temperature which alters the physiochemical environment, and for shelf species, may affect some habitats and nutrient cycling (Fig. 3). Changes in freshwater input may also affect some shelf species by altering pulses of productivity. Both shelf and pelagic sharks are likely to be affected by changing currents that may alter patterns of upwellings of nutrient rich water. These upwellings drive productivity and prey availability, especially in pelagic environments.

Bathyal sharks and rays had the lowest exposure of the six ecological groups with exposure driven by potential changes in temperature and ocean circulation,

Table 2 Description of the six ecological groups of Great Barrier Reef chondrichthyan fishes used in the integrated risk assessment for climate change

Ecological group	Number of species*	Habitat description (also see Fig. 3)	Examples of species
Freshwater and estuarine	4	Rivers and streams, intertidal zones of estuaries and bays, mangroves and salt marsh, intertidal seagrass beds, foreshores and mudflats	Freshwater sawfish *Pristis microdon*, freshwater whipray *Himantura dalyensis*, bull shark *Carcharhinus leucas*, speartooth shark *Glyphis glyphis*
Coastal and inshore	44	Habitats extending from coastal subtidal habitats to the midshelf platform or ribbon reefs. Includes estuaries and bays, subtidal seagrass beds, inshore fringing reefs, shallow coastal waters, rocky shoals, sponge gardens and other benthic habitats of the GBR lagoon to 30 m depth	Narrow sawfish *Anoxypristis cuspidata*, leopard whipray *Himantura leoparda*, Australian cownose ray *Rhinoptera neglecta*, pigeye shark *Carcharhinus amboinensis*, tiger shark *Galeocerdo cuvier*, bull shark *Carcharhinus leucas*, great hammerhead shark *Sphyrna mokarran*, giant shovelnose ray *Glaucostegus typus*
Reef	19	Habitats on and immediately adjacent to midshelf and outer shelf coral reefs, down to a maximum depth of 40 m in the GBR lagoon, to 60 m in the outer shelf reefs	Blacktip reef shark *Carcharhinus melanopterus*, grey reef shark *Carcharhinus amblyrhynchos*, epaulette shark *Hemiscyllium ocellatum*, bluespotted fantail ray *Taeniura lymma*, ornate wobbegong *Orectolobus ornatus*
Shelf	26	Deeper water and seabed habitats between the midshelf and outer reefs, extending to the continental slope edge. Includes waters from the surface to 200 m (approximately the shelf edge) and benthic habitats such as deepwater seagrass beds and *Halimeda* mounds, rocky shoals and sponge gardens (40–60 m depth)	Eastern angel shark *Squatina albipunctata*, short-tail torpedo ray *Torpedo macneilli*, piked spurdog *Squalus megalops*, white shark *Carcharodon carcharias*, pencil shark *Hypogaleus hyugaensis*, tiger shark *Galeocerdo cuvier*, spot-tail shark *Carcharhinus sorrah*, great hammerhead shark *Sphyrna mokarran*, argus skate *Dipturus polyommata*
Bathyal	54	Benthic habitats of the continental slope and beyond, extending down to 2000 m depth	Argus skate *Dipturus polyommata*, longspine chimaera *Chimaera macrospina*, blackfin ghostshark *Hydrolagus lemures*, bartail spurdog *Squalus notocaudatus*
Pelagic	10	Open ocean waters extending from the edge of the outer reefs and beyond into the Coral Sea	Oceanic whitetip shark *Carcharhinus longimanus*, blue shark *Prionace glauca*, whale shark *Rhincodon typus*, manta ray *Manta birostris*

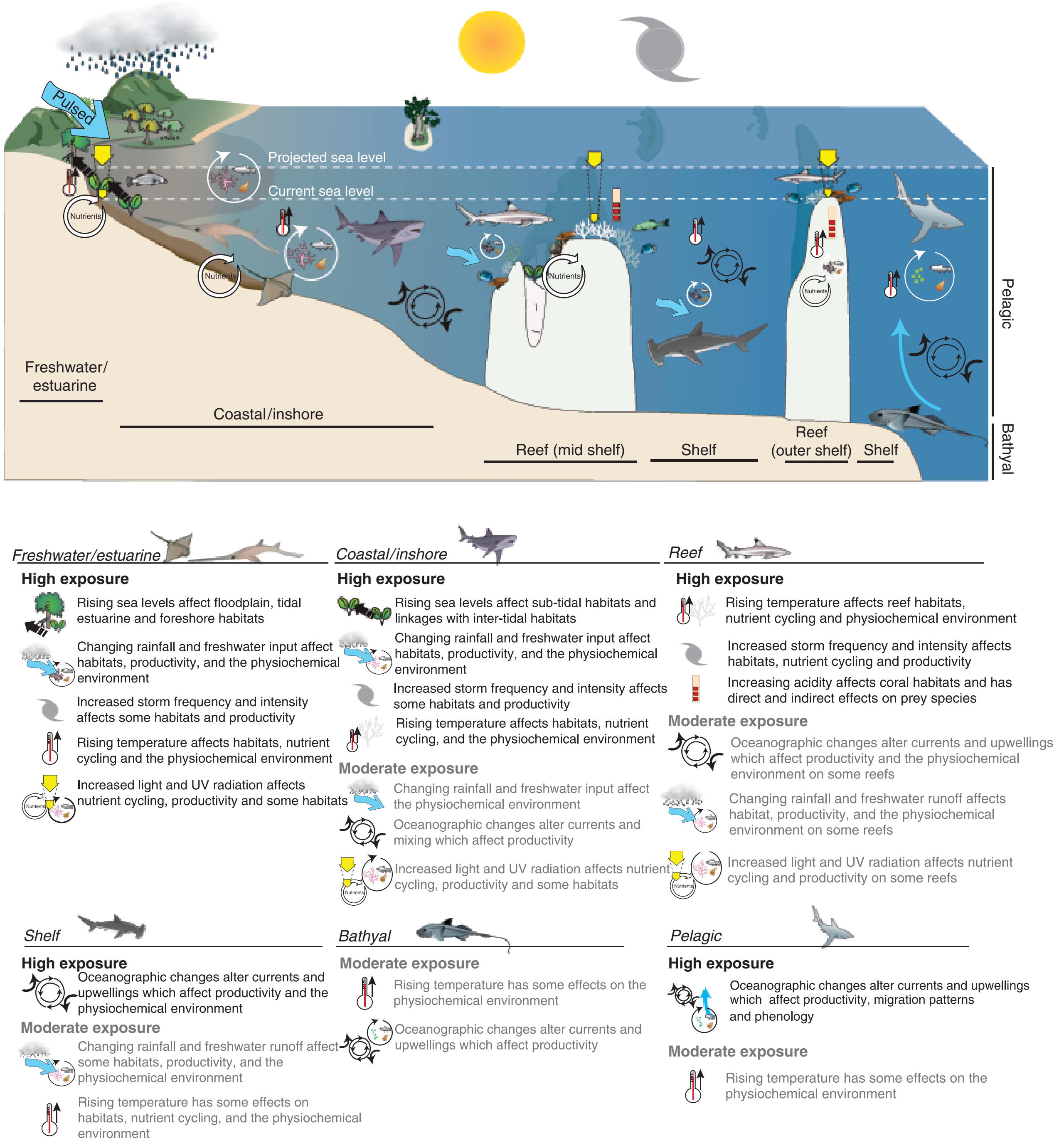
*Twenty-four species occur in more than one ecological group (see supporting information, Table S3).

which again may alter upwelling patterns that contribute to biological productivity (Fig. 3).

Across all groups, exposure was highest to temperature, freshwater input and changes in ocean circulation (currents, upwellings, etc). These factors thus appear to be the most significant climate change factors affecting GBR sharks and rays. However, the species, habitats and processes of oceanic and deepwater environs of the GBR are the least well understood, and certainty about potential climate change effects is lowest in these ecological groups.

Vulnerability of GBR sharks and rays

Overall, only 30 of the 133 GBR shark and ray species were ranked as ‘vulnerable’, two species (freshwater whipray *Himantura dalyensis* and porcupine ray *Urogymnus asperrimus*) being ranked as highly vulnerable and 28 species ranked as moderately vulnerable (Table 3). Many of these species belong to the freshwater/estuarine, coastal/inshore and reef ecological groups, and a cursory inspection of their component and attribute rankings revealed that many vulnerable species



Freshwater/estuarine

High exposure

Rising sea levels affect floodplain, tidal estuarine and foreshore habitats

Changing rainfall and freshwater input affect habitats, productivity, and the physiochemical environment

Increased storm frequency and intensity affects some habitats and productivity

Rising temperature affects habitats, nutrient cycling and the physiochemical environment

Increased light and UV radiation affects nutrient cycling, productivity and some habitats

Coastal/inshore

High exposure

Rising sea levels affect sub-tidal habitats and linkages with inter-tidal habitats

Changing rainfall and freshwater input affect habitats, productivity, and the physiochemical environment

Increased storm frequency and intensity affects some habitats and productivity

Rising temperature affects habitats, nutrient cycling, and the physiochemical environment

Moderate exposure

Changing rainfall and freshwater input affect the physiochemical environment

Oceanographic changes alter currents and mixing which affect productivity

Increased light and UV radiation affects nutrient cycling, productivity and some habitats

Reef

High exposure

Rising temperature affects reef habitats, nutrient cycling and physiochemical environment

Increased storm frequency and intensity affects habitats, nutrient cycling and productivity

Increasing acidity affects coral habitats and has direct and indirect effects on prey species

Moderate exposure

Oceanographic changes alter currents and upwellings which affect productivity and the physiochemical environment on some reefs

Changing rainfall and freshwater runoff affects habitat, productivity, and the physiochemical environment on some reefs

Increased light and UV radiation affects nutrient cycling and productivity on some reefs

Shelf

High exposure

Oceanographic changes alter currents and upwellings which affect productivity and the physiochemical environment

Moderate exposure

Changing rainfall and freshwater runoff affect some habitats, productivity, and the physiochemical environment

Rising temperature has some effects on habitats, nutrient cycling, and the physiochemical environment

Bathyal

Moderate exposure

Rising temperature has some effects on the physiochemical environment

Oceanographic changes alter currents and upwellings which affect productivity

Pelagic

High exposure

Oceanographic changes alter currents and upwellings which affect productivity, migration patterns and phenology

Moderate exposure

Rising temperature has some effects on the physiochemical environment

Fig. 3 Exposure of ecological groups of GBR sharks and rays to climate change factors.

had relatively high rankings of rarity and specialization. However, these patterns were not consistent across all species and groups. There are rare and specialized species in other groups that are *not* ranked as vulnerable, and there are many freshwater/estuarine, coastal/inshore and reef species that are not assessed as highly or moderately vulnerable. The vulnerability rankings for all species are available as supporting information, Table S3.

Of the six ecological groups, the freshwater/estuarine and reef ecological groups were assessed as most vulnerable to climate change (Fig. 4). Most freshwater/estuarine sharks and rays (four species) were ranked as having *moderate* or *high* vulnerability to climate change

Table 3 GBR sharks and rays that are vulnerable to climate change (i.e. have high or moderate overall vulnerability)

Ecological group	Family	Species name	Common name
High vulnerability			
Freshwater/Estuarine	Dasyatidae (Stingrays)	*Himantura dalyensis*	Freshwater whipray
Coastal/Inshore	Dasyatidae (Stingrays)	*Urogymnus asperrimus*	Porcupine ray
Moderate vulnerability			
Freshwater/Estuarine	Pristidae (Sawfishes)	*Pristis microdon*	Freshwater sawfish
	Carcharhinidae (Whaler sharks)	*Glyphis glyphis*	Speartooth shark
Coastal/Inshore	Pristidae (Sawfishes)	*Anoxypristis cuspidata*	Narrow sawfish
		Pristis clavata	Dwarf sawfish
		Pristis zijsron	Green sawfish
	Dasyatidae (Stingrays)	*Dasyatis fluviorum*	Estuary stingray
		Himantura granulata	Mangrove whipray
		Himantura leoparda	Leopard whipray
		Himantura toshi	Brown whipray
	Gymnuridae (Butterfly rays)	*Gymnura australis*	Australian butterfly ray
	Myliobatidae (Eagle rays)	*Aetomylaeus nichofii*	Banded eagle ray
	Rhinopteridae (Cownose rays)	*Rhinoptera neglecta*	Australian cownose ray
	Scyliorhinidae (Catsharks)	*Atelomycterus marnkalha*	Eastern banded catshark
Reef	Dasyatidae (Stingrays)	*Himantura fai*	Pink whipray
		Pastinachus atrus	Cowtail stingray
		Taeniura lymma	Bluespotted fantail ray
		Taeniurops meyeni	Blotched fantail ray
	Hemiscylliidae (Longtail carpetsharks)	*Hemiscyllium ocellatum*	Epaulette shark
		Hemiscyllium trispeculare	Speckled carpetshark
	Ginglymostomatidae (Nurse sharks)	*Nebrius ferrugineus*	Tawny shark
	Stegostomatidae (Zebra sharks)	*Stegostoma fasciatum*	Zebra shark
	Odontaspididae (Grey nurse sharks)	*Carcharias taurus*	Grey nurse shark
Shelf	Squatinidae (Angelsharks)	*Squatina albipunctata*	Eastern angelshark
	Torpedinidae (Torpedo rays)	*Torpedo macneilli*	Short-tail torpedo ray
	Urolophidae (Stingarees)	*Urolophus flavomosaicus*	Patchwork stingaree
	Lamnidae (Mackerel sharks)	*Carcharodon carcharias*	White shark
	Triakidae (Houndsharks)	*Hypogaleus hyugaensis*	Pencil shark
		Mustelus walkeri	Eastern spotted gummy shark

factors (Fig. 4). All these species had high exposure to all climate change factors except ocean circulation, and three of the four species in this group had high sensitivity (rare species with relatively high habitat specificity). However, these species are adapted to relatively harsh conditions and thus have moderate to low rigidity (i.e. high adaptive capacity) providing some compensation for their high exposure and sensitivity. The freshwater whipray *H. dalyensis* is the most vulnerable species in this group and is potentially the most vulnerable chondrichthyan species in the GBR region to climate change. In the reef ecological group (19 species), approximately half the sharks and rays had *moderate* vulnerability to all climate change factors (Fig. 4). Most of these species were stingrays (Dasyatidae) and longtail carpetsharks (Hemiscylliidae) (Table 3) that had moderate habitat specificity or immobility. Some species such as the grey nurse shark *Carcharias taurus* had high rarity. Less vulnerable reef sharks and rays included whaler sharks (Carcharhinidae), wobbegong sharks (Orectolobidae), and other stingrays and longtail carpetsharks.

The coastal/inshore (47 species), pelagic (10 species), shelf (26 species) and bathyal (54 species) ecological groups were assessed as having low overall vulnerability to climate change (Fig. 4).

While coastal/inshore sharks and rays had high to moderate exposure to climate change factors, two thirds of the species in this group were assessed as having low sensitivity and rigidity which reduced their vulnerability. The remaining species were more vulnerable sharks and rays that included the sawfishes (Pristidae), some stingrays, eagle rays (Myliobatidae) and Australian butterfly ray *Gymnura australis* (Table 3). These species

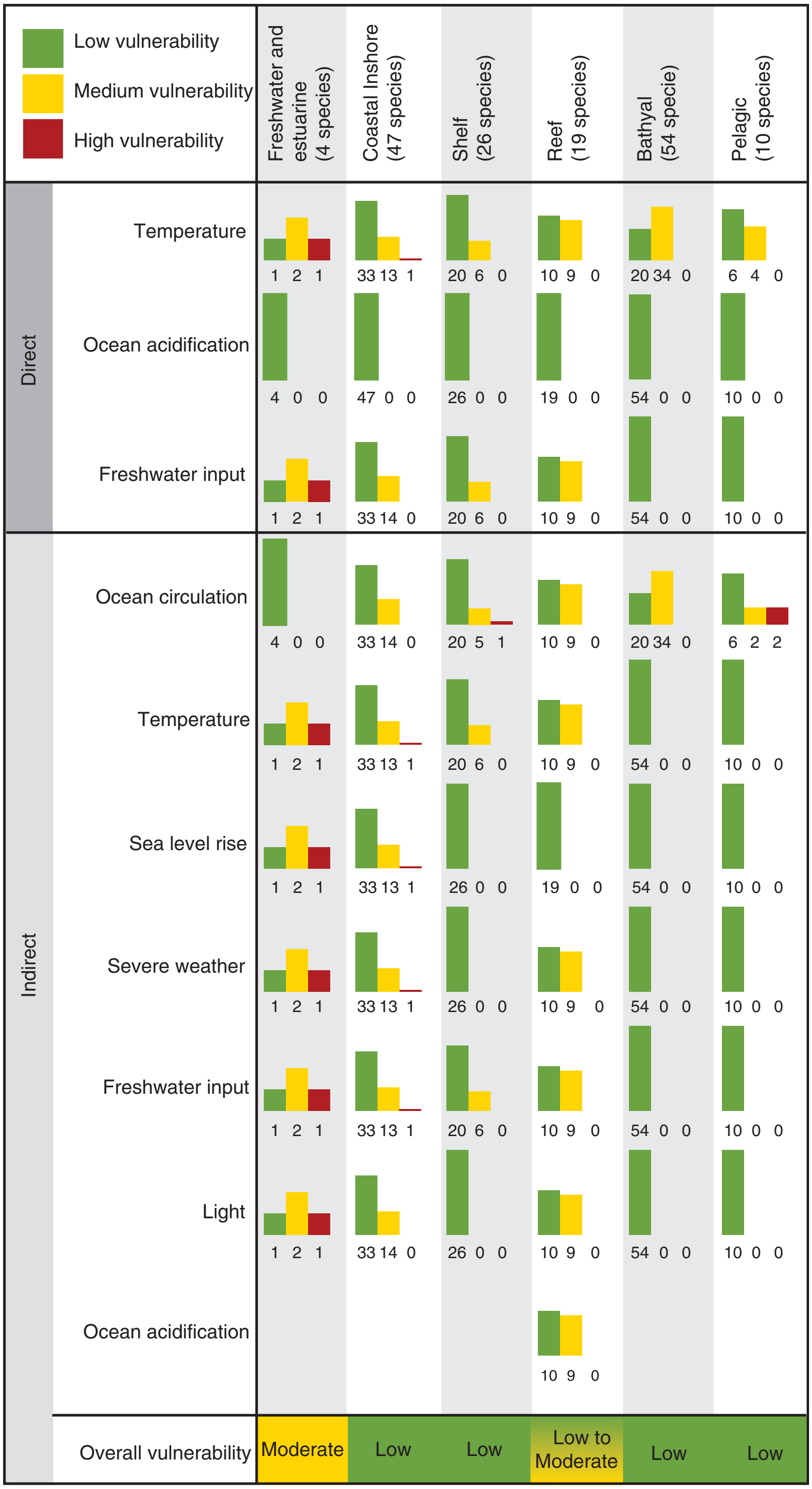


Fig. 4 Vulnerability of GBR sharks and rays in each ecological group to direct and indirect climate change factors.

tended to be rarer, less mobile and more specialized. The porcupine ray *U. asperrimus* had high vulnerability due to its rarity and immobility, and is one of the two GBR sharks and rays assessed as highly vulnerable.

Species in the shelf ecological group had low to moderate exposure to climate change factors with temperature, ocean circulation and freshwater input being the most significant climate change factors (Fig. 3).

Approximately one third of species in this group had moderate vulnerability including the angelsharks (Squatinidae), stingarees (Urolophidae), houndsharks (Triakidae) and the white shark *Carcharodon carcharias* (Table 3). These species tended to have moderate to high rarity, immobility or limited latitudinal range. Less vulnerable species in the group included the whaler sharks, weasel sharks (Hemigaleidae) and hammerhead sharks (Sphyrnidae). These species are more abundant and widespread, occur in a variety of habitats and feed on a wider range of prey.

Sharks and rays in the bathyal ecological group had low overall vulnerability (Fig. 4). While many of these species are believed to be relatively rare and moderately immobile, they had relatively low exposure compared with other ecological groups and many are also thought to be ecologically flexible (low specialization). While their low exposure combined with low to moderate rigidity greatly reduced their vulnerability, little is known about the biology and ecology of these species.

The species in the pelagic ecological group also had low vulnerability (Fig. 4). Exposure of pelagic sharks and rays to climate change occurs primarily through ocean circulation and temperature changes (Fig. 3). The manta ray/devilrays (Mobulidae) and whale shark *R. typus* are potentially the most vulnerable species in this group as they are plankton feeding specialists, and the whale shark and bentfin devilray *Mobula thurstoni* are relatively rare. However, these species have low exposure to most climate change factors so are ranked as having low overall vulnerability to climate change. All species in this group have low habitat specificity and low rigidity with the exception of plankton feeding specialists. The low exposure and rigidity give this group an overall ranking of low vulnerability to climate change (Fig. 4).

Discussion

Applying the IRACC

The number and diversity of published works on climate change in the marine environment has significantly increased since the early 1990s. While many publications include vulnerability assessments, these are usually focused on the interaction between single climate change variables and single habitats, species, or species groups (Harley *et al*., 2006). More recent assessments consider the interactions between multiple variables (e.g. Hobday *et al*., 2006; Poloczanska *et al*., 2007). Likewise, the IRACC integrates multiple climate change factors, ecosystem linkages, vulnerability components, as well as the biological and ecological attributes of the species being assessed. This approach has numerous advantages. Integrating multiple variables provides a more comprehensive account of the vulnerability of a system to climate change. Secondly, because the IRACC produces a separate assessment for each species, managers can identify the species at highest relative risk which will help to prioritize management responses (NRMMC, 2004). This approach also reduces potential errors arising from grouped assessments that use aggregated data which may mask significant impacts. For example, risk assessments using grouped data masked significant changes in the population structure of skates in the Northeast Atlantic, including dramatic declines of three large skate species (Dulvy *et al*., 2000). While some species groups are too numerous or diverse to assess as individual species, the IRACC can be scaled to an appropriate taxonomic level by selecting appropriate ecological groups and attributes to use in the assessment. The IRACC also allows specific interactions between species, vulnerability components and attributes to be explored. For example, while freshwater/estuarine sharks and rays were identified as being amongst those species most vulnerable to climate change, one species in this group, the bull shark, was assessed as having low vulnerability. Analysing the attribute rankings revealed that the vulnerable freshwater/estuarine sharks and rays were more at risk due to their rarity and specialization, suggesting that for these species, management responses should focus on addressing pressures that affect their abundance, habitats and prey availability. Lastly, the IRACC accommodates a range of data types and differing levels of uncertainty. The certainties of predicted climate change outcomes were clearly identified and considered in ranking exposure, and the framework accommodated uncertainty about GBR sharks and rays by allowing expert judgements based on a range of data including published, unpublished and proxy data. Additionally, where data were highly uncertain, the assessment was able to cope with these data by applying the precautionary approaches used in fisheries ERAs (Milton, 2001; Stobutzki *et al*., 2001, 2002; Walker, 2005; Hobday *et al*., 2007). Importantly, this did not arbitrarily increase the number of species assessed as high risk. The framework's logic structure is inherently conservative as it is unlikely that all three components for all ten climate change factors would be ranked as high due to uncertainty, and the assessment only produces a ranking of high vulnerability if the exposure, sensitivity *and* rigidity are high (see Fig. 2 and supporting information, Table S2).

The simplicity and flexibility of the IRACC should make it transferable to other contexts. Using the same process (Fig. 1), this framework could be applied to different ecosystems to assess the vulnerability of different species groups. The IRACC structure also allows transparency and review. Species assessments can be recorded in tables that clearly show the rankings of each attribute and vulnerability component for each species to each climate change factor. This documents how vulnerability was derived for every species assessed and can facilitate the involvement of stakeholders in the assessment process, potentially improving management outcomes (Fletcher, 2005). Such assessments can also be easily peer reviewed and updated as new information becomes available (e.g. Griffiths *et al*., 2006).

The vulnerability of GBR sharks and rays

The assessment identified 30 of the 133 GBR shark and ray species as moderately or highly vulnerable to climate change. Many of these species have relatively high rankings of rarity and specialization, and the two most vulnerable species of GBR sharks and ray (freshwater stingray *H. dalyensis* and porcupine ray *U. asperrimus*) are both relatively rare and have relatively high habitat dependency or trophic specificity. Rarity and specialization are recognized as increasing the extinction risk of species (Davies *et al*., 2004), and increasing the vulnerability of reef fishes and birds to climate change (Julliard *et al*., 2004; Munday, 2004). The IUCN also proposes that these attributes should be considered when assessing climate change risks to species (Foden *et al*., 2008). However, in this assessment rarity and specialization do not automatically confer vulnerability as there are rare and specialized GBR sharks and rays that were not assessed as vulnerable to climate change. While the significance of rarity and specialization is intriguing, testing the veracity of these relationships will require further analyses. At present, this assessment suggests that the vulnerability of a shark or ray species depends on the specific combination of its components and attributes, and there does not appear to be a single component or attribute that universally imparts vulnerability or resilience to climate change factors.

While species vulnerability is case specific, the assessment does suggest that the indirect climate change factors of temperature, freshwater input and ocean circulation could have the greatest effects on GBR sharks and rays, and that sea level rise may be especially significant to the freshwater/estuarine and coastal/inshore groups. Collectively these factors may affect the ecological services provided by habitats and processes. Many sharks and rays have strong habitat dependencies; seagrass beds, mangroves and other estuarine habitats are important breeding, nursery or foraging grounds for many species (Heupel & Hueter, 2002; Simpfendorfer & Heupel, 2004; Heupel *et al*., 2007). Some species repeatedly return to the same habitats and locations to mate, give birth or feed (Hueter *et al*., 2005), and sharks and rays may also rely on specific habitats at critical stages of their life history. Furthermore, these habitats are also important for prey species such as fishes, crustaceans, marine turtles and marine mammals (Cappo *et al*., 1998; Carruthers *et al*., 2002; Nagelkerken *et al*., 2008) and degradation of these habitats may affect prey availability. Declines in coral reefs may significantly affect reef teleosts which are important prey for reef sharks (Munday, 2004; Bellwood *et al*., 2006; Munday *et al*., 2008). The impacts of habitat degradation may be further compounded by interhabitat linkages. For example, the abundance and diversity of reef fishes has been linked to the presence of coastal mangroves (Mumby *et al*., 2004) and thus, loss or degradation of coastal habitats may affect prey availability for sharks and rays outside coastal areas. Biological productivity and nutrient cycling are closely linked to photosynthesis, the activity of microbial communities, and physical processes such as freshwater runoff and currents (Staunton-Smith *et al*., 2004; Clark, 2006; Kingsford & Welch, 2007; Sheaves *et al*., 2007; Webster & Hill, 2007). Changes in coastal vegetation and microbial communities, or in the timing of rainfall events could alter biological productivity and ultimately prey availability. In bathyal and pelagic systems, productivity is linked to currents and upwellings of nutrient rich water. Changes in El Niño and La Niña cycles will have significant effects on biological productivity and prey availability (Kingsford & Welch, 2007).

For many species, their exposure to these climate change factors is ameliorated by low sensitivity and rigidity. However, there are many knowledge gaps and this assessment applies several assumptions and considerations that should be recognized. One key assumption involves mobility. Many sharks and rays are highly mobile which has decreased their rigidity in this assessment. Indeed, climate related range shifts and altered distribution patterns have already been observed and in some cases, have been beneficial to sharks by facilitating range expansions. Perry *et al*. (2005) documented a shift in mean depth of the cuckoo ray *Leucoraja naevus*, with the species moving into deeper water as a response to ocean warming. Stebbing *et al*. (2002) linked warming of the North Atlantic with the immigration of warmer-water species to the Cornish coast of England, including the first record of the sharpnose sevengill shark *Heptranchias perlo* for the British Isles, and the first record of the tropical to warm-temperate bigeye thresher *Alopias superciliosus* for Cornwall. However, mobility assumes that individuals will be able to locate, move to and establish viable populations in new areas and this assumption should be treated with caution. Alternative habitats may not be available. Coral reefs have narrow environmental tolerances and these environments around the world are considered especially at risk to localized pressures, climate change and emerging threats such as ocean acidification (Hoegh-Guldberg *et al*., 2007; Carpenter *et al*., 2008; Veron, 2008). Global degradation of reef habitats could mean that mobile reef sharks may not be able to locate viable alterative habitats. Even if suitable refugia can be reached, they may be unavailable if competition or predation prevents the species from establishing a viable population. Some shark populations have been found to be close to limits of resource availability (Duncan & Holland, 2006) and both immigrants and residents may be unable to cope with increased competition. In these instances this assessment will have overestimated adaptive capacity.

Some pelagic sharks and rays are highly migratory and may travel between oceans to exploit seasonal productivity events and 'hot spots' (see Camhi *et al*., 2008 for review). Temperature has been correlated with seasonal aggregations of whale sharks *R. typus* off Western Australia and the abundance of basking sharks *Cetorhinus maximus* off southwest Britain (Wilson *et al*., 2001; Cotton *et al*., 2005). These seasonal and oceanographic events may be significantly affected by global climate change, and exposure of highly migratory species may be magnified as they may encounter multiple changes in multiple locations outside of the GBR. Additionally, climate related changes in timing (phenology) or magnitude of seasonal patterns may have dramatic impacts on migratory species, as illustrated by reproductive failures in seabird populations in the southern GBR (Smithers *et al*., 2003). Stewart & Wilson (2005) suggested that amongst the greatest threats to *R. typus* are coral bleaching events, which are related to increasing water temperatures and rapid climate change. In this case, the assessment may have underestimated exposure for these species.

Another assumption is that all the climate change factors and vulnerability components have equal significance to all GBR sharks and rays. For example, changes in ocean circulation are as significant as changes in temperature, and exposure is as significant as adaptive capacity. While this is highly unlikely, there is simply not enough information on the biology and ecology of GBR sharks and the functioning of these processes and habitat to assess the relative importance of these variables to different species. Further information about habitat dependencies and ecological processes, and the response of these habitats and processes to climate change, could allow factors and components to be weighted according to their significance. This approach has been used in fisheries assessments (Stobutzki *et al*., 2001) and could be applied to future applications of this framework once this information becomes available.

There are no data on the potential long-term effects of physiological changes resulting from climate change factors. While many sharks are able to tolerate a range of conditions (Fangue & Bennett, 2003; Carlson *et al*., 2004; Stensløkken *et al*., 2004; Pillans *et al*., 2005), the ramifications of increased energy costs to maintain homeostasis are unknown, as are physiological thresholds and capacity to cope with prolonged changes. Increasing temperature may be beneficial in some cases by increasing growth rates. Behavioural thermoregulation has been observed or suggested in leopard shark *Triakis semifasciata*, round stingray *Urobatis halleri* and bat ray *Myliobatis californica* with animals aggregating or moving into warmer water, potentially to optimize metabolic and physiological processes including reproduction (Matern *et al*., 2000; Hoisington & Lowe, 2005; Hight & Lowe, 2007). The effects of climate changes on the physiology of chondrichthyan fishes warrants further attention.

Interactions with other factors

Climate change does not occur in isolation and other pressures such as coastal development and fishing may increase the vulnerability of marine species (Poulard & Blanchard, 2005; Harley *et al*., 2006). Sharks and rays are particularly sensitive to intensive pressures due to their life history traits (Cortés, 2000) and there are many examples of overfished and collapsed shark populations (Camhi *et al*., 1998; Dulvy *et al*., 2000; Dulvy *et al*., 2008; Simpfendorfer, 2000). While there is little information on the status of GBR sharks, the available data suggest that some level of decline has occurred in some reef sharks (Robbins *et al*., 2006; Heupel *et al*., 2009). Commercial shark fishing in the GBR is targeted at coastal and inshore species and the fishery has recorded significant increases in landings since the late 1990s. However, the status of these species and the sustainability of current fishing levels are not known (Chin, 2005). These knowledge gaps need to be addressed to ensure sustainability of the fishery, let alone to assess how GBR fisheries affect the vulnerability of sharks and rays to climate change.

Coastal habitats on the GBR are under increasing pressure. Coastal development such as expansion of residential areas, aquaculture, agriculture, ports, and associated infrastructure (roads, causeways), has led to significant changes in coastal areas. Impacts arise from land clearing, reclamation, altered hydrology, and the input of pollutants such as pesticides and nutrients that can disrupt marine ecosystems (Haynes & Michalek-Wagner, 2000; Hutchings *et al*., 2005). Habitat loss is a significant threat to sharks and rays worldwide (Stevens *et al*., 2005) and further losses and degradation of these habitats in the GBR are likely to increase the vulnerability of sharks and rays to climate change.

Additionally, climate change may initiate human responses that increase these impacts. While the potential responses of GBR coastal communities are not well understood (Fenton *et al*., 2007), rising sea levels and greater variability in rainfall could prompt the construction of more dams and weirs, levees, sea walls and flood barriers, and possibly desalination plants. While this is speculative, such structures already exist in Queensland's coastal communities, and new dams and desalination plants are currently being considered. These structures could further disrupt hydrology and connectivity of coastal habitats and the timing and volume of freshwater flows. They may also create physical barriers that reduce the ability of coastal species to colonize suitable areas inland, leading to the loss of species and habitat assemblages with increasing sea levels (Waycott *et al*., 2007). Collectively, new structures could have significant impacts on ecological processes, biological connectivity and habitat quality, increasing pressure on sharks and rays along the GBR coast.

The synergistic effects of fishing and habitat loss are most likely to affect freshwater/estuarine, and coastal/inshore sharks and rays. Freshwater sharks and rays are generally at risk around the world due to their restricted distribution, their proximity to human pressures and the extent of human disturbance to these habitats (Last, 2002). Three of the four freshwater/estuarine sharks and rays in the GBR region are listed as threatened (IUCN, 2008). The coastal/inshore sharks are the most heavily exploited group of sharks and rays in the GBR by commercial fisheries. Uncertainty about the sustainability of current harvest levels, coupled with pressures from habitat loss, compounds the risk to these species. Taking these synergistic effects into account, we propose that that freshwater/estuarine species should be considered *highly vulnerable* to climate change, and that affected coastal/inshore species should be considered as *moderately vulnerable* to climate change.

Within the GBR, the vulnerability of these groups is likely to be expressed through changes in species distribution and abundance. Some sharks and rays may become rarer or even locally extinct as they alter their distribution in response to changing conditions. In extreme cases, rare and threatened species may even be extirpated from the GBR if they are unable to cope with the rate or magnitude of change. If this is the case, then these changes would be broadly consistent with those predicted for tropical marine systems (Cheung *et al*., 2009). However, it is difficult to identify how these changes might affect the wider GBR ecosystem. Functional roles vacated by extirpated sharks and rays may be effectively filled by other species. Then again, these losses could trigger significant changes in trophic structures with unpredictable outcomes (Stevens *et al*., 2000; Heithaus *et al*., 2008). Until more is known about the ecology of sharks and rays and their functional roles in the GBR, the effects of such changes are difficult to predict with any certainty.

Conclusions

The IRACC was successfully applied to assess the vulnerability of GBR sharks and rays. While the method has limitations, the framework allowed diverse and data poor species to be assessed, and provides a foundation for further research and the development of informed management responses. The IRACC identified that the freshwater/estuarine, coastal/inshore, and reef associated sharks and rays of the GBR are at highest risk to climate change. The process also revealed that vulnerability arises from many factors as well as the interactions between them. Accordingly, reducing the impacts of climate change on GBR sharks and rays requires numerous approaches. As some attributes such as a species' trophic specificity cannot be altered, management efforts should be focused on aspects of vulnerability that can realistically be addressed. Firstly, the habitats and ecological processes that sustain at risk species and species groups must be protected to maximize their resilience. In the GBR, this means protecting and preserving catchments and coastal habitats including riparian vegetation, seagrasses, mangroves and salt marsh, coastal foreshores and intertidal areas from pressures such as coastal development, pollution, eutrophication and disruption of water flows. Secondly, additional pressures such as fishing must be addressed to ensure that these activities are sustainable. Fisheries risk assessments and management plans should explicitly consider climate change impacts, and targeted research should be carried out on key sharks and rays to inform management decisions and assess sustainability. Thirdly, at risk species should be considered for specific conservation actions, particularly as many of these species are already at high risk from other factors. Fourthly, more information is needed about the biology and ecology of GBR sharks and rays, and of the ecological processes and habitats of the shelf, pelagic and bathyal habitat zones of the GBR. This is especially the case for pelagic and bathyal species, as well as highly migratory species that may encounter multiple, cumulative pressures throughout their range. Lastly, the core activities and processes driving human induced climate change must be addressed to reduce overall exposure to all climate change factors. Failure to adequately mitigate climate change will escalate risks to all species and increase the costs of addressing resilience issues while at the same time, making it harder for such initiatives to succeed.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Predicted outcomes and likely impacts on Great Barrier Reef (GBR) sharks and rays arising from climate change factors.
Table S2. Basis of the component integration matrix to determine species vulnerability.
Table S3. Species list, ecological groupings and vulnerability of Great Barrier Reef sharks and rays (sorted by vulnerability and then by phylogeny).
Table S4. Exposure of each ecological group to direct (physiological) and indirect (large-scale) climate change factors. Exposure (as a component of vulnerability) assessed as low (L), moderate (M) or high (H).