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Climate change scenarios in fisheries and aquatic conservation research

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Scenarios are central to fisheries and aquatic conservation research on climate change. Scenarios project future greenhouse-gas emissions, which climate models translate into warming projections. Recent climate research and global development trends have significantly changed our understanding of plausible emissions pathways to 2100 and climate sensitivities to emissions. Here, we review these developments and make recommendations for scenario use in fisheries and aquatic conservation research. Although emissions pathways are uncertain, recent research suggests that scenarios producing ~3.4–4.5 W/m^2 radiative forcing by 2100 (e.g. scenarios SSP2-3.4 and SSP2-4.5/RCP4.5) might be most plausible. This corresponds to ~2–3 degrees C global warming by 2100 with median climate sensitivities, or 1.5–4 degrees C considering climate-system uncertainties. Higher- and lower-emissions scenarios (e.g. RCP2.6 and RCP6.0) might be plausible and should be explored in research. However, high-emission scenarios (RCP8.5/SSP5-8.5, SSP3-7.0) seem implausible and should be used with clear rationales and caveats to ensure results are not misinterpreted by scholars, policymakers, and media. We analyse fisheries and aquatic conservation papers published from 2015 to 2022 in major journals, and find that RCP8.5/SSP5-8.5 are the most commonly used scenarios, though RCP4.5/SSP2-4.5 use has increased since 2020. Studies predominantly project quantitative rather than qualitative differences between these scenarios' impacts.

Keywords: climate change, mitigation, representative concentration pathways, scenarios, shared socioeconomic pathways, species on the move.

Introduction

Scenarios are central to climate change research, including in fisheries and aquatic conservation. Climate change scenarios explore hypothetical future trajectories of radiative climate forcing, and underlying trajectories of greenhouse-gas (GHG) emissions (van Vuuren *et al.*, 2011; Riahi *et al.*, 2017; IPCC, 2021). Climate models then convert these trajectories into projections of warming (Sherwood *et al.*, 2020; IPCC, 2021, 2022a,b).

Key climate change questions in fisheries and aquatic conservation research require projections of plausible climate forcing—and therefore, scenarios—as an input. Such questions include: will species evolve to cope with climate change (e.g. Eliason *et al.*, 2011; Crozier and Hutchings, 2014)? To where and how far will species shift their geographic ranges as climates change (e.g. Cheung *et al.*, 2010; Pinsky *et al.*, 2013; García Molinos *et al.*, 2016; Pecl *et al.*, 2017)? How will warming and species shifts associated with it impact trophic dynamics and food webs (e.g. Lotze *et al.*, 2019; Inagaki *et al.*, 2020; Nagelkerken *et al.*, 2020; Thorpe *et al.*, 2022)? How will climate change affect ocean currents (e.g. Hu *et al.*, 2020) and regional climates (e.g. Pershing *et al.*, 2015)? How will ocean acidification progress and what will its impacts be (e.g. Fabry *et al.*, 2008; Guinotte *et al.*, 2008; Sunday *et al.*, 2017)? Which coral reefs will survive this century (e.g. Hughes *et al.*, 2018, 2019)? How might climate change interact with other human pressures on aquatic species and ecosystems (e.g. Brander, 2007; Gaines *et al.*, 2018; Cheung *et al.*, 2021)? The answers to these questions have profound ramifications for ecosystems, coastal communities, and fisheries management.

The appropriate use of scenarios has recently become the topic of major controversy in climate and energy science. The debate surrounds whether some widely used high-emission scenarios are realistic or plausible and, if not, whether they are being used by researchers and communicated to the public in appropriate and scientifically defensible ways (see, e.g. Hausfather and Peters, 2020a,b; Schwalm *et al.*, 2020a,b; Field *et al.*, 2021; Burgess *et al.*, 2021a, 2022a; Pielke and Ritchie, 2021a,b). (Here, "high-emission," "low-emission," etc. refers to scenarios' net emissions, inclusive of sequestration.) Moreover, in the years between the last (Fifth) Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5; IPCC, 2014) and the Sixth Assessment Report (AR6; IPCC, 2021, 2022a,b), there have also been significant changes to our understanding of climate sensitivities (Sherwood *et al.*, 2020; IPCC, 2021) as well as near-term energy (e.g. IEA, 2021; Way *et al.*, 2021) and economic outlooks (e.g. see Burgess *et al.*, 2021b for review), due to the COVID-19 pandemic (e.g. Le Quéré *et al.*, 2020, 2021) as well as a variety of other pre-existing factors.

Here, we review these updates to our understanding of emissions and climate futures; and we review debates surrounding scenario use and recommend best practices for fisheries and aquatic conservation research. Our review is or-

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Table 1. Key assumptions of the SSP scenarios, based on table 2 of Riahi *et al.* (2017).

SSP1	**"Sustainability": Low challenges to mitigation and adaptation** Key Assumptions: The world displays a commitment to achieving sustainable development goals. This causes relatively fast economic growth and income convergence (causing low challenges to adaptation), and makes economies relatively less consumption and energy intensive, meaning that transitioning to low-carbon economy is relatively cheap (causing low challenges to mitigation).
SSP2	**"Middle of the Road": Medium challenges to mitigation and adaptation** Key Assumptions: Historical social, economic, and technological trends continue. Economic growth and income convergence proceed at an intermediate pace, relative to the range of expert opinion (causing medium challenges to adaptation). Economies' consumption and energy intensities decrease, but not as quickly as in SSP1 (causing medium challenges to mitigation).
SSP3	**"Regional Rivalry": High challenges to mitigation and adaptation** Key Assumptions: For various reasons related to competition and security, countries retreat from globalization and global cooperation, and focus on domestic or regional development and security. As a result, economic growth and income convergence are both relatively slow (causing high challenges to adaptation), and there is both relatively little prioritization of environmental goals and global cooperation towards those goals, leading to relatively consumption- and energy-intensive economies (causing high challenges to mitigation).
SSP4	**"Inequality": Low challenges to mitigation, high challenges to adaptation** Key Assumptions: Relatively fast economic growth in high-income countries combines with relatively slow economic growth in low-income countries to produce high inequality. Fast growth in high-tech sectors contributes to relatively low mitigation challenges, but slow growth in low-income countries produces high challenges to adaptation.
SSP5	**"Fossil-fueled Development": High challenges to mitigation, low challenges to adaptation** Key Assumptions: The world goes all-in on economic growth and open markets, and succeeds in producing fast economic growth and income convergence (causing low challenges to adaptation). Yet, the focus on open-market growth also produces high energy demands throughout the world (causing high challenges to mitigation).

ganized as follows. First, we provide a brief overview of the major scenarios used in climate change research. Second, we summarize the debate surrounding the use of high-emission scenarios. Third, we analyze scenario use in the 2015–2022 papers of four major fisheries and aquatic conservation journals, and five major generalist journals. Our analysis suggests that fisheries and aquatic conservation research often uses high-emission scenarios in ways being debated in climate and energy science. Fourth, we review emerging perspectives on plausible emissions and climate futures for the 21st century, aiming to provide a balanced representation of trends, uncertainties, and differing viewpoints. Fifth, we explore differences between projected impacts of high-emission scenarios and the potentially more plausible moderate-emission scenarios, using case studies and the papers we reviewed from the nine major journals. Sixth, we discuss other considerations (besides plausibility) that might influence scenario choice, some of which may justify the use of high-emission scenarios in certain contexts. Last, we bring all of these threads together to recommend best practices for climate change scenario use in future fisheries and aquatic conservation research.

The representative concentration pathway (RCP) and shared socioeconomic pathway (SSP) scenarios

The most commonly used scenarios and pathways in fisheries and aquatic ecology—as in most climate research—are the RCPs (Van Vuuren *et al.*, 2011), which are central to the IPCC's Fifth Assessment Report (AR5) (IPCC, 2014), and the more recent SSPs (Riahi *et al.*, 2017), which are central to the Sixth Assessment Report (AR6) (IPCC, 2021, 2022a,b).

The RCPs are pathways of radiative forcing derived from four "marker" scenarios from the IPCC AR5 database of >1 100 emissions scenarios (IPCC WGIII, 2014). The RCPs lead to radiative forcing in 2 100 of 2.6 W/m^2 (RCP2.6), 4.5 W/m^2 (RCP4.5), 6.0 W/m^2 (RCP6.0), and 8.5 W/m^2 (RCP8.5), respectively (van Vuuren *et al.*, 2011). Higher emissions lead to more forcing, and more forcing leads to more warming, all else equal. Thus, the higher-forcing RCP scenarios derive from higher-emission socioeconomic scenarios, and produce greater warming in climate models with equivalent climate sensitivities.

The SSPs define five socioeconomic "storylines" (Riahi *et al.*, 2017; Table 1) varying in mitigation and adaptation challenges (Figure 1a,b; Figure 1a is based on figure 1 in O'Neill et al., 2014), discussed below, from which 127 scenarios are derived (IIASA, 2018). SSP scenarios are labeled according to their socioeconomic storyline (e.g. SSP1) and their (though not exact) ~2100 radiative forcing level (IIASA, 2018). For example, SSP1-1.9 is a scenario having the SSP1 storyline and reaching ~1.9 W/m^2 radiative forcing by 2 100. There are seven SSP marker scenarios—four having analogous forcing to the RCP marker scenarios (SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5), plus three with additional 2100 forcing levels: SSP1-1.9, SSP2-3.4, and SSP3-7.0 (Figure 2a; Riahi *et al.*, 2017). The SSP pathways are meant to be updates to the RCP pathways, providing socioeconomic pathways that use more up-to-date assumptions but produce similar forcing pathways as the RCPs (plus the three additional marker pathways) (Riahi *et al.*, 2017).

Climate models, such as those of the Coupled Model Intercomparison Project (CMIP), project warming from forcing scenarios. Impact studies then project impacts from these warming projections (e.g. see IPCC, 2014, 2021, 2022a). Uncertainties in the climate system mean that a range of warming levels is possible for any given forcing pathway. This uncertainty comes both from uncertainty in climate sensitivity to forcing (IPCC, 2021), and from uncertainties in the potential for climate-system feedbacks—e.g. the released methane from melting permafrost amplifying existing warming (Sherwood *et al.*, 2020; IPCC, 2021). Figure 2b shows the ranges of warming (2081–2100, compared to the pre-Industrial, 1850–1900, baseline) the IPCC's (2021) AR6 associates with five of the

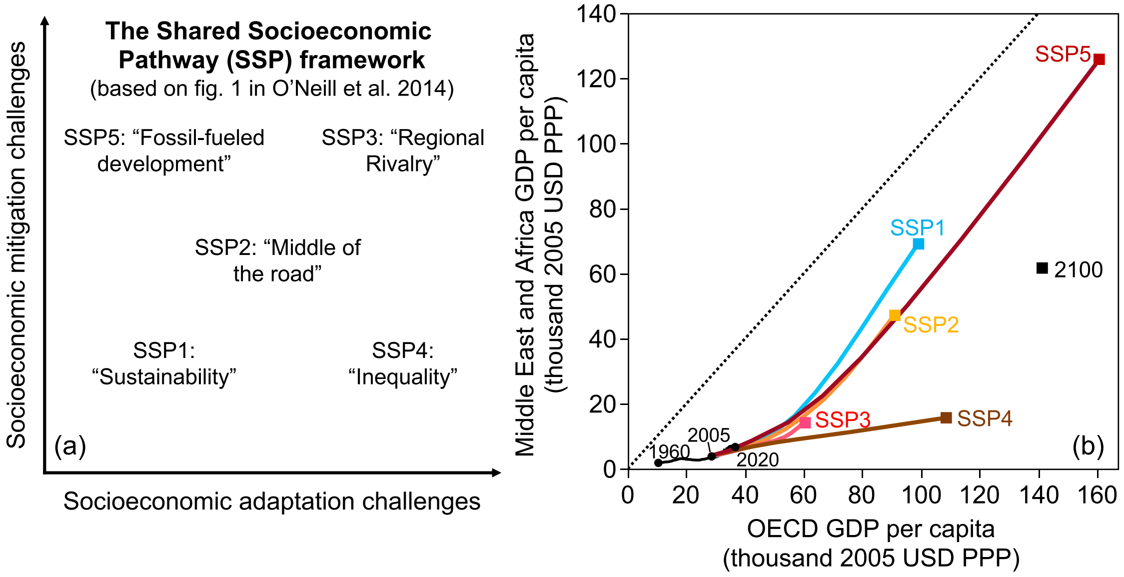

Figure 1. Panel a (based on figure 1 of O'Neill et al., 2014) illustrates how the SSP storylines vary according to mitigation and adaptation challenges. Panel b shows how the SSP storylines' variation in adaptation challenges manifests as different projections of GDP per capita trends (in purchasing-power-parity, PPP, units), in the Organization for Economic Co-operation and Development (OECD) countries (1990 members) and in the Middle East and Africa, throughout the 21st century. (These are the richest and poorest regional groupings in the SSP regional classification scheme; IIASA, 2018). Projection data come from IIASA (2018), using the marker scenarios within each storyline. Historical data come from Roser (2021). The dashed line is the 1:1, 45-degree line.

SSP marker scenarios (not including SSP2-3.4 and SSP4-6.0, which were not prioritized by CMIP6 (Eyring *et al.*, 2016) nor consequently used in AR6's Working Group I and II reports): from 1–1.8°C warming in SSP1-1.9 to 3.3–5.7°C warming in SSP5-8.5.

Focusing on the SSPs (since they are newer and reflect updated socioeconomic assumptions), the emissions level in a particular scenario arises, broadly speaking, from the mitigation and adaptation challenges assumed by the SSP storyline, in combination with the mitigation effort assumed by the specific scenario. Thus, within each of the five SSP storylines, there are scenarios that produce a wide range of emissions and consequent radiative forcing, but these ranges differ across storylines (Figure 2c; IIASA, 2018). Within each storyline, "baseline" scenarios are scenarios that assume no climate policy aimed at mitigation exists at all (including policies that already exist in the real world), and consequently baseline scenarios project the highest possible emissions within the given storyline (Figure 2c; see Riahi *et al.*, 2017; Pielke and Ritchie, 2021a).

Differences among SSPs in adaptation challenges are reflected in their contrasting projections of economic growth and economic inequality. Historically, affluence [measured as gross domestic product (GDP) per capita] has been a key determinant of resilience to climate and weather extremes (Kahn, 2005). Affluence in developing regions is an especially important determinant of adaptation, as these regions are disproportionately vulnerable to climate impacts (IPCC, 2022a). Figure 1b compares the SSPs' projections of 21st-century GDP per capita in the richest regional grouping (the OECD countries, using their 1990 membership; see IIASA, 2018) and the poorest regional grouping (the Middle East and Africa) in the IPCC/IIASA classification (IIASA, 2018). SSPs with high "challenges to adaptation" (SSP3, SSP4) (Figure 1a) project relatively slow economic growth, especially in poorer regions (which makes adaptation more challenging) (Figure 1b, Table 1; see also Dellink et al., (2017), and Riahi *et al.*, (2017)). Conversely, SSPs with low challenges to adaptation (SSP1, SSP5) project relatively high economic growth and high convergence between poor and rich countries. SSP2 is intermediate ("middle of the road") (Riahi *et al.*, 2017; Table 1).

Differences among SSPs in mitigation challenges affect how economically and sociopolitically feasible they assume emissions reductions and energy transitions will be, and consequently how much emissions reduction can be achieved at a given mitigation effort (Riahi *et al.*, 2017). SSP storylines with relatively low challenges to mitigation (SSP1, SSP4) assume relatively fast technological improvement and relatively less consumption- and energy-intensive economies (Riahi *et al.*, 2017; Table 1). SSP1 and SSP4 achieve greater emissions reductions, mitigation efforts being equal; and the converse is true for SSP3 and SSP5. SSP2 is again intermediate (Riahi *et al.*, 2017).

Intuitively, lesser mitigation efforts and greater challenges to mitigation result in higher emissions, all else equal (Figures 1a, 2c). Challenges to adaptation can affect projected emissions via GDP. All else equal, higher GDP means more energy demand and consequently greater emissions. This explains, for example, why SSP3-7.0 projects substantially lower emissions (and warming) than SSP5-8.5 (Figure 2a–c), even though both are baseline scenarios with high challenges to mitigation (Figures 1a, b). However, higher GDP per capita also comes with improved technology adoption, which contributes to, for instance, SSP4 baseline scenarios projecting greater emissions than SSP1 baseline scenarios (Figure 2c), despite SSP4 projecting lower GDP per capita in poorer regions (Figure 1b) and both storylines assuming low challenges to mitigation (Figure 1a).

The Working Group III contribution to AR6, released in April 2022 (IPCC, 2022b), introduces an expanded database

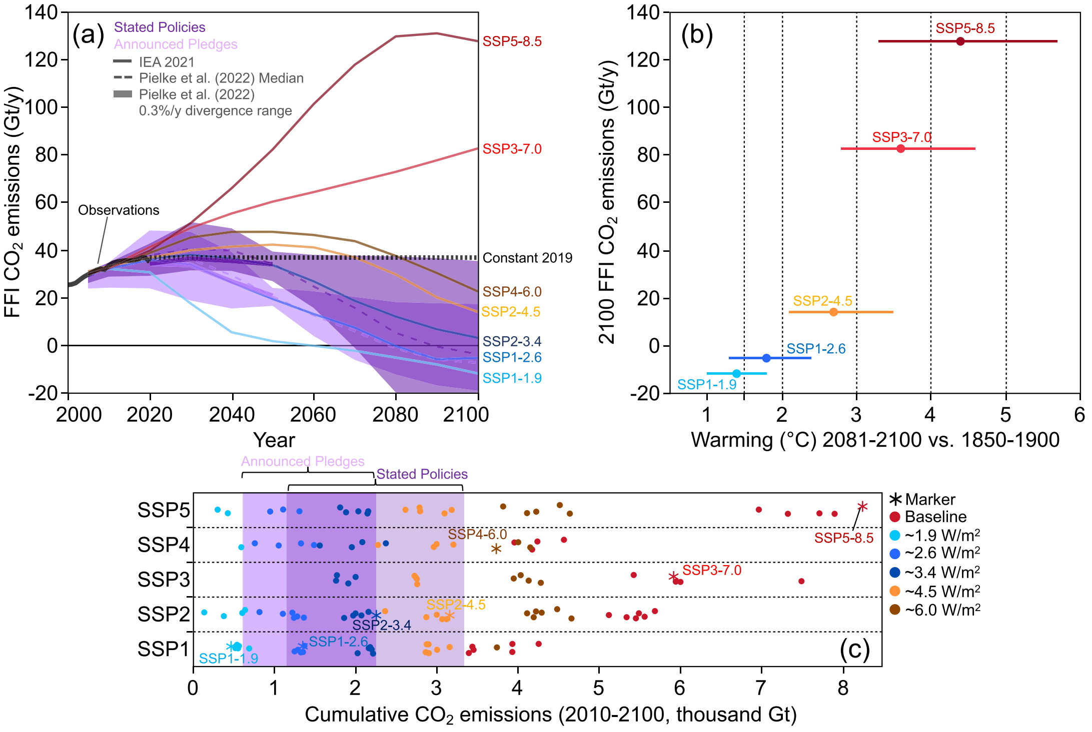

Figure 2. Panel a compares global fossil-fuel-and-industry (FFI) emissions trajectories in SSP marker scenarios (IIASA, 2018) to trajectories from: the International Energy Agency's (IEA) stated policies scenario (IEA, 2021) (dark purple, solid) and announced pledges scenario (light purple, solid); Pielke et al., (2022) ranges of AR5 (IPCC WGIII, 2014) and SSP (IIASA, 2018) scenarios with <0.3%/y emissions growth divergence from 2005–2050 from observations and IEA's stated policies (dark purple shaded region; dashed line indicates median) and announced pledges (light purple shaded region; dashed line indicates median) scenarios to 2050; and a hypothetical scenario with constant emissions post-2019 (black, dashed). Panel b shows the possible (5–95%) modeled warming ranges (2081–2100, relative to 1850–1900) from the IPCC's Sixth Assessment Report (AR6) (IPCC, 2021). Panel c shows the cumulative 2010–2100 emissions projected by each scenario within the SSP database (IIASA, 2018), grouped according to SSP storyline (rows), and color coded according to the 2100 forcing each is meant to correspond to (which is indicated in the database). The seven SSP marker scenarios are highlighted with asterisks. The ranges of cumulative emissions from AR5 (IPCC WGIII, 2014) and SSP (IIASA, 2018) scenarios from Pielke et al., (2022) consistent with the IEA's (2021) stated policies (purple shaded region) and announced pledges (pink shaded region) are shown.

of emissions scenarios including but not limited to the SSPs (IIASA, 2022), grouped into eight categories (C1-C8) according to their projected probabilities of resulting in various temperature increases, rather than their socioeconomic characteristics. This categorization has the advantage of emphasizing temperature—often most germane to impact studies (though not all impacts scale with temperature)—rather than specific socioeconomic assumptions. However, temperature projections are, of course, heavily influenced by socioeconomic assumptions, which determine emissions. Box SPM.1 Figure 1 in IPCC (2022b) shows the correspondence between the SSP marker scenarios and the C1–C8 categories.

The high-emission-scenarios (RCP8.5, SSP5-8.5, and SSP3-7.0) debate

Baseline scenarios—which include SSP5-8.5 and its 8.5 W/m² predecessor RCP8.5—have often been referred to as "business as usual" (BAU) scenarios in the literature, though this terminology has recently fallen out of favor (see Glossary in IPCC, 2021; see also Hausfather and Peters, 2020a; Pielke and Ritchie, 2021a), and some of the scenario architects did not intend them to be used as reference scenarios (e.g. van Vuuren *et al.*, 2012). Impact studies often focus on two marker scenarios—a higher-emissions one (often RCP8.5) and a lower-emissions one (e.g. RCP4.5 or RCP2.6), with the difference between these interpreted as benefits of mitigation or potential costs of inaction (e.g. as in Gattuso *et al.*, 2015; Thiault *et al.*, 2019, among many others). While this practice is intuitive, it should be noted that RCP creators advised against it:

> "The RCPs cannot be treated as a set with consistent internal logic. For example, RCP8.5 cannot be used as a no-climate-policy reference scenario for the other RCPs because RCP8.5's socioeconomic, technology, and biophysical assumptions differ from those of the other RCPs." (Moss *et al.*, 2010, p. 754).

The RCP8.5 scenario is widely used in climate impacts literature, in and beyond fisheries and aquatic conservation. For example, RCP8.5 was the most-often mentioned scenario, among the four RCP marker scenarios, in AR5 (IPCC, 2014) (34% of RCP mentions), in the most recent U.S. National Climate Assessment (USNCA) (U.S. Global Change Research Program, 2018) (57% of RCP mentions) (Pielke and Ritchie, 2021a), and (along with SSP5-8.5) in AR6's impacts report (53% of RCP or SSP mentions) (IPCC, 2022a) (Burgess *et al.*, 2022a). Climate impact projections based on RCP8.5 are also disproportionately reported by major news media, perhaps because they tend to be the most severe, and thus most attention-grabbing (Pielke and Ritchie, 2021a). RCP8.5 plays a role in U.S. fisheries and endangered species policy, as the National Marine Fisheries Service's (NMFS) benchmark scenario for determining threats to species under the Endangered Species Act (ESA) (NMFS, 2016). However, the incorporation of climate change in fisheries management more broadly is still relatively limited in most countries (see Bryndum-Buchholz *et al.* (2021) for review), and thus RCP8.5 does not have a major direct role in fisheries management globally.

The extent to which climate-impacts research has focused on high-emission scenarios (especially RCP8.5)—and the ways in which some studies interpret RCP8.5 (e.g. as BAU)—has recently become the subject of major controversy and debate in climate science. Several studies and commentaries have questioned the plausibility of assumptions in RCP8.5 and other high-emission scenarios, and have consequently criticized widespread use of RCP8.5 in climate research in general, and as BAU especially (Ritchie and Dowlatabadi, 2017; Grant *et al.*, 2020; Hausfather and Peters, 2020a,b; Burgess *et al.*, 2021a, 2022; Pielke & Ritchie 2021a,b). Others (e.g. O'Neill *et al.*, 2020) have suggested revisiting the assumptions of high-emission scenarios to better reflect recent developments in the energy system, without specifically criticizing past uses of these scenarios.

There have been two main critiques of high-emissions scenarios' plausibility. First, they project higher FFI emissions than have been recently observed, and substantially higher FFI emissions than the IEA's (and other major energy agencies') outlooks to mid-century project under BAU-like scenarios (Figure 2a; Hausfather and Peters, 2020a; Burgess *et al.*, 2021a; Pielke et al., 2022; see IEA, 2019, 2020, 2021, 2022). For instance, the IEA's (2021) Stated Policies scenario, which assumes that current policies continue, pledged policies are enacted to varying degrees, but no additional policies are introduced, and pledged targets are not necessarily met—projects 2050 FFI emissions that are only 40% of what SSP5-8.5 projects and 56% of what SSP3-7.0 projects (Figure 2a; IIASA, 2018). Second and relatedly, the high-emission scenarios project growth in demand for coal and other fossil fuels that is inconsistent with energy outlooks to even more extreme degrees, which some argue are highly implausible economically or possibly even physically (e.g. Ritchie and Dowlatabadi, 2017). For instance, while global coal use per capita is already declining, and the IEA (2021) projects it will nearly halve by 2050, SSP3-7.0 projects coal use per capita will more than double by 2100, RCP8.5 projects that it will more than triple, and SSP5-8.5 projects that it will increase by 6x (Figure 3a; see also Burgess *et al.*, 2021a). Indeed, even SSP2-4.5 and SSP2-3.4 project more coal use per capita in 2100 than the IEA (2021) projects under stated policies in 2050 (Figure 3a). Moreover, historically, the IEA has itself tended to over-project coal use and under-project renewable-energy growth, and thus has serially revised down its stated policies emissions projections from year to year (e.g. see Hausfather, 2020; Way *et al.*, 2021; Pielke *et al.*, 2022). If this trend continues, then the divergence between the high-emission scenarios and near-future emissions could be even greater than the divergence of these scenarios from IEA's (2021) stated policies projections.

The most widely cited defense of using RCP8.5 as a BAU-like reference scenario was published by Schwalm *et al.* (2020a). They argued that cumulative fossil-fuel emissions trajectories (which determine radiative forcing) in RCP8.5 are not yet off track from observations, and will not be off track from IEA's (2019) Current Policies and Stated Policies by a large enough margin by 2050 to render RCP8.5 obsolete as a reference scenario. (Current Policies was a scenario, discontinued by the IEA after 2019, that assumed only current policies continue, and no pledged policies or new policies are enacted; see IEA, 2019, 2020.) Schwalm *et al.* (2020a) projected that cumulative emissions consistent with these IEA scenarios by 2050 would be roughly halfway between RCP8.5 and RCP4.5 (see their figure 1). Looking to 2 100, Schwalm *et al.* (2020a) argued that RCP8.5 emissions were within the bounds of expert-elicitation-based projections and that uncertainties in climate sensitivity made the plausible warming ranges of RCP8.5 and current-policies-consistent scenarios substantially overlap (e.g. compare the ranges of possible warming from SSP2-4.5 and SSP5-8.5 in Figure 2b).

In a reply to Schwalm *et al.* (2020a), Hausfather and Peters (2020b) pointed out that key to Schwalm *et al.*'s (2020a) conclusion–that cumulative emissions under current policies to 2050 would be consistent with RCP8.5–was an assumption that land-use emissions will increase linearly in the future, linearly extrapolating an estimated 2005–2019 trend that global carbon budget's 2019 data (Friedlingstein *et al.*, 2019) appeared to show (Figure 3b). In contrast, all of the SSP scenarios assume land-use emissions will gradually decline throughout the 21st century, as land clearing slows, and restoration progresses in some regions (Hausfather and Peters, 2020b). Schwalm *et al.* (2020b) replied that this was a plausible assumption, given uncertainty in future land-use change (Figure 3b). Notably however, a 2021 revision to the global carbon budget's 2021 land-use emissions data (Friedlingstein *et al.*, 2021) now shows a recent declining 2005–2019 trend, rather than the increasing trend in their previous version of the data, on which Schwalm *et al.*'s (2020a) extrapolation was based (Figure 3b).

The economic assumptions of SSP5-8.5 have also been critiqued as implausible (Burgess *et al.*, 2021a). SSP5-8.5 projects GDP per capita of over 100 000 2005 USD in all world regions by 2100 (Figure 3c). In the SSP framework, growth must be this high for energy demand to reach 8.5 W/m^2, even in baseline scenarios with no climate policies and fossil-fuel dominated energy systems with rising coal demand (Figure 2c). (The AR5 scenario underlying RCP8.5 was able to reach 8.5 W/m^2 forcing with slower economic growth (IPCC, 2014), but refinements to integrated assessment model assumptions for the newer SSP framework made 8.5 W/m^2 forcing only possible in a single scenario–SSP5-8.5, and not in any other SSP storyline; as noted by Riahi *et al.*, (2017): "8.5 W/m^2 can only emerge under a relatively narrow range of circumstances" (p. 162).) Mora *et al.* (2017) project that the likely warming from RCP8.5 would make large parts of the tropics have deadly heat for more than 300 days per year (Figure 3d). Thus, SSP5-8.5 requires the world's most populous regions to be simultaneously rich and potentially unlivable, all the while doing absolutely nothing to curb their coal production or emissions. This does not make sense, nor is it socially plausible (as Burgess *et al.* (2021a) noted).

More broadly, recent economic growth has been lower than all of the SSPs projected (Figure 3e), even before the COVID-19 pandemic (Burgess *et al.*, 2021a), and many economists now argue for a slower long-run economic growth outlook than previously expected, due to aging populations, shifts from goods-based to service-based economies, countries such as China experiencing middle-income traps, and post-COVID retreats from globalization, among other factors (see Burgess *et al.* (2021b) for review). Economic forecasts have histori-

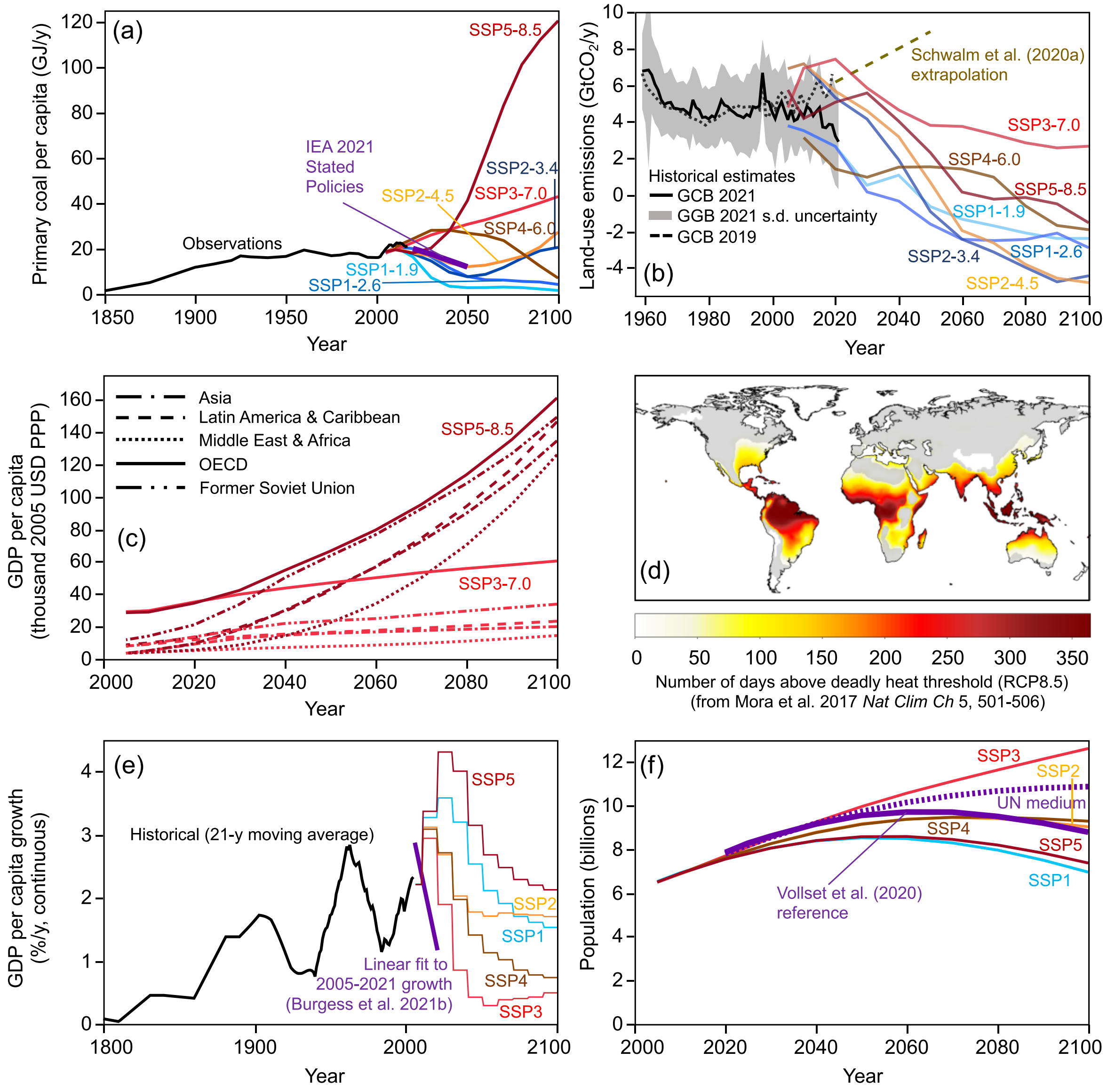

Figure 3. Panel a compares global coal consumption per capita from observations (Burgess *et al.*, 2021a), SSP marker scenarios (IIASA, 2018), and the IEA stated policies scenario (IEA, 2021; Pielke *et al.*, 2022). Panel b shows global land-use emissions [i.e. emissions from land-use and land-cover (LULC) change] trajectories in the SSP marker scenarios, compared to historical estimates from the 2021 global carbon budget (GCB; black and solid, with grey shaded region showing one-standard-deviation uncertainty) (Friedlingstein *et al.*, 2021), the 2019 GCB historical estimates (black, dashed) (Friedlingstein *et al.*, 2019), and Schwalm *et al.*'s (2020a) linear extrapolation of the 2005–2019 trend in the 2019 estimates (dark yellow, dashed). Panel c shows regional GDP-per-capita projections in SSP3-7.0 and SSP5-8.5 (IIASA, 2018). Panel d (reproduced, with permission, from Mora *et al.*, 2017) shows the number of days per year projected to exceed the deadly heat threshold in 2100 under RCP8.5 (Mora *et al.*, 2017). Panel e compares global historical GDP-per-capita growth and projections to 2100 in the SSP scenarios (IIASA, 2018; Burgess *et al.*, 2021b). Panel f compares global population projections to 2100 from the SSP scenarios (IIASA, 2018) to the United Nations (UN) Medium projection (UN, 2019) and Vollset *et al.*'s (2020) reference scenario.

cally tended to be biased high, especially in low-income countries (Frankel, 2011; Burgess *et al.*, 2020, 2021a). For world GDP per capita to reach SSP5 levels by 2100, global GDP per capita growth rates would need to nearly double the recent peak in the early 2000s, and do so almost immediately (since 2100 GDP per capita results from cumulative growth) (Figure 3e; Burgess *et al.*, 2022b). Some economists, however, argue that deep uncertainty could imply that the range of economic outlooks in the SSP scenarios is not large enough, and that scenarios having both higher (than SSP5) and lower (than SSP3) growth should be considered (Christensen *et al.*, 2018).

SSP3's (and, by extension, SSP3-7.0's) GDP-per-capita growth is more consistent with recent history than any of the other SSP storylines (Figure 3e). However, SSP3 also assumes substantially greater population growth [~13 billion people by 2100) than the U.N.'s (2019) Medium projection (~11 billion people by 2100] (Figure 3f). Meanwhile, many demographers now argue that even the UN's projections are too high, given that drivers of falling birth rates (e.g. urbanization, female education) are accelerating faster in developing countries today than they did in today's developed countries when they were developing [see Bricker and Ibbitson (2019) for review]. For instance, Vollset *et al.* (2020) recently projected ~8.5 billion people by 2100 as a reference scenario, with the global population declining late in the 21st century (similar to SSP2) (Figure 3f). Thus, even if 2100 per-capita GHG emissions were consistent with SSP3-7.0, Vollset *et al.*'s (2020) population projections would result in ~30% less total GHG emissions than SSP3-7.0 projects. Conversely, though, Vollset *et al.* (2020) project a ~20% larger population than SSP5.

This debate regarding the plausibility of high-emission scenarios occurred between AR5 (IPCC, 2014) and AR6 (IPCC, 2021, 2022a,b), and during that interval, the IPCC's perspective on RCP8.5 also seems to have shifted. In AR5 (IPCC, 2014), the IPCC stated the following, seeming to imply that considering RCP8.5 BAU was appropriate

> "The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5." (IPCC, 2014, page 8).

In contrast, in the new AR6, the IPCC acknowledges that RCP8.5 and SSP5-8.5 "have recently been argued to be implausible to unfold" (IPCC, 2021, page 4–13), and "are becoming less likely with climate policy and technology change" (IPCC, 2022b, page 3–13), citing Hausfather and Peters (2020a) and Burgess *et al.* (2021a). This reflects the two main reasons for the downward shift in what is considered BAU: (i) progress in low-carbon technologies and faster-than-expected shifts away from coal (e.g. Hausfather, 2021); and (ii) recent realizations that some high-emission-scenario assumptions may have been implausible all along (Ritchie and Dowlatabadi, 2017; Hausfather and Peters, 2020a; Burgess *et al.*, 2021a). However, AR6 also notes that "high-end concentration and warming levels may still be reached with the inclusion of strong carbon or climate feedbacks" (Ibid), citing Pedersen et al. (2020).

If a consensus emerges that the high-emission scenarios are indeed implausible, the debate will shift (and to some extent already has shifted) to the topic of what other uses (if any) exist for these scenarios, and whether or not it is urgent for climate research, policy, and communication to focus a smaller fraction of its research attention on these scenarios (e.g. see Hausfather and Peters, 2020a; Field *et al.*, 2021; Pielke and Ritchie, 2021a,b). We discuss some of these issues in the fisheries and aquatic conservation context in the sections below.

Scenario use in recent fisheries and aquatic conservation research

As the IPCC and broader climate and energy science communities begin to re-assess their scenario choices and interpretations, fisheries and aquatic conservation researchers have an opportunity to do the same. We evaluate recent fisheries and aquatic conservation research to assess whether: (a) it devotes a high fraction of its research attention to high-emission RCP/SSP marker scenarios (RCP8.5/SSP5-8.5), and (b) it has not yet broadly engaged with the debate surrounding the uses and plausibility of these scenarios. We find strong support for (a) and mixed support for (b).

Specifically, we examine papers published between January 2015 and August 2022 (i.e. since publication of AR5, and up to publication of AR6) in four major fisheries and aquatic conservation journals that are high impact (among field journals) and known for publishing climate papers—*Fish and Fisheries*, *Global Change Biology* (aquatic papers only, defined as those containing one or more of the following keywords: "fish," "aquatic," "sea," "estuary," "ocean," "marine," or "freshwater"), *ICES Journal of Marine Science*, and *Marine Policy*. We also examine papers on fisheries and/or aquatic conservation from five major generalist journals: *Nature*, *Nature Climate Change*, *Science*, *Science Advances*, and *Proceedings of the National Academy of Sciences* (*PNAS*), using the same search terms. In total, we found 213 papers that used at least one RCP or SSP scenario and focused on fisheries and/or aquatic conservation.

Among those papers that used RCP or SSP scenarios, we compare what fraction used each of the seven RCP or SSP marker scenarios (SSP1-1.9, SSP1-2.6 or RCP2.6, SSP2-3.4, SSP2-4.5 or RCP4.5, SSP4-6.0 or RCP6.0, SSP3-7.0, and SSP58.5 or RCP8.5) in these journals during this time period. The vast majority of pre-2021 papers used the RCPs, and none of the papers in our sample used SSP2-3.4. We also note what fraction of these papers referred to RCP8.5 or SSP5-8.5 as BAU or equivalent, and what fraction of papers used RCP8.5 or SSP5-8.5 as their only scenario. For papers published in 2021 and 2022 (at least one year since Hausfather and Peters' (2020a) high-profile commentary was published in *Nature*), we examine what fraction of papers cited the high-emission-scenarios debate. We hypothesized that these analyses would find: (i) that RCP8.5 or SSP5-8.5 would be the most frequently-used marker scenarios, which would be consistent with the pattern of scenario mentions Pielke and Ritchie (2021a) and Burgess et al. (2022a) found in AR5 (IPCC, 2014), AR6 (IPCC, 2022a), and other climate research; (ii) that RCP8.5 or SSP5-8.5 would frequently be referred to as BAU or equivalent; and (iii) that relatively few 2021 and 2022 papers using RCP8.5 or SSP5-8.5 cite the high-emission-scenarios debate, which would suggest that the debate does not yet prominently feature in this literature, rather than studies taking intentional positions on their uses of RCP8.5 or SSP5-8.5 in light of the debate (e.g. as in Schwalm *et al.*, 2020a).

We find that RCP8.5 and SSP5-8.5 indeed dominate the marker scenarios used in these journals and years (~90% or more of papers using scenarios, in all journals and years), with small differences across journals and years (Figure 4a and b). In fact, 73 papers (34%) use only RCP8.5 or SSP5-8.5, though this fraction has declined through time, especially after 2020 (Figure 4a). We find ~20% of papers refer to RCP8.5 or SSP5-8.5 as BAU or equivalent (Figure 4a and b), gradually declining from 29% in 2017 to 11% in 2021 and 17% in 2022 (Figure 4a).

Thus, a sizeable fraction of papers refer to RCP8.5 or SSP5-8.5 as BAU, but most (~80%) that use RCP8.5 or SSP5-8.5 do not refer to these as BAU. Other common terms used to describe RCP8.5 were "extreme" (e.g. Radinger et al., 2016), "worst-case" (e.g. Brandenburg *et al.*, 2019), or "high-emissions" (e.g. Asch *et al.*, 2019), which are less controversial descriptions. Indeed, a small number of papers framed RCP8.5 or SSP5-8.5 as unlikely scenarios (e.g. Ziegler *et al.*, 2021), or stated that a lower-emissions scenario (e.g. RCP4.5 in Shelton et al., (2021) was more likely.

Among 2021 and 2022 papers in these journals using marker scenarios, only 8/58 cited the debate (citing Schwalm *et al.* (2020a) and/or Hausfather and Peters (2020a) in most

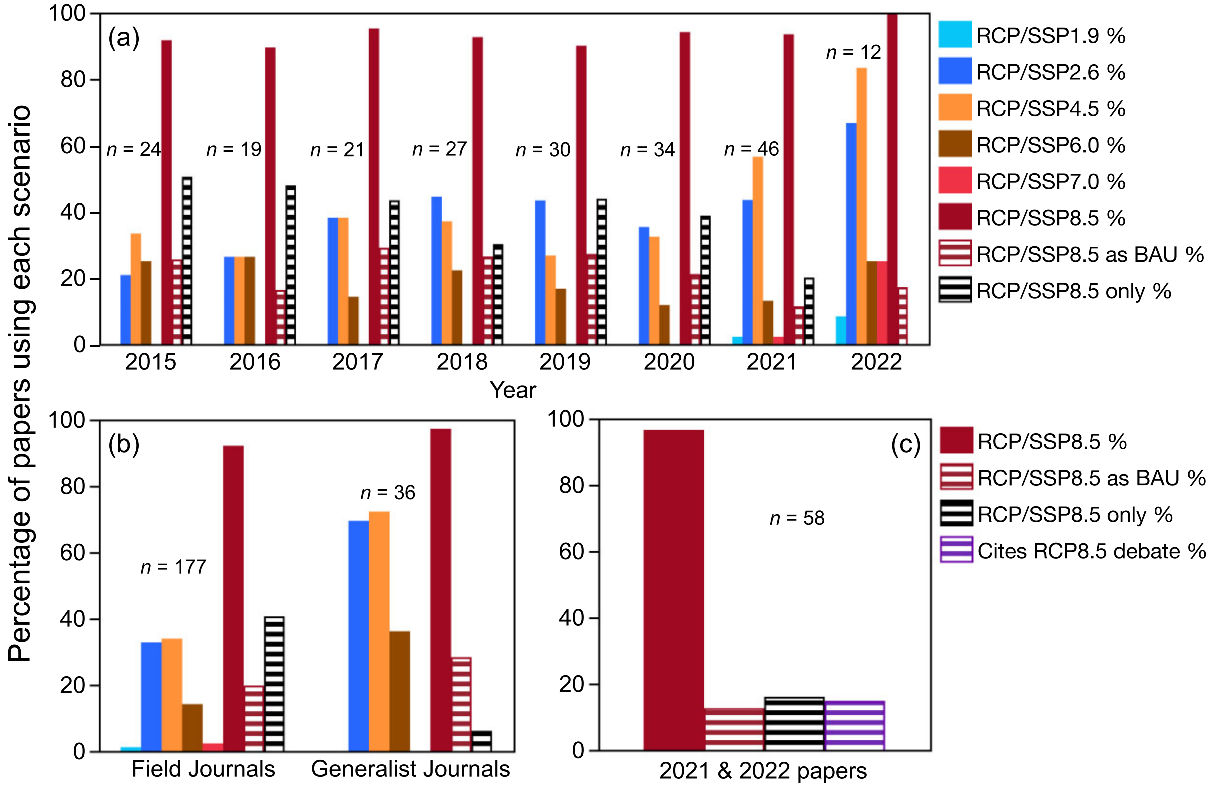

Figure 4. Panels a and b compare the percentage of fisheries and aquatic conservation papers using each of the RCP marker scenarios from January 2015 to August 2022 in five major generalist journals and four major field journals that publish fisheries and aquatic conservation papers. Panel a (b) shows these patterns by year (journal type). Panel c shows the number of 2021 and 2022 papers in these journals combined that use RCP or SSP marker scenarios, and compares the percentage that use RCP8.5 or SSP5-8.5, alone or combination with other scenarios, and shows which of those which do use this scenario cite any of the key papers in the recent debate regarding the use of these scenarios (Ritchie and Dowlatabadi, 2017; Hausfather and Peters, 2020a,b; Schwalm *et al.*, 2020a; Burgess *et al.*, 2021a; Pielke and Ritchie, 2021a,b; in one case, the citation was an earlier preprint version of the present paper). The fractions of papers that refer to RCP8.5 or SSP5-8.5 as BAU or equivalent are also shown in all panels.

cases), despite all but two (56/58) using RCP8.5 or SSP5-8.5 (Figure 4c). However, 2021 and 2022 papers use the RCP4.5 or SSP2-4.5 scenario at a higher rate than earlier papers (62% vs. 32%, Fisher's exact test $p = 0.001$; Figure 4a), and they also use RCP8.5 or SSP5-8.5 as the sole scenario at a lower rate (16% vs. 41%, Fisher's exact test $p = 0.003$)—with none doing so in 2022 (Figure 4a, c). Papers from 2021 and 2022 also call RCP8.5 or SSP5-8.5 BAU at a lower rate (12% vs. 24%, Fisher's exact test $p = 0.06$; Figure 4a, c). Papers in generalist journals also used RCP4.5 or SSP2-4.5 at a higher rate than those in specialist journals (72% vs. 34%, Fisher's exact test $p << 0.01$), and they used RCP8.5 or SSP5-8.5 as the sole scenario at a lower rate (6% vs. 40%, Fisher's exact test $p << 0.01$) (Figure 4b).

Taken together, these patterns suggest that using RCP8.5 or SSP5-8.5 is predominant, but is usually and increasingly combined with other scenarios; calling RCP8.5 or SSP5-8.5 BAU is common, but is declining and is not predominant; and only a small minority of studies that use RCP8.5 or SSP5-8.5 discuss potential concerns regarding the plausibility of these high-emission scenarios. Thus, the evidence is mixed regarding researcher awareness of the debate. On the one hand the debate is rarely cited and debated uses of high-emission scenarios are common. On the other hand, use of high-emission scenarios alone and reference to them as BAU are both declining, and increasing use of the more-plausible RCP4.5 or SSP2-4.5, suggest there may be some awareness of these issues, even when they are not directly discussed.

Perspectives on plausible emissions and climate futures

If high-emission scenarios, such as RCP8.5, SSP5-8.5, and SSP3-7.0, do not represent plausible emission outlooks to 2100, what are plausible outlooks? It is, of course, impossible to definitively answer this question due to the deep uncertainties involved in the climate system (see Figure 2b; Sherwood *et al.*, 2020; IPCC, 2021), and perhaps even more so in the socioeconomic system (e.g. Christensen *et al.*, 2018). Moreover, since humanity has control over the socioeconomic side, it is also possible for predictions to affect their own accuracy—e.g. if predicting a dire future motivates society to accelerate emissions cuts, thereby avoiding the predicted dire future (Merton's (1936) "self-defeating prophecy").

Despite these caveats, several lines of evidence in the recent literature seem to suggest a most plausible range of roughly 2–3°C of warming above pre-Industrial levels by 2100 with median climate sensitivities (i.e. between slightly <3.4 W/m^2 forcing and slightly >4.5 W/m^2 forcing)—closer to 2°C the more stringent mitigation efforts become. Climate system uncertainties (as they are currently understood) expand this most-plausible range to roughly 1.5–4°C warming. We summarize this evidence below.

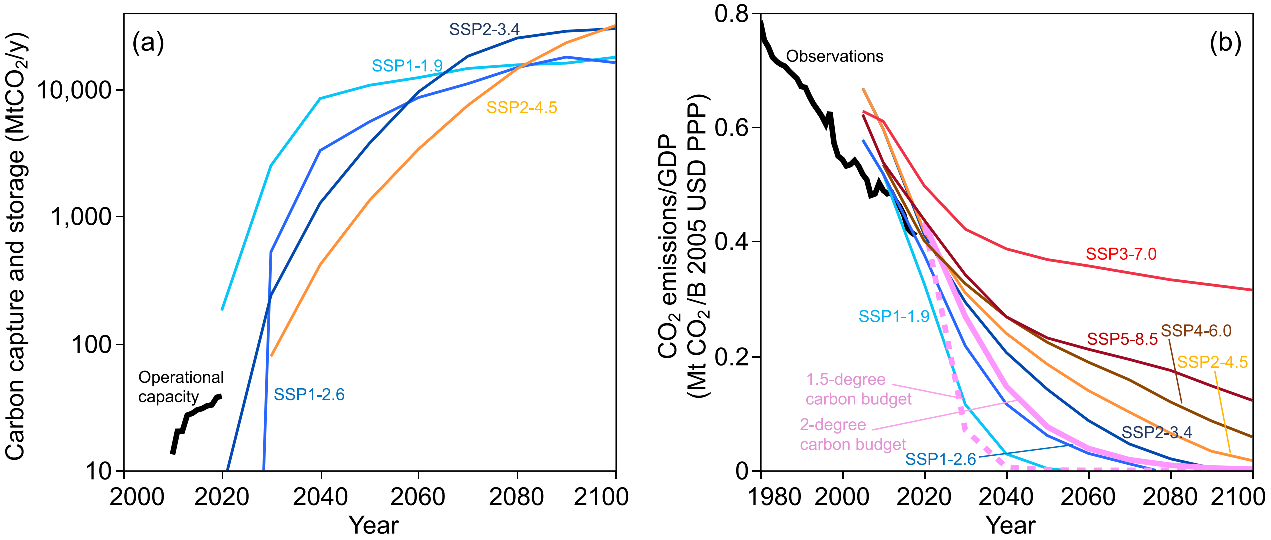

Figure 5. Panel a compares global carbon capture and storage (CCS) projections in SSP marker scenarios (IIASA, 2018) (SSP5-8.5, SSP3-7.0, and SSP4-6.0 are not shown, as they have little or no CCS) and observed operational capacity (Global CCS Institute, 2020). Panel b shows trends in the CO_2 intensity of GDP observed (Ritchie and Roser, 2021; Roser, 2021), in the SSP marker scenarios (IIASA, 2018), and in 1.5-degree- and 2-degree-consistent trajectories ("carbon budgets") with no carbon capture (Andrew, 2020), assuming GDP trajectories consistent with SSP3 GDP per capita and SSP2 population growth (from IIASA, 2018; see Figure 3e and f).

Although rising global emissions throughout the 21st century are theoretically possible, there is some evidence suggesting that a century-long plateau in emissions might be a worst-case plausible scenario. The IEA's (2021) Stated Policies scenario—which has historically tended to over-project emissions (Hausfather, 2020; Way *et al.*, 2021; Pielke *et al.*, 2022)—projects that global FFI CO_2 emissions will slightly decrease between 2020 and 2050 (Figure 2a). The AR5 (IPCC, 2014) and SSP (IIASA, 2018) scenarios with FFI CO_2 emissions growth rates most consistent with 2005–2020 historical observations and 2020–2050 IEA (2021) Stated Policies projections (differing on average by <0.3%/y) project a range of emissions trajectories, the highest of which result in roughly constant FFI emissions to 2100 (Figure 2a; Pielke *et al.*, 2022). With median climate sensitivities, nearly all of these scenarios project warming of 2–3°C by 2100 (between 3.4 and 4.5 W/m^2 forcing), above pre-Industrial levels (Figure 2a, c; see also figure 3 in Pielke *et al.*, 2022). The median scenario in this Stated-Policies-consistent range projects 2.2°C warming (Pielke *et al.*, 2022), and an emissions trajectory nearly identical to SSP2-3.4 (Figure 2a). With median climate sensitivity, constant emissions between 2019 and 2100 would result in ~3°C of warming (between SSP2-4.5 and SSP4-6.0; Figure 2a). Scenarios consistent with the IEA's (2021) Announced Pledges scenario project emissions trajectories similar to SSP1-2.6, with a 1.5–2.5°C warming range by 2100 (Figure 2a, c; see also figure 3 in Pielke *et al.*, 2022; and Liu and Raftery, 2021). The IEA's (2021) Announced Pledges scenario is new, and thus cannot be historically evaluated for accuracy. The 2022 Announced Pledges (IEA, 2022; see footnote above) has ~40% lower FFI CO_2 emissions in 2050. However, countries have predominantly failed to meet announced emissions-reduction pledges, historically (Victor *et al.*, 2017).

Other studies exploring emissions outlooks—with diverse methodologies—also suggest that 2–3°C of warming (with median climate sensitivities) may be a most-plausible range of warming to 2100 (see Hausfather and Moore, 2022, for review). Working Group III's contribution to AR6 (IPCC, 2022b) projects "implemented policies" to result in roughly constant emissions to 2100 and 3°C of warming. The Climate Action Tracker project projects that current "policies and action" would result in 2.5–2.9°C of warming by 2100; "pledges and targets" would result in approximately 2.1°C of warming by 2100; and their "optimistic scenario" would result in approximately 1.8°C of warming by 2100 (Climate Action Tracker, 2022). Sognnaes *et al.* (2021) evaluate uncertainty across seven integrated assessment models, based on current policies and pledges, and project a 2–3°C warming range. Ou *et al.* (2021) make similar projections using the GCAM model. Liu and Raftery (2021) probabilistically project emissions, based on country-level drivers, with a median projection resulting in roughly constant CO_2 emissions from present to 2100 (with RCP4.5 and RCP6.0 lying near the low and high ends, respectively, of the likely range). In contrast, Way *et al.* (2021) project that the energy transition could be substantially cheaper than previously anticipated, thus raising the plausibility of sub-2°C scenarios, although Cherp *et al.* (2021) provides a more pessimistic outlook on renewable energy growth in which 1.5°C-consistent scenarios seem more implausible. Moore *et al.* (2022) explicitly model the coupled climate-social-political-technical system. They project a modal pathway resulting in 2.3–2.4°C warming by 2100, and a 1.8–3.6°C warming range (Moore *et al.*, 2022).

While we reviewed the potential implausibility of high-emission (>3°C warming with median sensitivity) scenarios above, Figure 5 illustrates the stark challenge of limiting warming below 2°C by 2100. SSP1-1.9 assumes large-scale negative emissions in the second half of the 21st century (Figure 5a). To put this in perspective, carbon capture capacity able to remove ~25 $MtCO_2/y$ was brought online between 2010 and 2020 (CCS Institute, 2020). SSP1-1.9 and SSP1-2.6 assume that 2 511 $MtCO_2/y$ and 524 $MtCO_2/y$, respectively, will be captured by 2030 (IIASA, 2018). SSP1-1.9, SSP1-2.6, SSP2-3.4, and SSP2-4.5 each assume that carbon capture will remove more than 15 000 $MtCO_2$/y (15 Gt/y) by 2100 (Figure 5a; IIASA, 2018). Some are skeptical of the feasibility of such dramatic increases in the scale of carbon capture deployment (e.g. Anderson and Peters, 2016). Costs and other limiting resources (e.g. land) currently constrain large-scale deployment of negative emissions technologies (see National Academies of Science, Engineering, and Medicine (NASEM), 2019). On the other hand, if coal-use projections in SSP2-4.5 and SSP2-3.4 turn out to be overly pessimistic (see Figure 3a), this could significantly reduce the carbon capture demands needed for these emissions pathways. For instance, 20 GJ/y per person of coal, with 9 billion people, is equivalent to ∼35 $GtCO_2$/y emissions (using EPA's (2021) conversion factors)—significantly more than the carbon removal these scenarios assume in 2100 (Figure 5a).

Nonetheless, limiting forcing to 1.9 W/m^2 without any negative emissions would require dramatic global reductions in emissions over the next decade, reaching zero by mid-century (Figure 2a, 5b; IPCC, 2019; Andrew, 2020)—greater than the reductions (7%/y; Le Quéré *et al.*, 2021) that occurred during the COVID-19 pandemic and sustained continuously for three decades. Some consider these outcomes unlikely (e.g. Cherp *et al.*, 2021), though they certainly can be pursued aspirationally.

The carbon intensity of global GDP—the ratio of CO_2 emissions and GDP—is a key parameter measuring decarbonization in reference to affluence (Pielke *et al.*, 2008). It has been steadily declining for over a century (Ritchie and Roser, 2021; Roser, 2021), at an annual rate intermediate among the range of declines projected for 2005–2050 in the SSP marker scenarios (Figure 5b). Although SSP5-8.5 results in the highest emissions among the scenarios, its carbon intensity of GDP actually declines faster than in SSP3-7.0, due to the very high GDP-per-capita growth in SSP5 (Figure 3c and e). Scenarios consistent with limiting warming to 2 or 1.5°C above pre-Industrial levels require substantially accelerating reductions in carbon intensity of GDP (Figure 5b).

Uncertainties in climate sensitivity to emissions magnify the uncertainty in future warming, even within particular emissions scenarios. For instance, the IPCC's (2021) 5–95% range of expected warming from SSP2-4.5 is 2.1–3.5°C by 2100 above pre-industrial levels (Figure 2b). This range is larger—for this one scenario alone—than the one-degree range (2–3°C) emissions scenarios suggest when assuming median climate sensitivities. The IPCC's (2021) AR6 does not assess the warming range from low-priority scenarios such as SSP2-3.4 (despite the fact that it may be the most plausible marker scenario; Figure 2a; Pielke *et al.*, 2022) or SSP4-6.0 (see Figure 1b), but, based on the warming 5–95% ranges for SSP1-2.6 and SSP3-7.0 (Figure 1b), a scenario uncertainty that spans SSP1-2.6 to SSP4-6.0 pathways, combined with 5–95% climate sensitivity uncertainty would likely span ∼1.5–4°C of warming. For comparison, Hausfather (2021) estimates an uncertainty range from climate sensitivity of 2.2–4.1°C (median 3°C) of warming by 2100 under "current policies," and 1.9–3.3°C (median 2.4°C) by 2100 under "stated policies." Hausfather (2021) estimates that possible climate-cycle feedbacks (e.g. melting permafrost releasing methane, melting ice reducing albedo, etc.) increase this uncertainty to 2–5°C by 2100 under "current policies" and 1.7–4°C by 2100 under "stated policies."

This range of climate-system uncertainty exists despite recent improvements in our understanding of climate sensitivities. The range of warming predicted to occur as a result of doubling CO_2 concentrations relative to pre-Industrial levels (a widely used measure of climate sensitivity) has narrowed from 1.5–4.5°C in AR5 (IPCC, 2014) to 2.6–3.9°C in AR6 (IPCC, 2021), due to improvements in understanding of climate feedbacks related to clouds and ocean heat sinks (Sherwood *et al.*, 2020; see summary by Voosen (2020)). We note that this range of predicted climate sensitivities has mostly narrowed on the low end—increasing the challenge of limiting warming to 1.5°C by 2100.

Differences between high- and moderate-emission scenario impacts

The previous two sections show that fisheries and aquatic conservation studies predominantly use RCP8.5 or SSP5-8.5 for climate-impact projections, but more moderate scenarios such as RCP4.5 or SSP2-4.5 may be more plausible. This raises the question of what types of differences exist in projected impacts between these scenarios. We consider three broad types of differences between RCP4.5/SSP2-4.5 and RCP8.5/SSP5-8.5: no difference, a difference in degree (quantitative), and a difference in sign (beyond the margin of error) (qualitative).

There could be no difference between RCP4.5/SSP2-4.5 and RCP8.5/SSP5-8.5 for a particular impact for three broad reasons: either both scenarios have no effect on the impact; both scenarios have the same impact (e.g. extinction) that is essentially binary; or both scenarios have a non-zero quantitative impact that happens to be the same. An example of no effect: Clark *et al.* (2020) found negligible effects on coral reef fish behaviour of experimental acidification treatments similar to projected 2100 conditions under RCP8.5, compared to control (present-day) conditions, suggesting RCP4.5 effects would also be negligible. An example of an equivalent binary effect: Hoegh-Guldberg *et al.* (2017) project mass bleaching conditions for coral reefs throughout the Eastern Pacific, Caribbean, and Coral Triangle by 2100 under both RCP4.5 and RCP8.5 (albeit with greater mass mortality under RCP8.5; see their figure 7). Kim *et al.* (2019) provide an example of a roughly equal quantitative effect: they project vulnerability changes in 14 aquaculture species in Korea, which they project are highly similar between RCP4.5 and RCP8.5 in aggregate (see their figure 3).

A difference in degree between RCP4.5/SSP2-4.5 and RCP8.5/SSP5-8.5 impacts means that both scenarios are projected to have the same directional effect on a fishery or conservation outcome, but the extent of the effect differs—typically, it is greater under RCP8.5/SSP5-8.5. For example, species range shifts are projected to be similar in direction under both scenarios, but larger in magnitude under RCP8.5 (e.g. Oremus *et al.*, 2020)

A difference of sign between RCP4.5/SSP2-4.5 and RCP8.5/SSP5-8.5 impacts means either one scenario has a null impact and the other has a non-zero impact, or the impacts of the scenarios have opposite signs or directions. For instance, Bell *et al.* (2021) project severe impacts of climate change on Pacific Island states' tuna fisheries under RCP8.5, but negligible impacts under RCP4.5. McManus *et al.* (2021) project that eco-evolutionary adaptation might allow coral reef recovery in the Caribbean, the Southwest Pacific, and the Coral Triangle, despite climate change, over the next three centuries under RCP4.5, but not under RCP8.5. Similarly, Gaines *et al.* (2018) project that adaptive fishery management can increase catches and profits by 2100, compared to status quo under RCP4.5 (and under lower-emissions scenarios), but not under RCP8.5.

In our analysis of recent papers shown in Figure 4, we found 77 studies having projections under both RCP4.5 and RCP8.5. McManus *et al.* (2021) and Gaines *et al.* (2018), referenced above, provided two clear examples of a difference in sign. Kim *et al.* (2019), referenced above, provides an example akin to no change. In the remaining studies, differences in impacts were broadly differences of degree, albeit occasionally not statistically significant, or having few exceptions within a broad type of impact (e.g. for individual species within an assemblage, or for one of several metrics). This suggests that the vast majority of differences in impacts between RCP4.5/SSP2-4.5 and RCP8.5/SSP5-8.5 are differences in degree, which makes sense, given that the difference in warming between these scenarios is itself a difference of degree, on average (Figure 2b).

Other considerations in scenario choice

There are other considerations in scenario choice for climate change research in fisheries and aquatic conservation, besides which scenarios represent the most plausible or likely emissions pathways. Some such considerations may justify researchers using scenarios which have higher (or lower) emissions pathways than they deem plausible or likely.

One justification for using extreme scenarios is exploratory research, which is designed to explore hypothetical scenarios that are not necessarily plausible in order to better understand systems, especially those subject to deep uncertainty (Bankes, 1993). Using extreme scenarios such as RCP8.5 or SSP5-8.5 can allow researchers to more easily separate signal (human-caused climate change) from noise (e.g. internal variability) in their projections (e.g. Kay *et al.*, 2015), or to explore remote but important hypotheticals. For instance, on the high-emissions end, researchers may want to explore if and at what level of warming tipping points or collapses may arise in ecosystems (e.g. coral reef ecosystems (Hoegh-Guldberg *et al.*, 2007)) and the climate (e.g. the collapse of the West Antarctic ice sheet, and consequent sea-level rise, Shepherd *et al.*, 2019; extreme ocean-acidification impacts, McNeil and Matear, 2008; or stratocumulus clouds failing to form at >1 200 ppm atmospheric CO_2; Schneider *et al.*, 2019). Relatedly, a high-emissions scenario could be used to stress-test proposed management schemes, especially those that might be difficult to reverse. On the low-emissions end, it is worth exploring the consequences and potential benefits of achieving the international 1.5°C target, even if the world is off track (e.g. Sumaila *et al.*, 2019; in the context of fisheries).

The notion of deep uncertainty is another reason for research to explore extreme scenarios. History is full of examples of surprises that profoundly changed the course of history (Taleb, 2007)—the COVID-19 pandemic being a stark recent example. For this reason, some researchers have urged caution in limiting the scope of climate change scenarios considered (e.g. Lawrence *et al.*, 2020). Using a broad range of scenarios that included extremes may increase the chance of bracketing eventual future conditions.

A third reason researchers might use more extreme scenarios than they consider plausible might be limited availability of alternate scenarios in off-the-shelf models, and/or a study context in which the impacts of warming on species and ecosystems are not expected to depend on how (emissions vs. climate sensitivity) or when (e.g. by 2100 or 2300) the warming comes about. It is not uncommon for researchers in fisheries and aquatic conservation to use data products or processed results (such as Regional Ocean Modeling System outputs) from oceanographic research, which constrains their options for scenario choice to those selected by the data product creator(s) (e.g. García Molinos et al., 2016, used climate velocities from Burrows *et al.*, 2014, which were generated based on RCP4.5 and 8.5). As another example, the University Corporation for Atmospheric Research's (UCAR) bases their widely used Community Earth System Model Large Ensemble Project (Kay *et al.*, 2015) on RCP8.5, to facilitate parsing internal variability from human-induced change. If RCP8.5 reaches a warming level by 2050 that a more plausible scenario reaches by 2100, 2050 projections using RCP8.5 might provide useful insights into the consequences of that warming level, provided that timing was not important to the ecological process being studied. Relatedly, using a high-emissions scenario could allow researchers to explore warming levels plausibly reached beyond the 21st century in cases where a post-2100 warming model is not available. Indeed, climate change researchers are increasingly considering post-2100 impacts in their studies (e.g. Kikstra *et al.*, 2021, include post-2100 damages to calculate the social cost of carbon), including in fisheries and aquatic conservation (e.g. Moore *et al.*, 2018).

However, in some cases, the specific timing of warming likely does affect the anticipated outcomes. For instance, annual warming and incidence of extreme events in the future may shape if and how marine species adapt to climate change (Baltar *et al.*, 2019), and consequently how stocks respond to fisheries management coincident with climate change (e.g. Holsman *et al.*, 2020). In such cases, researchers should be quite cautious about using higher-emission scenarios as stand-ins for greater climate sensitivity or longer-term warming outcomes, and should thoroughly explain how such contradictions between their literal and intended symbolic use of the scenario may affect their conclusions.

Internal consistency is also an important consideration in scenario use (Pielke and Ritchie, 2021a), especially when researchers are projecting the socioeconomic impacts of climate change on fisheries and aquatic systems. Each of the SSP storylines (SSP1, …, SSP5) is associated with quite different human population sizes (Figure 3f), levels of affluence (Figure 3c, e), land-use patterns (Figure 3b), and challenges to mitigation or adaptation (Riahi *et al.*, 2017). These socioeconomic differences are central to the differences among these scenarios in emissions and therefore warming. Thus, for example, a study projecting a catastrophic impact of SSP5-8.5 on coastal livelihoods should also acknowledge that extreme affluence in all world regions is a key feature of SSP5-8.5, which allows its energy demand to be sufficient to produce its emissions. The difference in projected warming in SSP3-7.0 compared to SSP5-8.5 illustrates this—both of these scenarios assume no climate policies and their ∼1°C warming difference (Figure 2a and b) owes entirely to socioeconomic differences, especially in GDP-per-capita growth (Figure 3c and e). In contrast, some impact studies in fisheries (e.g. Cheung *et al.*, 2021) and other fields (e.g. Rode *et al.*, 2021) use SSP3 economics in combination with 8.5 W/m^2 forcing, which is internally inconsistent. In fact, the SSP architects specifically warned against this inconsistency: "The lack of other SSP scenarios with climate forcing of 8.5 W/m^2 or above has important implications for impact studies, since SSP5 is characterized by low vulnerability and low challenges to adaptation" (Riahi *et al*., 2017, p. 162; see also Figure 2c).

Relatedly, the fact that some climate-change impacts have turned out to be more severe than some models predicted, given observed levels of warming (e.g. Schewe *et al*., 2019), is not, on its own, a rationale for overstating the plausibility of high-emissions scenarios. It is, rather, a rationale for improving the accuracy of the impact models.

A final consideration—that may be especially relevant to synthetic research (reviews, meta-analyses, etc.)—is that the scenarios that are emphasized in fisheries and aquatic conservation research as a whole are likely to have outsized influence on research and management priorities. If the most-emphasized scenarios are not those which represent the most plausible outcomes (e.g. RCP8.5; Figure 4a and b), this could distort priorities in ways that may be detrimental to fisheries and aquatic systems. For instance, if climate change has severe impacts on Pacific Island states' tuna fisheries under RCP8.5, but negligible impacts under RCP4.5 (Bell *et al*., 2021), an overemphasis on RCP8.5 could distort the perceived risks climate change poses to fisheries relative to other factors affecting coastal livelihoods in this region. More generally, if emissions trajectories producing 3.4–4.5 W/m^2 forcing are potentially most plausible, then RCP4.5 (or SSP2-4.5) should arguably be explored in more than ~35% of studies (Figure 4a and b), and SSP2-3.4 should arguably be prioritized in climate modelling efforts such as CMIP (it is currently not; IPCC, 2021). On the other hand, in cases where more extreme climate change scenarios produce more extreme projections of the same problems as more plausible scenarios project, distortionary effects of scenario choices on management might be less immediately consequential and/or aligned with precautionary approaches to management. For instance, Hughes *et al*., (2017) note that most experimental warming studies of coral reefs use a warming treatment of greater than 4°C, even though reefs could be severely impacted at lower (including RCP4.5) warming levels (Hoegh-Guldberg *et al*., 2017).

Best practices for using scenarios in fisheries and aquatic conservation research

In light of the above-described trends and considerations, we recommend the following as best practices for using climate change scenarios in fisheries and aquatic conservation research.

Explore scenarios and their underlying assumptions before using them

We encourage researchers in fisheries and aquatic conservation to explore the assumptions underlying the scenarios they use for themselves, and we hope that this review offers an accessible starting point. The new SSP scenario framework is especially amenable to this, as its rationale and key assumptions are well documented (Dellink *et al*., 2017; Riahi *et al*., 2017), and the SSP and AR6 scenario databases—which include projections of population, GDP, emissions, and energy consumption from different sources, carbon capture, etc.—are publicly available (IIASA, 2018, 2022). Developing a deep understanding of the scenarios one uses in research is important for the same reasons as exploring one's raw data and visiting one's study system are important. It engenders a deeper understanding of the implications and limitations of one's results.

Be transparent about the purpose and intended plausibility of scenarios chosen

Is the analysis trying to bracket the range of possible outcomes by focusing on extreme ends? Is the analysis intended primarily for exploration, or is it intended to make projections or inform a specific policy or management process? The answers to these questions will determine which scenario uses are most appropriate, as well as how the results should be interpreted by readers. Thus, the rationales for scenarios chosen in an analysis should be communicated clearly.

Qualify results in light of rationales used for scenario choices

This is closely related to the previous point. An analysis that chooses scenarios as appropriate to pursue one question should be careful to avoid its results being misinterpreted in light of other questions. For example, a study that uses RCP8.5 or SSP5-8.5 to explore high-warming extremes should take care to not leave room for their results to be misinterpreted as projected outcomes under BAU.

Be aware of the media's tendency to sensationalize

This is a problem that fisheries science is already acutely aware of. For example, the famous headline that all fish would be gone by 2048 (e.g. Roach, 2006) misinterprets a single sentence on the last page of Worm et al.'s (2006) paper on ocean biodiversity and ecosystem services, but is regularly repeated in popular media to this day (e.g. in the recent film, *Seaspiracy* (Andersen, 2021)). Researchers ultimately do not control how the media uses their research, and certainly should not alter scientifically sound study designs for narrative purposes—neither to avoid sensationalism, nor, conversely, to downplay alarming results for fear of criticism from skeptics (Brysse et al., 2013). However, fisheries and aquatic conservation researchers using extreme high-emissions scenarios such as RCP8.5 and SSP5-8.5 should be aware of the potential for similar media sensationalism—especially since extreme scenarios are likely to generate attention-grabbing headlines—and should avoid characterizing future projections as likely outcomes. There can be similar incentives to sensationalize in academia, advocacy, and fundraising, which researchers should be aware of as well.

Try to avoid internal contradictions in scenario use, and acknowledge these when they arise

As mentioned in the previous section, the SSPs make specific socioeconomic projections which may in some cases contradict outcomes projected by studies that use them. In some cases, this may not be a major concern—for instance, the SSPs intentionally do not assume specific damages from climate change (in part to avoid contradictions with impact studies) (Dellink *et al*., 2017). However, in other cases, these contradictions may be important to consider and discuss. For instance, SSP5-8.5's very high 2100 affluence (>100 000 2005 USD PPP in all world regions; Figure 3c) is essential to the high energy demands in that scenario, but also inconsistent with some catastrophic socioeconomic climate impacts (e.g. as illustrated in the deadly heat example from Mora *et al*. (2017) in Figure 3d). This is important to consider when connecting SSP5-8.5-based climate projections to projecting and discussing livelihood impacts. Relatedly, studies should not pair

SSP5-8.5 warming projections with low-affluence (e.g. SSP3) economic projections.

Conclusion

In this paper, we have aimed to provide a concise and accessible summary of (i) key assumptions and features of marker scenarios of climate change commonly used in fisheries and aquatic conservation research and (ii) recent developments in our understanding of possible 21st-century emissions and warming trajectories. Informed by these developments, we provide recommendations for best practices in scenario use in fisheries and aquatic conservation research. Given how quickly the consensus on most likely scenarios has changed in climate change science (e.g. as evidenced by the different treatment of RCP8.5/SSP5-8.5 in the IPCC's AR6 compared to AR5 (IPCC, 2014, 2021, 2022b)), and how widely climate change scenarios are used in fisheries and aquatic conservation science (Figure 4), a primer on these developments for this audience is urgently needed.

The stakes are high in fisheries and aquatic ecosystems management in a changing climate–both for nature and people (e.g. Costello *et al.*, 2020; Duarte *et al.*, 2020). Using the best available science, and carefully matching rationales for specific research assumptions (in this case, scenarios) to resulting conclusions is essential to providing sound management advice and also to matching research priorities to most likely management challenges.

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Author Contributions

All authors contributed to designing the study. M.G.B., S.L.B., and R.E.L. collected and analyzed the data. M.G.B. wrote the first draft of the paper, and all authors contributed to revisions.

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Competing Interests

The authors declare no competing interests.

Data Availability

All data and code used in Figures 1–5 are publicly available at https://github.com/mattgburgess/climatekaya, with the exception of Figure 3d, which is reproduced (with permission) from Mora *et al.* (2017) (Springer Nature RightsLink License Number 5222771223466). Assistance navigating the data and code is also available upon request from the corresponding author.

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