exhibit unusually high density and growth rates". However, none of the works cited[1] actually provide data on seagrass population growth.

Over the last 250,000 years, the maximum abrupt warming experienced by the Mediterranean Sea was at 1–1.5 °C per century[12], half that of the annual warming projected by climate models for the current century (2.8 °C per century)[2]. No evidence to suggest that *P. oceanica* was unaffected by these comparatively moderate warming events in the past was presented by Altaba[1]. We do not argue that vulnerability to temperature renders conservation efforts worthless. What we actually claimed[2] was that "actions to mitigate other local impacts, although beneficial, will have a modest effect in the seagrass resistance to warming events". ❒

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COMMENTARY:

The challenge to keep global warming below 2 °C

Glen P. Peters, Robbie M. Andrew, Tom Boden, Josep G. Canadell, Philippe Ciais, Corinne Le Quéré, Gregg Marland, Michael R. Raupach and Charlie Wilson

The latest carbon dioxide emissions continue to track the high end of emission scenarios, making it even less likely global warming will stay below 2 °C. A shift to a 2 °C pathway requires immediate significant and sustained global mitigation, with a probable reliance on net negative emissions in the longer term.

On-going climate negotiations have recognized a "significant gap" between the current trajectory of global greenhouse-gas emissions and the "likely chance of holding the increase in global average temperature below 2 °C or 1.5 °C above pre-industrial levels"[1]. Here we compare recent trends in carbon dioxide (CO_2) emissions from fossil-fuel combustion, cement production and gas flaring with the primary emission scenarios used by the Intergovernmental Panel on Climate Change (IPCC). Carbon dioxide emissions are the largest contributor to long-term climate change and thus provide a good baseline to assess progress and examine consequences. We find that current emission trends continue to track scenarios that lead to the highest temperature increases. Further delay in global mitigation makes it increasingly difficult to stay below 2 °C.

Long-term emissions scenarios are designed to represent a range of plausible emission trajectories as input for climate change research[2,3]. The IPCC process has resulted in four generations of emissions scenarios[2]: Scientific Assessment 1990 (SA90)[4], IPCC Scenarios 1992 (IS92)[5], Special Report on Emissions Scenarios (SRES)[6], and the evolving Representative Concentration Pathways (RCPs)[7] to be used in the upcoming IPCC Fifth Assessment Report. The RCPs were developed by the research community as a new, parallel process of scenario development, whereby climate models are run using the RCPs while simultaneously socioeconomic and emission scenarios are developed that span the range of the RCPs and beyond[2].

It is important to regularly re-assess the relevance of emissions scenarios in light of changing global circumstances[3,8]. In the past, decadal trends in CO_2 emissions have responded slowly to changes in the underlying emission drivers because of inertia and path dependence in technical, social and political systems[9]. Inertia and path dependence are unlikely to be affected by short-term fluctuations[2,3,9] — such as financial crises[10] — and it is probable that emissions will continue to rise for a period even after global mitigation has started[11]. Thermal inertia and vertical mixing in the ocean, also delay the temperature response to CO_2 emissions[12]. Because of inertia, path dependence and changing global circumstances, there is value in comparing observed decadal emission trends with emission scenarios to help inform the prospect of different futures being realized, explore the feasibility of desired changes in the current emission trajectory and help to identify whether new scenarios may be needed.

Global CO_2 emissions have increased from 6.1±0.3 Pg C in 1990 to 9.5±0.5 Pg C in 2011 (3% over 2010), with average annual growth rates of 1.9% per year in the 1980s, 1.0% per year in the 1990s, and 3.1% per year since 2000. We estimate that emissions in 2012 will be 9.7±0.5 Pg C or 2.6% above 2011 (range of 1.9–3.5%) and 58% greater than 1990 (Supplementary Information and ref. 13). The observed growth rates are at the top end of all four generations of emissions scenarios

(Figs 1 and 2). Of the previous illustrative IPCC scenarios, only IS92-E, IS92-F and SRES A1B exceed the observed emissions (Fig. 1) or their rates of growth (Fig. 2), with RCP8.5 lower but within uncertainty bounds of observed emissions.

Observed emission trends are in line with SA90-A, IS92-E and IS92-F, SRES A1FI, A1B and A2, and RCP8.5 (Fig. 2). The SRES scenarios A1FI and A2 and RCP8.5 lead to the highest temperature projections among the scenarios, with a mean temperature increase of 4.2–5.0 °C in 2100 (range of 3.5–6.2 °C)[14], whereas the SRES A1B scenario has decreasing emissions after 2050 leading to a lower temperature increase of 3.5 °C (range 2.9–4.4°C)[14]. Earlier research has noted that observed emissions have tracked the upper SRES scenarios[15,16] and Fig. 1 confirms this for all four scenario generations. This indicates that the space of possible pathways could be extended above the top-end scenarios to accommodate the possibility of even higher emission rates in the future.

The new RCPs are particularly relevant because, in contrast to the earlier scenarios, mitigation efforts consistent with long-term policy objectives are included among the pathways[2]. RCP3-PD (peak and decline in concentration) leads to a mean temperature increase of 1.5 °C in 2100 (range of 1.3–1.9 °C)[14]. RCP3–PD requires net negative emissions (for example, bioenergy with carbon capture and storage) from 2070, but some scenarios suggest it is possible to stay below 2 °C without negative emissions[17–19]. RCP4.5 and RCP6 — which lie between RCP3–PD and RCP8.5 in the longer term — lead to a mean temperature increase of 2.4 °C (range of 1.0–3.0 °C) and 3.0 °C (range of 2.6–3.7 °C) in 2100, respectively[14]. For RCP4.5, RCP6 and RCP8.5, temperatures will continue to increase after 2100 due to on-going emissions[14] and inertia in the climate system[12].

Current emissions are tracking slightly above RCP8.5, and given the growing gap between the other RCPs (Fig. 1), significant emission reductions are needed by 2020 to keep 2 °C as a feasible goal[18–20]. To follow an emission trend that can keep the temperature increase below 2 °C (RCP3-PD) requires sustained global CO_2 mitigation rates of around 3% per year, if global emissions peak before 2020[11,19]. A delay in starting mitigation activities will lead to higher mitigation rates[11], higher costs[21,22], and the target of remaining below 2 °C may become unfeasible[18,20]. If participation is low, then higher rates of mitigation are needed in individual countries, and this may even increase mitigation costs for all countries[22]. Many of these rates assume that negative emissions will be possible and affordable later this century[11,17,18,20]. Reliance on negative emissions has high risks because of potential delays or failure in the development and large-scale deployment of emerging technologies such as carbon capture and storage, particularly those connected to bioenergy[17,18].

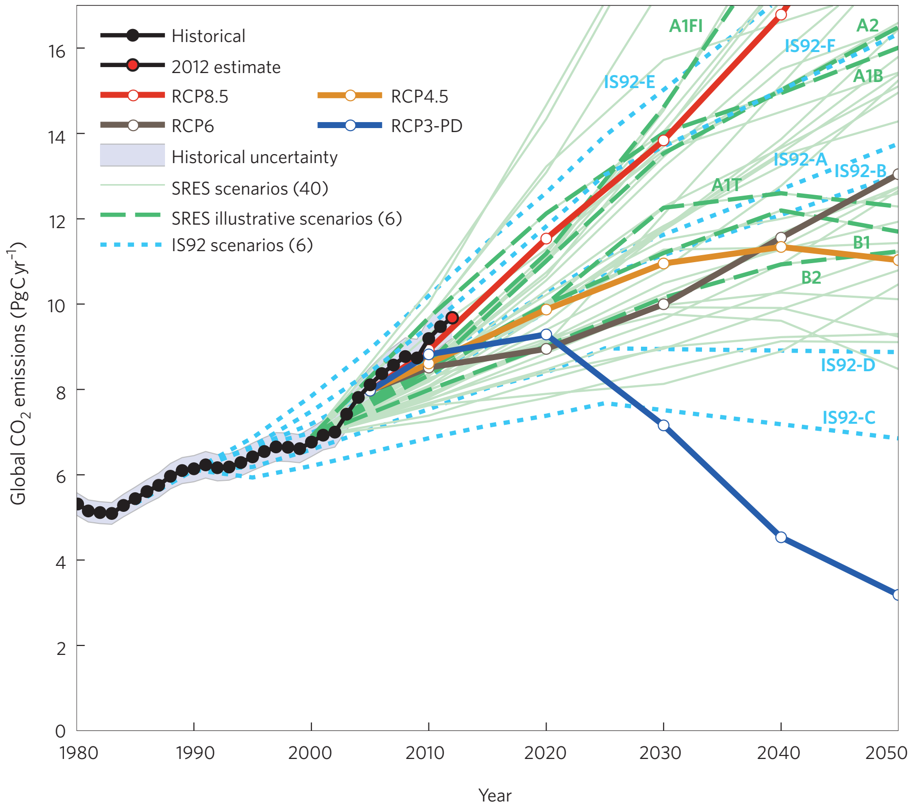

Figure 1 | Estimated CO_2 emissions over the past three decades compared with the IS92, SRES and the RCPs. The SA90 data are not shown, but the most relevant (SA90-A) is similar to IS92-A and IS92-F. The uncertainty in historical emissions is ±5% (one standard deviation). Scenario data is generally reported at decadal intervals and we use linear interpolation for intermediate years.

Although current emissions are tracking the higher scenarios, it is still possible to transition towards pathways consistent with keeping temperatures below 2 °C (refs 17,19,20). The historical record shows that some countries have reduced CO_2 emissions over 10-year periods, through a combination of (non-climate) policy intervention and economic adjustments to changing resource availability. The oil crisis of 1973 led to new policies on energy supply and energy savings, which produced a decrease in the share of fossil fuels (oil shifted to nuclear) in the energy supply of Belgium, France and Sweden, with emission reductions of 4–5% per year sustained over 10 or more years (Supplementary Figs S17–19). A continuous shift to natural gas — partially substituting coal and oil — led to sustained mitigation rates of 1–2% per year in the UK in the 1970s and again in the 2000s, 2% per year in Denmark in the 1990–2000s, and 1.4% per year since 2005 in the USA (Supplementary Figs S10–12). These examples highlight the practical feasibility of emission reductions through fuel substitution and efficiency improvements, but additional factors such as carbon leakage[23] need to be considered. These types of emission reduction can help initiate a transition towards trajectories consistent with keeping temperatures below 2 °C, but further mitigation measures are needed to complete and sustain the reductions.

Similar energy transitions could be encouraged and co-ordinated across countries in the next 10 years using available technologies[19], but well-targeted technological innovations[24] are required to sustain the mitigation rates for longer periods[17]. To move below the RCP8.5 scenario — avoiding the worst climate impacts — requires early action[17,18,21] and

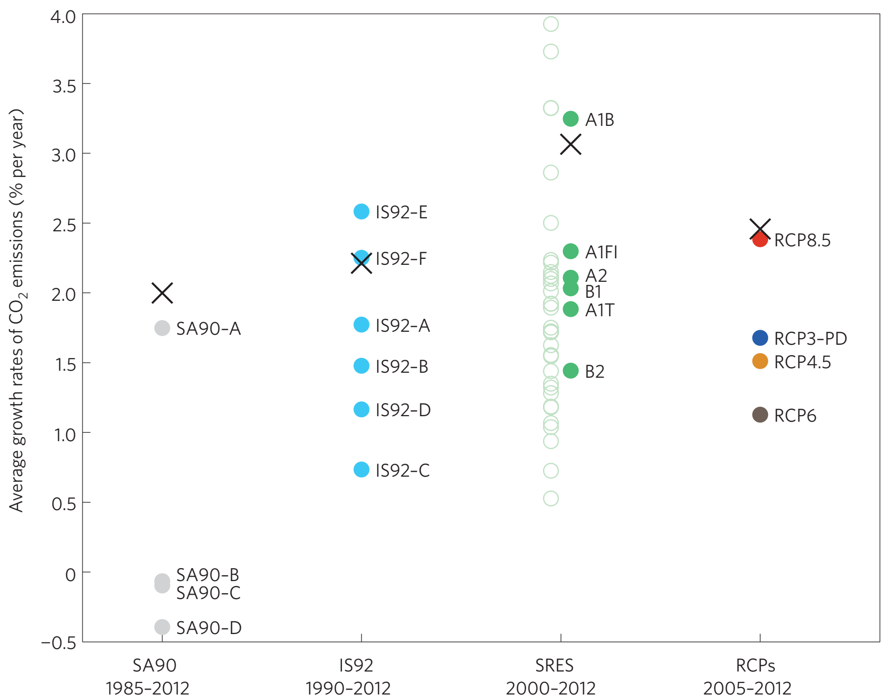

Figure 2 | Growth rates of historical and scenario CO_2 emissions. The average annual growth rates of the historical emission estimates (black crosses) and the emission scenarios for the time periods of overlaps (shown on the horizontal axis). The growth rates are more comparable for the longer time intervals considered (in order: SA90, 27 years; IS92, 22 years; SRES, 12 years; and RCPs, 7 years). The short-term growth rates of the scenarios do not necessarily reflect the long-term emission pathway (for example, A1B has a high initial growth rate compared with its long-term behaviour and RCP3PD has a higher growth rate until 2010 compared with RCP4.5 and RCP6). For the SRES, we represent the illustrative scenario for each family (filled circles) and each of the contributing model scenarios (open circles). The scenarios generally report emissions at intervals of 10 years or more and we interpolated linearly to 2012; a sensitivity analysis shows a linear interpolation is robust (Supplementary Fig. S14).

sustained mitigation from the largest emitters[22] such as China, the United States, the European Union and India. These four regions together account for over half of global CO_2 emissions, and have strong and centralized governing bodies capable of co-ordinating such actions. If similar energy transitions are repeated over many decades in a broader range of developed and emerging economies, the current emission trend could be pulled down to make RCP3-PD, RCP4.5 and RCP6 all feasible futures.

A shift to a pathway with the highest likelihood to remain below 2 °C above pre-industrial levels (for example, RCP3-PD), requires high levels of technological, social and political innovations, and an increasing need to rely on net negative emissions in the future[11,17,18]. The timing of mitigation efforts needs to account for delayed responses in both CO_2 emissions[9] (because of inertia in technical, social and political systems) and also in global temperature[12] (because of inertia in the climate system). Unless large and concerted global mitigation efforts are initiated soon, the goal of remaining below 2 °C will very soon become unachievable. ❐

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Author contributions

All authors contributed to the planning of the paper. G.P.P. led the work. G.M. and T.B. contributed the updated CO_2 emission data. R.M.A. prepared the figures and associated analysis. G.P.P. did the 2012 emission estimate and the analysis of the historical reduction rates. All authors contributed to data interpretation and to the writing of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for material should be addressed to G.P. All data presented in this paper, including the full global CO_2 budget for 2011, can be accessed at http://www.globalcarbonproject.org/carbonbudget/

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