

FISHERIES

Large benefits to marine fisheries of meeting the 1.5°C global warming target

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Translating the Paris Agreement to limit global warming to 1.5°C above preindustrial level into impact-related targets facilitates communication of the benefits of mitigating climate change to policymakers and stakeholders. Developing ecologically relevant impact-related targets for marine ecosystem services, such as fisheries, is an important step. Here, we use maximum catch potential and species turnover as climate-risk indicators for fisheries. We project that potential catches will decrease by more than 3 million metric tons per degree Celsius of warming. Species turnover is more than halved when warming is lowered from 3.5° to 1.5°C above the preindustrial level. Regionally, changes in maximum catch potential and species turnover vary across ecosystems, with the biggest risk reduction in the Indo-Pacific and Arctic regions when the Paris Agreement target is achieved.

The effort required to achieve the Paris Agreement target of limiting global warming to 1.5°C relative to the preindustrial level appears to be substantial (1). Demonstrating the benefits of moving toward the Paris Agreement's target may encourage countries to commit more ambitious plans for reduction of greenhouse gas emissions and promote voluntary actions from private sectors (1, 2). Climate change is affecting marine biodiversity and ecosystem services such as food provision, posing substantial risk to the well-being of coastal communities (3–5). Quantifying the relationship between fisheries impacts and global surface warming (and thus cumulative carbon emissions) enables us to estimate the benefits of meeting the Paris Agreement target (Fig. 1).

We analyze the outputs from 19 Earth system models used in the Fifth Assessment of the Intergovernmental Panel on Climate Change that participated in the Coupled Models Intercomparison Project Phase 5 (CMIP5) under the Representative Concentration Pathway (RCP) 2.6 (strong mitigation) and 8.5 (high emission) scenarios (see supplementary materials). We evaluate the relationship between the projected global mean atmospheric surface warming between 1950 and 2100 and changes in oceanographic variables that drive changes in marine ecosystems (6, 7). The focus of our analysis is on the system of large marine ecosystems (fig. S2), which host more than 90% of the global catches and most of the diversity of exploited species. We find that global warming scales nearly linearly with ecosystem drivers at the sea surface averaged over all large marine ecosystems in all individual models under both RCP 2.6 and RCP 8.5 (6, 8) (Fig. 2; see supplementary materials). These drivers, including global mean sea surface temperature (SST), surface oxygen (O₂), and net primary production (NPP) integrated over the top

100-m depths of the ocean, are projected to change by $0.75 \pm 0.00^\circ\text{C}$ (coefficient of determination $R^2 = 0.99$, Fig. 2A), $-3.41 \pm 0.02 \text{ mmol}\cdot\text{m}^{-3}$ ($R^2 = 0.97$, Fig. 2C), and $-0.19 \pm 0.01 \text{ Pg C}\cdot\text{year}^{-1}$ ($R^2 = 0.26$, Fig. 2E), respectively, for every degree Celsius increase in global mean atmospheric surface temperature. Temperature and O₂ at sea bottom (Fig. 2, B and D), however, continue to change even when sea surface conditions are stabilized because of the relatively slow surface-to-deep ocean transport of heat and carbon.

We quantify the reduction in the impacts on marine fisheries from achieving the Paris Agree-

ment target globally, and regionally, using a Dynamic Bioclimate Envelope Model (DBEM; see supplementary materials). DBEM is a marine species distribution model that simulates the interactions between changes in ocean conditions, ecophysiology, population dynamics, dispersal, habitat productivity, and suitability, as well as fishing, in determining abundance and catches. With ocean warming, populations are projected to shift their distributions following gradients of habitat suitability (9), while changes in energy available from NPP for species' biomass production will also affect their potential catches (10, 11). DBEM is applied to 892 species of exploited marine fishes and invertebrates that are shown to be representative of total catches (see supplementary materials). Outputs from the DBEM include changes in abundance and catches driven by scenarios of ecosystem drivers obtained from the Earth system models. We use outputs from 3 of the 19 Earth system models that have the full set of ecosystem drivers under both RCP 2.6 and 8.5 scenarios, and that do not share the same ocean biogeochemical submodel (see table S1).

We express impacts to fisheries by changes in maximum catch potential (ΔMCP) (10) and turnover of exploited species ($\Delta\text{SppTurn}$) (12) (number of species newly occurring plus locally extinct relative to species richness in years 1950 to 1969) (see supplementary materials). MCP is a proxy for maximum sustainable yield, which is a commonly used reference point for fisheries management (see supplementary materials).

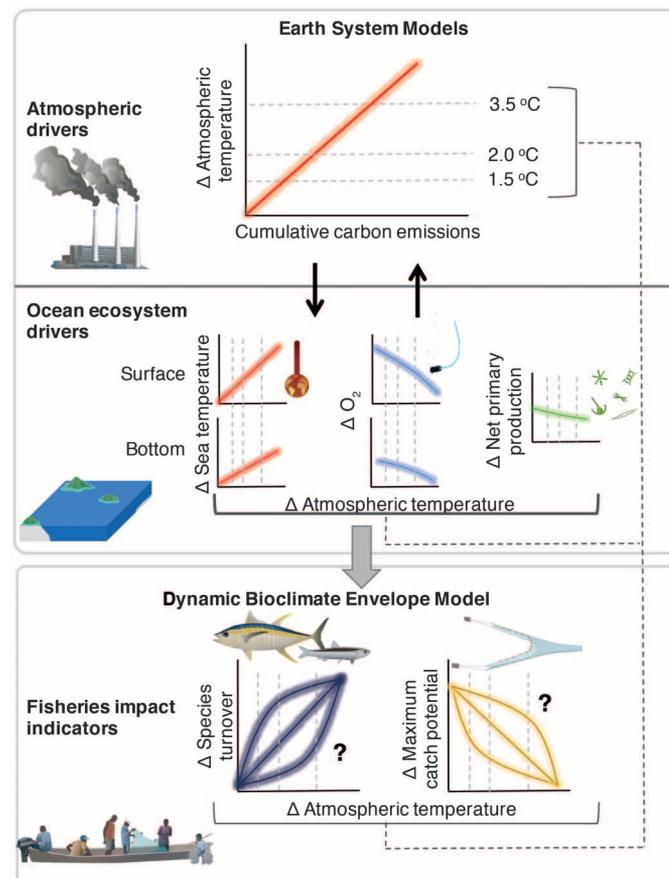


Fig. 1. Conceptual diagram explaining the framework of this study to establish ecologically relevant impact-related targets and the implications of such targets for understanding the benefits of meeting the Paris Agreement global warming target.

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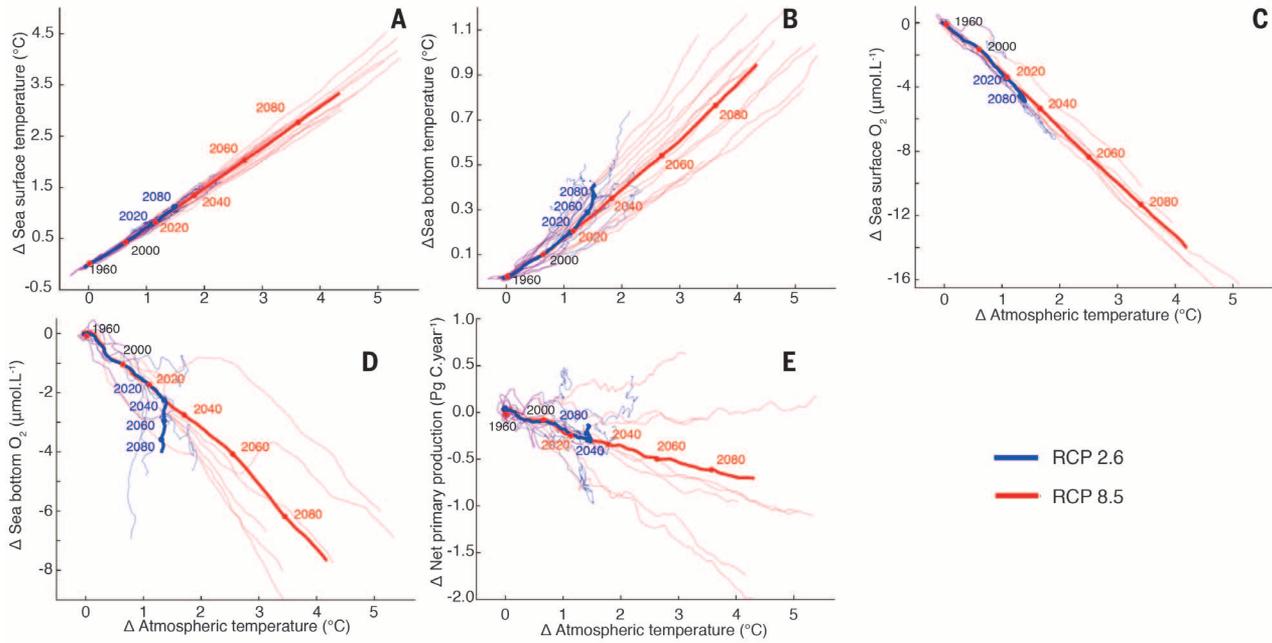
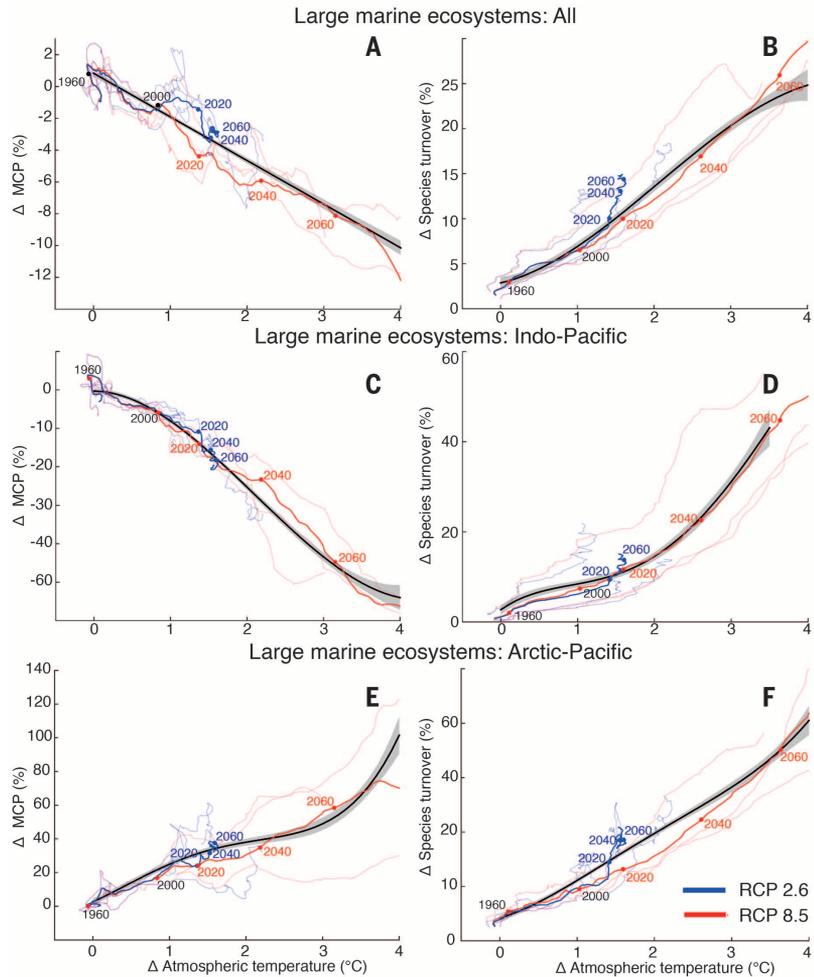


Fig. 2. (A to E) Scaling between global changes in marine ecosystem drivers and simulated surface air temperature relative to 1950 to 1969 (see supplementary materials). The thinner lines represent individual model projections, while the thicker lines represent multimodel averages. The time series are smoothed by a 10-year running mean.

Fig. 3. Projected global and regional ΔMCP (A, C, and E) and ΔSppTurn (B, D, and F) versus atmospheric surface warming relative to 1950 to 1969. The thinner lines represent individual model projections, while the thicker lines represent multimodel averages. The black lines and gray bands represent the selected regression model and their 95% confidence limits. The time series are smoothed by a 10-year running mean.



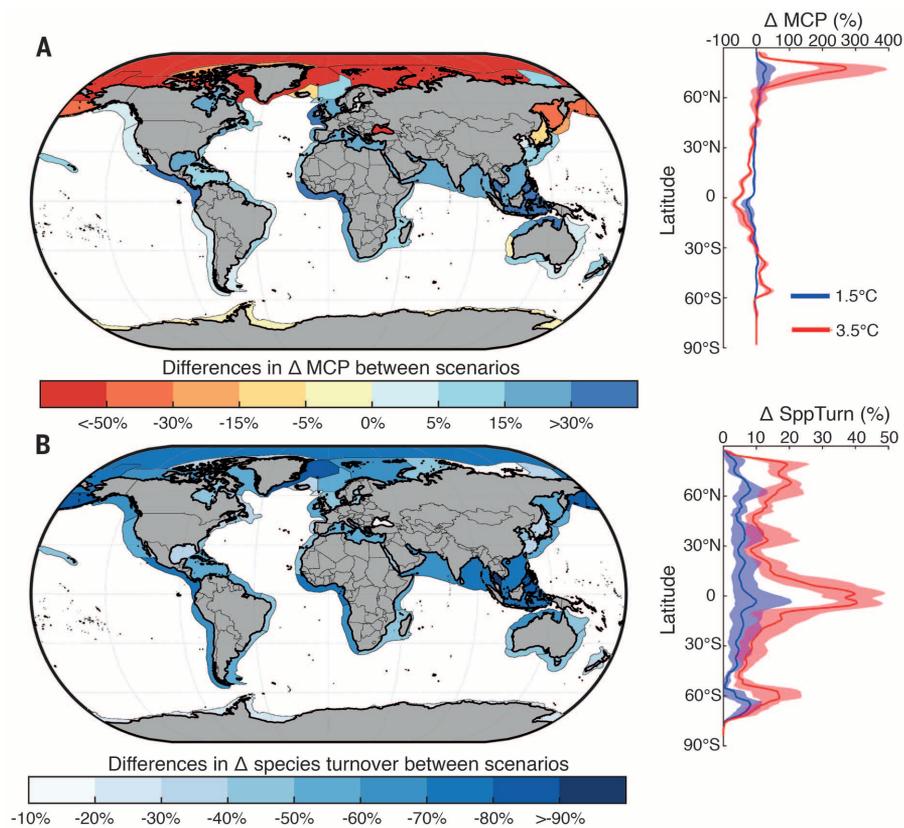


Fig. 4. Projected differences in ΔMCP (A) and $\Delta\text{SppTurn}$ (B) if global surface temperature were to be effectively limited from 3.5° to 1.5°C relative to the preindustrial level. Gridded outputs are averaged by large ecosystem systems. The right panels are latitudinal zonal averages over the large marine ecosystems under the 3.5°C (red) and 1.5°C (blue) scenarios. Solid lines represent averages, while the bands represent maximum and minimum values across projections from the three Earth system models.

Projected ΔMCP integrated over all the large marine ecosystems scales negatively and nearly linearly with average atmospheric warming (Fig. 3A; see supplementary materials). The loss of catch potential is projected to be $2.8 \pm 0.15\% \text{ } ^\circ\text{C}^{-1}$ warming or $3.4 \times 10^6 \pm 0.37 \times 10^6$ metric tons $^\circ\text{C}^{-1}$, assuming a baseline global maximum catch potential of 1.23×10^8 metric tons (i.e., average of the top 10-year global annual catches since 1950, which is slightly higher than the average catches from 2001 to 2010; www.seararoundus.org). Under 1.5°C global atmospheric warming relative to the preindustrial level, ΔMCP is projected to be $-2.5 \pm 0.2\%$ relative to the MCP at 0.27°C warming from preindustrial level (i.e., level of warming in the 1950s; see supplementary materials). In contrast, under 3.5°C global atmospheric warming relative to the preindustrial level (estimated the end of 21st-century warming level according to the published greenhouse gas emission reduction commitment by countries; see supplementary materials), we project a tripling of impacts from the 1.5°C target, with ΔMCP of $-8.0 \pm 0.34\%$.

The average species turnover ($\Delta\text{SppTurn}$) across all the large marine ecosystems is projected to increase with global atmospheric warming (Fig. 3B). With average atmospheric warming of 3.5°C relative to the preindustrial level, species turnover is projected to be $21.6 \pm 0.33\%$ of the

average species richness between 1950 and 1969. However, if warming is restricted to 1.5°C, average species turnover is reduced to $8.3 \pm 0.05\%$.

Regional scaling between fisheries impacts and atmospheric warming is generally nonlinear in the tropics and Arctic, suggesting that the 1.5° to 2.0°C global warming target represents a threshold above which substantial fisheries impacts are projected to occur. In the Indo-Pacific region (including the Bay of Bengal, Gulf of Thailand, South China Sea, and Sulu-Celebes Sea; see supplementary materials), ΔMCP is projected to be $-46.8 \pm 1.2\%$ under 3.5°C warming. However, ΔMCP is reduced to $-11.5 \pm 0.6\%$ and $20.2 \pm 0.6\%$ under 1.5° and 2.0°C warming, respectively (Fig. 3C). Similarly, $\Delta\text{SppTurn}$ is projected to be $36.4 \pm 2.1\%$ under 3.5°C warming but decreases to $9.2 \pm 0.8\%$ and $12.1 \pm 0.8\%$ under 1.5° and 2.0°C warming (Fig. 3D). In contrast, in the Pacific-Arctic (including the Bering Sea, Chukchi Sea, and Sea of Okhotsk), ΔMCP increases from $29.1 \pm 1.6\%$ to $55.0 \pm 3.9\%$ when global atmospheric temperature increases from 1.5° to 3.5°C (Fig. 3E), whereas $\Delta\text{SppTurn}$ increases from $13.1 \pm 0.4\%$ to $30.5 \pm 1.0\%$ (Fig. 3F). Alternative patterns of scaling of fisheries impacts and average warming appear in some large marine ecosystems because of specific interactions between changes in ocean conditions and the

biological responses (see figs. S3 and S4 and tables S2 and S3). In the Norwegian Sea (figs. S3 and S4), for example, MCP increases initially with atmospheric warming through species gains and increasing abundance of exploited species, but then decreases at a high level of warming; the latter is driven by the decrease in projected NPP due to enhanced stratification and the onset of nutrient limitations in the Arctic (13). In the Antarctic region, the decrease and then increase in MCP under global warming are driven by the decrease in abundance of existing species, followed by the gain of lower-latitude species.

Climate-risk reduction for fisheries is projected to be the largest in tropical oceans under 1.5°C warming, partly because of the avoided local extinction (Fig. 4). Countries such as Ecuador, Costa Rica, Ghana, Thailand, the Philippines, and Indonesia, with their exclusive economic zones and fisheries in these large marine ecosystems, will benefit substantially from meeting the Paris Agreement. In contrast, the increase in habitat suitability and productivity in the Arctic Ocean corresponds to an increase in ΔMCP and $\Delta\text{SppTurn}$. Particularly, the low baseline MCP in the high Arctic under current climate results in a large projected increase in MCP under warming. For mid-latitude regions, projected ΔMCP and $\Delta\text{SppTurn}$ are lower than in polar and tropical regions.

The nonlinear scaling of ΔMCP and $\Delta\text{SppTurn}$ is due to changes in environmental conditions beyond the species' physiological tolerance limits or when new suitable habitats become available (14, 15). Specifically, in the model, each species has its characteristic temperature preferences and limits, and other ocean conditions such as oxygen content and primary production would indirectly modify that. Species will become locally extinct if temperature goes beyond those limits (see supplementary materials). In the tropics, temperature and ocean conditions are projected to exceed what the species have experienced in the last century (16, 17). As the tropics generally represent one end of the environmental limits (17), a large proportion of these species are projected to become locally extinct if they cannot physiologically adapt to changes beyond these limits (17, 18). In contrast, warming and the rapid retreat of sea ice in the Arctic Ocean open up new habitats for marine species for sub-Arctic and temperate species to expand into (19, 20). Polar species, however, have evolved narrower temperature tolerance limits because of the historically stable climatic conditions relative to the temperate environment, rendering them more sensitive to ocean warming (9, 21). In addition, species turnover is suggested to cause indirect impacts through alteration of ecosystem structure and food web interactions (18, 22). These impacts pose social and economic challenges to fisheries—for instance, through decrease in revenues, livelihood, and food availability (3, 4).

The patterns of our projections generally agree with observations and model simulation studies on climate change impacts on marine species (18, 21, 23). For example, the decrease in potential

catches of Atlantic cod in the Gulf of Maine driven partly by rapid ocean warming has contributed to the collapse of the cod fisheries (24). In the Gulf of Mexico, turnover of fish species in sea-grass assemblages as a result of species gains and losses between the 1970s and 2000s have been reported (25). In the Barent Sea, recent warming since the early 2000s has resulted in northward retraction of Arctic fish communities (e.g., bigeye sculpin and Greenland halibut) but expansion of the sub-Arctic and temperate communities (e.g., Atlantic cod and haddock) (26). The projected changes to fisheries estimated from our study under the 3.5°C warming scenario are very likely more severe than these observations.

Assumptions in four aspects of the models may affect our results: linearity between cumulative carbon emissions and ocean changes, uncertainty in projections of ecosystem drivers, evolutionary adaptation of marine species, and effects of ocean acidification. We show that the first assumption is generally valid for sea surface variables, but sea-bottom variables exhibit a lag to surface warming. Thus, our projected fisheries impacts may be more conservative (fig. S5). Second, accuracy of the projections is contingent on the outputs from the Earth system models (6, 11). Sensitivity analyses show that projected Δ MCP is most sensitive to temperature in all biomes, followed by NPP (fig. S7). At the same time, regional comparison of present-day ecosystem drivers with model projections shows that global and regional-scale patterns are relatively well represented for SST and surface O_2 , but not well simulated for bottom O_2 and NPP (fig. S8). Specifically, NPP is largely underestimated in all models in the large marine ecosystems (see supplementary materials). The uncertainties of projections of ecosystem drivers are particularly relevant to interpretation of our findings for small-scale and recreational fisheries that operate in inshore areas where these uncertainties are higher (7). Third, in DBEM, species' environmental preferences are based on the assumption that their current distributions are in equilibrium with the environment and species' traits do not evolve as environmental conditions change. Experimental studies suggest that there may be standing genetic variability that would allow species to adapt evolutionarily to warming, while transgenerational adaptations may also be possible for a few studied species (27). Species distribution models that assume adaptation potential for species' thermal tolerance project lower species local extinction, particularly in the tropics (18). However, the extent of such adaptation responses is unclear, as empirical analysis of species turnover in the tropics is currently understudied. Moreover, climate impacts on habitats such as coral reefs and estuaries may further increase the impacts on the associated species. Last, this study does not consider the effects of ocean acidification and potential interactions with other human drivers such as pollution or socioeconomic development on marine fisheries. Empirical evidence suggests that

exploited mollusks and echinoderms are sensitive to ocean acidification. Although the direct effects of ocean acidification on finfishes in general are inconclusive (28), indirect impacts on primary and secondary production, behavior, and trophic interactions may negatively affect finfish productivity (29). Thus, the addition of ocean acidification effects would further strengthen the conclusion that reduction in CO_2 emissions, which also reduces ocean acidification directly, reduces impacts on fisheries (5).

This study highlights the clear benefits for fisheries from achieving the Paris Agreement's target and fills in an important gap for the oceans on the implications of limiting global average temperatures to 1.5°C.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Author Contributions

Figs. S1 to S9

Tables S1 to S3

References (30–53)

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PLANT SCIENCE

Precursor processing for plant peptide hormone maturation by subtilisin-like serine proteinases

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Peptide hormones that regulate plant growth and development are derived from larger precursor proteins by proteolytic processing. Our study addressed the role of subtilisin-like proteinases (SBTs) in this process. Using tissue-specific expression of proteinase inhibitors as a tool to overcome functional redundancy, we found that SBT activity was required for the maturation of IDA (INFLORESCENCE DEFICIENT IN ABSCISSION), a peptide signal for the abscission of floral organs in *Arabidopsis*. We identified three SBTs that process the IDA precursor in vitro, and this processing was shown to be required for the formation of mIDA (the mature and bioactive form of IDA) as the endogenous signaling peptide in vivo. Hence, SBTs act as prohormone convertases in plants, and several functionally redundant SBTs contribute to signal biogenesis.

Small posttranslationally modified peptides function as extracellular signaling molecules in plants (1). Such peptides control plant growth and development, as well as interactions between plants and their environment (1, 2). Addressing the biogenesis of plant peptide hormones, we focused on a peptide that

serves as a signal for the abscission of floral organs (petals, sepals, and stamens).

Abscission is on full display during autumn, when deciduous trees shed their leaves. The abscission process is also agriculturally important, as it facilitates the dispersal of fruits and seeds. In most flowering plants, including *Arabidopsis*

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Editor's Summary

Marine benefits of the Paris Agreement

Keeping recent global agreements to limit temperature increases to 1.5° to 2°C above preindustrial levels will have benefits across terrestrial ecosystems. But what about marine ecosystems? Cheung *et al.* modeled the influence of temperature increases on two key measures of fishery sustainability, catch and species turnover (see the Perspective by Fulton). Limiting temperature increases to 1.5°C substantially improved catch potential and decreased turnover of harvested species. These results provide further support for meeting this important goal.

Science, this issue p. 1591; see also p. 1530

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