ENVIRONMENTAL STUDIES

Fishers' response to temperature change reveals the importance of integrating human behavior in climate change analysis

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Climate change will reshape ecological dynamics. Yet, how temperature increases alter the behavior and resource use of people reliant on natural resources remains underexplored. Consequent behavior shifts have the potential to mitigate or accelerate climate impacts on livelihoods and food security. Particularly within the small-scale inland fisheries that support approximately 10% of the global population, temperature changes likely affect both fish and fishers. To analyze how changing temperatures alter households' fishing behavior, we examined fishing effort and fish catch in a major inland fishery. We used longitudinal observational data from households in Cambodia, which has the highest per-capita consumption of inland fish in the world. Higher temperatures caused households to reduce their participation in fishing but had limited net effects on fish catch. Incorporating human behavioral responses to changing environmental conditions will be fundamental to determining how climate change affects rural livelihoods, food production, and food access.

INTRODUCTION

Climate change reduced global marine fish catch by 4.1% from 1930 to 2010 (*1*). Future warming projections threaten an additional 3 to 13% fall in global fish harvest by 2050 (*2*). These realized and projected declines in fish catch could have staggering global consequences for the availability of fish for human consumption and detrimental impacts on global access to critical dietary nutrients supplied by fish (*3*). Moreover, falling fish catch could jeopardize the well-being of people most reliant on fisheries: 10% of the population in low and middle income countries relies primarily on fisheries for their incomes, food security, and nutrition (*4*, *5*). In particular, the livelihoods of small-scale fishing households, which comprise 90% of global fishers and are concentrated within developing nations, will be acutely affected (*5*).

Existing models of climate effects on fisheries highlight foreboding ecological effects of global temperature rise (*2*). Yet, the ultimate consequences of climate change for fish-dependent people reflect not only these ecological changes but also how households respond to these changes. Whether rising temperatures and new weather patterns drive people to fish lakes, rivers, and coastlines more intensively; leave fishing for more lucrative livelihoods; or adjust fishing methods or target species will shape both the ecological ramifications of climate change and the consequences for people's incomes and access to nutritious fish.

Fish catch is a function of ecological conditions that determine the availability of fish and the adaptive behavior of fishers who harvest those fish with varying degrees of effort and efficiency (Fig. 1). Our analyses disentangled these two pathways. The behavioral pathway reflects household adaptation to changing weather conditions and was captured using data on decisions about whether to fish at all and, if so, hours spent fishing and gears used. The ecological pathway includes the effects of rising temperature on fish populations and, in turn, fish catch. We indirectly captured the ecological effects of temperature on fish catch by controlling statistically for the temperature effects that are attributable to human behaviors. The climate change literature on fisheries has largely focused on ecological effects without explicitly considering human behavior, which simultaneously affects fish populations and responds to climate stimuli. We show that accounting for the behavioral pathway is imperative to accurately estimate climate change impacts on fishing communities.

While the ecological impact of climate on inland, freshwater fisheries remains relatively underexamined relative to marine systems, we expect climate change to exacerbate demands on inland fisheries and fundamentally alter aquatic ecosystems (*6*, *7*). Inland fisheries often rely on shallow, hydrologically distinct water bodies, which may be particularly susceptible to warming and limit adaptations for fish that cannot easily migrate between isolated inland waters as temperatures become unfavorable (*8*). Under climate change scenarios, evaporation and erratic rainfall may increase eutrophication (*9*), while human demands for and conflict over freshwater may restrict fish habitat (*10*). Freshwater aquatic species across the world already face overlapping threats from human impacts, low warming tolerances, high extinction and species invasion rates, and low evolutionary rates compared to their marine counterparts (*11*, *12*). At the same time, current thermal conditions may not predict fish species' capacity to acclimate (*13*), and nonlinearities or threshold effects at temperatures outside currently observed ranges may exist. Primary productivity may also benefit from increased CO_2 concentrations and higher temperatures, and some fish populations have thrived under warming temperatures (*1*). Thus, the net effect of warming temperatures on fish populations and aggregate catch is ambiguous.

Likewise, for people dependent on freshwater fisheries, the behavioral implications of climate change may take many forms. These behavior changes have complex drivers, including how temperature affects people's perceptions of fishery viability, effectiveness and the

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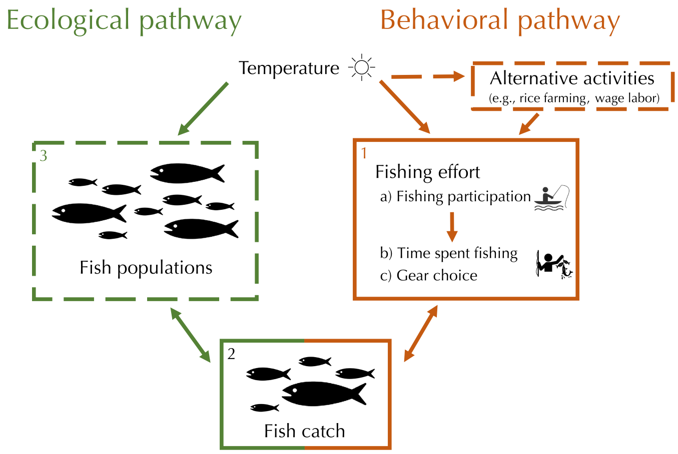

Fig. 1. Ecological and behavioral pathways from temperature to fish catch. Climate change projections typically focus on the ecological pathway and how temperature affects fish populations and thereby shapes fish catch. Our analysis also examined a behavioral pathway, through which changing temperature affected (1) fishing effort, including (a) fishing participation (any fishing in the previous week), (b) time spent fishing (person-days), and (c) gear choice (active or passive), to ultimately affect (2) fish catch. Adjusting for multiple dimensions of fishing effort, we then measured how changing temperature and rainfall shapes (3) fish catch to indirectly isolate the ecological effect of temperature on fish populations. Dashed lines represent unobserved phenomena.

desirability of fishing activities, and demands and opportunities within alternative activities (e.g., agriculture and wage labor). Small-scale fishers are often simultaneously engaged in other activities and may alter their livelihood portfolios by leaving fishing altogether in favor of other activities (*14*, *15*) or shifting time spent fishing, gears, or fishing grounds (*14*, *16*, *17*). Limited evidence from small-scale fisheries already suggests worrisome climate impacts on fisher behavior. In West Africa, small-scale marine fishers report traveling further in response to climate change (*18*), and Ugandan fishers perceived climate change effects on their fishing activities (*19*). Commercial marine fishers have long coped with changing fish availability by adjusting gears or fishing grounds and are projected to respond to climate change through poleward shifts (*20*). Further, recent evidence shows that climate variability reduces commercial fishing employment (*15*). Inland fishers' behavior is geographically and technologically limited relative to their marine and industrial counterparts (*21*), increasing their vulnerability.

How small-scale and inland fishers respond to climate change is critically important because dependence on inland fish resources is particularly high within poor and food insecure communities around freshwaters (*22*, *23*). Even as the extent of inland fish harvest is systematically underestimated (*24*), national economies are acutely vulnerable to climate change impacts on fisheries (*25*). Just 16 countries harvest nearly 80% of inland fish globally, 13 of which are low or middle income and half of which are in Asia (*26*). Our study focuses on Cambodia, which has the fifth largest global inland fish harvest (509,350 tonnes) and highest per-capita inland fish catch (16 to 35 kg) (*26*). The highly diverse fisheries feature nearly 500 fish species that are targeted with highly specialized gears, including those that require active effort to rake mud, cast nets, or spear fish, and passive traps and nets that fishers set and return to harvest (*27*). Fishers in this setting also make use of diverse habitats, including rice fields, flooded forest, streams, tributaries, and the Tonle Sap Lake (*28*). Among Cambodian households, rice farming and other agricultural activities are often primary, and off-farm opportunities are growing (*29*). Given both its livelihood diversity and heavy dependence on fisheries, Cambodia provides an ideal setting to examine the responses of freshwater fishers and fisheries to warming temperatures.

We disentangled empirically how temperature changes affected the behavioral pathway and indirectly affected the ecological pathway, with both pathways contributing to small-scale fishers' catch. We used observed, longitudinal, and household-level fish catch and fishing behavior data. Our approach highlights the importance of household responses to warming temperatures and their influence on fish catch and, ultimately, on livelihoods and well-being in changing fisheries.

To capture the complexity of the monsoon-driven, flood pulse fishing system in Cambodia's rice field fisheries, we used a unique, high-frequency dataset containing the catch and fishing activities of 414 fishing households in the Tonle Sap Lake basin across 19 bi-monthly time points from 2012 to 2015. We also used monthly temperature and rainfall aggregates from remotely sensed data. As seasonal changes in water levels across the floodplain are the well-established primary drivers of fishery productivity and fishing activities in this setting, we controlled for rainfall, flood extent, and month to isolate the temperature effect. Our analyses focused on temperature impacts because modeling analyses of the region consistently predict rising temperatures, while predictions about precipitation patterns are inconsistent (*7*). We used fixed effects, and correlated random effects distributed lag regression models fit to repeated observations (see Materials and Methods) (*30*). This approach provided strong controls for time invariant household characteristics, allowing us to identify the causal effects of exogenous temperature changes within the observed range while controlling for seasonality, spatial, hydrological, and rainfall variation, and the delayed and nonlinear effects that temperature may have on fish catch and fisher behavior. To account for the way temperature and rainfall in previous periods affect current period fish populations and, thereby, fish available to catch, we include lagged temperature and rainfall variables. Our selection of a 2-month lag structure was based on a time series analysis diagnostic process; sensitivity analyses demonstrated highly similar results with varied lag structures (see Materials and Methods).

Our analysis disentangled the behavioral effects of temperature on fish catch via fishing effort, as distinct from the ecological effects of temperature on fish catch via shifting fish availability. We statistically identified the relationships between air temperature and multiple dimensions of fishing behavior (Fig. 1), including (1a) fishing participation (any fishing in the previous week), (1b) time spent fishing (person-days), and (1c) gear choice (active or passive) and (2) fish catch. We then examined (3) fish catch while holding all dimensions of fishing behavior constant to indirectly isolate the net ecological effects of sustained warmer temperatures on fish catch. Our analysis thus triangulated the causal effects of temperature change on both fishing behavior and fish catch by isolating the behavioral effects and indirectly isolating the ecological effects induced by shifting environmental conditions.

RESULTS AND DISCUSSION

The behavioral pathway analysis demonstrated that fishers responded to higher temperatures primarily by opting out of fishing (Fig. 2).

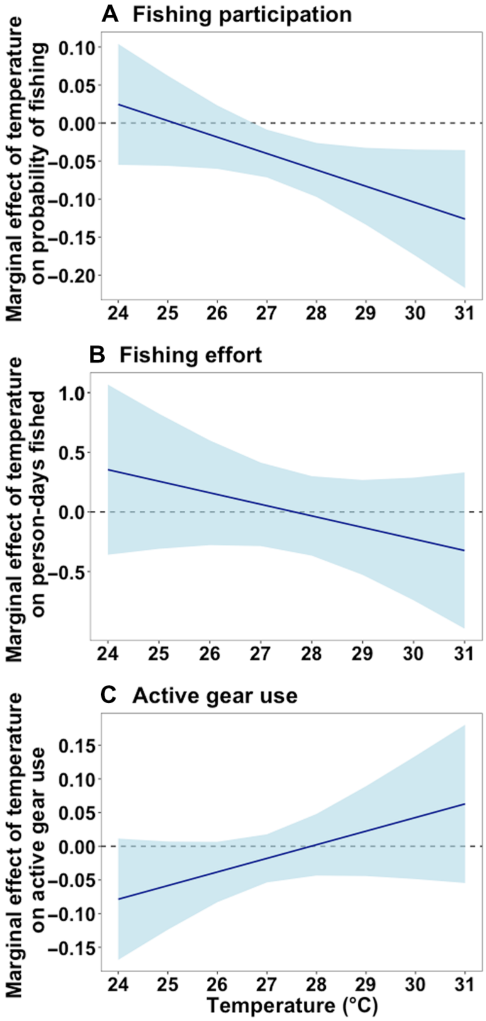

Fig. 2. Effect of temperature on fishing participation, effort, and gear use. Temperatures above the current mean of 28°C reduced (**A**) fishing participation (any fishing in the previous week), although there is no impact of rising temperatures on (**B**) fishing effort (person-days) or (**C**) whether a household used active gear. Plots depict the estimated marginal effect of sustained, single-degree temperature changes across the temperature distribution, accounting for lags and polynomial terms (table S2, models 1 to 3). Dashed lines show 95% confidence intervals. This plot represents a marginal effect rather than a trendline; therefore, this and subsequent plots are interpreted as follows, using (A) as an example: The value at 28°C represents the estimated change in probability of fishing participation when temperatures increase from 28° to 29°C (6% reduction). The value at 29°C represents the change in probability of fishing when temperatures increased from 29° to 30°C (8%). The probability of fishing participation under a two-degree temperature increase from 28° to 30°C is the sum of each single-degree change (14%).

The magnitude of the effect on fishing behavior differs at different temperatures (e.g., larger effect at higher temperatures), so we present marginal effects, which show the varied effects of a 1°C temperature increase across the temperature distribution. An increase in air temperature from 28° to 29°C, sustained over 2 months, reduced the probability of fishing in a given period by 6%, while a sustained increase from 29° to 30°C reduced the probability of fishing by 8%. These effects are additive, so a sustained 2° rise from 28° to 30°C decreased the probability of fishing by 14%. Among those who fished

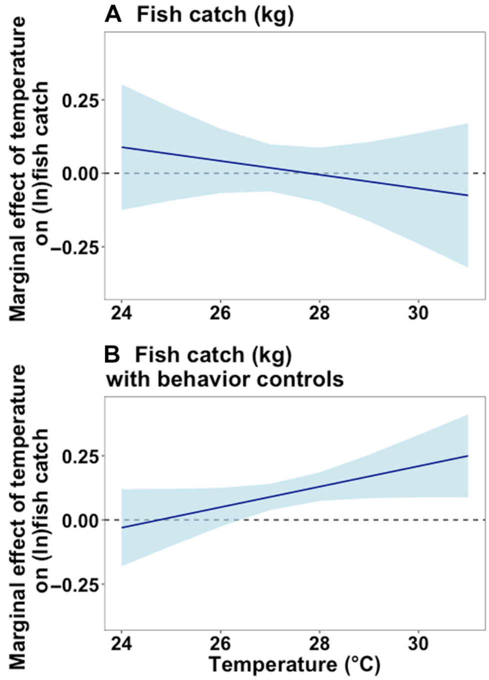

Fig. 3. Effect of temperature on fish catch. The effects of a sustained 1° increase in temperature above 28°C were (**A**) mildly negative and statistically insignificant, when taking into account the aggregated "ecological" and "behavioral" effects of temperature on fish catch. Yet, when we controlled for fishing behavior (**B**), we found a statistically significant increase in fish catch attributable to the ecological effects of rising temperature while holding fishing effort constant, a metric analogous to isolating fish catch (kilograms)-per-unit-effort. However, the potential positive ecological effect on fish availability from warming temperatures is offset by human behavioral responses that reduced fishing effort, and, ultimately, there was no effect on fish catch.

at a given time point, we found no clear effect of higher temperatures on time spent fishing or use of active gear.

We next examined the implications for fish catch. To indirectly identify the ecological effect, we estimated the net causal effect of temperature on fish catch in two steps. First, we directly estimated the effect of temperature on fish catch and found a negative but statistically insignificant relationship (Fig. 3A). Second, we added controls for multiple dimensions of human behavior (fishing participation, time spent fishing, gear choice, and flooding) to statistically isolate the ecological pathway from the behavioral pathway. We found a positive and statistically significant association between temperature and fish catch after accounting for multiple dimensions of human behavior (Fig. 3B). Our findings apply within the observed temperature range, where the majority of temperatures were under 30°C. A sustained temperature increase from 28° to 29°C was associated with a 13% increase in fish catch. A sustained 2° increase was associated with a 30% increase in fish catch. Measuring fish catch while holding fishing behavior constant can be interpreted as analogous to an increase in catch-per-unit-effort, a metric commonly used to understand the extent and effectiveness of fishing pressure.

Our findings suggest that, in this system, a sustained 1° to 2°C temperature increase had a positive effect on fish catch via the indirectly measured ecological pathway (Fig. 3B). Yet, the net effect of temperature on fish catch (Fig. 3A) is statistically insignificant, likely because sustained temperature increases also induced people to reduce fishing effort (Fig. 2, A and B), thereby offsetting the positive ecological effect. The observation of reduced fishing effort alongside positive ecological effects of temperature increase signals simultaneous higher returns to fishing effort and higher opportunity costs of fishers' time as temperature increases. In short, when temperatures increased, people engaged in alternative livelihood activities to fishing, despite ecological conditions improving their potential catch.

We also examined the effects of temperature on two other aquatic harvests within inland Cambodia: catch of other aquatic animals (e.g., snakes and frogs) and the harvest of aquatic plants. Households harvested an average of 4.96 kg of fish/week, while average catch of other aquatic animals and aquatic plant harvest reached 1.26 and 1.58 kg/week, respectively. These aquatic resources are key components of Cambodian livelihoods and diets and may also be affected by warming temperatures, or could provide alternative livelihood opportunities if households reduced fishing effort. Higher temperatures reduced participation, time spent harvesting, and whether active gear was used in capture of other aquatic animals (fig. S1). The net harvest, a measure of catch including the ecological effect and harvest behavior, of other aquatic animals (Fig. 4A) and plants (Fig. 4C) increased significantly with higher temperatures, except for aquatic animals at the highest temperatures. Decreased harvest effort of other aquatic animals and plants only partially offset the increased yields (Fig. 4, B and D).

Our findings suggest notably consistent human behavioral and ecological responses to warming temperatures across the harvest of different resources, including fish, other aquatic animals, and aquatic plants. Households responded to warmer conditions by not participating in aquatic harvest of all kinds. In addition to a consistent behavioral pathway, these results further point to a consistent ecological mechanism, where our indirect estimates of the ecological pathway suggest that slightly higher sustained temperatures increased the productivity of fish, other aquatic animals, and aquatic plants. If warming temperatures increased primary productivity, which is highly plausible given that the large majority of temperatures observed were below 30°C, that may have contributed to a rise in fish catch. Such a finding would be consistent with a range of studies that suggest warming temperatures may increase aquatic plant productivity (*31*), although the time horizon for increased fish and other aquatic animal productivity is likely to vary considerably by species and trophic level. At the same time, warming temperatures may alter the catchability of fish and other aquatic animals by shifting the habitats they use, driving them into deeper waters, or altering diel cycles (*8*).

Without accounting for fisher behavioral responses to higher temperatures, it would appear that temperature had no effect on fish catch (Fig. 2A) and a positive effect on other aquatic resources harvest (Fig. 4A). Yet, what we actually observed was fewer households fishing or harvesting aquatic resources in response to warming. Climate projections tailored to the study region anticipate a temperature increase of approximately 2°C by 2060 (*32*) and largely overlap with the observed range of our data (fig. S2). With a 2°C sustained rise above the average temperature, we found that households were 14% less likely to fish. The effort reductions observed are substantial as, in any given survey time period, 67% of households

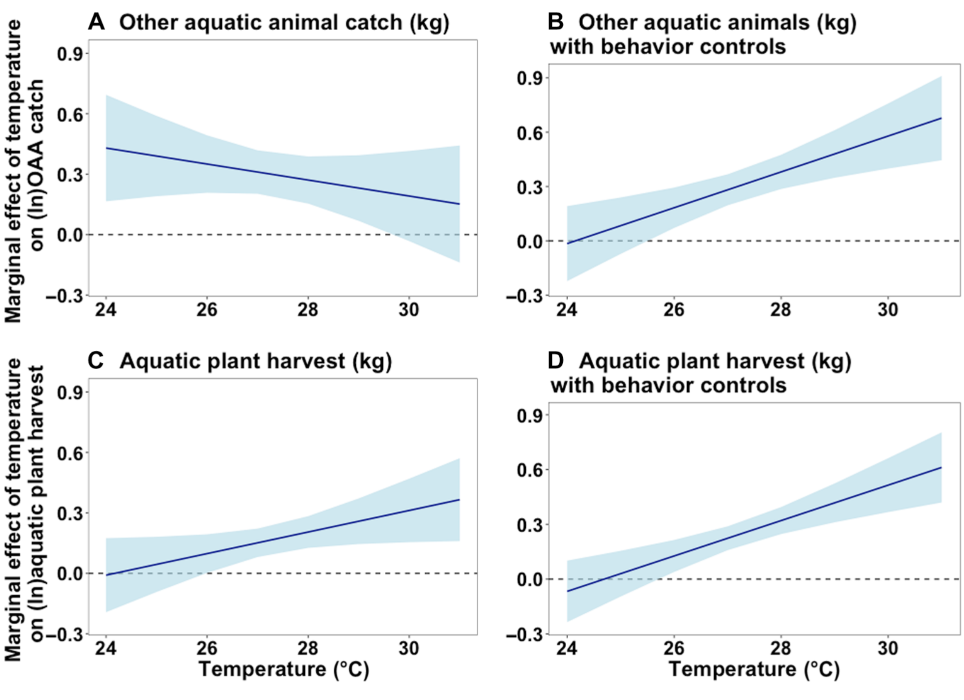

Fig. 4. Effect of temperature on other aquatic animal (OAA) and aquatic plant harvest. For other aquatic animals, (**A**) we found that the aggregate ecological and behavioral effect of temperature on other aquatic animal harvest is positive, except at the most extreme temperatures. For aquatic plants, (**C**) we found that the aggregate ecological and behavioral effect of temperature on aquatic plant harvest is positive and greatest at the highest temperatures. For both (**B**) other aquatic animals and (**D**) aquatic plants, when we controlled for harvest effort (we use fishing effort as a proxy for aquatic plant harvesting effort, which was not available), we found a slightly larger increase in harvest attributable to ecological effects of rising temperature while holding effort constant, a metric analogous to isolating harvest (kilograms)-per-unit-effort. This finding suggests reductions in effort as temperature rise is limiting harvest.

fished for an average of 3.3 person-days/week. These meaningful responses to environmental change are easily overlooked when human behavior is not integrated in analyses.

Although our data do not enable us to identify the activities to which households reallocated their time in response to higher temperatures, rising temperatures plausibly affect alternate activities. Households within our study largely consider rice farming as their primary livelihood activity (*33*). If higher temperatures also increase pest and weed pressure (*34*), households may choose to divert effort from fishing to protect their rice crops, a pattern that has been documented in other tropical cropping systems (*35*). Fishing participation may similarly fall as households pursue other local opportunities or members migrate, even if only temporarily, to growing urban sectors within Cambodia and in nearby Thailand (an estimated 25 and 6% of the rural population, respectively) (*36*–*38*). Ultimately, access to natural resources, agricultural land, education, and urban markets will shape decisions, constraints, and disparities in response to temperature across households.

Rural households generally, and within our study communities in particular, engage in a complex portfolio of livelihoods, many of which depend on natural resources (*33*). Our findings that households are less likely to fish despite rising catch-per-unit-effort suggests a rebalancing of this livelihood portfolio as households respond to temperature effects on fishing activities or on nonfishing activities' desirability or productivity. While temperatures within our study were largely below 30°C, nonlinearities and threshold effects could produce different ecological or behavioral responses at temperatures beyond those observed. Further, climate and environmental changes (e.g., dams) are projected to not only raise temperatures in Cambodia but also alter rainfall and flooding regimes with effects across a range of rural livelihoods (*7*). Human behavioral responses to these changes promise to be complex and multifaceted, and the consequences of these responses are uncertain. The households we study consumed over 70% of the fish they caught and 87% of other aquatic animals. Declining aquatic food catch, whether as a result of altered effort or ecological conditions, could reduce the nutritional quality of local diets by reducing households' access to these nutrient rich foods. Alternatively, the type of household adaptations we observed may successfully buffer the impact of ecological change on income and diets.

Failure to account for the human behavioral dimensions of rising temperatures has profound implications for understanding climate change. Given the complexity of resource-dependent livelihoods in the developing world, misestimating climate impacts threatens to misdirect the response needed for climate change among the most vulnerable households. The rural households most closely tied to agricultural systems and the harvest of natural resources will undoubtedly be among the first and most severely affected by rising temperatures. Understanding and mitigating the effects of climate change within these communities around the world, however, will ultimately hinge on accurate prediction and integration of both the human behavioral and the ecological dimensions of climate change.

MATERIALS AND METHODS

Data

We used household data collected by WorldFish and partner NGOs that we matched to georeferenced satellite imagery and weather data. Household panel data were collected from 414 households every 2 months over a 3-year period (19 time points), from November 2012 through November 2015. Data were collected in conjunction with monitoring of 40 Community Fish Refuges (CFRs), community-managed inland protected areas within the rice field fisheries. All households were located in an area where ongoing programs support CFR management and fish habitat improvements (*39*). The survey sample was selected in two stages; the households selected in the second stage provided that data used in this study. The first stage was a random sample from an enumerated sampling list of 16 households in one to three villages adjacent to each CFR that met the inclusion criteria of participating in fishing, cultivating a rice field, and not planning to migrate seasonally. The second stage purposively selected 10 households from the initial 16 to capture households with children under 5 years old. Further details on the procedures used can be found in the Supplementary Materials and project documentation (*28*, *40*). After attrition due to missing data in key variables, our current estimation sample consists of an unbalanced panel of 414 households. All households were interviewed in at least one follow-up time point so no households are lost to follow up, and 308 (74%) are present in all panel periods. We test whether attrition might bias our parameter estimates and find that it has no meaningful effect (see the Supplementary Materials).

Air temperature data come from a combination of the National Oceanic and Atmospheric Administration National Centers for Environmental Information's Global Historical Climatology Network and the Climate Anomaly Monitoring System (*26*). Rainfall data come from the Global Land Data Assimilation System Version 2. Flooding data come from the European Commission's Joint Research Center Global Surface Water Explorer, which maps seasonal and permanent surface water including paddy fields using United States Geological Survey (USGS) Landsat 5, 7, and 8 (*41*).

Statistical methods

We model two distinct pathways through which temperature can affect fish catch. The first is the behavioral response of the fisher to temperature change. This could be due to physical discomfort with high or low temperatures, changing opportunity costs of time spent fishing—rather than in crop or livestock agriculture, nonfarm work, domestic chores, or leisure—under different temperature regimes, or fisher expectations of fishing conditions signaled by temperature. The second is an ecological effect via the availability of fish in the system, due to the effect of temperature on fish spawning and development, water quality and nutrient concentrations, and/or fish migratory responses (e.g., seeking deeper or cooler water). We are able to directly identify the behavioral effects and indirectly identify the ecological effects. The use of catch data to understand fish population dynamics is a widely used and long-standing approach in fishery stock management (*42*). While catch-per-unit-effort measures can produce biased fish stock estimates over long time horizons and without careful accounting for gear (*43*, *44*), our relatively short time horizon, inclusion of gear types, and use of household-level data minimize this concern within our study.

We analyze the behavioral pathway by investigating whether fishers' participation (1a), effort conditional on participation (1b), and gear choice conditional on participation (1c) are affected by temperature change (Fig. 1). We then investigate the composite effect of temperature on fish catch, inclusive of both ecological and behavioral pathways together (2). Last, we control for behavior in examining how temperature relates to catch (3), allowing us to indirectly estimate the ecological effect. Together, these analyses allow us to describe the causal effect of temperature on fish catch separately for each pathway and descriptively explore the ways that households use adaptive strategies.

All models are estimated with model-specific fixed effects to control for time-invariant characteristics in the cross-sectional units, as well as month fixed effects to control for seasonality common to all sample households in average years. Household fixed effects are included in (1a to 1c) models. CFR fixed effects account for the notable diversity of CFR types within this system in (2) and (3) models, for which we use the Honoré correlated random effects estimator (*30*), approximating a household fixed effect in a random effects Tobit model (*45*, *46*). Using fixed effects models allows us to compare the relationship between a given household's temperature experience and its outcomes over time by identifying the causal effect of temperature in within-household variation in fishing effort and catch over time. We cluster SEs at the CFR level, as that was the locus of the survey design.

We allow for the possibility that temperature has a nonlinear, quadratic relationship with fish catch as fish species in this system are understudied, providing very limited life history information. Our findings are relevant within the range of temperatures observed, and outside this range, further nonlinearities or threshold effects are possible. We determined the optimal lag structure via Akaike and Bayes Information Criteria (AIC and BIC) for each potential model. The AIC and BIC test results consistently favor an optimal specification of one, two, or three lags, with no substantive difference, so we estimate the more parsimonious single lag. Please see the full details of statistical methods and model specifications in the Supplementary Materials.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/18/eabc7425/DC1

REFERENCES AND NOTES

1. C. M. Free, J. T. Thorson, M. L. Pinsky, K. L. Oken, J. Wiedenmann, O. P. Jensen, Impacts of historical warming on marine fisheries production. *Science* **363**, 979–983 (2019).
2. W. W. L. Cheung, M. C. Jones, G. Reygondeau, C. A. Stock, V. W. Y. Lam, T. L. Frölicher, Structural uncertainty in projecting global fisheries catches under climate change. *Ecol. Model.* **325**, 57–66 (2016).
3. C. D. Golden, E. H. Allison, W. W. L. Cheung, M. M. Dey, B. S. Halpern, D. J. McCauley, M. Smith, B. Vaitla, D. Zeller, S. S. Myers, Nutrition: Fall in fish catch threatens human health. *Nature* **534**, 317–320 (2016).
4. FAO, *State of the World's Fisheries and Aquaculture* 2016 (State of the World's Fisheries and Aquaculture series, FAO, Rome, 2016).
5. FAO, State of the World's Fisheries and Aquaculture 2014 (State of the World's Fisheries and Aquaculture series, FAO, Rome, 2014).
6. C. Harrod, A. Ramírez, J. Valbo-Jørgensen, S. Funge-Smith, in *Impact of Climate Change on Fisheries and Aquaculture*, M. Barange, T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith, F. Poulain, Eds. (FAO, Rome, Italy, 2018).
7. L. P. Hoang, H. Lauri, M. Kummu, J. Koponen, M. T. H. van Vliet, I. Supit, R. Leemans, P. Kabat, F. Ludwig, Mekong River flow and hydrological extremes under climate change. *Hydrol. Earth Syst. Sci.* **20**, 3027–3041 (2016).
8. A. D. Ficke, C. A. Myrick, L. J. Hansen, Potential impacts of global climate change on freshwater fisheries. *Rev. Fish Biol. Fish.* **17**, 581–613 (2007).
9. P. Kratina, H. S. Greig, P. L. Thompson, T. S. A. Carvalho-Pereira, J. B. Shurin, Warming modifies trophic cascades and eutrophication in experimental freshwater communities. *Ecology* **93**, 1421–1430 (2012).
10. M. A. Xenopoulos, D. M. Lodge, J. Alcamo, M. Marker, K. Schulze, D. P. van Vuuren, Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Glob. Chang. Biol.* **11**, 1557–1564 (2005).
11. J. D. Olden, M. J. Kennard, F. Leprieur, P. A. Tedesco, K. O. Winemiller, E. García-Berthou, Conservation biogeography of freshwater fishes: Recent progress and future challenges. *Divers. Distrib.* **16**, 496–513 (2010).
12. L. Comte, J. D. Olden, Climatic vulnerability of the world's freshwater and marine fishes. *Nat. Clim. Change* **7**, 718–722 (2017).
13. L. Comte, J. D. Olden, Evolutionary and environmental determinants of freshwater fish thermal tolerance and plasticity. *Glob. Chang. Biol.* **23**, 728–736 (2017).
14. L. L. Colburn, M. Jepson, C. Weng, T. Seara, J. Weiss, J. A. Hare, Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. *Mar. Policy* **74**, 323–333 (2016).
15. K. L. Oremus, Climate variability reduces employment in New England fisheries. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 26444–26449 (2019).
16. M.-C. Badjeck, E. H. Allison, A. S. Halls, N. K. Dulvy, Impacts of climate variability and change on fishery-based livelihoods. *Mar. Policy* **34**, 375–383 (2010).
17. S. Coulthard, in *Adapting to Climate Change: Thresholds, Values, Governance*, W. N. Adger, I. Lorenzoni, K. L. O'Brien, Eds. (Cambridge Univ. Press, 2009), pp. 255–268.
18. D. Belhabib, V. W. Y. Lam, W. W. L. Cheung, Overview of West African fisheries under climate change: Impacts, vulnerabilities and adaptive responses of the artisanal and industrial sectors. *Mar. Policy* **71**, 15–28 (2016).
19. L. Musinguzi, J. Efitre, K. Odongkara, R. Ogutu-Ohwayo, F. Muyodi, V. Natugonza, M. Olokotum, S. Namboowa, S. Naigaga, Fishers' perceptions of climate change, impacts on their livelihoods and adaptation strategies in environmental change hotspots: A case of Lake Wamala, Uganda. *Environ. Dev. Sustain.* **18**, 1255–1273 (2016).
20. B. J. McCay, Shifts in fishing grounds. *Nat. Clim. Chang.* **2**, 840–841 (2012).
21. P. Morand, A. Kodio, N. Andrew, F. Sinaba, J. Lemoalle, C. Béné, Vulnerability and adaptation of African rural populations to hydro-climate change: Experience from fishing communities in the Inner Niger Delta (Mali). *Clim. Change* **115**, 463–483 (2012).
22. P. B. McIntyre, C. A. Reidy Liermann, C. Revenga, Linking freshwater fishery management to global food security and biodiversity conservation. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 12880–12885 (2016).
23. S. Funge-Smith, A. Bennett, A fresh look at inland fisheries and their role in food security and livelihoods. *Fish Fish.* **20**, 1176–1195 (2019).
24. E. Fluet-Chouinard, S. Funge-Smith, P. B. McIntyre, Global hidden harvest of freshwater fish revealed by household surveys. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 7623–7628 (2018).
25. E. H. Allison, A. L. Perry, M.-C. Badjeck, W. Neil Adger, K. Brown, D. Conway, A. S. Halls, G. M. Pilling, J. D. Reynolds, N. L. Andrew, N. K. Dulvy, Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.* **10**, 173–196 (2009).
26. FAO, *State of the World's Fisheries and Aquaculture 2018* (State of the World's Fisheries and Aquaculture series, FAO, Rome, Italy, 2018).
27. E. Baran, P. Chheng, V. Ly, J. Nasielski, S. Saray, B. Touch, J. Tress, K. Kaing, S. Tan, Fish resources in Cambodia (2001–2011), in *Atlas of Cambodia*, S. Brod, R. Sandoval, Eds. (Save Cambodia's Wildlife, Phnom Penh, Cambodia, 2014).
28. S. Freed, Y. Kura, V. Sean, S. Mith, P. Cohen, M. Kim, S. Thay, S. Chhy, Rice field fisheries: Wild aquatic species diversity, food provision services and contribution to inland fisheries. *Fish. Res.* **229**, 105615 (2020).
29. M. Keskinen, The lake with floating villages: Socio-economic analysis of the Tonle Sap Lake. *Int. J. Water Resour. Dev.* **22**, 463–480 (2006).
30. B. E. Honoré, Trimmed LAD and least squares estimation of truncated and censored regression models with fixed effects. *Econometrica* **60**, 533–565 (1992).
31. P. Zhang, B. M. C. Grutters, C. H. A. van Leeuwen, J. Xu, A. Petruzzella, R. F. van den Berg, E. S. Bakker, Effects of rising temperature on the growth, stoichiometry, and palatability of aquatic plants. *Front. Plant Sci.* **9**, 1947 (2019).
32. C. McSweeney, M. New, G. Lizcano, X. Lu, The UNDP Climate Change Country Profiles Improving the Accessibility of Observed and Projected Climate Information for Studies of Climate Change in Developing Countries, in *Bulletin of the American Meteorological Society* (UNDP, 2010), pp. 157–166.
33. T. T. Nguyen, T. L. Do, D. Bühler, R. Hartje, U. Grote, Rural livelihoods and environmental resource dependence in Cambodia. *Ecol. Econ.* **120**, 282–295 (2015).
34. K. Ramesh, A. Matloob, F. Aslam, S. K. Florentine, B. S. Chauhan, Weeds in a changing climate: Vulnerabilities, consequences, and implications for future weed management. *Front. Plant Sci.* **8**, 95 (2017).
35. M. Jagnani, C. B. Barrett, Y. Liu, L. You, Within-season producer response to warmer temperatures: Defensive investments by Kenyan farmers. *Econ. J.* **131**, 392–419 (2021).
36. U. UNESCO, IOM, and UN-Habitat, *Brief 2: Country Brief—Cambodia* (Policy Briefs on Internal Migration in Southeast Asias series, 2018).
37. C. Gray, V. Mueller, Drought and population mobility in rural Ethiopia. *World Dev.* **40**, 134–145 (2012).
38. M. Bylander, *Working Paper 7: Cambodian Migration to Thailand: The Role of Environmental Shocks and Stress* (Global Knowledge Partnership on Migration and Development, 2016).

39. K. J. Fiorella, E. R. Bageant, M. Kim, V. Sean, V. Try, H. J. MacDonell, E. Baran, Y. Kura, A. C. Brooks, C. B. Barrett, S. H. Thilsted, Analyzing drivers of fish biomass and biodiversity within community fish refuges in Cambodia. *Ecol. Soc.* **24**, 18 (2019).
40. O. Joffre, How important are the rice field fisheries?, in *A livelihood baseline survey around the Tonle Sap Lake for the Rice Field Fisheries Enhancement Project* (USAID, WorldFish, 2013).
41. J.-F. Pekel, A. Cottam, N. Gorelick, A. S. Belward, High-resolution mapping of global surface water and its long-term changes. *Nature* **540**, 418–422 (2016).
42. R. Hilborn, C. J. Walters, *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty* (Springer, 1992).
43. M. N. Maunder, J. R. Sibert, A. Fonteneau, J. Hampton, P. Kleiber, S. J. Harley, Interpreting catch per unit effort data to assess the status of individual stocks and communities. *ICES J. Mar. Sci.* **63**, 1373–1385 (2006).
44. S. J. Harley, R. A. Myers, A. Dunn, Is catch-per-unit-effort proportional to abundance? *Can. J. Fish. Aquat. Sci.* **58**, 1760–1772 (2001).
45. A. Levin, C.-F. Lin, C.-S. James Chu, Unit root tests in panel data: Asymptotic and finite-sample properties. *J. Econom.* **108**, 1–24 (2002).
46. A. Inoue, G. Solon, A portmanteau test for serially correlated errors in fixed effects models. *Economet. Theor.* **22**, 835–851 (2006).

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