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Dried fish provide widespread access to critical nutrients across Africa

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Aquatic foods are essential in supporting food security and nutrition across the tropics, with "dried" fish particularly affordable, available, and nutritious. However, dried fish food systems are often hidden and overlooked due to data scarcity, limiting understanding of how dried fish contribute to nutrient intakes. Here, we combine nutrient analysis of fish samples with national household surveys from across East and West Africa to understand the importance of dried fish in diets. We find that small portions of dried fish contribute over 15% of recommended intakes for multiple essential dietary nutrients (calcium, iodine, iron, selenium, zinc, and vitamins B12 and D), with low heavy metal concentrations, and are consumed weekly by ~one-third of households in six countries (Côte d'Ivoire, Ghana, Nigeria, Malawi, Tanzania, and Uganda) (~144 million people). Dried fish consumption was more prevalent than fresh fish, reaching 54% more people, particularly those in poor households and near to marine coastlines or urban centers. The widespread prevalence of nutritious dried fish suggests that these foods and their distribution networks play critical roles in food security and nutrition, even in households distant from fisheries or urban centers. Dried fish can fill nutrient gaps across the tropics but will require policies that mitigate negative effects of overfishing, environmental changes, and competition with international markets, while providing postharvest support to fish processors.

fisheries | aquatic foods | diets | food security | heavy metals

Significance

Dried fish are affordable and nutritious foods, caught by small-scale fisheries and distributed by informal networks throughout the tropics. Yet data scarcity on nutrient and contaminant contents, consumption rates, and fisheries catches has meant that dried fish contributions to diets remain overlooked. We analyzed sun-dried and smoked fish from East and West Africa, and the Indian Ocean, finding that small amounts of dried fish contribute significantly to recommended nutrient intakes for young children and women. Using household surveys from across Africa, we estimate that dried fish reach one-third of households and are consumed by more people than fresh fish. Our results provide a large-scale analysis of dried fish consumption, underlining their importance for global food security and nutrition.

Aquatic foods play a critical role in preventing and reducing malnutrition, especially among vulnerable populations (1–3), providing essential vitamins, minerals, and long-chain omega-3 fatty acids (4, 5). Fish caught in oceans, lakes, and rivers across Africa and Asia are particularly important sources of nutrition that, when dried, provide large supplies of affordable and nutritious foods that can be stored for long periods of time and easily transported (6, 7). Most countries with fishing histories have strong cultural associations with dried fish (8), from the trade of sun-dried tuna (*Maldive fish*) across Asia in the 1300s (9) to trans-Atlantic Iberian salt cod (*Bacalau*) during European colonialism (10). Dried fish remain important local nutrient-rich foods and regional commodities across Africa (8, 11), Asia (12, 13), and Small Island Developing States (14, 15). Yet, there is a poor understanding of the status and importance of dried fish food systems, due in part to its informal nature and data limitations. For example, dried fish come predominantly from small-scale fisheries that are underrepresented in catch statistics (5, 16), can involve the movement of products over large distances through informal trade networks (17, 18), and involve highly variable consumption patterns (19), with sparse nutrient composition data (20, 21). As a result, the role of dried fish in supporting food security and nutrition is often undervalued and hidden, limiting our understanding of how dried fish contribute to healthy diets.

Drying provides a means of preserving animal-source foods with fluctuating production levels (e.g., seasonal climate and weather) (22), helping maintain year-round supply, even for countries without direct access to the resource, such as land-locked countries accessing marine catch and regions with limited access to refrigeration. Fish that are dried are typically caught in large quantities from productive and diverse ecosystems, including freshwater lakes, coastal upwellings, and coral reefs (7). Open-water habitats are particularly important for dried fish supply, such as West Africa's coastal upwellings (23) and East Africa's Great Lakes (24) that support productive populations of small-bodied "pelagic" fishes. Nearshore ecosystems such as coral reefs also support fisheries for larger species that are dried whole or as fillets, which can be important aquatic foods for island states (25,

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26). Dried fish are among the most nutritious animal-source foods (2), but some products can be associated with elevated risk of bacterial contamination and exposure to heavy metals (27, 28). Once processed, dried fish can be stored without refrigeration, permitting long-distance trade, distribution to remote inland areas, and storage over months (7, 8, 29). Dried fish are thus widespread but data-poor, meaning that we lack understanding on how nutrient and contaminant content vary among species, ecosystems, and drying processes (e.g., smoked or sun-dried). Furthermore, while links between fish consumption and access to fisheries and markets are well established (30–32), dietary studies often do not delineate between fresh and dried forms, limiting understanding of who eats dried fish.

Here, we assess the nutritional value of tropical dried fish and examine drivers of fish consumption of fresh and dried forms. We sampled species representative of dried fish systems situated in marine and freshwater systems across five countries and contrasted sun-dried, smoked, and powdered products with fresh fish to quantify the dietary contributions of dried fish to women and young children. We then pair this information with fish consumption data from nationally representative household surveys across six African countries, using statistical models to assess socioeconomic and geographic drivers of dried and fresh fish consumption. These models enabled us to quantify associations between fish consumption and household wealth and physical access to fisheries, and to predict the number of people accessing fresh and dried fish in each country. We conclude by examining the status of dried fish value chains, focusing on opportunities for protecting and enhancing dried fish supply for food security and nutrition.

Results and Discussion

Nutrient and Heavy Metal Content of Dried Fish. We collected and analyzed dried and fresh whole-body composite samples from 19 species of fish, mostly small-bodied, including freshwater species from the Great Lakes of Africa (e.g., Lake Victoria cyprinid, *Rastrineobola argentea,* locally known as dagaa, mukene, or omena), marine coastal species from West Africa (e.g., Madeiran sardinella, *Sardinella maderensis*), and reef-associated species from the Indian Ocean (e.g., rabbitfish, *Siganus sutor*) (*SI Appendix*, Fig. S1 and Dataset S1). We assessed fish nutrient content relative to recommended nutrient intakes for women and children, quantifying the contribution of a fixed weight fish portion to Nutrient Reference Values (NRV) for minerals, vitamins, and fatty acids. We also estimated the nutrient density of dried and fresh fish, defined as the cumulative contribution of nine nutrients to NRV, which had a maximum value of 900% (33, 34). Using published portion sizes from quantified diet surveys (*SI Appendix*, Table S1), our analysis showed that a 9 g portion of dried fish had an average nutrient density of 233 to 403% for young children (6 mo - 5 y old) (Fig. 1*A*), providing over half of the NRV for calcium (53%), selenium (69%), and vitamin B12 (85%), and contributing to NRVs for iron (18%), iodine (20%), omega-3 fatty acids (eicosapentaenoic acid, EPA and docosahexaenoic acid, DHA) (12%), zinc (15%), and vitamin D (19%). Very small portions of dried fish were a significant dietary source of five minerals, omega-3 fatty acids, and vitamins B12 and D (e.g., less than 15 g provides >15% NRV) (Figs. 1*B* and 2*A*). For a nonpregnant woman (15 to 49 y old), a larger dried fish portion (41 g) provided over half the NRV for calcium (78%), iodine (56%), selenium (89%), vitamin B12 (63%), and vitamin D (63%) and was a dietary source of iron (20%), omega-3 fatty acids (36%), and zinc (24%) (*SI Appendix*, Fig. S2). Our results were based on average dried fish portion sizes reported in diet surveys of children (9 g) and women (41 g) in fishing communities, though we note that portion sizes can vary between one-fifth to three times of this average value (*SI Appendix*, Table S1). All dried fish were highly nutritious, though nutrient concentrations varied between marine and freshwater species, and by processing form. Powdered and smoked marine species, for example, had the highest iron and omega-3 fatty acid concentrations, whereas freshwater species from Lake Victoria (dagaa/mukene/omena and haplochromine species) had relatively higher calcium and zinc concentrations (>40% NRV for children 6 mo–5 y old) (*SI Appendix*, Figs. S1 and S3).

Heavy metals such as mercury and other contaminants such as dioxins and polychlorinated biphenyls can also be concentrated in fish (35), and consumption of smoked fish has been associated with health risks, due to the formation of carcinogenic polycyclic aromatic hydrocarbons (PAHs) during the smoking process (27, 36). As with nutrients, concentrations of contaminants vary among fish species (e.g., bioaccumulation of mercury in fish at upper trophic levels) but are also influenced by the animals' environmental conditions (37, 38), while processing methods may increase concentrations or introduce additional contaminants (e.g., smoking) (36). These factors together influence an individual's dietary exposure to contaminants (39), but data on contaminant risks for tropical small fish remain lacking (35). Here, for a 6 kg child, a 9 g portion of dried fish contributed to 1 to 4% of the tolerable weekly intake (TWI) of mercury and <1% of the provisional tolerable monthly intake (PTMI) of cadmium (*Methods*) (*SI Appendix*, Fig. S4). Three samples were above the maximum regulatory limit for lead, including two sun-dried anchovy samples that were also concentrated in cadmium (but below its provisional tolerable intake). Larger-bodied, sun-dried reef fishes had highest mercury risks (5 to 9% of tolerable intake) (*SI Appendix*, Fig. S5). These levels of heavy metal contaminants in dried fish, combined with high concentrations of essential dietary nutrients, broadly support recommendations that the health benefits of fish consumption outweigh the risks from heavy metal and contaminant exposure (35, 40). Nevertheless, processing-specific risks, such as microbial contamination and PAHs in smoked fish, and environmental effects on contaminant levels in fresh fish, warrant further investigation, particularly for small species in areas with high fish consumption (7).

Processing of fish by sun-drying and smoking concentrates essential nutrients into smaller, shelf-stable portions, such that all dried fish forms had a higher nutrient density than fresh fish, for equivalent portion sizes (Fig. 1). However, dried and fresh fish contributions to NRV varied between nutrients, whereby a fresh fish portion must be, on average, four times larger than dried fish to provide a source of minerals for young children (23 g vs. 6 g, respectively), but 50% smaller to be a source of vitamins (15 g vs. 28 g) (*SI Appendix*, Fig. S2). These differences reflect the combined effect of both degradation (e.g., nutrient denaturation through heat) and concentration of nutrients (e.g., through water evaporation) during drying processes. Water content of dried samples varied between 8 to 53% (72 to 81% in fresh samples), indicating the concentration of nutrients through drying varied between sun-dried, smoked, and powdered samples. After correcting dried fish nutrient concentrations for this water loss, we found that drying degraded vitamins and omega-3 fatty acids (40 to 80% decrease in concentration) more than calcium, iodine, selenium, and zinc (4 to 27% decrease) (Fig. 2*B*). Some samples increased in concentration after drying (and correcting for water loss), particularly iron (+60%), cadmium (+37%), and lead (+197%), suggesting unmeasured effects of processing (e.g., contamination), or varying

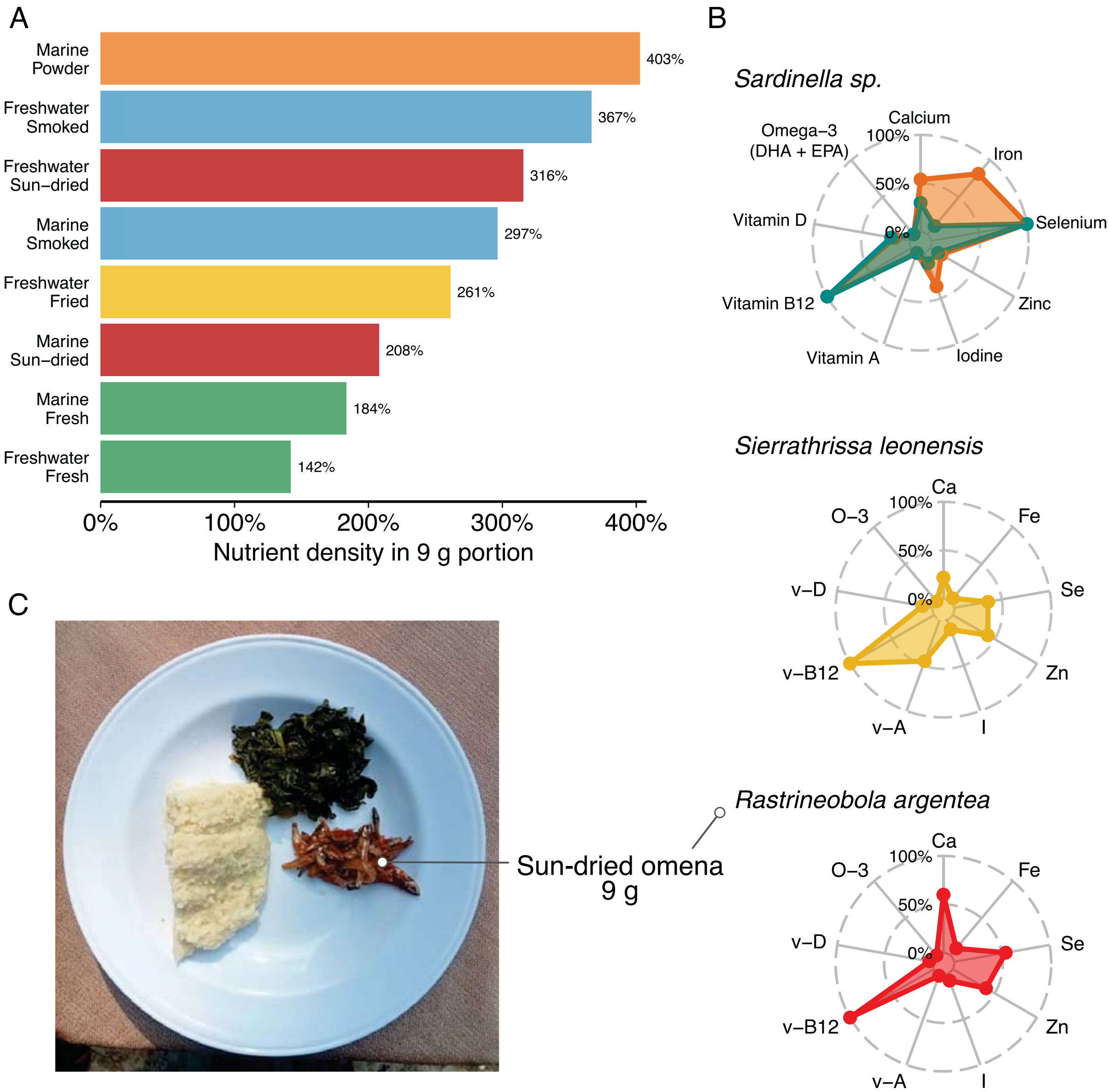

Fig. 1. Nutrient content of tropical whole small fish in different processing forms. (*A*) Nutrient density of different processing forms of wild-caught small fish species. Nutrient density (%) is the combined contribution to NRV for young children (0.5 to 5 y) from a 9 g portion (maximum = 900%). (*B*) Contribution of a 9 g portion to NRV for selected species. Radar plots show contribution between 0-100%, colored by processing type (orange = powder, blue = smoked, yellow = fried, red = sun-dried). (*C*) 9 g portion of sun-dried *Rastrineobola argentea* (dagaa/mukene/omena), with maize meal and green vegetables. *SI Appendix*, Figs. S1 and S3 show the NRV for each species and processing form. NRV were averaged for children 0.5 to 5 y old, for a portion of 9 g and nutrient density of calcium, iodine, iron, selenium, zinc, omega-3 fatty acids (EPA + DHA), and vitamins A, B12, and D. Nutrient density estimates for "fresh," unprocessed fish were based on a dried fish portion, which is typically smaller than a fresh portion.

environmental influences on the metal content of individual fishes, requiring further research to untangle.

Our findings reinforce the potential of dried fish to fill key nutrient gaps in vulnerable populations (41, 42). Calcium, iron, and zinc were concentrated in most small fish species and processing forms, aligning with previous work suggesting that dried fish could be leveraged in food-based approaches to help prevent micronutrient deficiencies in women and young children in Africa (43, 44), South and East Asia, and the Pacific (45). Similarly, omega-3 fatty acids, iodine, and selenium are critical for thyroid health and infant brain development during the critical growth period of the first 1,000 d, but are difficult to source from other foods (20). Products accessible to young children, such as powdered small fish, can therefore have particular nutritional benefits during the complementary feeding phase, as powder can be combined with other food products (e.g., flour) to produce highly nutritious meals (46) that can be used to treat severe malnutrition (47). We recognize that while increasing fish consumption can lead to improved health outcomes (20), there are multiple underlying drivers of malnutrition, including inadequate access to healthy diets, lack of water, sanitation and hygiene, poor environmental conditions, and high prevalence of chronic infections (48, 49). Further research is required to identify holistic strategies for leveraging dried fish for nutrition and health in low resource settings.

Drivers of Household-Level Dried Fish Consumption. We next extracted information on fish consumption from Living Standards and Measurements Surveys (LSMS) for six African countries (Côte d'Ivoire, Malawi, Nigeria, Senegal, Tanzania, Uganda) to understand the prevalence of dried fish consumption at large scales. These are neighboring countries that use similar

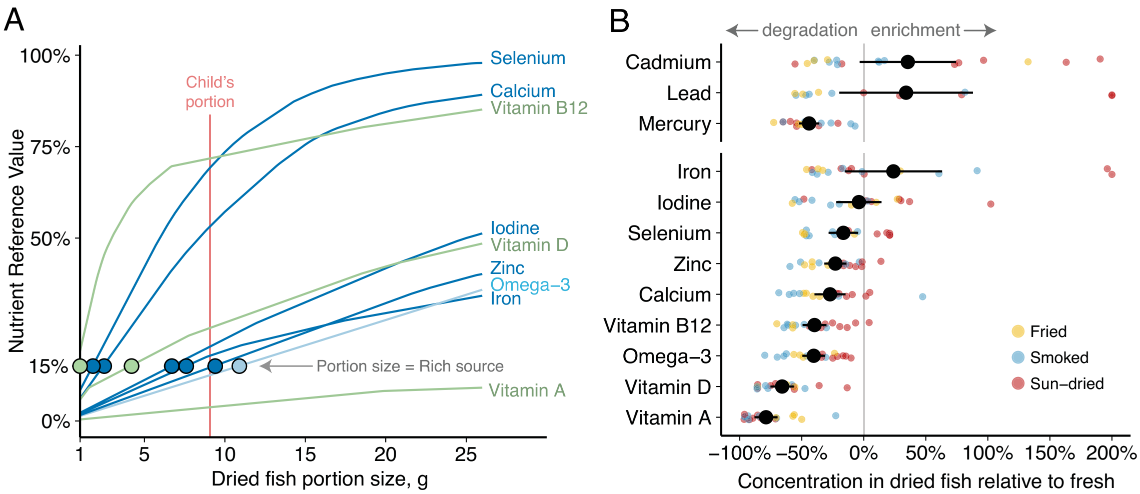

Fig. 2. (*A*) Contribution of the average dried fish to NRV for children (0.5 to 5 y) for different portion sizes (1 to 25 g) (mean across species and sun-dried, smoked, powder, fried forms). Points on the dashed horizontal line indicate the portion that classifies dried fish as a nutrient source (≥15% NRV), relative to average portion size of 9 g (red line). See *SI Appendix*, Fig. S2 for adult women NRV. (*B*) Change in nutrient concentration from fresh fish to a dried form, accounting for water loss. Black points show mean values ± 2 SEM and underlying points are fish samples colored by each drying process. Values were capped at 200%, indicating samples with significantly more nutrient or contaminant than would be expected from water evaporation.

methods to dry similar species, with high fish consumption and high fisheries productivity (*SI Appendix*, Table S1). In LSMS, interviewers collected information on the diets and livelihoods of 38,918 households (between 2010-19), stratified across socio-economic and geographic regions (e.g., income status, religion, rural, and urban) to capture the living standards of ~407 million people (*SI Appendix*, Table S2). Food consumption surveys in LSMS recorded the consumption of fresh and dried (sun-dried or smoked) by each household in the preceding 7 d, which we used to quantify prevalence of fresh and dried fish consumption. Surveys also recorded fish quantities, but, as most surveys used semiquantitative units, we were unable to estimate the quantity of fish consumption across the full dataset (*Methods*). Across the six countries, 36 to 91% of households consumed fish in any form, 16 to 86% consumed fresh forms, and 24 to 67% consumed sun-dried or smoked forms (*SI Appendix*, Table S2). Dried fish were particularly prevalent in Senegal, Malawi, and Côte d'Ivoire, but consumed in less than half of households in Nigeria, Tanzania, and Uganda.

Regional and subnational differences in fish consumption likely reflect variability in people's physical and economic access to and preference for dried fish (19, 50, 51). Previous studies have linked fish consumption with proximity to water bodies (31, 52), income (53), and urban/rural areas (51), but these multiple drivers of fish consumption may differ for shelf-stable dried products and have not yet been assessed at large, multinational scales. We fitted Bayesian hierarchical models to quantify the probability of household-level fish consumption, using explanatory covariates derived from LSMS and accounting for spatial clustering of household surveys (*SI Appendix*, Fig. S6 and Table S3). These models allowed us to make statistical inferences about the underlying drivers of the prevalence of fresh and dried fish consumption, drawing on information from a large multinational survey dataset. Explanatory covariates were proxies for fish prices and households' physical access to fisheries, including the distances from the nearest marine coastline and nearest permanent inland waterbody (lake ≥ 50 km^2 or reservoir ≥ 0.5 km^3), the proximity to urban centers (minutes of travel time by fastest surface transport to nearest urban center with >50,000 inhabitants) (54), as well as household wealth and size (*Methods*). We used these models to understand the prevalence of weekly, household consumption of fresh and dried fish among countries, and to identify general drivers of fish consumption in East and West Africa. This approach allowed us to build on small-scale dietary studies (43, 55, 56) while refining knowledge from large-scale models of drivers of fish consumption and dietary diversity (31, 52, 57).

The prevalence of fish consumption varied strongly among countries and between dried and fresh forms (Fig. 3*A*). More households consumed fresh than dried fish in Senegal (Fresh =

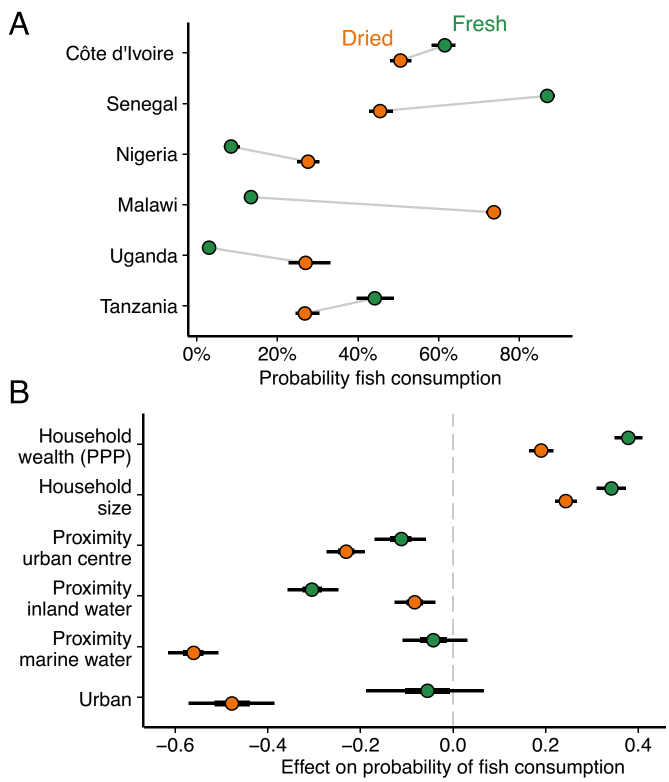

Fig. 3. Drivers of dried fish consumption across six countries. Points are the median posterior effect size of covariates in dried and fresh fish consumption models, showing the probability of a household consuming fish for (*A*) country intercepts and (*B*) covariate effect sizes. Thick and thin lines are 50% and 95% highest posterior density intervals (HPDI), respectively.

87%, Dried = 45%) and Tanzania (F = 44%, D = 27%), while dried fish was more prevalent in Nigeria (F = 8%, D = 28%), Malawi (F = 14%, D = 73%), and Uganda (F = 3%, D = 27%), and both forms were consumed at similar frequency in Côte d'Ivoire (F = 62%, D = 50%). Geographic and socioeconomic drivers contributed to these across-country differences, with fish consumption more prevalent in larger households that were located near (within 5 km) to inland water bodies, marine coastlines, and urban centers (Fig. 3*B*). Previous research has also linked fish consumption with proximity to aquatic resources (58), showing that higher physical access to fish correlates with higher dietary diversity (31) and food security (52). Dried fish was generally consumed by more households than fresh fish, particularly by poor and rural households, suggesting population-level benefits from fish consumption likely accrue primarily through dried products. For example, across the six countries, one-fifth of households lived within 20 km of a marine coastline or inland waterbody, where people were almost twice as likely to consume dried as fresh fish (dried = 58% [40 to 74%], fresh = 31% [8 to 68%]).

The probability of fish consumption declined with increasing distance from fisheries and travel time to urban centers, though distance effects varied between dried and fresh forms, and on the fishery type (inland or marine) (Fig. 4*A*). Fresh fish was most strongly predicted by the interaction between marine and inland water, such that the highest probability of consumption was predicted for inland households distant from marine coastlines (86% [64 to 99%]) (*SI Appendix*, Fig. S7). Less than 1% of households were in these inland fresh fish hotspots, primarily those near Lake Victoria. The probability of fresh fish consumption declined with increasing distance from inland water, reflecting the importance of large waterbodies, such as the African Great Lakes, in producing food (19). Household wealth also had a strong positive effect on probability of fish consumption, with the wealthiest households over four times more likely to consume fresh fish than the poorest households (wealthiest = 85% [63 to 99%]; poorest = 19% [4 to 48%]) (Figs. 3*B* and 4). Poorer households were less likely to consume dried fish (36% [19 to 53%]) than the wealthiest (73% [57 to 88%]), though this wealth effect was weaker than for fresh fish. While we did not directly model the influence of food prices on fish consumption, tropical aquatic foods can be more affordable than other animal-source foods, especially in East and West Africa and South East Asia (59), and species that are dried, particularly small pelagic fishes, are typically more affordable than fresh fishes (60). Lower prices likely explain why poorer households were more likely to consume dried than fresh fish, whereas wealthier households were more likely to consume both products (*SI Appendix*, Fig. S8). Further research on market prices of dried fish could be used to inform economic models for dried and fresh fish products (61), developing understanding on how fish prices may respond to changes in demand, market composition, and catch supply.

The probability of fish consumption also decreased as travel time to urban centers increased, but at a faster rate for dried fish (Fig. 3*B*), likely reflecting positive effects of market access on dietary diversity (62, 63). Fresh fish thus persisted relatively further from urban centers (but at lower consumption than dried fish), possibly due to rural access to rivers and smaller temporal lakes and wetlands that were not captured in our freshwater distance variable (*Methods*). As LSMS did not record fish species or production sources (wild/farmed), we assumed that dried fish were represented by our nutrient analysis (e.g., wild-caught, small-bodied pelagic fishes, reef-associated species), whereas fresh fish consumption was likely represented by different species and sources (e.g., larger-bodied species, frozen fish imports, aquaculture). Household fish consumption may therefore correlate with fisheries production levels, suggesting that LSMS data could be used to explore influence of seasonality, fishery status, and fishing effort on diets. Nevertheless, the widespread distribution and consumption of dried fish, from a smaller supply base than fresh, further underlines the importance of marine and inland fisheries in supporting diet quality (64), particularly for rural communities that may lack access to other animal-source foods (31).

Dietary studies of fish consumption confirm that most dried fish species in these countries include the species that we sampled, particularly *Rastrineobola argentea* and *Sardinella* species (*SI Appendix*, Table S1), enabling us to estimate population-level nutrient intakes from dried fish. Scaling modeled estimates of the prevalence of household dried fish consumption (Fig. 3, *Methods*) to recent population estimates, we estimate that dried fish is consumed (weekly) by up to 144 million people [95% highest posterior density intervals (HPDI): 132 to 155 million] in Côte d'Ivoire, Malawi, Nigeria, Senegal, Tanzania, and Uganda, reaching 54% more people than fresh fish (weekly fresh fish consumption by 94 million people, 95% HPDI: 85 to 103 million). The high nutrient density and consumption by households across gradients in proximity to fisheries suggest that dried fish are important contributors to critical nutrient requirements for 35% (95% HPDI: 32 to 38%) of people living in these six countries. Though we were unable to assess dried fish consumption by households in other countries in Africa, our analysis spanned marine and inland fisheries and included households across rural/urban gradients, in diverse cultural and socioeconomic contexts. As such, we expect that dried fish consumption is similarly prevalent in

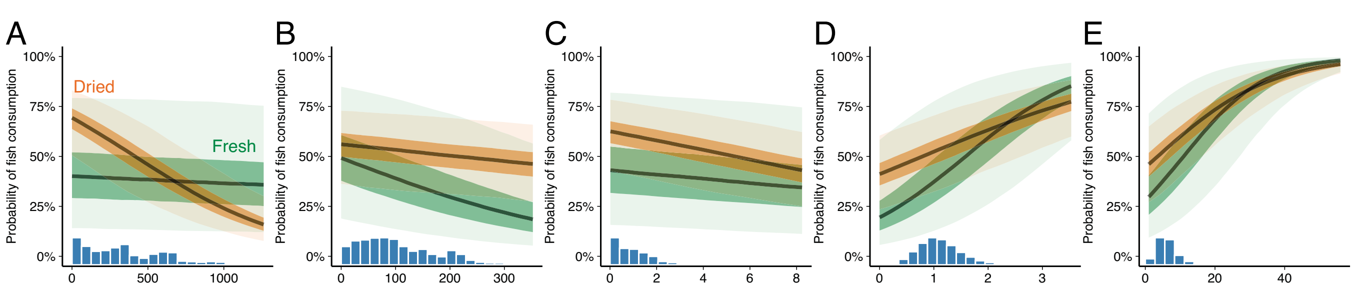

Fig. 4. Change in the probability of dried and fresh fish consumption with geographic and socioeconomic covariates. Panels show (*A*) distance to marine water, (*B*) distance to inland water, (*C*) proximity to urban center, (*D*) household wealth, and (*E*) household size, where lines are the median posterior predicted probability that a household consumed dried (orange) or fresh fish (green) (shading = 50% and 95% posterior density intervals). Household wealth represents monthly expenditure (0 = lowest, 1 = highest), standardized separately for each country. Each posterior prediction holds other covariates at their mean (0). *Inset* histograms show distribution of observed data. See *SI Appendix*, Fig. S8 for equivalent panels for low and high household wealth households.

other countries that have access to small fish catch (from fisheries and trade) and cultural history of drying, smoking, and other preservation methods (8, 65).

Sustaining Dried Fish Catches and Value Chains. Catches that are available for drying are primarily influenced by the resilience and productivity of fish stocks, their responses to environmental changes, fisheries dynamics and management strategies, and on distribution of catches for consumption (e.g., trade) (66, 67). As such, continued availability of small fish catches may vary between species and marine and inland ecosystems, while also being strongly influenced by the nature of fishing activities in individual countries. For example, silver cyprinid (*R. argentea:* mukene, dagaa, or omena) is a key dried fish resource in East Africa (24, 68), and although fishery-independent surveys suggest population biomass in Lake Victoria has remained steady as fishing effort has increased (69), the total catch and nutrient supply available to consumers have declined (70). Coral reef fishes that are dried are often caught in aggregations (e.g., *Siganus sutor* and *Plectropomus areolatus*) that can be highly vulnerable to aggregation fishing (71, 72), while fisheries for other reef species have been impacted by climate-driven shifts in coral habitat (73). For pelagic marine fish, *Sardinella* species caught in the Eastern Central Atlantic have supplied almost 400 kt annually (on average) to fish supply in West Africa, but fishing pressure has intensified, and most small pelagic stocks are now overfished (74, 75). These stocks also face rapidly changing environmental conditions, with altered ocean temperatures, primary production, and upwelling intensity associated with shifts in stock composition (23, 76, 77). Finally, across East and West Africa, the species caught and processed into dried fish face growing demand from nonfood sectors, whereby aquafeeds are used to support growing production of aquaculture and poultry (78). Together, the rise of fish processing factories (79), increasing access for foreign fishing fleets (80) and international trade of nutrient-rich catch (67, 81), and prevalence of Illegal, Unreported, and Unregulated (IUU) fishing (82), threatens local and regional supply of dried fish, undermining a critical nutrient resource.

This dried fish supply also confers benefits that extend beyond nutritional value, with actors along the value chain able to gain economic benefits, fulfill cultural roles, nurture social networks and ties, and obtain material goods (83, 84). These benefits contribute to various dimensions of social well-being for those who operate within these value chains, particularly women across the Global South (85, 86). For example, women fish processors are able to exert their agency through specialized processing skills that enhance the quality and safety of fish, and efficient marketing strategies that enable access to affordable fish (87, 88). Dried fish value chains are typically small-scale and informal, with high associated loss of fish, indicating that investments to minimize postharvest loss (89) may help enhance the supply of dried, small fish while protecting livelihoods and associated economic and cultural benefits. For example, improved storage and drying equipment (e.g., solar dryers) can help to prevent spoilage and contamination (36, 90), while removal of financial barriers (e.g., through accounting and entrepreneurial training or the provision of grants or loans) can support entry of marginalized groups and women into fish food systems (91). However, such interventions should be developed in ways that avoid creating new or exacerbating existing inequalities (e.g., associated with gender, class) (92), and include training, infrastructure, and engagement to enhance uptake by fishing communities (89). Policies also need to minimize risks associated with value chain commercialization that impact fishers, processors, and consumers (82, 85, 92), particularly for poorer households that are most reliant on dried fish.

Conclusion

Our nutrient analysis built nutrient composition tables for dried, small fish species that are widely caught and consumed across East and West Africa, including fisheries in pelagic ecosystems in the Great Lakes and eastern tropical Atlantic Ocean, and coral reefs in the Indian Ocean. These species represent diverse ecosystems, small-scale fisheries that are often data limited, and regional and informal trade networks, underlining the widespread significance of dried, small fish as a source of dietary nutrients in low- and middle-income countries. We found that very small portion sizes contributed significant amounts of iron, zinc, calcium, omega-3 fatty acids, and iodine to the recommended nutrient intakes of women and young children. Many vitamins and minerals deficient in diets (45) are concentrated in small fish, reinforcing the potential for leveraging dried fish to help achieve SDG 2 "Zero Hunger," including eliminating "hidden hunger" by 2030 (3). Policies to enable and encourage the consumption of dried fish, especially among young children and women, are needed in places where micronutrient deficiencies are prevalent but small dried fish are abundant. Indeed, while cereal fortification programs have been widely implemented to boost intakes of nutrients that are concentrated in dried small fishes (93), dried fish are largely overlooked as a source of micronutrients by food-based dietary guidelines. Practical strategies can involve the inclusion of dried fish products in complementary feeding and malnutrition treatment products (94), school feeding programs (95), and national food aid programs (96). Although we were unable to assess the health status of consumers of dried fish, we note that nutrient deficiencies are high and increasing in vulnerable populations in Africa (45, 97), despite widespread fish consumption. Given the potential small dried fish have on alleviating the burdens of malnutrition, more rigorous studies evaluating their impact on child and nutrition outcomes are needed (20).

Using large-scale diet survey data from six countries, we estimated that 36% of households across East and West African countries consume dried fish, placing dried fish as a more prevalent aquatic food than fresh fish. We also uncovered subnational variability in fish consumption, identifying higher prevalence of dried fish in households that were near to fishery sources across all wealth gradients. Our results also suggest greater dependence of poorer households on dried fish as a critical nutrient source, reinforcing the importance of protecting small fish catches for local consumption instead of animal feeds (78) and investing in value chains to maximize access to dried fish supply (89). Policies to prioritize local consumption might, for example, focus on eliminating IUU fishing of pelagic small fish stocks, prioritizing catch allocation for small-scale domestic fleets over industrial foreign fleets (82), and improving dried fish quality and preservation (98). Fisheries policies should therefore recognize the multiple dimensions of dried fish, including their cultural, economic, social, and "relational" dimensions (5, 99), at both the harvest and postharvest stages of production.

Methods

Fish Samples. We collected composite samples of small fish species from markets in Kenya, Ghana, Malawi, Lakshadweep Archipelago (India), and Seychelles (Dataset S1), following whole fish nutrient sampling procedures (100). Our core sampling, in Kenya and Ghana, focused on species that are widely sun-dried or smoked, and caught by fisheries operating in inland water bodies (e.g., *R. argentea:* mukene, dagaa, or omena in Lake Victoria) and along marine coastlines (e.g., Sardinella species in Accra, Ghana). During sampling, we also purchased market species that were typically dried, smoked, or fried before sale, and eaten whole (e.g., haplochromines in Lake Victoria). We collected fresh ("wet") and dried samples of each species, where possible, obtaining 5 × 100 g samples of each species and processing type, from random market stalls according to ref. 100. Market sellers were briefly interviewed about the origin of the sample and type of processing (e.g., time since capture). We supplemented this dataset with opportunistic samples that aimed to broaden the taxonomic diversity of our dataset. We collected dried pelagic fishes from Malawi (by T.A.C.L.) and dried reef-associated species from Seychelles (N.A.J.G.) and the Lakshadweep archipelago (R.K.). These samples were purchased at fish markets and landings sites. Species from Lakshadweep and Seychelles are representative of dried fish in island states, where catches of reef-associated rabbitfish (*Siganus sutor* in Seychelles) and emperorfish (*Lethrinidae* in Lakshadweep) are dried for local consumption. Reef fish samples were fillets or samples without heads and thus may differ from the whole fish samples collected for pelagic species. We note that Lakshadweep also supports a tuna fishery that processes dried tuna fillets, but these are primarily exported and were not included in our analysis (30).

Chemical Analyses. Fish samples were analyzed for proximal composition, metals, vitamins, and fatty acid content at the Institute for Marine Research in Bergen, Norway. The chemical analyses were performed using accredited methods according to NS-EN ISO/IEC 17025, except for iron which is validated, not accredited. All samples were homogenized. Aliquots of homogenized samples of raw fish were freeze-dried before analyzing crude protein and minerals. For all other analyses, the samples were analyzed wet and homogenized samples of dried fish were analyzed without further drying. However, moisture content was analyzed by oven drying. Detailed information on measurement range, measurement uncertainty (%), overview of certified reference material used for each method, overview of internal control material, in addition to instrument used and procedure for preparing and determining the analytes, is described in ref. 101. Because processing does not remove all moisture content (moisture content across all processed samples ranged between 7 to 53%), "wet weight" is used to describe the partial moisture content of processed ("dried") samples. All values are provided on a wet weight basis.

Dietary Analysis. We assessed the dietary contributions of dried fish by comparing nutrient concentrations to NRVs for nonpregnant women aged 15 to 49 y and young children 0.5 to 5 y old, for five minerals (calcium, iodine, iron, selenium, and zinc), three vitamins (A, B-12, and D), and long-chain omega-3 fatty acids (specifically EPA and DHA) (*SI Appendix*, Table S4). For this analysis, we chose the NRVs that cover the nutrient requirements of approximately 98% of the population (102). NRVs were selected on a case-by-case basis, after assessing the available evidence for each nutrient. For iron, calcium, and vitamins B12 and D, we used the NRVs provided by the Food and Agricultural Organization of the United Nations (FAO) and the World Health Organization (WHO), estimating 10% iron bioavailability (i.e., diets that contain a moderate amount of phytates and some fish/meat). These values align with other studies on women and children's nutritional intake in low- and middle-income countries (103). For iodine, selenium, zinc, and vitamin A, we used the harmonized NRVs from (104), which directs us either to Recommended Dietary Allowances from the United States Institute of Medicine, or Population Reference Intakes from the European Food Safety Authority (the selection for each is in *SI Appendix*, Table S4). These values included updated NRVs for vitamin A and zinc based on new evidence (105) and assumed zinc bioavailability for diets characterized by higher-phytate plant-based foods. For omega-3 fatty acids, we used adequate intake (AI) values (106), noting that fish omega-3 fatty acid content is dominated by EPA and DHA. AI values are established when there is a lack of evidence to generate an NRV that covers the requirements of 98% of the population.

Health risks from contaminants are assessed at different exposure timescales, such that cadmium and mercury are assessed on a monthly and weekly tolerable level (respectively, due to differences in element half-lives). In accordance with international standards, we also identified the contaminant risk of consuming each dried fish species, using PTMI for cadmium (107) and TWI for mercury (108) (*SI Appendix*, Table S4). Provisional tolerable intakes determined exposure to health risks and were determined for a child weighing 12.8 kg (10th percentile for a 36-mo-old girl) (109) and nonpregnant adult woman of 65 kg. TWI for mercury relates to the consumption of methylmercury, which is the dominant form in aquatic foods. We analyzed total mercury and thus conservatively assume our tissue estimates are 100% methylmercury. For lead, the PTWI was revised from 0.05 to 0.025 mg/kg body weight in 1993, but, in 2010, lead exposure was linked to increased systolic blood pressure in adults and impaired neurodevelopment in children (107). As a result, the PTWI was withdrawn, as it was no longer deemed health-protective, and no new value has been established. As no PTWI is available for lead, we compared the concentrations in the dried fish to the EU maximum permissible level of 0.3 mg/kg wet weight for lead in fish muscle meat (110).

NRVs and contaminant exposures were estimated for an average portion size of 9 g for young children (0.5 to 5 y) and 41 g for nonpregnant adult women based on quantified fish intake data (*SI Appendix*, Table S1). We summed NRVs to estimate the nutrient density of each species and processing form (the combined contribution to daily NRV across all nutrients, %) (111). We also estimated the contribution of the average dried fish to daily NRV across a range of portion sizes from 1 to 20 g and used these values to evaluate portion sizes at which dried fish is considered a "source" of a nutrient (≥15% NRV). Our source cutoff is based on EU legislation (112) but derived from the most up-to-date international NRV guidelines. We use this to demonstrate when fish can contribute to nutrient intakes, acknowledging that most NRVs are reached through a combination of foods in a healthy diet.

Household Fish Consumption Surveys. We extracted surveys of 38,918 households from the LSMS (microdata.worldbank.org) in six countries (Côte d'Ivoire, Malawi, Nigeria, Senegal, Tanzania, Uganda) (113–118) (*SI Appendix*, Fig. S6 and Table S2). LSMS provide standardized information on household-level fish consumption, specifically on whether processed forms of fish are consumed (fresh, dried, smoked), providing nationally representative datasets for assessing dried fish consumption (52). Although LSMS have not been recently conducted in four of our sampling locations (Ghana, Kenya, Lakshadweep, Seychelles), the six LSMS countries also catch, process, and consume similar small fish species. For example, fishers in Senegal catch *Sardinella* species that we sampled in Ghana, and these are typically smoked before consumption (119), while fishers in Uganda also catch and sun-dry large quantities of *Rastrineobola argentea* (known locally as mukene in Uganda, and dagaa and omena in Kenya) from Lake Victoria, comanaging this fish stock with Kenya and Tanzania (69). We did not, however, have household surveys from island states, and thus lack information on consumption of coral reef fishes.

For each country's LSMS, we extracted information on weekly household fish consumption and variables that we expected to correlate with fish consumption (*SI Appendix*, Table S3). These surveys recorded whether households consumed dried or fresh fish in the previous 7 d, which we used to estimate the prevalence of fish consumption, assigning each household a 1 (dried or fresh fish consumption) or 0 (no dried or fresh fish consumption). Surveys also recorded the quantity of fish consumed, but food quantity units were typically semiquantitative, such as cup, heap, piece, or whole fish, and thus, we were unable to standardize quantities across all country datasets. For each household, we also extracted the Global Positioning System (GPS) coordinates and used these geolocations to estimate three proxies for access to dried fish: the proximity to marine coastlines and proximity to inland waterbodies (access to catch), and proximity to urban centers (access to markets). Proximity to marine coastlines or inland water bodies was the shortest line distance (km), and inland water was defined as any large, permanent inland waterbody (lakes ≥ 50 km^2 or reservoirs with storage capacity ≥ 0.5 km^3) (120). Proximity to urban centers was the least-cost, minimum travel time (minutes) via surface transport (road, rail, vessel, or on foot) to the nearest urban center (at 1 km grid resolution, where an urban center is a "contiguous area with 1,500 or more inhabitants per km^2 or a majority of built-up land cover coincident with a population center of at least 50,000 inhabitants") (54). We assumed that our three proximity covariates reflected each household's level of access to fish catch (for coastline or waterbody), or to informal, seasonal, or permanent food markets where fresh or dried fish could be purchased (for urban centers). Further distances meant that fish were less physically accessible and more expensive. To prevent disclosure of locations, LSMS data providers jittered each household's GPS coordinate by 0 to 5 km, but this was applied equally across all households, and is unlikely to bias our analysis that spanned hundreds of km in proximity to water and markets (52). Finally, we quantified household wealth using the LSMS on monthly expenditures and extracted survey data on household size (number of people) and location (urban/rural). We estimated an equalized household wealth metric (monthly expenditure divided by the square root of household size), standardized to Purchasing Power Parity (121) for each country, facilitating comparisons between countries of different income status.

We then used logistic hierarchical models to quantify the probability that a household had consumed dried or fresh fish in the previous 7 d (Bernoulli distribution). We fitted models separately for dried and fresh fish, with six fixed covariates (proximity to marine coastline, proximity to nearest inland water body, proximity to nearest city, household size, household wealth, urban/rural), and a random varying intercept of survey area ("household cluster," *b*), nested in country *a* (1). Random intercepts were used to account for unmeasured sources of variation between survey strata, with each strata nested in its country-level intercept. We included an interaction between proximity to marine and inland water to capture potential effects of having access to both marine and inland fisheries (or lack of access to marine/inland). Household wealth and proximity to nearest city were $\log_{10}$ transformed, and all continuous covariates were then scaled to a mean of zero. We used weakly informative priors for random intercepts and continuous covariates [$N(0,1)$] and group-level SD [$Cauchy(0,10)$]. Models were run for 3,000 iterations over 3 chains, and we ensured that chains converged by inspecting Rhat (<1.01) and the number of effective samples. Models were fitted using brms (122) and Stan (123) in R 4.3.3.

$$\gamma_i = country_a + cluster_b + \beta_1 prox_{marine_i} * \beta_2 prox_{inland_i} + \beta_3 prox_{urban_i} + \beta_4 hh_{size_i} + \beta_5 hh_{wealth_i} + \beta_6 rural_i. \quad [1]$$

We used the posterior distributions of dried and fresh fish models to visualize changes in the probability of fish consumption between countries and along gradients in household wealth and size, and distance to marine coastlines, inland waterbodies, and urban centers. We also combined the median predicted posterior probability of consuming fish, based on country-level intercepts and median covariate values, with recent estimates of each country's adult population (in 2023) (124), to estimate the total number of people likely to eat dried (or fresh) fish at least once a week. This approach was unable to quantify intrahousehold fish consumption or food quantities or account for variation in portion sizes between countries. We thus assumed that the prevalence of household fish intake was representative for men and women of all ages (i.e., modeled probability of consumption) and that our portion size estimates collated from small-scale diet surveys were representative of population-level intakes of dried fish (*SI Appendix*, Table S1).

Data, Materials, and Software Availability. R code and data have been deposited in https://github.com/jpwrobinson/dried-fish/ (125).

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