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Fishers' ecological knowledge points to fishing-induced changes in the Peruvian Amazon

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Abstract

Scientists increasingly draw on fishers' ecological knowledge (FEK) to gain a better understanding of fish biology and ecology, and inform options for fisheries management. We report on a study of FEK among fishers along the Lower Ucayali River in Peru, a region of exceptional productivity and diversity, which is also a major supplier of fish to the largest city in the Peruvian Amazon. Given a lack of available scientific information on stock status, we sought to identify temporal changes in the composition and size of exploited species by interviewing fishers from 18 communities who vary in years of fishing experience since the mid-1950s. We develop four FEK-based indicators to assess changes in the fish assemblage and compare findings with landings data. We find an intensification of fishing gear deployed over time and spatiotemporal shifts in the fish assemblage and reported declines in species weight, which point to a fishing-down process with declines across multiple species. This finding is reflected in a shifting baseline among our participants, whereby younger generations of fishers have different expectations regarding the distribution and size of species. Our study points to the importance of spillover effects from the nearby Pacaya-Samira National Reserve and community initiatives to support the regional fishery. Reference to fishers' knowledge also suggests that species decline is likely underreported in aggregated landings data. Despite the dynamism and diversity of Amazonian floodplain fisheries, simple FEK-based indicators can provide useful information for understanding fishing-induced changes in the fish assemblage. Fishers hold valuable knowledge for fishery management and conservation initiatives in the region.

KEYWORDS

fish assemblages, fishery management, fishing-down, inland fisheries, landings data, local ecological knowledge, tropical rivers, Ucayali River

INTRODUCTION

Inland fisheries provide sustenance and income to millions of rural people in developing countries (FAO, 2020, p. 18). Increasingly, the capacity of inland fisheries to feed growing populations and to maintain ecosystem services is thought to be compromised (Welcomme et al., 2010). In Amazonia, commercial fishing has selected for large-bodied higher-value species, and there is evidence of overfishing especially near urban centers (Castello, Arantes, et al., 2015; Coomes et al., 2020; Hallwass & Silvano, 2016; Keppeler et al., 2018; Lopes et al., 2018; McGrath et al., 1993; Pinho et al., 2012; Tregidgo et al., 2017). However, data for more remote areas are sparse and limited in time, and methods for assessing fish stocks that can be efficiently and rapidly deployed are needed (FAO, 2020; Shephard et al., 2020).

Conducting stock assessments that rely on data-intensive methods is often impracticable in floodplain-dominated tropical regions such as Amazonia (Castello et al., 2023; Shephard et al., 2020). There, fish size and abundance are heavily influenced by interannual variability in flooding as the flood pulse controls the availability of spawning, nursing, and feeding habitat, and species respond differently to hydrological stimuli and environmental pressure (Castello, Isaac, & Thapa, 2015; Welcomme, 1999). Additionally, fishers employ a diversity of fishing gear and capture a wide range of species, which adds considerable complexity to estimating catch per fishing effort and may mask declines in the abundance of fish stocks (Hallwass & Silvano, 2016; Hallwass et al., 2023; Lorenzen et al., 2016; Shephard et al., 2020; Welcomme, 1999). Choosing valid reference points is also problematic in areas where relatively little is known of the ecology of local fish species and fishers have long exploited fish stocks (Barletta et al., 2010; Jézéquel et al., 2020; Ortega & Hidalgo, 2008; Shephard et al., 2020; Soga & Gaston, 2018).

Scientists increasingly turn to fishers' ecological knowledge (FEK) as an alternative way to assess changes in fish abundance (Berkes et al., 2000; Johannes et al., 2000; Shephard et al., 2020; Silvano et al., 2022; Silvano & Valbo-Jørgensen, 2008). FEK relies on fishers' recall and their knowledge of the environment to gain information that is difficult to obtain otherwise, such as fish distributions, life-cycle events, and long-term historical trends in fish stocks (Anadón et al., 2009; Castello, Arantes, et al., 2015; Castello et al., 2023; Johannes et al., 2000; Silvano & Valbo-Jørgensen, 2008; Tesfamichael et al., 2014). By and large, FEK has been shown to be concordant with results derived from conventional scientific methods, although memory biases can be an important source of error when recalling past fishing events (Anadón et al., 2009; Beaudreau & Levin, 2014; Damasio et al., 2015; Daw et al., 2011; Fogliarini et al., 2021; Koriat et al., 2000; Pauly, 1995; Tesfamichael et al., 2014; Thurstan et al., 2016).

Still, while the value of FEK in data-poor environments is widely recognized, methods for FEK acquisition, analysis, and integration are less developed, especially for multispecies floodplain fisheries (Shephard et al., 2020). In Amazonia, quantitative studies of FEK have focused on analyzing fishing gear, fish body mass, and catch to assess spatially fishing pressure and estimated past catch per unit effort or identified most frequently caught species to assess temporal changes (Coomes et al., 2020; Hallwass et al., 2013, 2020; Tregidgo et al., 2017). To our knowledge, few studies have relied on FEK to assess the changes in species size over time in tropical floodplain systems (Castello et al., 2023), and none in the Amazon, yet such information is essential to identify and understand the impacts of fishing-induced changes (Allan et al., 2005; Hsieh et al., 2010; Shephard et al., 2020). Moreover, no studies have combined FEK with species functional traits to directly detect the fishing-down process, whereby species with longer body length, late sexual maturity, and low fecundity and higher-trophic-level species are gradually removed from the fish assemblage (Castello, Arantes, et al., 2015; Pauly et al., 1998). At the same time, monitoring trends of species of high commercial value is also important, as species of higher value are often targeted (Hallwass & Silvano, 2016).

In this paper, we present the results of a study drawing on FEK in one of the most productive but least studied regions of Amazonia. We have two specific objectives. Our first is to identify spatiotemporal changes within the fish assemblage by relying on four FEK-based indicators, the first three being largely inspired by studies conducted elsewhere in the Amazon (Coomes et al., 2020; Hallwass et al., 2020; Tregidgo et al., 2017): (1) changes in fishing gear, (2) changes in the weight of individuals caught within a given species, (3) changes in daily catch, and (4) changes in the functional structure of the fish assemblage. Our second objective is to examine how fishers' knowledge can complement landings data to understand historical changes in fisheries. To do so, we assess (1) the congruency between fishers' perception of species declines and landings data and (2) whether shifts in functional structure identified with FEK are also evident in landings data.

STUDY AREA

Our study area is located within the Department of Loreto, in northeastern Peru, along the Ucayali River (Figure 1). The Ucayali River is a white-water river that flows 2670 km from the high Andes down into

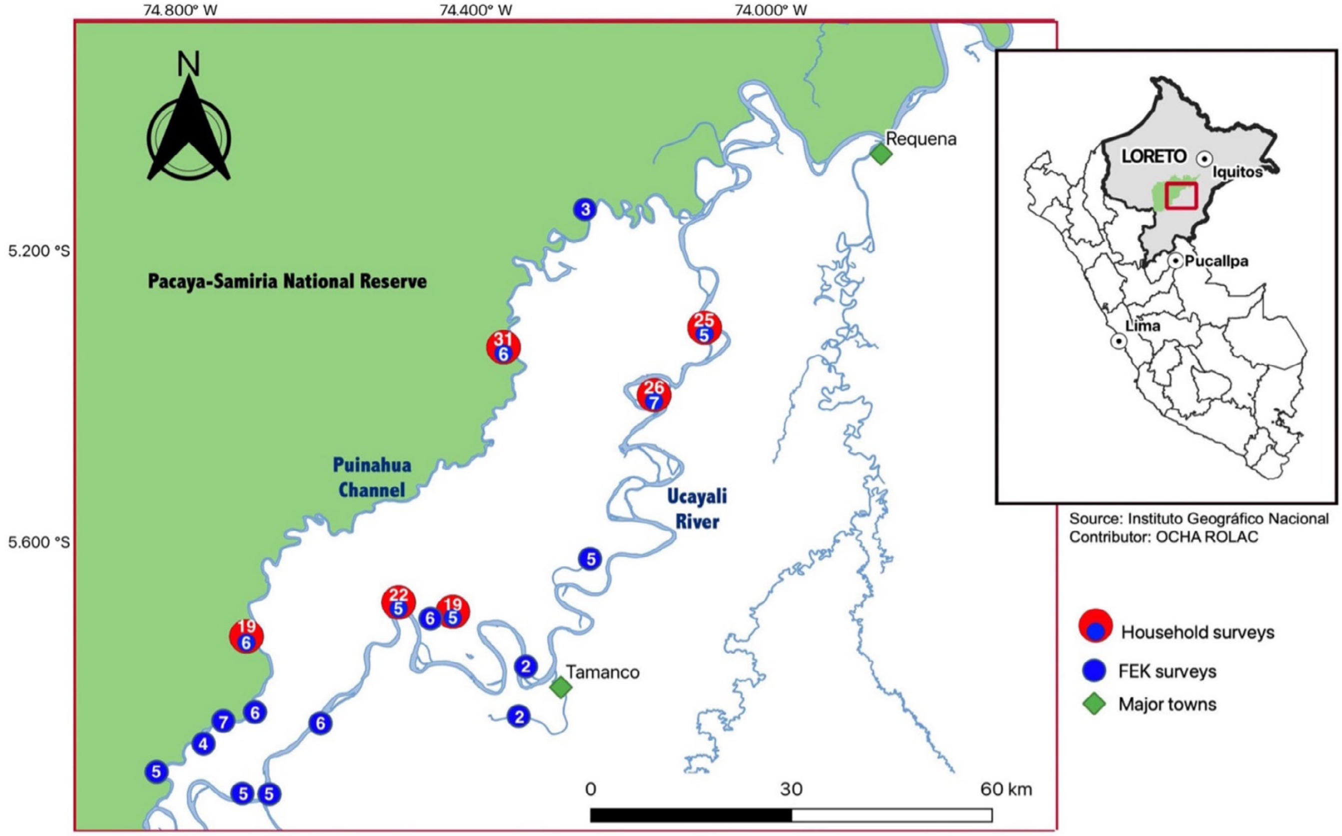

FIGURE 1 Communities visited during fieldwork (2019) along Lower Ucayali River. Numbers represent sample size (i.e., number of interviews).

the Amazonian lowlands (Schwenk et al., 2017). The dynamism of the Ucayali River creates a landscape characterized by an extensive floodplain and abundant oxbow lakes and side channels (Schwenk et al., 2017). The flood pulse typically peaks in early April, when the flood water level is 8 m above its lowest point (Kvist & Nebel, 2001). The river bifurcates in our study area—the main Ucayali River (east) and the Puinahua Channel (west)—and rejoins to form one channel once again about 200 km downstream. The Puinahua Channel delimits the eastern border of the Pacaya-Samira National Reserve (PSNR), which serves as a shelter for many vulnerable aquatic species (Coomes et al., 2004).

People living along the Lower Ucayali River generally either belong to the Kokama-Kokamilla Indigenous group or are mestizos, descendants of Indigenous and Iberian peoples. The population is mostly rural and lives in riverine towns and communities ranging from 10 to a few 100 households. Small-scale farming, logging, hunting, nontimber forest product extraction, and fishing are the most common livelihoods (Kvist & Nebel, 2001). Fishing is ubiquitous, provides vital protein, and enables the rural poor to cope with shocks such as illness (Coomes et al., 2010; McDaniel, 1997) or extreme flood events (Coomes et al., 2010; Langill & Abizaid, 2020; Takasaki et al., 2010). Fishing is an activity generally undertaken by men, although women are widely involved in selling, transport, and transformation activities (Langill, 2021; Poissant et al., 2023).

Fishers can sell their catch to a resident or nearby middleman, who coordinates with passenger boats to transport and sell in cities, although they may choose to sell to a passing fish buyer or other community members (Chibnik, 1994; Garcia et al., 2009). The catch leaving the region is mainly transported to Iquitos, the political economic and administrative center. Fishing regulations in the Peruvian Amazon include the prohibition of predatory fishing techniques (e.g., using dynamite or poison [Rodgers, 1987]) and restrictions on fishing seasons and/or length for a limited number of species (Ortega & Hidalgo, 2008). As the government has a limited capacity to enforce fishing regulations, many communities in the Lower Ucayali, as elsewhere in Amazonia, have taken the initiative to protect local lakes by enforcing locally designed fishing rules (Anderson et al., 2009; De Castro & McGrath, 2003; Garcia et al., 2009; Smith et al., 2001).

We selected the Lower Ucayali for study because the reach hosts a highly productive fishery (Tello & Bayley, 2001) and has become one of the main suppliers of fish for the cities and towns of the Peruvian Amazon (Álvarez Gómez & Torres, 2009; De Jesús, 2004). The Lower Ucayali lies some 300–500 km (river distance) from Iquitos and as such is a relatively remote region that has been spared from major road development, large-scale deforestation, and land degradation (Schleicher et al., 2017; Schwenk et al., 2017). To date, no studies have assessed fish stocks along the Lower Ucayali—despite its ecological and economic importance—though earlier reports examine more generally the state of the fishery in the Peruvian Amazon (see De Jesús, 2004; Garcia et al., 2009).

METHODS

Data collection

Data were gathered from FEK surveys and government landings records. FEK surveys used a purposive sampling and reached 87 fishers distributed in 18 communities (Figure 1). An additional household survey, conducted in a subset of six communities, provided additional information on fishing gear and socioeconomic data (Appendix S1). Details on sampling methods for FEK and household surveys are also available in Appendix S1. Additional socioeconomic data on visited communities that were gathered earlier by the Peruvian Amazon Rural Livelihoods and Poverty (PARLAP) project (https://parlap.geog.mcgill.ca) are also found as supplementary information in Appendix S1. Both FEK questionnaires and relevant excerpts of the household questionnaires are included in Appendix S2. Our research protocol was approved by the Research Ethics Board of McGill University (REB No. 290-0114).

Government landings data are collected by the Dirección Regional de la Producción de Loreto (DIREPRO) in 11 ports distributed over the Department of Loreto, the port of Iquitos being the largest (see Garcia et al. [2009] for more details). The data set covers 1984 to 2016 and includes landings in Loreto for 81 species. The Ucayali River supplies between 29% and 57% of total catch in Loreto, depending on estimates (Álvarez Gómez & Torres, 2009, p. 18; Garcia et al., 2009, p. 54).

FEK-based indicators

All statistical analyses were performed in R (version 4.2.1). We relied on mixed-effect models to control for the clustered structure of our observations (e.g., community, species, and individual fishers, as specified below). Linear and logistic mixed models were calculated with R's lme4 package version 3.1-3 (Bates et al., 2015). To assess the validity of our models, we ensured that underlying model assumptions were met (i.e., overdispersion, homogeneity, and homoskedasticity of residual) using the performance package version 0.9.2 (Lüdecke et al., 2021). We also tested for influential outliers with robust linear mixed models (using the "rlmer" function in R's robustlmm package version 2.5-1 [Koller, 2016]).

Changes in fishing gear

We asked all participants whether they possessed any of nine specific fishing assets when they had started fishing; that is, cast nets, gill nets, large entangling nets, beach purse seine nets, circling nets, fish hooks, harpoon, trident spear, and a boat motor. We compiled data available from the FEK and household surveys ($n = 211$ observations), making sure that fishers interviewed in both surveys were only counted once in the analysis. We recorded gill nets, beach purse seine nets, circling nets, and large entanglement nets in a single "fishing nets" category. We then estimated six different logistic models using fishers' years of experience to assess how the fishing gear used has changed over time.

The number of fishing nets and mesh size at the beginning of career were only recorded during household surveys for 84 households. We estimated two linear mixed-effect models in order to evaluate changes in (1) the mean fishing net mesh size and (2) total number of fishing nets owned over time and by subregion (i.e., Ucayali River or Puinahua Channel). For all models on fishing gear, we controlled for unobserved local community-level factors by adding a community random intercept.

Reported changes in weight and daily harvest

We sought to track changes in species length over time by asking the mean weight of catches at start of a fisher's career and now for five species: *Prochilodus nigricans* (*Boquichico*), *Colossoma Macropomum* (*Gamitana*), *Arapaima* sp. (*Paiche*), *Piaractus brachypomus* (*Paco*), and *Cichla monoculus* (*Tucunare*). All five species are well known locally, important for commercial sale, and have different body length, life history, trophic, and migratory characteristics, which we deemed useful for comparison. We referred to fish weight rather than length because fishers in the study area are more familiar with kilograms than centimeters, with the noticeable exception of *Arapaima* sp., for which we asked about the size in pieces since this is the common metric used by locals for this species. To assess how harvests have changed over time, we asked fishers how many kilograms of fish they would expect to catch on a good day when they started fishing versus now. We use a "good day" because the type of fishing gear employed by participants was highly heterogeneous and had changed markedly over time. Using a "good day" approach is sensitive to respondent subjectivity and may be subject to bias as some participants may have increased disproportionately the amount of fishing gear they used. We maintain that examining individuals' perception of changes in a good day's harvests would nevertheless give a measure of perceived changes in relative fish abundance.

We calculated the change in fish weight (in kilograms or pieces) for each of the five species and expected catch (in kilograms) between the current period (2019) and when the fisher started fishing. For estimating changes in fish weight, we subtracted the reported mean weight at present from the reported mean weight when the fisher began fishing. Similarly, we subtracted a fisher's expected fish yield on a good day at present (log transformed) from that at the start of their fishing career (log transformed). We then constructed six mixed-effect linear models using the number of years of fishing experience and subregion as predictors. We included a community-level random intercept. To control for outliers, we estimated these relationships using robust linear mixed-effect models.

Changes in species abundance

We asked fishers whether they had noticed a change in the abundance of 20 fish species since they first started fishing. The 20 fish indicator species were selected as they constitute the bulk of landings, are well known to fishers, and encompass a wide variety of functional traits. The possible responses were (1) disappeared, (2) decreased, (3) stable, (4) increased, or (5) never present. For each selected species, we calculated the percentages of fishers reporting disappearance, decline, no change, or an increase in abundance.

We then estimated time trends for each of the 20 species in landings data using robust linear regression analysis. The relative proportion of species in yearly landings was scaled (i.e., landings for a species in a given year was first centered by subtracting the species landings mean and then scaled by dividing by species landings SD) so estimates are comparable across species. We compared slope estimates (i.e., proportion of landings over time) with the percentage of fishers who reported declines.

Shifts in functional assemblage

We tested six variables that we hypothesize could influence the likelihood that a fisher reported a decline for any given species: (1) years of fishing experience; (2) subregion; (3-5) three key functional traits (i.e., body length, trophic level, life-history strategy—see Table 1); and (6) market value (Table 2). We constructed four logistic mixed models, each using reported decline in abundance as the dependent variable, with one model built around each functional variable (market value, body length, trophic strategy, and life history strategy) as a predictor. We then tested whether the decline of each functional group varied according to subregion by adding interaction terms between functional groups and subregion. We included random intercepts at the community, individual fisher, and species levels.

For our analysis of changes in functional assemblages in landings, we followed an approach similar to that described earlier. We log-transformed and scaled to the mean landings for each species. We then used four robust linear mixed regression models and included interaction terms between functional groups and years to evaluate how functional groups had changed over time in landings. We added years as a random intercept to control for interannual fluctuations in landings across species. Robust methods were used to downweigh the influence of extreme years.

RESULTS

The oldest fisher interviewed during FEK surveys started fishing 66 years ago, and the mean number of years of fishing experience was 28 years (SD: 11.97 years). There was no statistical difference in the years of experience of fishers between the two subregions ($p = 0.57$).

Changes in fishing gear

Analysis of past fishing gear possession revealed that the type of fishing gear used changed markedly over time (Figure 2). We found that fishing nets and boat motors grew in popularity and fishers increased the number of nets used and decreased the net mesh size. For each decade going forward in time, fishers were 2.01 times more likely to own a fishing net ($p < 0.001$) and 1.71 times more likely to own a motor ($p < 0.001$). Likewise, for each additional decade, mesh size decreased by 0.35 inches on average ($p < 0.001$), and the average number of nets owned increased by 1.62 times ($p = 0.011$)

TABLE 1 List of predictors used for species temporal trends.

Predictor	Functional groups	Description
Market value[a]	0–50	Species that fetch prices at the market that lie between the lowest value and the median of the distribution of all fish prices. Species in the 0–50 category are species of the lowest market value.
	51–75	Species that fetch prices at the market that lie between the median value and the 75% break of the distribution of all fish prices. Species in the 51–75 category are species of medium value.
	76–90	Species that fetch prices at the market that lie between the 75% and 90% breaks of the distribution of all fish prices. Species in the 76–90 category are species of high value.
	91–100	Species that fetch prices at the market that lie above the 90% breaks of the distribution of all fish prices. Species in the 90–100 category are species of very high value.
Body length[b]	...	Maximum length of fish species (in centimeters)
Life history strategies[c]	Equilibrium with maturation at large size	Maturation at large size (>170 mm standard length [SL]), low batch fecundity, large oocytes, well-developed parental care, and maximum size >400 mm SL
	Equilibrium with maturation at small sizes[d]	Maturation at small size (<120 mm SL), low batch fecundity, large oocytes, well-developed parental care, and maximum body length between 97 and 269 mm SL
	Periodic strategists with maturation at large size	Maturation at large size (>164 mm SL), batch fecundity highly variable, small oocytes, no parental care, and maximum size >253 mm SL
	Periodic strategists with maturation at small size	Maturation at small size (between 63 and 148 mm SL), varied batch fecundity size (average ~ 4000), small oocytes, maximum size between 137 and 410 mm SL, and no parental care
	Intermediate strategists	Batch fecundity between 1000 and 9000, relatively large oocytes, and intermediate development of parental care
Trophic strategies[c,e]	Detritivores	Predominantly ingest fine particulate organic matter and nonliving macrophyte tissues, but also feed on filamentous algae. This group also ingests phytoplankton and zooplankton
	Omnivores	Omnivores: Ingest combinations of plant material, detritus, and invertebrates
	Piscivores	Ingest adult, juvenile, or larval fish, either whole or in pieces, including scales and fins. Can also ingest significant fractions of diverse terrestrial or aquatic macroinvertebrates (e.g., Ephemeroptera, Chironomidae, Coleoptera, Crustacea)

[a]Prices (Peruvian soles) were obtained by data provided by the Dirección Regional de Producción de Loreto. Prices were sampled during 2011.
[b]Maximum body lengths were obtained in "Check List of the Freshwater Fishes of South And Central America" (Warren, 2004).
[c]Descriptions of functional groups were closely paraphrased from Arantes, Fitzgerald, et al. (2019, p. 6).
[d]The equilibrium-small functional group was represented by a single species, *Bujurqui* (*Satanoperca jurupari*), and was thus removed from further analysis.
[e]Species trophic classification by Dirección Regional de Producción de Loreto.

(see detailed model table in Appendix S3: Tables S1 and S2). In contrast, cast nets and trident spears markedly fell out of favor, while harpoons and hooks both showed a modest decline (see detailed model in Appendix S3: Table S1). We also found that fishers living along the Ucayali started their fishing career with more nets than their counterparts along the Puinahua Channel, with an average of 7.76 extra nets at any given time ($p < 0.027$, Figure 2b,c and Appendix S3: Table S2).

Reported changes in weight and daily harvest

The majority of fishers reported a decline in weight for the five indicator species: *Arapaima* sp. (81%), *C. macropomum* (79%), *P. nigricans* (69%), *P. brachypomus* (68%), and *C. monoculus* (51%). The extent of reported weight decline was largely influenced by the years of fishing experience and geographical location

TABLE 2 Fish species included in analysis and associated functional groups.

Species (local names)	Scientific name	Maximum length (cm)	Trophic levels	Life history strategy	Market price in 2011 (Peruvian soles)	Market value group (quantile)
Paiche	*Arapaima sp.*	395	Piscivore	Equilibrium-large	22	91–100
Acarahuazu	*Astronotus ocellatus*	21	Piscivore	Equilibrium-large	7	51–75
Sabalo	*Brycon* spp.	26	Omnivore	Periodic-large	7.5	76–90
Tucunare	*Cichla monoculus*	33	Piscivore	Equilibrium-large	9	91–100
Gamitana	*Colossoma macropomum*	100	Omnivore	Periodic-large	12	91–100
Fasaco	*Hoplias malabaricus*	49	Piscivore	Intermediate	2.5	0–50
Maparate	*Hypophthalmus edentatus*	57.5	Detritivore	Periodic-large	4.5	51–75
Carachama	*Hypostomus oculeus*/*Pterygoplichthys* sp./*Pseudorinelepsis* sp.	30	Detritivore	Equilibrium-large	4	0–50
Palometa	*Mylossoma albiscopum*	25	Omnivore	Periodic-small	8	76–90
Turushuqui	*Oxydoras niger*	100	Omnivore	Periodic-large	3	0–50
Paco	*Piaractus brachypomus*	71	Omnivore	Periodic-large	7.5	76–90
Corvina	*Plagioscion squamosissimus*	80	Piscivore	Periodic-large	8	76–90
Llambina	*Potamorhina altamazonica*	27	Omnivore	Periodic-small	1.5	0–50
Boquichico	*Prochilodus nigricans*	37	Detritivore	Periodic-large	4.5	51–75
Ractacara	*Psectrogaster* sp.	16	Detritivore	Periodic-small	7	51–75
Zungaro Doncella	*Pseudoplatystoma punctifer*	100	Piscivore	Periodic-large	10	91–100
Bujurqui	*Satanoperca jurupari*	18.5	Omnivore	Equilibrium-small	4.5	51–75
Lisa	*Schizodon fasciatus*	40	Omnivore	Periodic-small	4	0–50
Paña	*Serrasalmus* sp.	20	Piscivore	Intermediate	2	0–50
Sardina	*Triportheus angulatus*	16	Omnivore	Periodic-small	3	0–50

Note: Information on species functional groups is from Arantes et al. (2019, Supplementary Information).

(Figure 3, Table 3). Respondents who have been fishing for longer reported greater declines in fish weight for four of the five indicator species (i.e., *P. nigricans*, *C. macropomum*, *Arapaima* sp., and *C. monoculus*). Only the decline in the weight of the *P. brachypomus* did not show a clear relationship with the years of fishing experience. Fishers located along the Ucayali River reported larger declines in the weight of the large-bodied and high-valued species, *Arapaima* sp. and *C. macropomum*, than fishers along the Puinahua Canal, which borders the PSNR, as indicated by the subregion dummy variable (Table 3). Most fishers (74%) reported lower catches now compared to when they started, with a reported mean decrease of 133 kg fish on a good day. Fishers with the most years of fishing experience also reported greater declines, although the result was not statistically significant (Table 3).

Species abundance decline

Total fish landings in the Department of Loreto averaged 12,700 tons per year over the 32-year study period, with a minimum of 8629 tons in 2014 and a maximum of 23,165 tons in 2010, only 4 years prior (Figure 4). Our subset of 20 species represented, depending on the year, between 81% and 93% (mean = 87.5%) of annual landings in Loreto. Fishers' perceptions were consistent with trends observed in landings data for 16 of the 20 species (Figure 5). The two species most frequently reported as having declined in abundance were *C. macropomum* and *Arapaima* sp., with over 75% of fishers reporting a decrease (or extirpation). In contrast, fewer than 25% of respondents reported declines for less valuable species such as *Hypostomus oculeus*/*Pterygoplichthys* sp./*Pseudorinelepsis* sp. (*Carachama*), *Potamorhina altamazonica* (*Llambina*), and *Serrasalmus* sp. (*Paña*). Notable disparities between landings and fishers' perceptions are observed for *H. oculeus/Pterygoplichthys* sp./*Pseudorinelepsis* sp., which were reported by fishers as having remained stable or increased but which showed a sharp decline in landings. In addition, fishers reported a decline in the abundance of *Brycon* spp. (*Sabalo*), *P. punctifer* (*Zungaro Doncella*), and *A. ocellatus* (*Acarahuazu*) when these species showed an increased share in landings. A graph showing smoothed averages of landings and

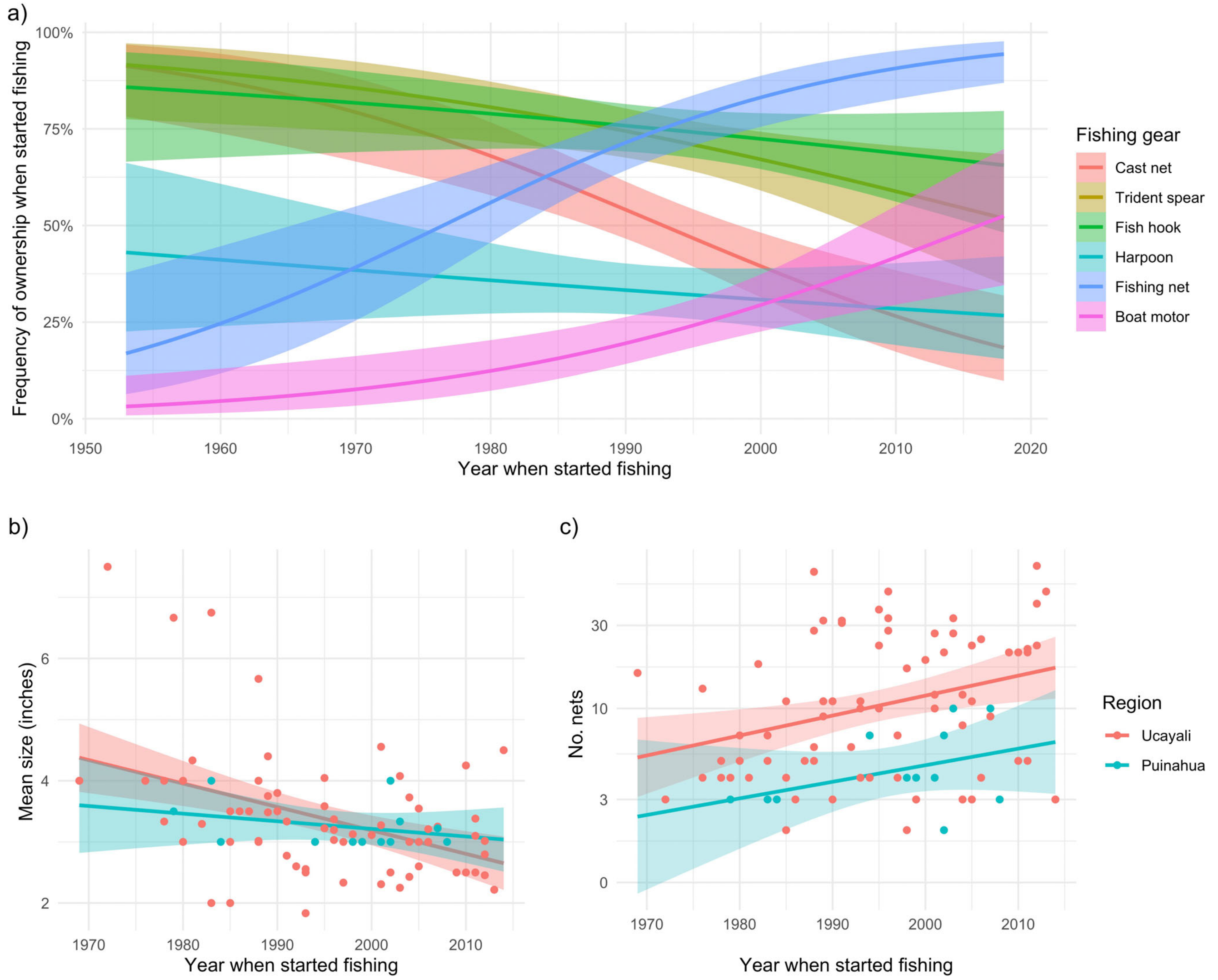

FIGURE 2 Evolution of gear owned (a) at start of fishing career according to fishers' ecological knowledge and household surveys; (b) mean mesh size of gill nets, and (c) total no. fishing nets owned according to household surveys.

proportion over time for our 20 studied species is available in Appendix S3 (Figure S1).

Shifts in functional assemblage

The FEK models that best predicted declines were market value (marginal $R^2 = 0.27$), fish body length (marginal $R^2 = 0.21$), and fish life cycle (marginal $R^2 = 0.25$). Trophic levels explained the least variance in fish abundance (marginal $R^2 = 0.15$). Each extra year of experience increased the likelihood that fishers would report a decline by 1.06-fold, and reported declines were also affected by species functional groups. In contrast, life history strategies and body length were the functional traits that best explained trends in the fish landings (marginal $R^2 = 0.10$ and 0.08, respectively). The market value and trophic model explained less variance in fish landings (marginal $R^2 = 0.05$ and 0.01, respectively). Species body length and market value are correlated ($r = 0.83$), so those models were expected to have similar outcomes. Detailed model tables are available in Appendix S3 (Tables S3–S14).

Market value

The likelihood that a given species was in decline increased steadily with market value; species in the highest value group (market value: 91–100) were 8.77 times more likely to have been reported as declining compared species of lowest value (Figure 6). Fishers living

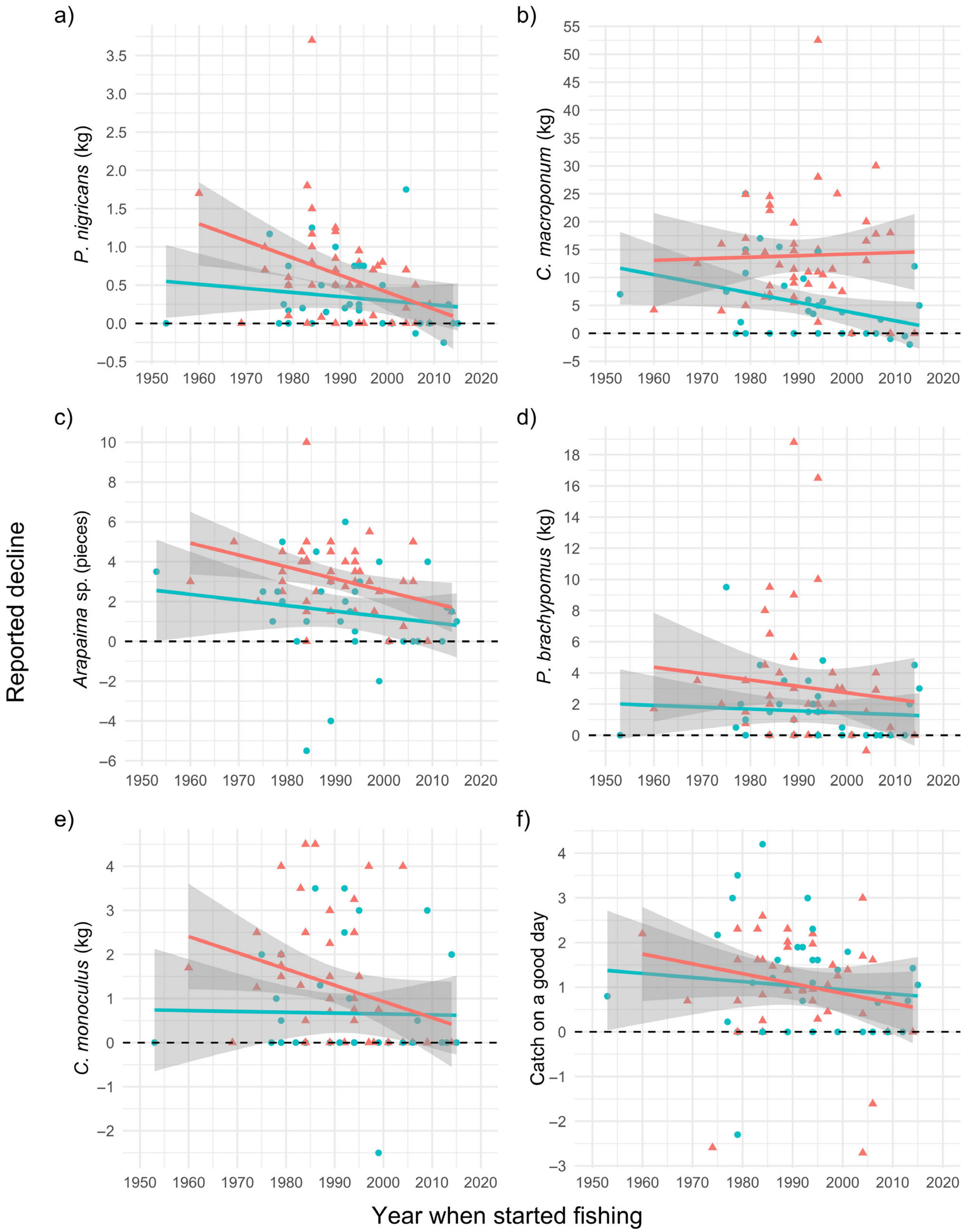

FIGURE 3 Fishers' perceptions of changes in weight for five species and changes in harvests on a good day since they started fishing. Gray area around lines represents 95% CI.

TABLE 3 Nested mixed-effect multivariate models testing the relationship between years of fishing experiences and reported weight decline for five fish species and decline in expected fish yield.

Predictor	*Prochilodus nigricans*[a]	*Colossoma macropomum*[a]	*Arapaima* sp.[b]	*Piaractus brachypomus*[a]	*Cichla monoculus*[a]	Expected catch on a good day[c]
Intercept	−0.06	1.41	0.35	0.82	−0.04	0.57
CI (95%)	−0.35 to 0.22	−3.67 to 6.49	−0.67 to 1.37	−0.54 to 2.17	−0.80 to 0.72	−0.10 to 1.23
p-value	0.668	0.586	0.498	0.238	0.917	0.094
Years of fishing experience	**0.01**	**0.12**	**0.05**	0.02	**0.02**	0.02
CI (95%)	**0.01 to 0.02**	**0.00 to 0.24**	**0.02 to 0.08**	−0.02 to 0.06	**0.00 to 0.04**	−0.00 to 0.03
p-value	**0.001**	**0.044**	**0.003**	0.313	**0.030**	0.078
Subregion: Ucayali	0.23	**7.47**	**1.32**	0.89	0.59	0.16
CI (95%)	−0.03 to 0.48	**2.34 to 12.59**	**0.56 to 2.09**	−0.31 to 2.08	−0.17 to 1.35	−0.43 to 0.75
p-value	0.084	**0.004**	**0.001**	0.146	0.126	0.595
σ^2	0.16	33.21	2.80	3.61	0.80	0.86
τ_{00} Community	0.03	20.02	0.00	0.69	0.42	0.17
ICC	0.17	0.38	0.00	0.16	0.35	0.17
N Community	18	18	17	18	18	17
N fishers	81	81	79	81	81	81
Marginal R^2/Conditional R^2	0.172/0.315	0.239/0.525	0.224/0.224	0.057/0.209	0.113/0.420	0.042/0.203

Note: Results with ($p < 0.05$) are bolded.
Abbreviations: CI, confidence interval; σ^2, residual variance for each model; τ_{00}, variance explained by random intercepts for community clusters in each model; ICC intraclass correlation coefficient, which ranges from 0 to 1 and describes the strength of the association of observations within the same group (community in our case).
[a]Weight decline for species is measured as species weight before (in kilograms) minus weight now (in kilograms).
[b]Weight decline for *Arapaima* sp. is measured in pieces instead of kilograms. Piece is the area unit commonly used by locals for measuring the size of *Arapaima* sp. We estimate, based on interviews, that an *Arapaima* sp. of one to two pieces would weigh about 20–40 kg. An *Arapaima* sp. of three pieces weighs about 80 kg, and the weight increases 40 kg for each additional piece.
[c]Expected catch on a good day was measured as log-transformed weight of a good harvest before (in kilograms) minus weight of a good harvest now (in kilograms).

along the Ucayali River were also more likely to report a decline in the high-value groups relative to those living along the Puinahua Channel. When considering landings in Loreto, while the highest-market-value species are generally related to greater catch at the beginning of the study period, they have decreased in the total catch over time (as indicated by the interaction term). Our models also show that landings for species in "market value: 51–75" and "market value: 76–90" have stagnated when compared to landings for the lowest value species.

Body length

Species within the highest body length group (80–395 cm) were 4.16 times more likely to be reported as declining compared to species of the smallest body length (Figure 7). Fishers living along the Ucayali River were also more likely to report that larger species declined as compared to fishers along in the Puinahua Channel. When considering landings in Loreto, we found that landings for species with smaller body length increased over time, especially species below 25 cm of maximum body length. Species of intermediate length (25–34 and 35–79 cm) showed a relative decline compared to small species. The body length models also suggest that species whose length exceeded 80 cm experienced marked declines, as indicated by the interaction term.

Trophic level

Piscivorous and omnivorous species were respectively 3.71 and 2.88 times more likely to be reported declining in the Ucayali River compared to detritivorous species, a relation not found in the Puinahua Channel (Figure 8). The omnivore category was the only trophic level that significantly increased in landings. Other trophic levels shifted dramatically in landings and had no significant linear trajectories over time.

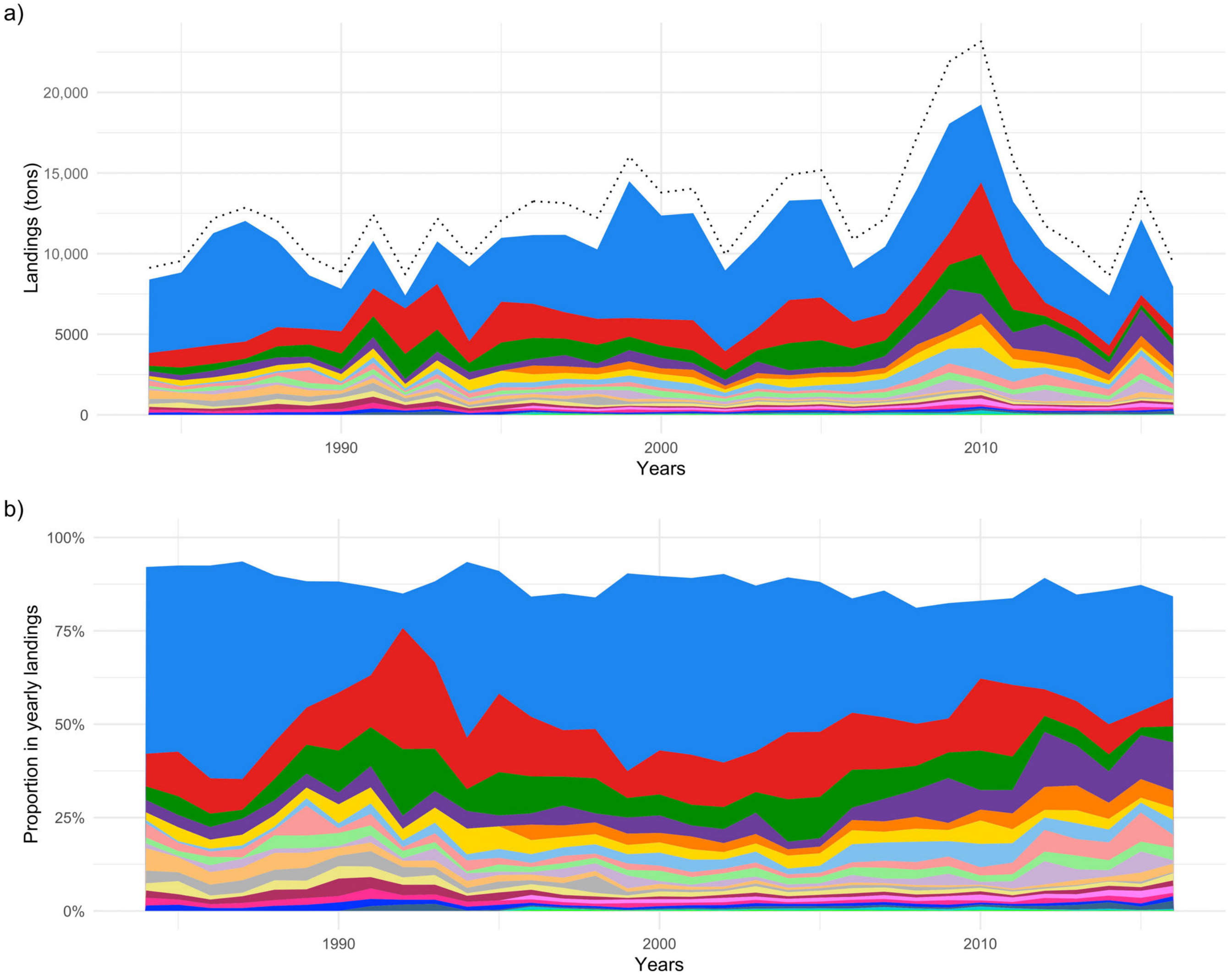

FIGURE 4 Fish landings by species in Department of Loreto from 1984 to 2016. (a) Landings in tons; (b) proportion in yearly landings. The dotted line in panel (a) represent total landings, including species excluded from our analysis. Panel (b) represents only species included in our analysis. Percentage values next to species name represent mean proportion in yearly landings for study period. Data source: Dirección Regional de la Producción de Loreto.

Life history

Fishers were significantly less likely to perceive a decline among species that had an "intermediate" (12.5 times less likely) and "periodic-small" (6.7 times less likely) life history strategy when compared to species within the equilibrium-large group (Figure 9). Species in the periodic-large life cycle group were more likely to be reported in decline by fishers living in the Ucayali River. Landings data indicate that species that reproduce at large sizes (i.e., periodic-large and the equilibrium-large group) show significant declines in share of landings over time. Indeed, although the periodic-large interaction term with years is positive ($B_{\text{years}\times\text{periodic-large}} = 0.03$), adding the years main effect ($B_{\text{years}} = -0.04$) results in the periodic-large group having a slight decreasing trend over time, whereas small species groups maintain positive trends over the years (Figure 9a and Tables S3–S14 in Appendix S3).

DISCUSSION

This study of FEK points to the intensification of fishing in recent decades along the Lower Ucayali River and a corresponding decline in fish stocks. The perceived severity of declines for each species is related to the functional traits of fish, years of fishing experience, and subregions of fishing activity. Here we discuss each factor in turn and then consider how our FEK findings complement conclusions drawn from official government data on fish landings.

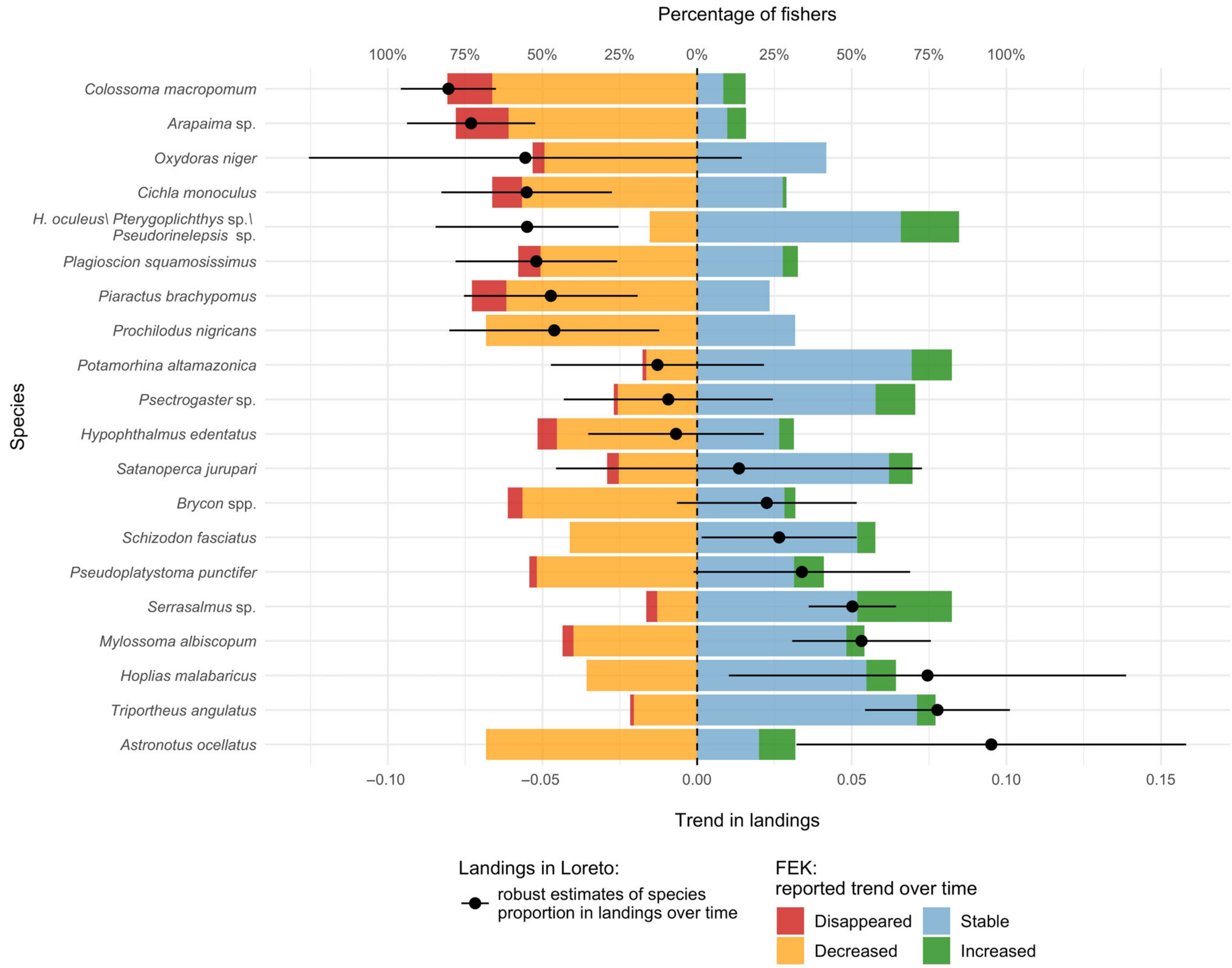

FIGURE 5 Estimates of landings over time in Department of Loreto (black points) compared to fishers' perception in Lower Ucayali River (color bars). Range around points represents 95% CI.

Status of fish stocks

Our analysis of fishers' reports from the Lower Ucayali River found clear signs of "fishing-down" (Allan et al., 2005; Castello, Arantes, et al., 2015), especially in the Ucayali subregion, where larger species and species of high value showed a steeper reported decline. We also found evidence of decline among species in higher trophic levels in the subregion and those species that had slower reproduction rates in both subregions.

Species of intermediate value (market value 76–90 and 51–75) were more often reported as declining when compared to the lesser-valued fish (market value 0–50). In that regard, market value explained the most variance among our models that relied on FEK, pointing to the importance of market pressure in influencing species-specific fishing effort. The importance of markets in driving fishing pressure and selectiveness is well documented in Amazonian fisheries (see Ames, 2015; Garcia et al., 2009; Gray et al., 2015; McGrath et al., 1993). Of particular significance in the Peruvian Amazon, recent changes in the transport chain over the last two decades have favored greater participation of riverine communities in commercial activities by supplying city markets with fresh fish (García-Vasquez et al., 2012). Our finding that fisheries in the Lower Ucayali have become increasingly gear intensive (widespread adoption of fishing nets and boat motor) and the tendency of commercial fishers to cover larger areas and target specific species of higher value (Hallwass & Silvano, 2016) brings an important insight for understanding changes in fishing behavior there and for explaining decline of high value species in the area.

Apart from changes in the fish assemblage, most fishers reported weight declines, pointing to the truncation of age structures due to significant fishing pressure

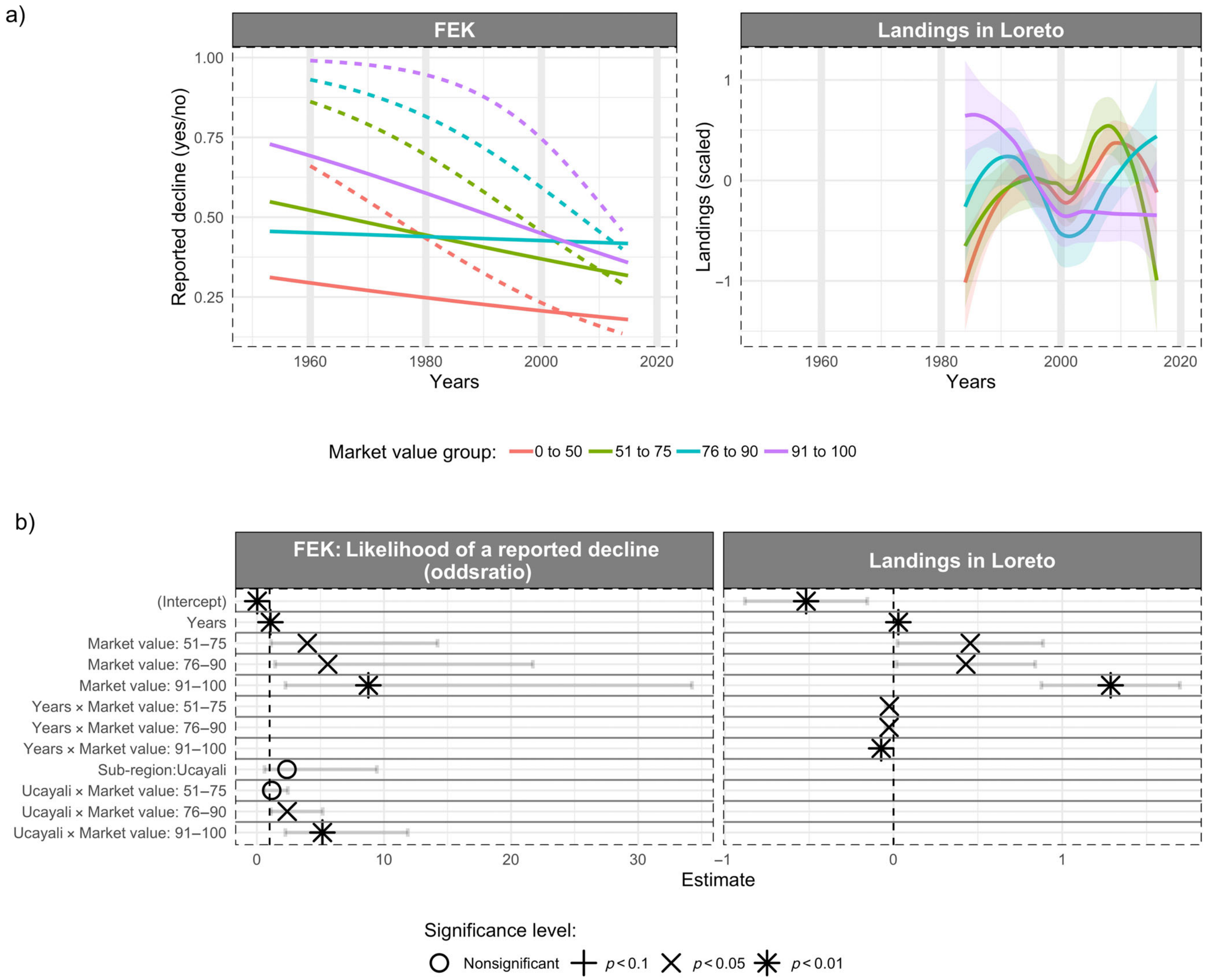

FIGURE 6 Trends in species aggregated by market value in perception of fishers from Lower Ucayali with fish landings in Loreto: (a) raw data and (b) mixed model estimates with 95% CI. Leftmost columns indicate likelihood that fishers reported a decline for a species since the time when they started fishing; dotted lines represent fishers located along Ucayali River; full lines represent fishers located along Puinahua Channel. Right column shows change in species landings in Loreto according to market value. Estimates for the "market value: 0–50" group are absent in (b) because this group is used as the control in the models.

on all five studied species (Allan et al., 2005). Extirpation of larger individuals within a species is problematic when fishing targets immature individuals, a problem exacerbated by the use of increasingly small mesh sizes that do not discriminate against juveniles of large species (Allan et al., 2005; Castello, Arantes, et al., 2015). This scenario appears to be unfolding in the Lower Ucayali, as some fishers we interviewed reported that juvenile *Arapaima* sp. were often caught and killed in small-mesh gill nets or captured by circling nets.

Our FEK-based indicators do not provide representative length distribution and biomass estimates for species, so we cannot determine whether stocks have reached or will be reaching recruitment impairment (Frank & Brickman, 2001; Hsieh et al., 2010). Further, R^2 values are generally low throughout the study (0.05–0.65), which is expected as our models aim to predict perceptual responses and trends in landings of 20 different species in a complex flood pulse-driven fishery over a 32-year period (Castello, Isaac, & Thapa, 2015; Vela et al., 2013). Nevertheless, our findings raise concern over the use of increasingly small mesh size in the area and point to the alteration of the fish assemblage with potential impacts on ecosystemic processes in the Lower Ucayali, such as the removal of larger predators (Campos-Silva et al., 2021), the decline of large seed

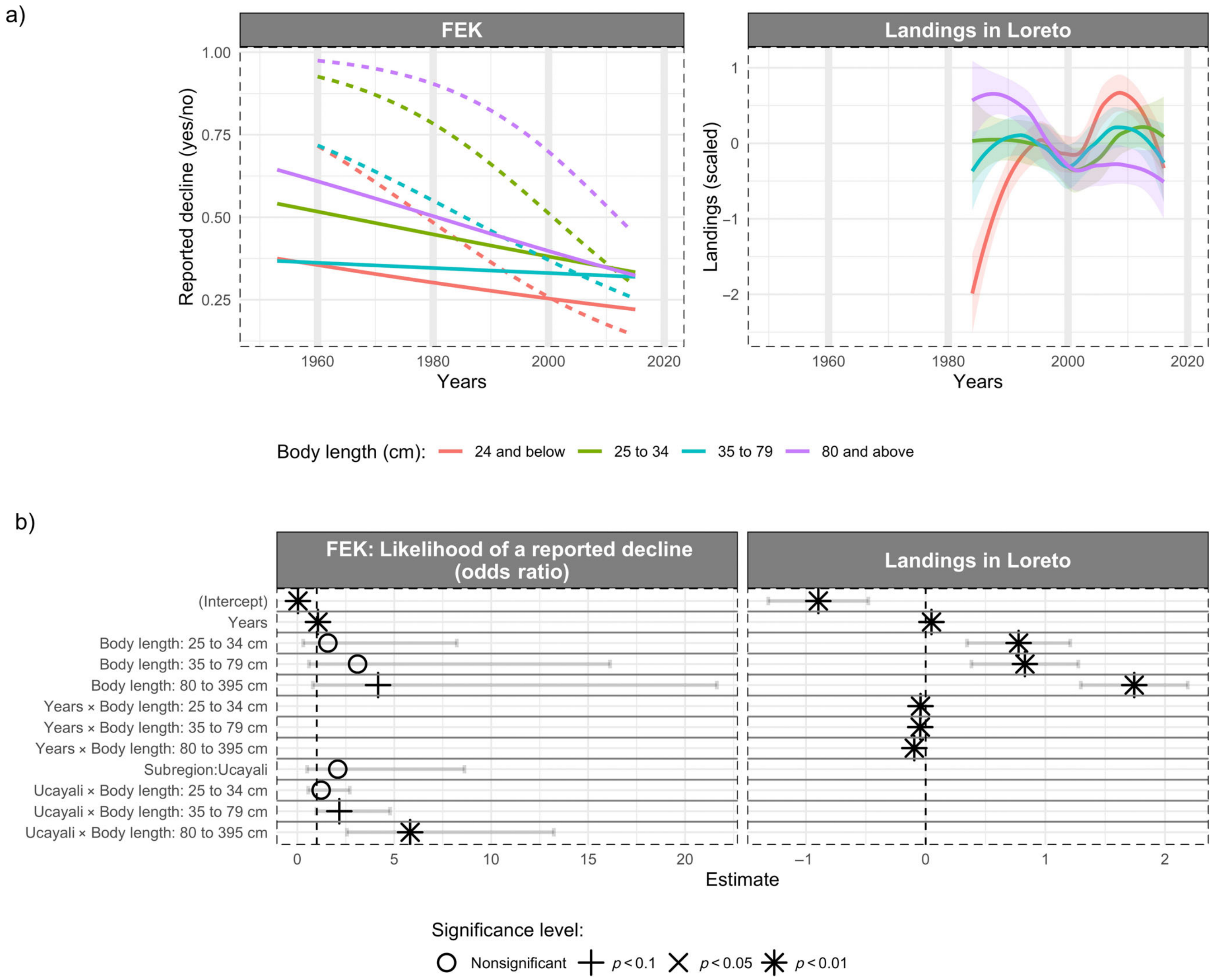

FIGURE 7 Trends in species aggregated by fish body length in perception of fishers from Lower Ucayali with fish landings in Loreto: (a) raw data and (b) mixed model estimates with 95% CI. Leftmost columns indicate likelihood that fishers reported a decline for a species since the time when they started fishing; dotted lines represent fishers located along Ucayali River; full lines represent fishers located along Puinahua Channel. Right column shows how species landings have changed over time in Loreto according to body length. Estimates for the 24 cm and below group are absent in (b) because this group is used as the control in the models.

dispersers (Correa et al., 2015; Tregidgo et al., 2017), and the degradation of age structures (Allan et al., 2005). Our findings also highlight the need for monitoring a larger array of fish species than the ones normally considered to be susceptible to overfishing.

Differences in perceptions among fishers

Our study demonstrates the value of studying differences in perceptions among fishers. More fishing experience was associated with a higher likelihood of reported declines in abundance, steeper reductions in fish size for *Arapaima* sp., *C. macroponum*, *P. nigricans*, and *C. monoculus*, and lower expected catches on a good day. These results point to the presence of a shifting baseline syndrome, whereby younger fishers know only an environment with fewer fish and thus have a lower reference point for comparisons over time than do older fishers (Papworth et al., 2009; Pauly, 1995). Although the shifting baseline syndrome is commonly encountered in studies of inland aquatic wildlife (Humphries & Winemiller, 2009), our study is one of the few to show evidence of this among fishers in Amazonia (see also Hallwass et al. [2020]). Our evidence of a shifting baseline should, however, be taken with caution, as fishers' recall of past catch may become increasingly overestimated over longer time periods (Thurstan et al., 2016).

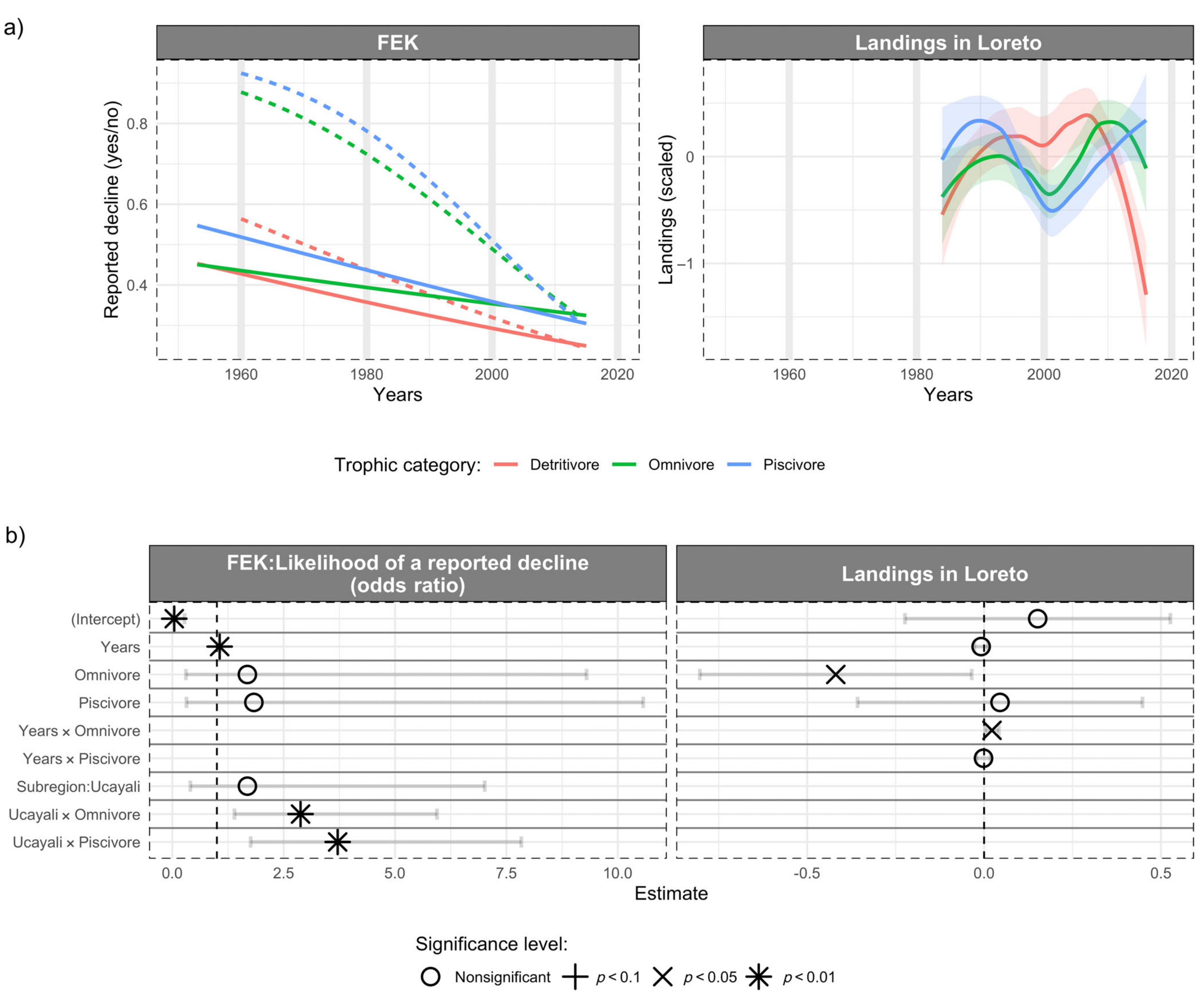

FIGURE 8 Trends in species aggregated by trophic category in perception of fishers from Lower Ucayali with fish landings in Loreto: (a) raw data and (b) mixed model estimates with 95% CI. Leftmost columns indicate likelihood that fishers reported a decline for a species since when they started fishing; dotted lines represent fishers located along Ucayali River; full lines represent fishers located along Puinahua Channel. Right column shows how species landings have changed over time in Loreto according to trophic categories. Estimates for detritivore group are absent in (b) because this group is used as the control in the models.

Fishers along the Ucayali River subregion were more likely to report a decline in species abundance and other signs of declines in stocks than those along the Puinahua Channel. Ucayali fishers also used more efficient fishing methods than fishers in the Puinahua Channel for comparable harvests (results shown in Appendix S1: Figure S3), seemingly reflecting the need to intensify fishing effort to adapt to fish depletion. A likely explanation for the relative stability of fish abundance in the Puinahua Channel lies in its proximity to the vast wetlands of the PSNR, where fishing is restricted. Protected areas such as the PSNR may benefit fisheries via the spillover effects, whereby juveniles and adults migrate to neighboring areas (Gell & Roberts, 2003; Silvano et al., 2009). In addition to proximity to a protected wetland, the relative stability of fish stocks in the Puinahua Channel may also arise because local communities generally enforce a greater number of and stricter fishing regulations than communities along the Ucayali River (results shown in Appendix S1: Figure S1). Indeed, fishers living in communities that enforced regulations frequently pointed to the added value of protecting local lakes; accounts of an increase in the size of *Arapaima* sp. were all reported in communities that enforced stricter regulations. Our findings offer further evidence of the importance of large conservation areas and community initiatives for maintaining fish stocks in Amazonia (Arantes et al., 2021;

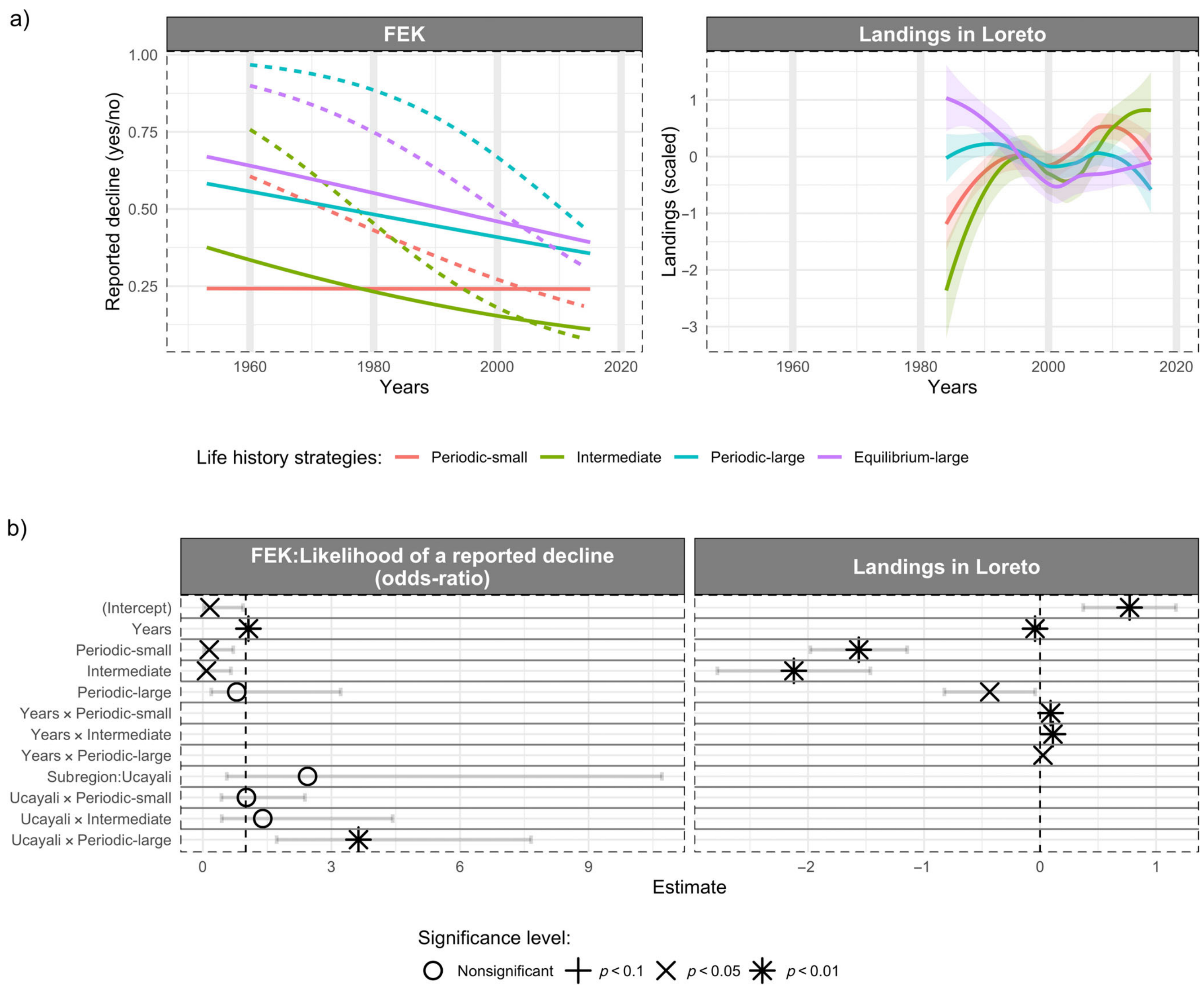

FIGURE 9 Trends in species aggregated by life history strategies in perception of fishers from Lower Ucayali with fish landings in Loreto: (a) raw data and (b) mixed model estimates with 95% CI. Leftmost columns indicate likelihood that fishers reported a decline for a species since the time when they started fishing; dotted lines represent fishers located along Ucayali River; full lines represent fishers located along Puinahua Channel. Right column shows how species landings have changed over time in Loreto according to life history strategies. Estimates for equilibrium-large group are absent in (b) because this group is used as the control in the models.

Hallwass et al., 2020; Lopes et al., 2018; Medeiros-Leal et al., 2021). The steeper decline of fish stocks we observed in the Ucayali River subregion compared to the Puinahua Channel suggests a need for improved support for community-led initiatives in this subregion.

Complementarity of FEK and official landings data

Previous studies using official government landings data in Loreto found that highly valued and larger-bodied fish species had declined since the mid-1980s and pointed to the problem of overfishing for city markets (De Jesús, 2004; Garcia et al., 2009; Ortega & Hidalgo, 2008; Tello & Bayley, 2001; Vela et al., 2013). Our findings based on FEK and analysis of more recent official landings data are largely consistent and corroborate this conclusion.

Still, our FEK surveys from the Lower Ucayali identified important trends that remain undetected in aggregate fish landings data for Loreto. Indeed, our finding that older fishers were most likely to report declines suggest that fish stocks in the Lower Ucayali were already impacted by fishing activities before the start of data collection by the state in the mid-1980s. Being aware that fish stocks for certain species were impacted by fishing activities before the collection of landings data is crucial for the fishery management in the region, as trends perceivable in official statistics may not capture longer historical changes in exploited fish stocks (Sáenz–Arroyo et al., 2005). Fishers also reported declines for a few species that are generally not considered vulnerable to fishing pressure (e.g., *A. ocellatus*, *Brycon* spp.) and whose decline is not perceivable in landings data. Further, whereas landings showed a relative stability in volume over the study period, the vast majority of fishers reported important declines in catch rates since they began fishing and, at the same time, an intensification of fishing gear used. This finding highlights the prospect of hyperstability in fish landings data; that is, when catch per unit effort remains constant but true fish abundance declines (Erisman et al., 2011). Overall, our study suggests that FEK may be more sensitive to local stock declines compared to landings data aggregating multiple fisheries over a wider area (Daw et al., 2011; Lima et al., 2016) and obviates other problems associated with an exclusive reliance on fish landings records in Amazonia, such as blindness to illegal and informal fishing activities and increasing remoteness of fish sources serving cities (Batista et al., 1998; Cavole et al., 2015; Garcia et al., 2009).

Data needed for our FEK-based indicators can be readily collected on a large scale, and the indicators are easily interpretable both for decision makers and fishers without formal training, which favors a shared understanding by stakeholders of stocks status and future directions needed for the fishery (Castello et al., 2023; Shephard et al., 2020). Fishers we interviewed were very astute and reported numerous ecological changes that went well beyond our focus on the indicators presented here. Most importantly, fishers were aware of regional management issues associated with accelerated rates of fish harvesting in their nearby lakes. The use of toxic products and small-mesh nets by fishers from elsewhere were commonly reported, and feelings of disempowerment by fishers and community leaders over control of access to local lakes and of fishing methods were widespread. In this area of unique fish fauna diversity and where fishing supports the well-being of many, effective strategies that ensure access to viable fish populations for local communities are needed.

CONCLUSION

Developing sampling methods for assessing fish stocks in data poor areas has become a global priority, and scientists are increasingly relying on FEK to inform our understanding of Amazonian fisheries. Our field experience suggests that FEK is especially useful in studying flood pulse-driven floodplain fisheries where the environment is highly dynamic, fishers pursue multiple species with a variety of gear, and households employ flexible livelihood strategies. Our simple FEK-based indicators provide strong evidence that fish stocks have been impacted by "fishing down" along the Lower Ucayali, an area where no long-term reliable data are available. Our study brings further credence to the added value of FEK for gaining insights unavailable from fish landings data and to the important role that fishers must have for developing fishery management priorities and scientific research on floodplain fisheries.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Poissant, 2024a) derived from FEK, household, and Peruvian Amazon Rural Livelihoods and Poverty (PARLAP) surveys are available in Dryad at https://doi.org/10.5061/dryad.qfttdz0h9. Code (Poissant, 2024b) is available in Zenodo at https://doi.org/10.5281/zenodo.7632550. Landings data supporting this research are restricted and not available to the public; the aggregated data set of landings in Loreto from 1984 to 2016 is the property of the Dirección Regional de la Producción Loreto, and these data are available to qualified researchers, who must contact the Director of the Dirección Regional de la Producción Loreto (https://www.gob.pe/institucion/regionloreto/funcionarios).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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