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Tough fishing and severe seasonal food insecurity in Amazonian flooded forests

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Abstract

1. Billions of people rely on harvesting wildlife for food, and must contend with catch rates that vary in space (e.g. overharvesting near communities) and time (e.g. seasonal migrations). Yet, research has overlooked potential linkages between reduced wildlife catch rates (catch-per-unit-effort) and food security. Moreover, assumptions that people living in biologically rich environments are food secure lack empirical testing. This is problematic given that food security rests on having *stable access* to sufficient food, rather than there *being* sufficient food.
2. We examine spatiotemporal variation in fish catch rates and perceived food security among rural communities in Amazonian flooded forests. We also assess social inequities in food insecurity. We used structured interviews to collect data on fishing, hunting, chicken and beef consumption, and perceptions of food security. We did so during 556 household visits along a spatial gradient (1,267 km) of commercial fishing pressure, during high- and low-water seasons.
3. We provide the first empirical evidence of simultaneous seasonal crashes in wildlife catch rates and food insecurity. During the high-water season, fish catch rates were 73% lower, and the probability of not eating for a whole day was four times higher. With a third of households skipping meals and a sixth not eating for a whole day during this season, food security can be classed as severe. However, less-deprived households tended to avoid severe food insecurity. Fish catch rates and perceived food security did not vary along a spatial gradient of commercial overfishing. River-dwelling Amazonians increased fishing and hunting efforts during the high-water season, without eating more chicken and beef, emphasizing the importance of stable access to wild fish and bushmeat.
4. This study shows how wildlife catch rates and food security can crash seasonally and simultaneously, demonstrating the fallacies of environmental and social policies which assume stability of food availability in resource-rich areas. Our results have implications for degraded habitats where falls in catch rates also occur. This suggests that overharvesting, as with other causes of reduced catch rates, could cause food insecurity in wildlife-reliant populations.

KEYWORDS
CPUE, food security, food stability, hunting, nutrition transition, yield

1 | INTRODUCTION

Billions of people worldwide rely on wild fish and bushmeat as major sources of protein, fats, calories and micronutrients (Cawthorn & Hoffman, 2015; Golden et al., 2016; Hicks et al., 2019; Lynch et al., 2016). It is commonly assumed that the food security of these wildlife-reliant populations is jeopardized by the ongoing fall in vertebrate abundance (e.g. Golden et al., 2016; Nasi, Taber, & Van Vliet, 2011; WWF, 2018), which in recent decades is estimated to have declined by 60% (WWF, 2018). Perhaps the most dramatic estimate is that one-fifth of the world's population is vulnerable to nutrient deficiencies due to declines in global marine fish catch (Golden et al., 2016). These evaluations are partly based on the sound theoretical basis that wildlife abundance dictates both catch rates (catch-per-unit-effort: CPUE) and catch (yield; according to equations in Supporting Information). However, we lack empirical evidence that wildlife abundance, catch rates and catch are actually related to food security.

In addition to the loss of aquatic and terrestrial vertebrates, fishers and hunters may also be subjected to natural seasonal fluctuations in wildlife catch rates and catch, and therefore theoretically to food security. For example, Serengeti wildlife abundance is dramatically influenced by mass seasonal influxes of migratory herbivores, which is positively associated with human meat consumption frequency (Nyahongo, Holmern, Kaltenborn, & Røskaft, 2009). Moreover, fish become 'diluted' in flood-pulse waters, resulting in lower catch rates and catch (Endo, Peres, & Haugaasen, 2016), and reduced fish consumption in Amazonia (Begossi, Silvano, Amaral, & Oyakawa, 1999; Da Silva & Begossi, 2009; Saint-Paul, Zuanon, & Correa, 2000) and the Congo (Poulsen, Clark, Mavah, & Elkan, 2009). Although these studies did not measure food security, their results suggest that seasonal food insecurity may be characteristic of wild food systems, just as it is common in agricultural systems (Ferro-luzzi, Morris, Amato, & Nazionale, 2001; Roba et al., 2019; Vaitla, Devereux, & Swan, 2009).

Of the four dimensions of food security (availability, access, stability and utilization), food stability—the need for people to have adequate food *at all times*—is considered to have made the least progress towards improvement (Ashley, 2016) and remains the least studied (Cruz-Garcia, Sachet, Vanegas, & Piispanen, 2016). Although more associated with conflicts and natural disasters, food instability occurs most commonly on a seasonal basis (Vaitla et al., 2009). Even mild food insecurity can be detrimental to the health of vulnerable groups (Bailey, West, & Black, 2015; Gernand, Schulze, Stewart, West, & Christian, 2016; Schmeer & Piperata, 2017), and studies have demonstrated seasonal malnutrition in pregnant women (Jiang, Christian, Khatry, Wu, & West, 2005) and wasting and stunting in children (Ferro-luzzi et al., 2001; Hillbruner & Egan, 2008).

A body of evidence suggests declines in wildlife catch rates and catch might cause food instability, yet no study has combined methods and insights from ecology with food security assessment. In this study, we examine spatial and seasonal variation in food security and in catch and catch rates of fish among Amazonian *ribeirinhos* living in and around seasonally inundated floodplain forests. *Ribeirinhos* are a marginalized group of river-dwelling, Portuguese-speaking, non-indigenous, traditional people, of mixed (indigenous Amazonian/European/African) descent. Paradoxically, given the wildlife-rich and relatively intact environment in which they live (Raudsepp-Hearne et al., 2010), many *ribeirinhos* exhibit chronic malnutrition (Alencar et al., 2008; Guerra, Espinosa, Bezerra, Guimarães, & Lima-Lopes, 2013). They are also highly dependent on wild fish and bushmeat (Dufour, Piperata, Murrieta, Wilson, & Williams, 2016; Murrieta & Dufour, 2004; van Vliet et al., 2015); access to which varies spatially due to overharvesting (Keppeler et al., 2018; Parry & Peres, 2015; Tregidgo, Barlow, Pompeu, Almeida, & Parry, 2017) and seasonally due to floods (Da Silva & Begossi, 2009; Saint-Paul et al., 2000).

In this paper, we ask five research questions, and outline our hypotheses in Table 1. The main questions are (1) how does seasonality affect the food security of *ribeirinhos*? and (2) how variable is rural food security in space? We then scrutinize the link between food security and catch rates, by asking (3) are spatiotemporal crashes in fishing catch rates (CPUE in biomass: CPUEb) associated with food insecurity? We then ask (4) what behavioural responses do *ribeirinho* households employ to low fish catch rates? Lastly, in recognizing that food security can be determined by socioeconomic factors (e.g. Harris-Fry et al., 2015), we examine (5) which kinds of rural households are most vulnerable to food insecurity?

2 | METHODS

2.1 | Study area and social context

This study was undertaken in *ribeirinho* communities in and around white-water river floodplains (*várzeas*) of the River Purus (Figure 1), in the central Brazilian Amazon. With an area of around 100,000 km^2 (Wassman & Martius, 1997), *várzeas* cover a small proportion of the Amazon basin (*c.* 8 million km^2), but are thought to be home to the majority of the rural population in Brazil's largest Amazonian states: Amazonas and Pará (Junk, Piedade, Schöngart, & Wittmann, 2012). This is partly due to the exceptional richness of forest and aquatic wildlife in *várzeas* (Junk et al., 2012), with high productivity driven by nutrient-rich white-waters and the effect of the flood-pulse (Castello, Isaac, & Thapa, 2015; Junk et al., 2012). Despite this great availability of edible animals within their local environment (Alencar,

TABLE 1 Hypotheses of spatiotemporal variation in food security, the measure employed in this study to test them, the rationale behind them and references supporting these hypotheses, relating to each of the five research areas

Hypothesis	Measure	Rationale	References
(1) Seasonal variation in food security			
Perceived food insecurity will be more prevalent and severe in the high-water season	High-water and low-water season repeated sampling	Dilution of fishes due to greater river volume in high-water season	Non-specific season (1–5)
(2) Spatial variation in food security			
Perceived food insecurity will be more severe closer to metropolitan and provincial urban centres	Fluvial travel distance to the metropolitan centre of Manaus and the closest urban settlement	Depleted fish nearer urban settlements due to overfishing	None known
(3) The importance of fish catch rates in driving food insecurity			
Fish catch rates will be lower …			
… during the high-water season	Fish catch rates (CPUEb)	Dilution of fish in greater volumes of water	(6)
… closer to urban centres	Fish catch rates (CPUEb)	Depletion from commercial overfishing	(6, 7)
(4) Responses to low fish catch rates			
Where and/or when fish catch rates are lower …			
… fishing effort will be greater	Household fishing effort (hr), and the chance (0/1) of going fishing	Compensatory to try to maintain fish harvest	(8, 9)
… hunting effort will be greater	The chance (0/1) of going hunting	Compensatory to try to maintain hunted harvest	(6, 10)
… domestic meat (chicken and beef) consumption will be greater	Frequency of household chicken and beef consumption in the past month	Compensatory to try to maintain animal protein	Fish-domestic meat switch (11, 12)
(5) Household vulnerability to food insecurity			
Perceived food insecurity will be less severe where …			
… household wealth is greater	Household floor area	Poor have less purchasing power	(13)
… household population is smaller	Household size (number of inhabitants)	Fewer mouths to feed	(13–15)
… education level is greater	Maximum resident's years of education	Education is a key determinant of production	(13, 14, 16)
… a lower proportion of the household is dependent	Proportion of household that is of dependent age (<16 and >59 years) to those that are not	Dependents consume, but likely to contribute less to money and food acquisition	(14, 15)
… people receive government cash transfers (GCTs)	At least one monthly GCT received in the household	This monetary income can be used to purchase food	*Bolsa Família* (17), pensions (18)

Note: 1–5: (Ferro-luzzi et al., 2001; Hillbruner & Egan, 2008; Hoorweg, Foeken, & Klaver, 1995; Panter-Brick, 1997; Trowbridge & Stetler, 1982); 6: (Endo et al., 2016); 7: (Cinner et al., 2016); 8, 9: (Geheb & Binns, 1997; Watson et al., 2013). 10: (Brashares et al., 2004); 11, 12: (de Jesus Silva, de Paula Eduardo Garavello, Nardoto, Mazzi, & Martinelli, 2016; Wilkie & Godoy, 2001); 13: (Harris-Fry et al., 2015); 14: (Bashir et al., 2012); 15: (Baulch & McCulloch, 1998); 16: (Mutisya, Ngware, Kabiru, & Kandala, 2016); 17: (Duarte, Sampaio, & Sampaio, 2009); 18: (Machado & de Oliveira Neto, 2016).
Abbreviation: CPUEb, catch-per-unit-effort in biomass.

Yuyama, de Varejão, & Marinho, 2007; Beckerman, 1979) and impressive wildlife harvesting skills, *ribeirinhos* appear vulnerable to food insecurity.

As fish is the main source of protein and a major energy source for *ribeirinhos* (Dufour et al., 2016; Murrieta & Dufour, 2004; van Vliet et al., 2015), they are likely to be sensitive to crashes in fishing success, which might occur spatially and temporally. Spatial variation in Amazonian wildlife populations has been associated with commercial overharvesting, with depletion of wild animals in rivers and forests having been detected hundreds of kilometres from Amazonian urban centres (Parry & Peres, 2015; Tregidgo et al., 2017). Moreover, the annual flood-pulse transforms the floodplain into flooded forest for up to 6 months per year, reducing catch rates during the high-water season (Pinho, Marengo, & Smith, 2015; Saint-Paul et al., 2000), as fish disperse into the greater volume of water and far into the flooded forest.

Ribeirinhos experience multidimensional poverty, including (but not exclusive to) low levels of education; income and healthcare; a high disease burden and marginalization. In the Brazilian Amazon, levels of education and monetary income are among the lowest in the country. For example, almost half (46%–49%) of people living in the largest Brazilian Amazonian states of Amazonas and Pará live

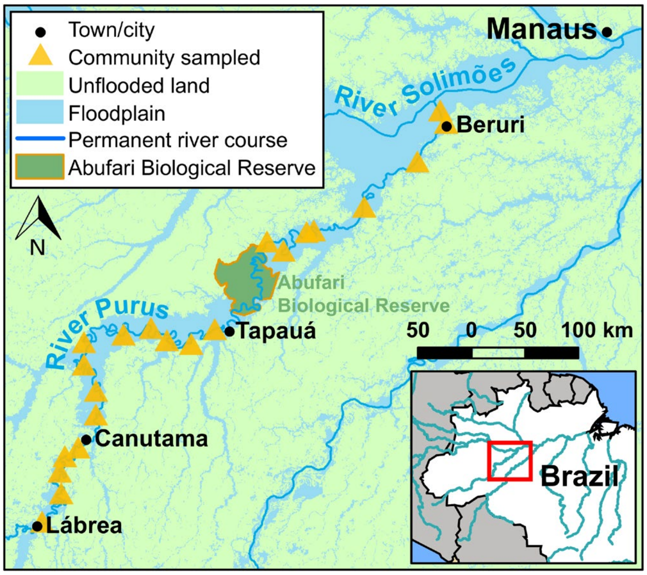

FIGURE 1 Floodplain map of the study area

in income poverty, almost double the Brazilian national average (25%; IBGE, 2017). Furthermore, malnutrition among *ribeirinhos* is exacerbated by poor environmental health, and limited access to quality healthcare; both of which contribute to a high burden of insect-borne (Katsuragawa et al., 2010), water-borne and intestinal parasitic disease (Piperata, 2007). Our focus on *ribeirinhos* is significant, as in contrast with indigenous populations, they are often considered 'invisible' to policymakers and Brazilian society (Fraser, 2018; Parry et al., 2019).

The Purus sub-basin is well-suited to study how seasonal changes and overfishing impact food security. The River Purus is the main fishing ground of the Amazon's largest city—Manaus (Batista & Petrere Júnior, 2003; Cardoso, Batista, Henry, Júnior, & Martins, 2004), presenting a distance gradient of urban remoteness and fishing pressure, where commercial overfishing has been evidenced (Keppeler et al., 2018; Tregidgo et al., 2017). The studied municipalities are otherwise relatively intact, with high forest cover (>94%) and low population densities (<0.9 people per km^2; Table S1). It is also an ideal location for comparing seasonal hydrological differences due to the water level amplitude of around 15 m (Castello & Macedo, 2016) being among the largest seasonal fluctuations in river levels on the planet, and hence we expect a uniquely large variation in fish catch rates.

2.2 | Sampling

Data were collected during a high-water (April–July 2014) and a low-water (August–November 2014) field season. We avoided collecting data during the fishing closed season (*defeso*; 15 November 2013–15 March 2014 and 15 November 2014–15 March 2015), to avoid additional variation in fishing activity or potential reporter bias. We descended the river to accompany the water levels, intending to sample communities at approximately the maximum and minimum of annual water levels, based on long-term seasonal averages (Coe, Costa, Botta, & Birkett, 2002).

We sampled 22 rural communities, at least 13 km apart, between the town of Lábrea and the confluence with the River Solimões (Figure 1), covering a fluvial travel distance of 1,267 km, as calculated using the travel network function in ArcGIS 10.2.2 (ESRI, 2014). Our sampling design aimed to capture spatial (urban distance gradient), temporal (seasonal repeated sampling) and social (multiple households per community) variation. Some avoidable ecological and social variation was controlled for by standardizing sample community size (10–30 houses) and avoiding sampling in the strictly regulated Abufari Biological Reserve. See methods in Supporting Information for further details.

We sampled ≤20 households per community per season, and randomly selected households using a 'lottery' system if a community had more than 20 inhabited houses (Table S2). We first interviewed the self-declared household head or principal food-preparer (irrespective of gender) to collect social data, which largely concerned household food insecurity and domestic meat consumption. This interviewee also informed us which household members had been fishing or hunting in the past 30 days (hereon referred to as fisher and hunter respectively, or harvester collectively), and we interviewed all adult (≥16 years old) harvesters concerning their harvesting activities.

2.3 | Fishing and hunting data

Harvest studies are increasingly utilizing interviews to gain important knowledge (Thurstan, Buckley, Ortiz, & Pandolfi, 2015), including catch and CPUE (catch rate) data. Commercial CPUE is probably the most widely used index of abundance in marine fisheries (Edwards, Hillary, Levontin, Blanchard, & Lorenzen, 2012). CPUE has also been widely used in studies of bushmeat hunting (Gill, Fa, Rowcliffe, & Kümpel, 2012; Parry, Barlow, & Peres, 2009; Rist, Milner-Gulland, Cowlishaw, & Rowcliffe, 2010) and tropical inland fisheries (Almeida, Lorenzen, & McGrath, 2002; Hallwass, Lopes, Juras, & Silvano, 2011; Pinho, Orlove, & Lubell, 2012), in which remoteness and low observation rates impede collection of ecological field data. Collecting data on harvester catch and effort can be cheaper and more efficient than traditional methods, yet with comparable accuracy and precision for estimating CPUE (Rist et al., 2010; Thurstan et al., 2015).

We restricted interviews to harvesting trips that occurred within 2 hr (via motorized canoe) from a harvester's home to ensure interviews were spatially representative of the respective community. This criterion also represents a limitation to our methodology by also excluding the rare occasions, whereby a sustenance harvester would travel over 2 hr, which may occur in more depleted areas, for example. We were careful not to double-count records from multi-fisher trips, and excluded occasions where someone had gone just to help out (e.g. just paddling the canoe). In addition, fishers were asked in detail about the catch, effort and catch methods of every fishing trip (whether successful or not) that they had undertaken within the 72 hr prior to the interview. Respondents were asked to report the species (or lowest taxonomic rank) and quantity landed. These catch data were converted into biomass using standard species weights that we collected along the River Purus. We also recorded time spent fishing (excluding travel time), fishing gear used, as well as gillnet area and mesh size where relevant. Multispecies catch rate (CPUEb) was calculated as catch (kg) divided by effort (hours fishing), or as catch divided by net area (m^2) divided by effort for gillnets. See methods in Supporting Information for further details, particularly on how standard species weights were generated.

Hunting within the previous 72 hr was too rare to permit statistical analysis, so instead we used hunting recall data from the previous 30 days, which only included the species (or lowest taxonomic rank) and quantity. We calculated hunted biomass using published species body weights (Table S3).

2.4 | Food security

We measured perceptions of food security using the context-specific Coping Strategies Index (CSI), which has been widely applied by national governments and non-governmental organizations, and correlates highly with other food security benchmarks (Maxwell et al., 1999; Maxwell, Caldwell, & Langworthy, 2008; Maxwell, Vaitla, & Coates, 2014). Other commonly utilized food security indices, such as the Brazilian Household Food Insecurity Scale (IBGE, 2010), were considered inappropriate to our study system, mainly due to their strong focus on food purchase; of secondary importance to a population that fishes and plants most of their protein and calories, respectively (Murrieta & Dufour, 2004). However, the CSI is based on the severity and frequency of locally defined coping strategies, thereby permitting us to tailor the index specifically to the study population (Maxwell, 1996; Maxwell & Caldwell, 2008).

'What do you do when you don't have enough food?' was asked in several focus groups during a pilot study in *ribeirinho* communities along the River Purus. The most common responses were transformed into six questions (Table 2), capturing different aspects of reduced food consumption and food switching. Hence, we do not assess *anxiety* about acquiring insufficient food, which alone is associated with mild food insecurity, but instead we assess *behavioural manifestations* of food insecurity (i.e. eating less, not eating or eating non-preferred foods; Ballard, Kepple, & Cafiero, 2013; IBGE, 2010). Consequently, when comparing to other scales, our questions are capable of identifying the presence or absence of moderate or severe food insecurity, whereas it cannot distinguish between food security and mild food insecurity. To correspond to food security at household level, it was stressed that questions related to activities taking place in the home and not, for example, in another house or while fishing. The same six food security questions were asked during both the high- and low-water seasons.

We calculated the food insecurity index based on the frequency and severity of coping strategies (Maxwell et al., 1999). Coping strategy frequencies (undertaken in previous 30 days) were pooled into five categories: never, less than once a week, 1–2 times a week, 3–6 times a week or every day. A frequency score was assigned to each category, corresponding to the relative frequency listed in each category (e.g. 3–6 times a week = 4.5). *Ribeirinhos* ranked the severity of the six coping strategies, whereby focus group members discussed which of the six coping strategies were more severe, until a consensus was made. Based on these perceived severity rankings, each coping strategy was assigned a weight from 1 (least severe) to 6 (most severe; Table 3). The frequency score was multiplied by the severity weight to obtain food insecurity scales for individual strategies, and summed for the cumulative food insecurity index.

TABLE 2 Coping strategies interview questions

In the last 30 days has anyone in the household …?
Gone the whole day without eating anything (having just a *merenda* snack was included as eating nothing, because it often comprised just coffee and crackers)
Gone the whole day without eating any fish or meat (wild or domesticated)
Skipped lunch or dinner at home (if a harvester skipped a meal while harvesting or undertaking other work in the field this was not included, as it is common due to impracticalities or unexpected delays)
Eaten only *farinha* (toasted manioc flour) for lunch or dinner at home (known as *chibé* or *jacuba*, this dish is generally despised (personal observation), but not uncommonly eaten when working in the field for convenience; it consists only of *farinha*, water and either salt or sugar)
Had to eat less fish or meat than they would have liked to at lunch or dinner
Substituted fish or meat with an alternative protein source such as eggs, beans, canned meat or fish, or hotdog sausages

2.5 | Domestic meat consumption

Due to the growing importance of domestic meats in the diets of river-dwelling Amazonians (Chaves, Monroe, & Sieving, 2019; van Vliet et al., 2015), we measured the frequency of consumption of chicken and beef within households during the past 30 days. We used the same frequency categories as with the food insecurity scale. We also asked whether these chicken and beef were community-reared livestock or imported. We estimated total household chicken consumption assuming consumption of one whole chicken per consumption event, using 2.2 kg as the mean weight of a slaughtered chicken in Brazil (IBGE, 2016).

2.6 | Statistical analysis

Variation in perceived food security was assessed using linear mixed-effects models. Community and household I.D. were included as random factors, which dealt with seasonal repeated and independent (absent household during one season) sampling. For fishing analyses, random factors included were fisher I.D. for models analysing fishing trip catch rates, and household I.D. for household-level analyses of catch

TABLE 3 Food insecurity model results. Results of linear mixed models of household food security, and the frequency of coping strategies, in increasing order of severity, with the 'severity' rating corresponding to the weight used in calculating the food insecurity scale. All statements were asked about coping strategies undertaken in the 30 days prior to interview. Distance (km) to urban centres was divided by 100

		Distance to Manaus		Distance to nearest town		Seasons		Mean weekly frequency	
Food insecurity index	Severity	Coefficients & *SE*	*z*	Coefficients & *SE*	*z*	Coefficients & *SE*	*z*	High water	Low water
Accumulated Index	NA	−0.022 (0.020) NS	−1.06	0.002 (0.105) NS	0.02	−0.880 (0.022)***	−40.08	NA	NA
To eat something else instead of fish or meat	1	−0.018 (0.014) NS	−1.30	−0.077 (0.073) NS	−1.06	−0.179 (0.041)***	−4.36	1.27	1.07
To not eat any fish or meat for a whole day	2	−0.123 (0.036)***	−3.45	−0.048 (0.177) NS	−0.27	−0.973 (0.106)***	−9.15	0.31	0.14
To skip lunch or dinner	3	−0.112 (0.043)*	−2.59	0.294 (0.220) NS	1.34	−0.683 (0.083)***	−8.23	0.43	0.22
To reduce the quantity of fish or meat consumed	4	0.014 (0.021) NS	0.68	−0.017 (0.108) NS	−0.16	−1.329 (0.076)***	−17.43	0.79	0.23
To eat *farinha* with salt/sugar and water	5	−0.007 (0.108) NS	−0.07	−0.267 (0.612) NS	−0.44	−0.413 (0.269) NS	−1.54	0.04	0.04
To eat nothing all day	6	−0.073 (0.072) NS	−1.02	0.182 (0.359) NS	0.51	−1.321 (0.201)***	−6.58	0.12	0.03

Abbreviation: NS, not significant.
*$p < 0.05$; ***$p < 0.001$;

and effort. Due to the high number of households with zero hunt catch, or that did not fish at all in the previous 72 hr, we used zero-inflated GLMM with community as a random factor to model the probability of hunting or fishing. All models testing seasonal and spatial variation used season (fixed factor high- or low-water season), and fluvial travel distance from Manaus and the closest town as explanatory variables.

Models testing intra-community variation in food security used travel distance to Manaus and the nearest town as fixed explanatory variables, in addition to house type (either a *flutuante* floating house or a stilted house on land), years of formal education (of the most educated household member), household population size, floor area of the house (an indicator of wealth), the proportion of the household that are classed as dependents (aged <16 and >59) and a categorical variable showing whether households were eligible for and received government cash transfers (GCTs; the Brazilian *Bolsa Família* conditional cash transfer and retirement pensions; see methods in Supporting Information). As the literature suggests that greater insight can be gained from understanding the individual effects of wealth and household population size on food insecurity (Bashir, Schilizzi, & Pandit, 2012; Harris-Fry et al., 2015; Sen, 1981), these two individual factors were treated separately rather than together (floor area per person), which together would also overlook economies of large scale and differing needs of children and adults. To assess the relative importance of household variables in explaining perceived food security, we used the dredge function to compare AIC (Akaike's information criterion) values, considering those with a delta-AIC < 2 as plausible models (Dziak, Coffman, Lanza, & Runze, 2012).

Statistical analyses were performed in R statistical software version 3.1.3 (R Core Team, 2015). Zero-inflated GLMMs used the GLMMADMB package while other multivariate analyses were undertaken in the LME4 package. Model diagnostic plots were subsequently inspected, and *p* values were calculated using likelihood ratio tests.

2.7 | Ethics

Our research proposal was assessed and approved by the Lancaster University ethics council. We explained study intentions and obtained informed consent, first from each community leader, then from each household head and then from each interviewee before undertaking interviews. Article 37 of Brazilian law 9,605 from 1998 states that killing an animal is not a crime when it is carried out to satisfy the hunger of the harvester or their family. As we intentionally do not specify which fishing and hunting activities were commercial, we do not associate any person or community with illegal activities in order to maintain anonymity.

3 | RESULTS

We undertook 566 household interviews in total; 270 and 296 in the respective high- and low-water seasons. These relate to 331 different households of which 235 were interviewed during both seasons, and 96 were interviewed just once where a household was absent in one season. We collected detailed information on 886 fishing trips undertaken in the 72 hr prior to interview by 385 different fishers in the high- (n = 517 trips) and low-water seasons (n = 369 trips).

3.1 | Severe seasonal food insecurity

Our analyses show that perceived food insecurity was much greater (strong effect and highly significant) during the high-water season as compared to the low-water season (n = 561; Figure 2a). Additionally, when analysed by frequency of individual coping strategies (unweighted), we find that five of the six were undertaken significantly more often in the high-water season (i.e. all apart from eating only *chibé*, which was the rarest; Table 3). The order of severity of coping strategies ranked by focus group members is shown in Table 3.

3.2 | Mixed evidence of spatial determinants of food security

This study found little evidence of spatial trends in perceived food security, which we hypothesized to worsen with proximity to urban centres. Overall, perceived food security was not significantly influenced by distance to Manaus, or the nearest town. However, two individual coping strategies were significantly more common near Manaus: to not eat any fish or meat for a whole day and to skip lunch or dinner (Table 3).

3.3 | The importance of fish catch rate in driving food insecurity

Our findings show that severe food insecurity occurs in the high-water season—a period of depressed fish catch rates. A major finding was that the overall multispecies and multi-gear fish catch rate was 73% lower in the high-water season (M = 1.55 ± 0.2 kg/hr) than in the low-water season (M = 5.73 ± 0.4 kg/hr; p < 0.001; Figure 2b). For those gear types used regularly in both seasons (Figure 3; ≥8% of trips per season), mean gillnet catch rate was 96% lower in the high-water than the low-water season (p < 0.001; M = 0.33 and 8.09 kg 100 m^{-2} hr^{-1}, respectively; Figure S1), and 72% lower with hooks on rods or hand-lines (p < 0.001; high-water: M = 1.37 and 4.85 kg/hr, respectively; Figure S2). Fishing trips that landed no catch at all were 37% less likely in the low-water (only 4.6% of trips; p = 0.047, n = 886) than the high-water season (7.4% of trips), but there was no significant difference in trip duration (mean of 5.8 and 13.9 hr, respectively; p = 0.75, n = 55). Fluvial travel distance to Manaus or the nearest town, respectively, did not significantly affect multispecies multi-gear fish catch rate (p = 0.82 or 0.77), or when split into gillnets (p = 0.20 or 0.28) or hooks (p = 0.69 or 0.67).

The mean biomass of fish caught per household in the 72 hr prior to interview in the high-water (16.9 kg) was approximately half of that in the low-water season (32.1 kg; p < 0.001; Figure 2c). There was no significant trend found in biomass caught per household with distance to Manaus (p = 0.73) or the nearest town (p = 0.99).

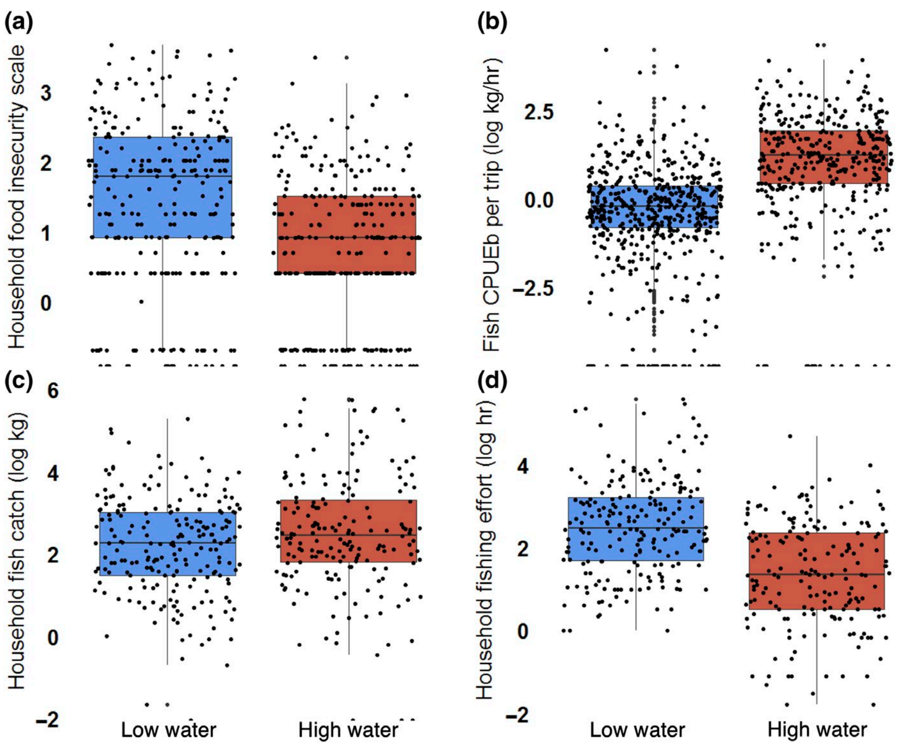

FIGURE 2 Food insecurity and fishing activity in the high- and low-water seasons. Boxplots showing seasonal comparisons of (a) household food insecurity (log weighted score), (b) fish catch rate (CPUEb; log kg/hr) per trip, (c) household fish catch (kg caught within previous 72 hr by all adult household members) and (d) household fishing effort (hours of spent fishing by all adult household members). Individual data points are jittered. Seasonal differences between all four variables were tested with linear mixed-effects models, and all were significant to p < 0.001 level. CPUEb, catch-per-unit-effort in biomass

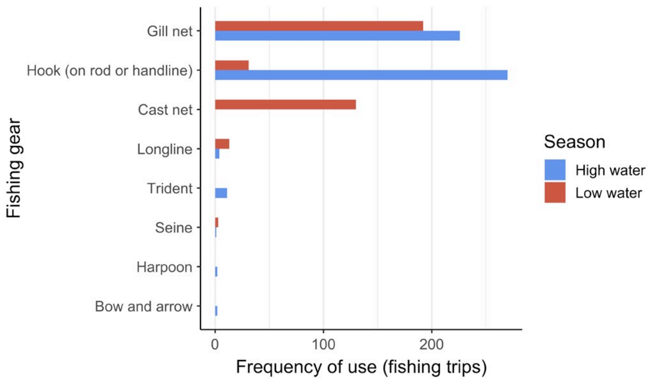

FIGURE 3 Fishing gear used in the high- and low-water seasons. Frequency of fishing trips that utilized different fishing gear, split by season

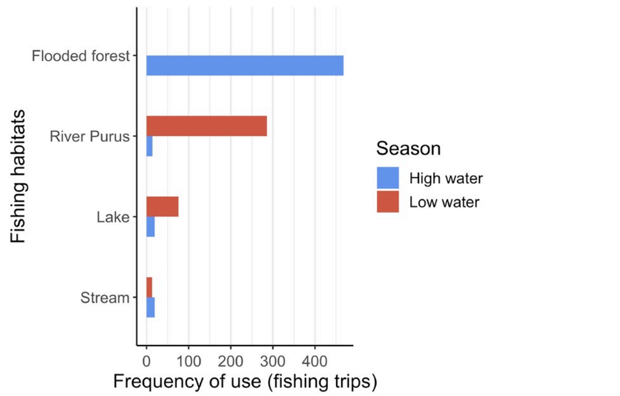

FIGURE 4 Fishing habitats used in the high- and low-water seasons. Frequency of fishing trips undertaken in different fishing habitats, split by season

3.4 | Responses to low fish catch rate

Our results show that harvesting effort increases when fish catch rate is lower, in the high-water season. Households expended almost three times the fishing effort in the high-water season (mean biological fishing effort in previous 72 hr = 10.2 hr) than the low-water season (M = 3.88 hr; $p < 0.001$, n = 780; Figure 2d). In the high-water season, around two-thirds (69.9%) of adults had fished in the past 30 days, compared to around half (53.9%) in the low-water season ($p < 0.001$, n = 1,466). There was no significant trend found in household fishing effort with distance to Manaus (p = 0.83) or the nearest town (p = 0.41). Hunting was also more prevalent during the high-water season (14.7% of interviewees) than the low-water season (5.9%; $p < 0.001$, n = 1,466). Moreover, the probability (0/1) of having harvested at least some bushmeat in the previous 30 days was more than twice as likely during the high- (20.7% of households) versus the low-water season (8.1%; $p < 0.001$, n = 566). Distance to Manaus or a local town was not related to the harvesting of bushmeat.

Fishing strategies varied seasonally (Figure 3), and although gillnets were common in both the high- (43.7% of fishing trips) and low-water seasons (52.0%), hooks were mainly used in the high-water season (52.2%), while cast nets were employed more in the low-water season (35.2%). Almost all fishing was undertaken in the *várzea* flooded forest in the high-water season (90.0%), and mainly in the river channel (76.3%) and lakes (20.3%) during the low-water season (Figure 4).

We calculate that, across seasons, households (incorporating only adults) catch a mean of 5,507 ± 1,591 g of fish and 271 ± 70 g of bushmeat, and consume a mean of 175 ± 9 g of chicken per day. Given the mean household size of 4.6 inhabitants, this equates to 1,197 g of fish and 59 g of bushmeat caught, and 38 g of chicken consumed per person per day. Chicken was eaten on average twice a month, and in the majority of households (67%) in the previous 30 days, while beef had been eaten once a month and in the minority (27.2%). While the frequency of neither chicken (p = 0.12, n = 566) nor beef (p = 0.12, n = 566) consumption varied between seasons, chicken consumption was more frequent nearer small towns (p = 0.007; Figure 5a) and nearer Manaus (p = 0.0027; Figure 5b), and beef consumption was more frequent nearer small towns ($p < 0.001$; Figure 5c). Moreover, 94% of the households that had reported chicken consumption had consumed frozen purchased chicken.

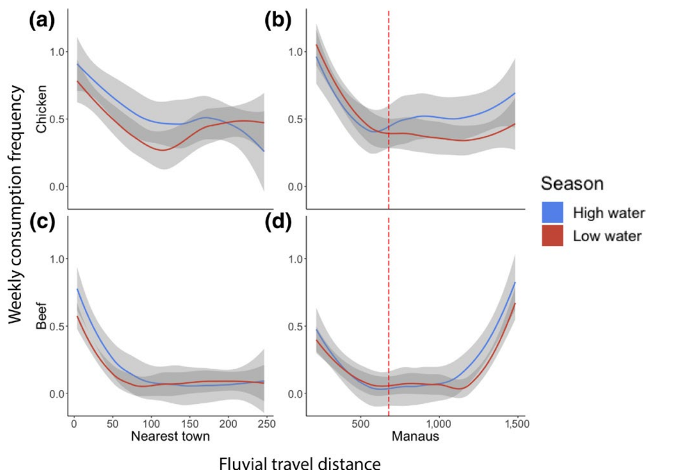

FIGURE 5 Spatial relationships in domestic meat consumption in relation to urban markets. The relationship between weekly household consumption frequency of chicken and fluvial travel distance to (a) the nearest town and (b) Manaus, and beef and fluvial travel distance to (c) the nearest town and (d) Manaus, split by season. The vertical red dotted lines in (b,d) represent the limit of Manaus-based ferry boats that buy fish, sell domestic meat and deposit ice (the midpoint between sampled communities that do and do not have such access)

3.5 | Household vulnerability to food insecurity

Two-thirds of households sampled were on stilts on land (64.3%), mean floor area was 57 m^2 and households had a mean of 4.6 inhabitants. The most educated person per household had a mean of 5.2 years of formal education. On average, almost half (45.3%) of residents were dependents (children or older people). It was rare for

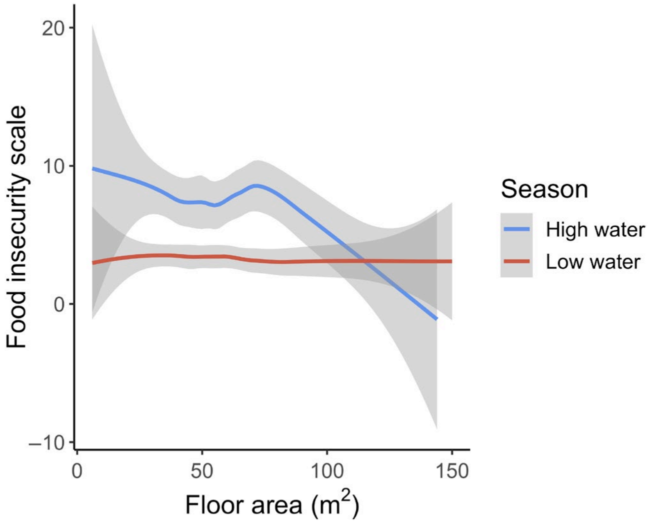

FIGURE 6 The relationship between household floor area (proxy for wealth) and food insecurity in the high- and low-water seasons [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Important household predictors of high-water season food insecurity in descending order of model plausibility. The best approximating linear mixed-effects models (ΔAICc < 2 from top-ranked model) determining food insecurity in the high-water season, with associated AIC values. Other predictors were distance to nearest town and the GCT variable. ΔAICc is the difference between AICc of the top-ranked and current model

Model ranks	Model (explanatory variables)	AICc	ΔAICc
1	Floor area + household size	1,689.4	0.00
2	Floor area + household size + education	1,689.6	0.24
3	Floor area + household size + house type	1,690.7	1.33
4	Floor area + household size + proportion age dependent	1,691.0	1.57
5	Floor area + household size + education + house type	1,691.2	1.78
6	Floor area + household size + education + proportion age dependent	1,691.3	1.87
7	Floor area + household size + distance to Manaus	1,691.3	1.94
8	Null model	1,695.5	6.08

Abbreviations: AIC, Akaike's information criterion; GCT, government cash transfer.

households to have no dependents (13.5%). Three-quarters (73.1%) included dependents and received GCTs, whereas 13.5% contained dependents but did not receive GCTs.

Perceived food insecurity was more severe in households that were smaller in floor area (a proxy of wealth; Figure 6), and with more inhabitants, given these variables were selected in all of the best approximating models (Table 4). Perceived food insecurity was also more severe in less educated households and in floating houses. Other variables showing some association with perceived food insecurity were distance from Manaus and the demographic dependency ratio (Table 5).

TABLE 5 Results summary table

Hypothesis	Do results support hypothesis?
(1) The seasonal variation in food security	
Perceived food insecurity will be more severe in the high-water season	Yes
(2) The spatial variation in food security	
Perceived food insecurity will be more severe closer to metropolitan and provincial urban centres	Mainly no, but some coping strategies show a trend
(3) The importance of fish catch rates in driving food insecurity	
Fish catch rates will be lower …	
… during the high-water season	Yes
… closer to urban centres	No
(4) Responses to low fish catch rates	
Where and/or when fish catch rates are lower …	
… fishing effort will be greater	Yes
… hunting effort will be greater	Yes
… domestic meat consumption will be greater	No
(5) Household vulnerability to food insecurity	
Perceived food insecurity will be less severe where …	
… household wealth is greater	Yes
… household population is smaller	Yes
… education level is greater	Limited support
… a lower proportion of the household is of 'dependent age'	Limited support
… people receive government cash transfers	No

4 | DISCUSSION

This study reveals severe seasonal food insecurity among wildlife-reliant people in an area of great natural wealth. We present the first empirical evidence that food insecurity can result from lower catch rates of fishes. Furthermore, our findings demonstrate that more deprived households are more susceptible to seasonal food insecurity. Perceived food insecurity was significantly more severe during the high-water season, providing evidence of low *stability* in this food system. Given the central role of inland fisheries in the diets of poor communities in the Amazon and other contexts in the Global South (Fluet-Chouinard, Funge-Smith, & McIntyre, 2018), seasonal crashes in fish catch rate might partially explain malnutrition and poor health outcomes (e.g. Piperata, 2007; Piperata, Schmeer, Hadley, & Ritchie-Ewing, 2013).

4.1 | Evaluating the seasonal variation in food security

Our data show a seasonal crash in perceived food security during the high-water season. The high prevalence of food insecurity may seem paradoxical for inhabitants of Amazonian *várzea* forests that are biologically rich and have low human population densities, and striking given this population is so highly dependent on this seasonally transformed ecosystem (Pinedo-Vasquez, Ruffino, Padoch, & Brondízio, 2011). Nonetheless, we show that *ribeirinhos* are experiencing food insecurity that the FAO consider as moderate by (a) compromising on quality and variety, (b) reducing quantities and (c) skipping meals, and as severe by (d) experiencing hunger (Ballard et al., 2013). In the high-water season, this specifically includes at least monthly occurrences of (a) most (85%) households eating something else instead of fish or meat, (b) two-thirds (65%) of households reporting eating less than they would like, (c) a third (33%) of households skipping a meal and (d) a sixth (17%) of households not eating for a whole day (see Table S4).

The perceived food insecurity identified in this study is congruent with evidence of widespread malnutrition among rural Amazonians (Piperata, 2007; Piperata et al., 2013), which is likely to partly relate to inadequate dietary intake (UNICEF, 1990). Moreover, even wealthier *ribeirinho* households are subject to non-food risk factors such as inadequate access to clean water and healthcare, and high vulnerability to gastroenterological infections and insect-borne disease (Katsuragawa et al., 2010; Piperata, 2007). Hence, our findings are not trivial and must be placed in context of the multidimensional poverty commonplace in rural Amazonia.

4.2 | The apparent lack of spatial food insecurity

Counter to our predictions, neither fish catch rate nor perceived food security varies significantly with remoteness from urban areas. It appears that Amazonian fishers are able to maintain multispecies catch rate (Section 4.3) and food security along a spatial gradient that is known to be commercially overfished for a target species, *Colossoma macropomum* (Keppeler et al., 2018; Tregidgo et al., 2017). This species is also the favourite of *ribeirinhos* to eat, and hence its depletion nearer to Manaus could explain the increased frequency of eating a meal containing no fish or meat in this area. Moreover, as five of the six coping strategies in this study occurred more frequently nearer Manaus (albeit just two showed a significant trend; Table 3), we cannot completely refute the hypothesis that perceived food insecurity is more severe nearer Manaus. This study shows that the role of domestic meats increases nearer urban centres (Figure 5), which supports previous work by van Vliet et al. (2015), who additionally show that the role of wild fish and bushmeat decreases in these areas. Hence, it is also possible that when wild food consumption is lower, food security is maintained by substituting wild foods with purchased foods. However, to investigate this, it would be necessary to establish consumption patterns using dietary recall.

4.3 | The importance of fish catch rate in driving food insecurity

A seasonal crash in fish catch rate was associated with perceived food insecurity. We show that in the high-water season *ribeirinhos* encounter far lower catch rates of fish—their principal form of animal protein (Dufour et al., 2016)—and experience significantly greater food insecurity (Figure 2a,b). Depressed fish catch rates have previously been observed during seasonal flood-pulses (Da Silva & Begossi, 2009; Endo et al., 2016; Poulsen et al., 2009) because fish become 'diluted' and spill over into the flooded forests (Saint-Paul et al., 2000), making them harder to catch. The importance of fish catch rates for household diets is clear because household fish catch exceeded bushmeat harvest and chicken consumption by more than an order of magnitude.

Contrary to our hypothesis, multispecies fish catch rate was not lower nearer urban areas, despite known overfishing nearer Manaus (Keppeler et al., 2018; Tregidgo et al., 2017). A commercially overfished tropical mixed fishery can be characterized not by a fall in multispecies fish biomass, but by a community whose larger commercially desired fish have been replaced by smaller undesired fish (Allan et al., 2005). This can occur when smaller fish experience reduced predation and a freeing up of resources following the selective removal of larger fish, which have greater resource consumption rates (known as density compensation; Allan et al., 2005; Lorenzen & Almeida, 2006; MacArthur, Diamond, & Karr, 1972). Alternatively, we may have failed to detect a real decline in fish biomass nearer Manaus, if catch rates remain stable despite fish populations declining; as fish shoal more densely and fisher knowledge permits them to locate remaining shoals (known as hyperstability; Castello, McGrath, & Beck, 2011; Erisman et al., 2011; Hamilton et al., 2016).

4.4 | Responses to low fish catch rate

We found that rural households respond to a seasonal crash in fish catch rates by increasing their fishing and hunting effort, adopting different fishing techniques (using more hooks), and fishing in different habitats (mainly the shallower waters of the flooded forest). By changing fishing techniques and fishing grounds, and increasing effort, overall fish catch in the high-water season was only 47% lower, despite a 73% reduction in catch rate. Catch of dwindling fish stocks (with lower catch rates) can be maintained by increased effort (e.g. Watson et al., 2013), and technological advances in fishing vessels, fish capture and refrigeration (McGrath, 1989; Roberts, 2007). However, in this study, we observed a crash in catch rates and severe perceived food insecurity in the high-water season despite attempts to maintain fish catch through these various adaptations to harvesting practices.

A key finding of this study was that harvesters respond to low fishing catch rates by increasing hunting effort. While fishing may usually be favoured over hunting in the *várzea* because it is more reliable (greater proportion of successful trips), the increased chance of a fishing trip yielding no catch at all in the high-water season reduces the relative risk of hunting (Endo et al., 2016). Our finding confirms other global evidence that hunting may increase when fish catch rates fall (Endo et al., 2016) or consumers experience a decline in fish supplies (Brashares et al., 2004). Hence, we advance this mounting global evidence of a fish–bushmeat substitution by demonstrating its occurrence during periods of food insecurity for the first time.

Contrary to our hypothesis, households did not appear able to compensate for lower fish catch by eating more chicken or beef, which remained rare, and did not increase during the lean high-water season. Domestic meat consumption reported was almost entirely purchased frozen chicken, yet increasing its consumption may be difficult due to limited refrigeration capacity, large distances to shops (Chaves, Wilkie, Monroe, & Sieving, 2017) and low purchasing power (Nunes, Peres, Constantino, Santos, & Fischer, 2019). Moreover, raising livestock in floodplains is a high-risk alternative strategy (Chibnik, 1994) due to losses from drowning and pests (Coomes, Takasaki, Abizaid, & Barham, 2010). Additionally, switching from wild or domestic fish and meat to alternative foods (canned meats and fish, beans, eggs and sausages) was the most common coping strategy reported, occurring more than weekly during both seasons, and significantly more so during the high-water season (Table 3). Hence, it appears that the consumption of these foods is an important food insecurity coping strategy in times of poor fish catch, and likely more so than fresh domestic meat (which is generally much more expensive), supporting recent findings by Chaves et al. (2019) who show that processed meat is the second most consumed meat type after fish.

4.5 | Household vulnerability to food security

Perceived food insecurity during the high-water season was more severe in poorer households with larger family sizes. It is well established that deprived households are more vulnerable to food insecurity (Bashir et al., 2012; Harris-Fry et al., 2015; Sen, 1981), and our results demonstrate that social inequities co-determine the outcomes of environmental shocks and hazards. The relationship between deprivation and perceived food security reveals that only the wealthiest minority of rural households are protected from seasonal food insecurity (Figure 6). However, when fishing is good (low-water season), the protective effect of being less-poor disappears, as food security is maintained across the socio-economic gradient (Figure 6). This further supports our conclusion that seasonality is a principal determinant of perceived food insecurity in our study system.

The fact that large, deprived households are regularly missing meals in the high-water season could have serious nutritional and developmental consequences for more vulnerable household members such as young children and pregnant women (Dufour et al., 2016; Schmeer & Piperata, 2017). Our data do not explain how wealthier households avoid food insecurity, so we can only presume that they may purchase fish or bushmeat locally, or have refrigeration facilities to preserve fish or meat for days when fish catch is poor (this would only be true in the minority of communities with reliable ice or electricity supplies). Future studies could investigate local food security solutions using positive deviance analysis (Levinson, Barney, Bassett, & Schultink, 2007). However, our evidence that the less-poor avoid seasonal food insecurity shows the continuing importance of poverty eradication (Mascie-Taylor, Marks, Goto, & Islam, 2010), particularly in light of ongoing weakening of Brazil's welfare system (Collucci, 2018).

4.6 | Wider application and policy implications

This is the first study to present evidence linking wildlife catch rates with food security. The novel findings from our study have important implications for policy debates affecting wildlife-reliant populations in Amazonia and elsewhere. Due to the ecological and social diversity of wildlife harvesting systems, our specific findings apply primarily to white-water sub-basins in Amazonia, but we can take important lessons away to other systems.

Because the Purus River undergoes one of the greatest annual variations in water levels on the planet, our seasonal sampling regime represents a natural experiment, which simulates declines in fish abundance. This is because the 'dilution' of fishes during seasonal flooding results in local fishers experiencing clear declines in fish CPUE (catch rates), which is also a widely used proxy of fish abundance (Edwards et al., 2012). Hence, our results suggest that the ongoing global decline in vertebrate populations (WWF, 2018) could threaten the food security of wildlife-reliant human populations worldwide and could also trigger further overharvesting as harvesters intensify effort to try to maintain catch. Nevertheless, the nature of the trends observed in this study is likely to differ where commercial harvesting is less intense, where catch rates drop more subtly or gradually, or where levels of human adaptive capacity differ, for example in terms of physical and financial access to alternative food types.

The United Nations' Sustainable Development Goals call for an end to hunger while preserving ecosystems (UN, 2015), and the Millennium Ecosystem Assessment highlights the neglect of wild food systems in food security research (Kasperson et al., 2005). Our study confronts both these concerns by highlighting the extent to which the food security of marginalized rural communities living in a biologically research-rich area rely on the stable availability of wildlife. Food security research has traditionally taken a primary focus on having enough food (availability), which is often assumed as being true in tropical contexts with high forest cover and low human population density. However, due to the natural seasonal variation in the availability of many wildlife species (e.g. Nyahongo et al., 2009), often exacerbated by anthropogenic changes to ecosystems (e.g. Castello, Bayley, Fabré, & Batista, 2019), we may be overlooking food instability in wild food systems, which is potentially very common and dangerous for human health

(Ferro-luzzi et al., 2001). Food security measures should therefore be considered alongside ecological monitoring in order to achieve sustainable exploitation of wildlife and food stability, particularly during lean periods.

5 | CONCLUSIONS

This study supports the hypothesis that the severity of food insecurity among Amazonian *ribeirinhos* is determined by seasonal crashes in fish catch rates, in combination with social inequalities. Although harvesters attempt to compensate for tough fishing in the high-water season by fishing and hunting more, there is a huge dip in returns on labour, and consequently many householders experience severe food insecurity. This is particularly true in larger more deprived households. We conclude that the welfare of these historically marginalized floodplain inhabitants is inextricably linked to their instable access to wildlife, which provide a large proportion of their calories, macronutrients and micronutrients. To our knowledge, ours is the first study to provide mechanistic evidence linking reduced wildlife (terrestrial or aquatic) availability (e.g. Endo et al., 2016) to household food security (e.g. Piperata et al., 2013). Consequently, this work advances our understanding of food stability, which has been neglected within food security research (Cruz-Garcia et al., 2016), and almost completely ignored in the context of wild food systems. Environmental and political changes make our findings particularly relevant, as *ribeirinhos* are experiencing increasing exposure to extreme floods and droughts (Barichivich et al., 2018) and an uncertain future regarding the direction of social policy (Collucci, 2018).

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

All authors conceived of the project and methodology. D.T. collected the data, performed the analyses and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data from this study are archived on Dryad Digital Repository: https://doi.org/10.5061/dryad.44j0zpc9q (Tregidgo, Barlow, Pompeu, & Parry, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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