Rice field fisheries: Wild aquatic species diversity, food provision services and contribution to inland fisheries

Sarah Freed[a,*], Yumiko Kura[a], Vichet Sean[a], Samonn Mith[a], Philippa Cohen[b], Miratori Kim[a], Somony Thay[c], Savry Chhy[c]

[a] *WorldFish Cambodia, 34 Street 228, Phnom Penh, Cambodia*
[b] *WorldFish Headquarters, 11960 Bayan Lepas, Penang, Malaysia*
[c] *Department of Aquaculture Development, Fisheries Administration, 186 Norodom Blvd., Phnom Penh, Cambodia*

ABSTRACT

The need to produce sufficient food for people whilst also maintaining biodiversity and ecosystem integrity is one of the most pressing challenges in the 21st century. This challenge is exemplified in wetlands and deltas of Southeast Asia that have been transformed to intensify rice production and have subsequently lost the naturally present wild aquatic species that previously bolstered local food and nutrition security. In contrast, rice producing areas where natural hydrologic flows and ecosystem processes are retained can sustain aquatic biodiversity and fisheries. These rice field ecosystems are present in many Asian countries, but are sparsely documented, underappreciated, and currently face development pressure including farming intensification and habitat fragmentation from infrastructure development. To understand the fisheries and food security contributions of wild aquatic species in contemporary rice field ecosystems, we examine the Tonle Sap region of Cambodia. We used household surveys and experimental fishing to measure wild aquatic species richness present in rice field ecosystems and in local catch. We also used household surveys to estimate rice field fishery productivity (as annual catch weight per hectare) and to examine variation in fishing effort and total catch weight across seasons and habitats. Finally, we investigated catch use and the contribution of fish catch to household consumption. We identified a total of 158 wild aquatic species, which included around twice the number of finfish species (n = 135) identified by previous studies (n = 35–70). Overall, 92% of fish catch (by weight) was from five habitat types within rice field ecosystems. Fishing effort and catch weights were relatively evenly spread across habitats during the dry season and were primarily from rice fields during the flood season. In both flood and dry seasons, rice field fishery catch provided around 60% of the fish and aquatic animals consumed in surveyed households. Our findings illustrate the substantial contributions rice field fisheries make to household food security and to national fisheries production. Drawing on lessons from rice farming intensification across the region, we discuss the implications of our findings for rice field ecosystems, food security, and rice intensification policy futures in Cambodia and other rice-producing nations.

1. Introduction

Food and nutrition security and biodiversity conservation represent two of the leading sustainable development challenges of the 21st century (Brussaard et al., 2010; Campbell et al., 2017; Tscharntke et al., 2012). The maintenance or restoration of biodiversity can support food and nutrition security (Frison et al., 2006; Johns et al., 2013), as modelled in many "multifunctional" rural landscapes where agriculture, natural resource use, and biodiversity or habitat conservation are carried out in mosaic, successional or simultaneous ways (Liu et al.,

2013; Padoch and Sunderland, 2013; Tscharntke et al., 2012). In these landscapes, biodiversity is supported through the presence of wild (generally native and naturally occurring, sometimes also managed) species and through diversified agricultural production that also supports local and/or domestic food security, as found in parts of the Brazilian Cerrado where forests and small scale farms coexist in integrated landscapes (Wittman et al., 2017). In many multifunctional landscapes, wild species not only contribute to biodiversity, but are collected and consumed, thereby contributing to local food and nutrition security (i.e. servicing farmers and farming communities in rural

areas, rather than distant markets). This has been demonstrated in rice field landscapes in Laos where wild aquatic species are collected and consumed (Garaway et al., 2013) and in other landscapes globally (Bharucha and Pretty, 2010; Powell et al., 2015).

Rice production covers 160 million ha globally, which is equivalent to around half the total land area of India (FAOSTAT, 2013). The portion of this that can be characterised as rice field ecosystems (i.e. includes the paddy where the rice is grown, but also includes diverse wetland and aquatic habitats that connect with the rice paddies during seasonal flooding; Shams, 2007) is unknown, but it's likely that rice field ecosystems are the most expansive multifunctional landscapes. Natural flooding of rice fields enables both rice production and the maintenance of high biodiversity (Bouman et al., 2007; Verhoeven and Setter, 2010). Wild aquatic species readily populate rice fields when floods connect the fields with other aquatic habitats, especially perennial water bodies (Amilhat et al., 2009; Nguyen Khoa et al., 2005). For fish, rice fields provide habitat, nutrients, and organic material necessary for seasonal spawning and feeding (Heckman, 1979; Lawler, 2001; Nguyen Khoa et al., 2005). Rice field ecosystems contain a variety of wild species of fish, molluscs, crabs, prawn, frogs, snakes, insects, waterbirds, and aquatic plants (e.g. Heckman, 1979). Rice field fisheries involve the harvest or capture of these wild aquatic species from rice fields and other habitats within the rice field ecosystem, such as canals, ponds, and ditches (Gregory, 1997). The diversity of wild species occurring in rice field ecosystems have been dietary mainstays for many societies and their importance is reflected in the cultures of many Asian countries (Gregory et al., 2018; Lu and Li, 2006).

In stark contrast to the closely monitored production and high data availability for farmed crops, livestock, and fish, quantitative data on the presence, production, and food provision from wild species are sparse (Pimentel et al., 1997; Scoones et al., 1992). When missing from national statistics, as is often the case, wild harvests are overlooked in decision-making arenas and in policy (Bharucha and Pretty, 2010; Garaway et al., 2013; Halwart, 2006). Whilst some wild harvest case studies have provided recommendations for policy and management practices, the species, use, and benefits of wild harvests are highly variable (Angelsen et al., 2014; Pascual and Perrings, 2007; Powell et al., 2015) suggesting a need for contextualized data to guide decision-making related to wild foods.

In the Lower Mekong region there is political and economic pressure to intensify rice production through irrigation infrastructure development and investments (Baran et al., 2007; Johnston et al., 2014; Nguyen Khoa et al., 2005). To inform these impending decisions, this study employs the largest geographic area and longest time period of any rice field fishery study in the region to illustrate the diversity, magnitude, and trends in the presence and use of wild aquatic species within rice field ecosystems. Our objectives were to: 1) make an inventory of wild aquatic species present in rice field ecosystems and in local catch; 2) estimate rice field fishery productivity; 3) describe fishing practices and elucidate habitat and seasonal patterns in fishing effort and catch weight; and 4) assess catch contributions to food provisioning and other aspects of livelihood for fishers and their households.

2. Background

2.1. Regional background

In Southeast Asia, rural livelihoods and food and nutrition security are experiencing negative effects from agricultural intensification employed in pursuit of national economic development and food production targets (Broegaard et al., 2017; Cramb et al., 2017). In Malaysia and Vietnam, intensification of rice production came at the expense of wild fish populations and species diversity (Ali, 1990; Berg et al., 2017). In Malaysia, ten fish species were reported as absent, rare, or endangered in rice fields following increased use of fertilizer, greater

usage of pesticides and changes to water management (Ali, 1990). In Vietnam, farmers observed losses of wild fish and other species corresponding with increased agrochemical use and loss of connectivity between rice fields and surrounding habitats due to installation of canal and dike infrastructure (Berg et al., 2017). Although data on wild species in rice field ecosystems remain sparse and at best highly localized, concerns over habitat decline and species loss have been raised for rice field ecosystems of Laos and Cambodia (Garaway et al., 2013; Shams, 2007). This could be particularly consequential for Cambodia, a nation considered to have the fifth most productive inland fishery in the world (Funge Smith and Bennett, 2019), around 30% of which is contributed by rice field fisheries (unpublished data Fisheries Administration, 2017).

Rice field ecosystems make up the majority of the Lower Mekong region's agricultural land (Ingalls et al., 2018) and represent the conversion of approximately 86% of the total wetland area in the Lower Mekong Basin (Hortle et al., 2008). Vietnam's experience shows that rice intensification, the resulting farmer dependency on income from rice, and sinking prices for rice can lock farmers into a positive feedback loop (i.e. farmers continue intensification in an effort to maximize production, to the point of causing a decline in rice field fertility; Berg et al., 2017) with ultimately negative consequences for agricultural productivity, the environment, and farmer livelihood. Rice intensification in Vietnam has also affected food security of rural households through greater seasonal variation in wild food harvests, reduced availability of wild fish in particular, and reduced consumption of all fish, with effects greatest for poor households (Nguyen et al., 2018). Despite (or perhaps due to) these experiences, irrigation investments continue alongside growing recognition that sustainability and food and nutrition security outcomes must be improved upon (e.g., Asian Development Bank (ADB), 2015). The maintenance of habitat connectivity and aquatic biodiversity, e.g. through 'fish-friendly' irrigation and water management infrastructure and practices (Baumgartner et al., 2016; Mccartney et al., 2019) could prove a more food secure and environmentally and economically viable option. However, most of the Lower Mekong region lacks baseline data to guide the development and understand the impact of such innovations.

2.2. Study site background

Cambodia's rice production is predominantly rain-fed and connected to natural flood regimes. Despite a number of recent and upcoming irrigation and water management projects (MAFF, 2017), irrigation covers only 17% of Cambodia's rice landscape (MAFF, 2018) and primarily serves a loss prevention role for wet season rice crops rather than an intensification role for dry season rice production (Johnston et al., 2014). While other countries adopted high-yield rice varieties and built up irrigation systems during the Green Revolution, Cambodia faced a socio-political crisis during and following the Khmer Rouge regime (1975–1979) that caused severe drops in rice production and famine (DeFalco, 2014). Over the past 20 years, Cambodia has experienced tremendous economic growth and employment creation, yet agriculture remains a significant contributor to national GDP (The World Bank, 2017) and the majority of the population remains rural (Ingalls et al., 2018). Farming remains predominantly a smallholder activity in Cambodia, with average area of agricultural holding per household at 1.6 ha (MoP, 2015). Total household agricultural holdings are 3.3 million ha, over 70% of which is used for rice production (MoP, 2015). Rice is the predominant crop grown in the Tonle Sap region (MoP, 2015) and land for rice cultivation makes up one third of Tonle Sap wetlands (Arias et al., 2014). Rice farming is rarely a sole livelihood in the region, as two studies conducted in separate provinces found (Sok et al., 2019; Teh et al., 2019). Fisheries played a role in a variety of livelihood strategies, including in 'rice monocropping' livelihoods, 'large farmer' livelihoods, and diversified livelihoods (with 11%, 12%, and 46% of income from fishery related activities, respectively; Sok

Table 1

Aquatic habitats of the rice-field ecosystem (and associated rice field fishery) in the Tonle Sap region of Cambodia described by their structure and connectivity, roles as fish habitat, and fishing access.

Habitat	Description	Role as fish habitat	Fishing access
Rice field	Seasonally connected to permanent water bodies during flood periods	Reproduction and feeding in flood season	Land is privately held; flood waters on the rice field are a "commons" accessible to all for wild aquatic species harvest
Streams and channels	Waterways that connect water bodies and rice fields during flood periods; may contain some water year-round; includes irrigation and drainage channels, natural streams	Migration routes between permanent water bodies and flooded areas; some also provide refuge in dry season	Commons
Reservoir	Semi-permanent water body where water level may fluctuate, connected to rice field ecosystem through streams and channels	Dry season refuge, semi-permanent habitat for residential species	Most often a commons; in some cases access is limited to ownership or a management committee
Individual pond	Small water body in or adjacent to a rice field; seasonally connected to rice fields and permanent water bodies during flood period; may be conserved, dry up, or be pumped dry during dry season	Dry season "refuge" (most often, this type of pond will be emptied and fish will be captured)	Privately held water body based on land ownership, access must be granted by owner
Community pond	Mid to large size water body communally owned; seasonally connected to rice fields and permanent water bodies during flood period; usually contains at least some water year-round	Dry season refuge (but fish will be captured if the pond dries up)	Commons
Community Fish Refuge (CFR)	All or part of a communally owned water body; seasonally connected to rice fields and other water bodies during flood period; retains water year-round	Dry season refuge	Community-managed protected area, fishing not allowed

et al., 2019).

The Tonle Sap lake and floodplain are seasonally inundated through dynamic flood pulses that foster high biological productivity (Junk et al., 1989; Sabo et al., 2017). The Tonle Sap region hosts the largest wetland ecosystem in Southeast Asia, providing a diverse array of interconnected wetland habitats to support its high aquatic diversity (Arias et al., 2014). The rice field ecosystem within the Tonle Sap wetland is made up of various interconnected habitats such as irrigation channels, streams, ponds, and reservoirs, in addition to the rice fields themselves (Shams, 2007). Altogether, the flood pulse, habitat connectivity, and slow pace of agricultural intensification allows for co-occurrence of wild aquatic species and agricultural production.

Rice field fisheries occur in a variety of habitats within the Tonle Sap rice field ecosystem (Table 1). When the rainy season begins, fish migrate from permanent water bodies to flooded wetlands, including rice fields, to spawn and feed. As rains cease and floodwaters recede, the fish retreat to deeper waters to wait out the dry season. Rice field wetlands are used both by floodplain resident species (known as black fish; e.g., snakehead of genus *Channa*) and local or long distance migratory riverine species (respectively known as grey and white fish; e.g., barbs of genus *Puntius*; Gregory, 1997; Welcomme, 2001). While rice fields are privately owned, fishing rights throughout the rice field ecosystem are formally recognized, allowing the fishery to operate as a "commons" resource (Gregory, 1997; Hortle et al., 2008; Shams, 2007). Previous studies on rice field fisheries in Cambodia provided rich information on fishing practices (e.g., Balzer et al., 2005; Gregory and Guttman, 1996; Hori et al., 2011; Hortle et al., 2008; Shams, 2007), but were conducted across small geographic scales and short time periods (up to eight months), most often during the wet season with the assumption that catch was negligible during the dry season. These studies present a range of findings, such as 35–70 finfish species present in or caught from the rice field ecosystem (Balzer et al., 2005; Hortle et al., 2008; Shams, 2007), fishery yield of 119 kg ha^{-1} (wet season yield, Hortle et al., 2008), and consumption of 54% of catch (measured during flood recession season, Shams, 2007). Analyses of rice field fisheries patterns across multiple seasons and habitats are needed to ensure the fishery is appropriately accounted for in policy and decision-making, especially for irrigation development, and could substantially improve the way the fishery is managed in the future.

Cambodia's Fisheries Administration has adopted an approach to enhance productivity of rice field fisheries through the designation of Community Fish Refuges (CFRs), comprised of all or part of a permanent water body that is connected to a rice field system and protected from fishing. This decision and national policy was adopted in response to observations and preliminary research findings that suggested CFRs contribute to increased water security, fisheries production, and household food security. By mid-2011 the Fisheries Administration had designated around 670 CFRs, but the efficacy of these CFRs in preventing fishing and serving as a dry season refuge for fish was highly variable and not well evidenced (Joffre et al., 2012).

In response to the dearth of knowledge on CFR outcomes and best practices, a project (Rice Field Fisheries Enhancement Project, funded by United States Agency for International Development) commenced in 2012. The objective was to develop evidence of CFR management best practices that would enhance rice field fisheries productivity. The project research team, with input from the Fisheries Administration and communities, nominated 40 CFRs and surrounding communities within the Tonle Sap region as research sites (Fig. 1). These 40 sites were selected based on high rates of local participation in rice field fisheries (at least 75% of the community's households) and a willingness of communities to engage in a participatory research process with the project team. The majority of the sites selected were within or in close surrounds to the Tonle Sap floodplain (between 9 and 72 km from the Tonle Sap lake, average distance 38 ± 15 km), predominantly in the lowland rain-fed ecozone for rice production, but also in lowland deepwater and upland irrigated and rain-fed ecozones. Based on scoping data, the number of rice crops at each site depends on water availability, with paddy dikes generally around 30 cm, fertilizer application ranging from 50 − 600 kg per ha, herbicide from 0 to 1.8 L per ha, and pesticide from 0 to 1.5 L per ha.

3. Methods

3.1. Sampling procedures

We collected data through two sampling procedures: experimental fishing and household catch recall surveys. We set experimental fishing gears within the CFRs (n = 40 sites), the only rice field ecosystem habitat protected from fishing and therefore expected to contain the most biodiversity, and conducted surveys with male and female heads of ten households each in 40 villages (n = 400 households) adjacent to the CFRs over a 36-month period from November 2012 to November 2015 (Table 2). Sampling events (13 for experimental fishing, 19 for household surveys) were evenly spaced throughout the study period. We used experimental fishing and household surveys, as opposed to landings surveys, because rice field fisheries lack designated landing sites (i.e.
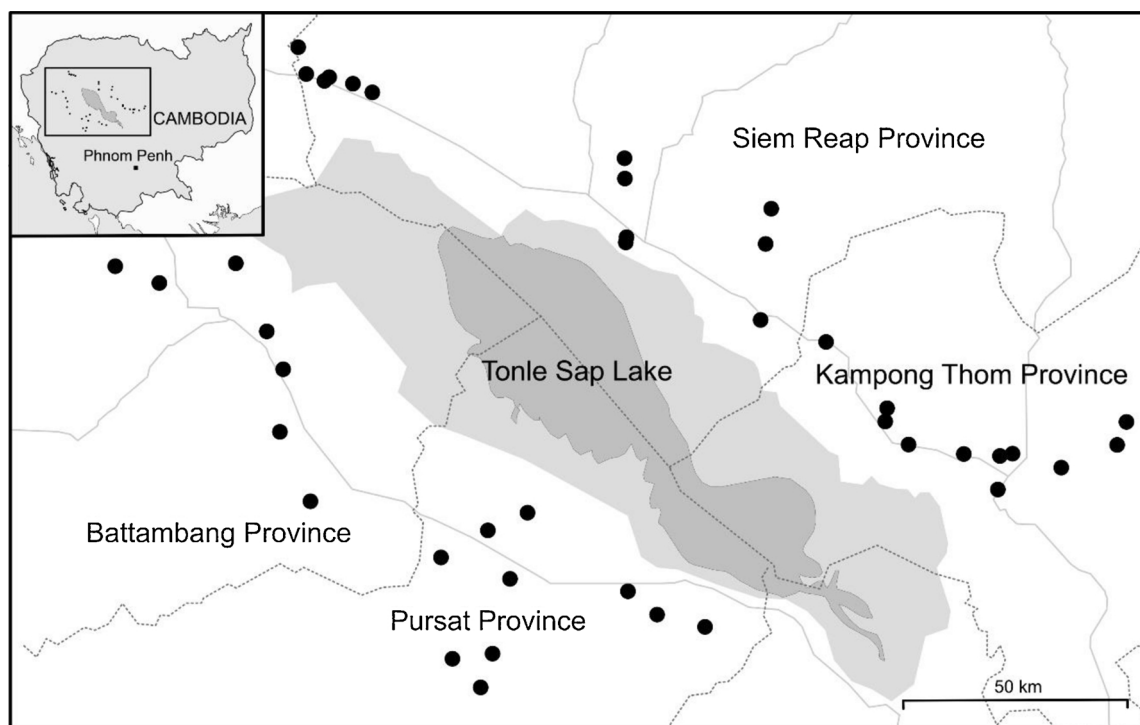
Fig. 1. Location of 40 study sites of rice field ecosystems, including Community Fish Refuges, around Tonle Sap lake, Cambodia.

fishers are mainly moving on foot between fishing sites and home and are not constrained by water entry and exit points) which makes landings surveys logistically demanding and/or low in accuracy. Interviews or household recall surveys tend to be the most reliable methods for diffuse, remote, or data-poor fisheries (Barnes-mauthe et al., 2013; Bayley and Petrere, 1989; Mccluskey and Lewison, 2008). This sampling procedure generated the most comprehensive dataset on Cambodia's rice field fisheries to date.

To conduct experimental fishing, community members worked alongside the project team in a participatory approach to increase co-ownership of the research process and also to help disseminate observations and raise community awareness of the changes in fish species presence and abundance in the CFRs throughout the project's implementation. To maximize the potential of recording the variety of species present in the CFRs while avoiding use of illegal indiscriminate gears (i.e., electrofishing), we used three types of gear for experimental fishing: nylon gill nets which were 9 m or 18 m in length (length of net used depended on the size of the CFR) with graduated mesh size; pole and line with multiple hooks; and fyke traps (a funnel trap built of wire and nylon net). The sampling periodicity of each gear (Table 2) differed because of time constraints when setting and retrieving gear. All three gear types were set overnight and were checked for catch in the morning. The field teams recorded species present in catches using Latin names. Identification was assisted by photographs in the

following texts: Balzer et al. (2005) and Rainboth (1996).

The surveys targeted households that were known to be involved in fishing. For this reason, our data on catch and consumption are more representative of fishing households rather than an "average" household in that community. We surveyed the same households across sampling events whenever possible. Occasionally, a household was not available for the survey during a sampling event. When this occurred, we surveyed a new household to maintain site representation. Respondents provided seven-day recall of household fishing activities, including type of catch (finfish, other aquatic animal, or aquatic plant), numbers of fishers and fishing days, gear used to catch finfish and other aquatic animals, and the total catch weight for each catch type over the seven days. We asked respondents to disaggregate total catch by habitat (rice field ecosystem habitats, see Table 1, and habitats outside of the rice field ecosystem), using aids such as stones or seeds to represent the total catch and then the allocation to each habitat. We also asked respondents to disaggregate total catch by species, and then by use (consumption, sale, processing, other), again using aids to represent total catch and allocations to each species and use. We recorded each species by both local and Latin names: enumerators and respondents discussed the local names for the catch, and then used the same texts and photos from the experimental fishing methods to identify and record the Latin name of each species (except for catch of waterbirds and insects which were not identified by Latin names). A subset of surveys

Table 2

Sampling design for harvest recall surveys and for experimental fishing by gear type. Number of sites, sampling events, households, and gear replicates are reported. Gear replicates are reported as average number (min-max) per sample. "NA "means not applicable to the data collection method.

	Harvest recall surveys	Experimental fishing		
		Gill net	Fyke trap	Pole and line
Number of sites	40	40	40	40
Number of sampling events	19	13	4	9
Sampling seasons	All (6 times/year)	All (4 times/year)	Flood recession (1 time/year)	Dry and flood (3 times/year)
Number of households per site	10	NA	NA	NA
Number of gear replicates (sets)	NA	7.5 (2−8)	7.5 (2−8)	5.6 (1−8)

from 46 households provided information on the age and gender of fishers. Starting from September 2013 (i.e., on 14 sampling events), we also asked respondents to report weight of finfish and other aquatic animals by source (i.e., fresh household catch, processed fish from previous household catch, household aquaculture, market purchase, gift) that were consumed in the household over the seven-day recall period. Households provided weights for catch and consumption as estimates rather than using scales for measurement. We recorded weights in kilograms with precision to tenths because weights tended to be small (often less than 10 kg and including reports less than 1 kg). This recall and estimation approach for reporting catch and consumption weights has some limitations. Some studies have found recall surveys can overestimate catch (e.g., Kuster et al., 2006), especially when conducted over months-long time periods and with more frequent fishing trips (Fisher et al., 1991). However, surveys or interviews spanning multiple fishing trips are appropriate in temporally and spatially variable fisheries (Mccluskey and Lewison, 2008). We determined that the robust representation of fishing effort gained from a seven-day timeframe and sampling at household level warranted a tradeoff in catch weight accuracy. Recognizing the limits of the catch weight reports, we analyzed the data primarily through proportion-based and/or within-group comparisons rather than absolute measurements (for the fishery productivity estimate, we addressed the limits to the data through other means as described in Section 3.3).

3.2. Wild aquatic species inventory

To assess species richness of catch from the rice field ecosystem in Tonle Sap region, we pooled reports from the household surveys. This pooled approach suited our aim of compiling a species inventory (rather than describing gear selectivity) and has been demonstrated in other studies (e.g., Gotelli and Colwell, 2001; Moreno and Halffter, 2001; Vásquez-Yeomans et al., 2011), including previous rice field fisheries assessments (e.g., Hortle et al., 2008; Shams, 2007). During the household surveys, species catch reports were elicited separately from catch reports by habitat. Because of this, we excluded from the pooled samples the survey responses that reported catch from habitats outside the rice field ecosystem. To assess the selectivity of catch, we compared the pooled species richness from the household surveys with pooled species richness from experimental fishing in CFRs.

3.3. Rice field fisheries productivity

Estimation of the annual per hectare productivity of rice field fisheries required two steps: 1) determining the area of rice field ecosystem fishing grounds and number of households and 2) an estimation of the total annual catch within those grounds. For the first step, we delineated fishing ground area at each of the 40 study sites through consultation with expert fishers, representatives from the fisheries authorities, and men and women from the adjacent rice farming households. These experts provided an estimate of the radius of the fishing ground, radiating out from each CFR. To calculate fishing ground area, we plotted the fishing grounds in ArcGIS (2012) excluding the area of roads, residences, and other areas where flooding and fishing did not occur (see sample map in Supplementary Fig. 1). With the resulting maps, we consulted with village chiefs, community members, and local authorities to estimate the number of households in the catchment of each fishing ground to extrapolate total catch per fishing ground. Due to inconsistencies in household estimation, we excluded 3 fishing grounds from further analysis.

For the second step, we summed catch (kg household^{-1} week^{-1}) reported in the household survey from rice fields, individual ponds, streams and channels, community ponds, and reservoirs from within the 37 fishing grounds. Then, adjusting for the proportion of surveyed households that did not fish during the survey event, we multiplied catch to account for all households within the fishing ground

catchments (e.g.; when 40% of surveyed households did not fish, we multiplied catch by 60% of all households within the fishing ground catchments). This provided an "upper bound" estimate of total weekly catch within fishing grounds, since the survey sample overrepresented fishing households. We also calculated a "lower bound" estimate using 50% of all households within each fishing ground catchment (e.g.; when 40% of surveyed households did not fish, we multiplied catch by 30% of all households within the fishing ground catchments). This was based on the Nasielski et al. (2016) finding that 50% of households fished from an unbiased sample of both fishing dependent and non-fishing dependent rural communities. For both upper and lower bound estimates, we summed total estimated catch for the six sampling periods in each year. We then multiplied these six-week estimated catches by 8.67 (that is, 52/6) to provide full year catch estimates. Finally, we averaged the annual estimates from 2013, 2014, and 2015, to obtain average upper and lower bound estimates of annual per-hectare productivity in rice field fisheries.

Due to survey question phrasing, it is possible that some of the reported catch from streams and channels, community ponds, and reservoirs (collectively referred to as Habitat Group 1) came from outside the fishing grounds. To account for this in the fisheries productivity estimates, we adjusted catch reports from Habitat Group 1 by the proportion of reported rice field and individual pond (Habitat Group 2) catch from within the fishing ground. For households that reported catch from Habitat Group 1, but not from Habitat Group 2, we used an average of the proportion of Habitat Group 2 catch across households that fished in both habitat groups. Finally, we excluded Habitat Group 1 catch reports at sites where none of the corresponding habitat type was present inside the fishing ground.

3.4. Fishing practices, effort, and weight

To describe fishing practices, we used the household survey results to assess the proportion of households fishing during each survey event, numbers of fishers and fishing days per household, and top reported gears. We used the subset of surveys that provided fisher age and gender to report fisher demographics.

We also evaluated fishing effort and catch weight from the household survey data, conducting separate analyses for fish (finfish and other aquatic animals) and for aquatic plants. We investigated habitat and seasonal patterns to account for the seasonal flooding and heterogeneous habitats within rice field ecosystems. Because catch reports were at household level rather than specified by fisher or fishing day, we treated reported household catch from each habitat within the seven-day period as separate fishing events (i.e., during a survey event, households could report at most one fishing event per habitat). We summed the number of fishing events by habitat to obtain a relative measure of fishing effort across habitats, which we used along with the catch weights provided in the habitat catch reports for the habitat and seasonal analyses.

3.5. Catch use and total household fish consumption

We evaluated the frequency and seasonal patterns for a variety of uses (consumption within the household, sale, processing, and other uses) for each type of catch (finfish, other aquatic animal, and aquatic plant) reported in the household surveys. To evaluate seasonal patterns, we grouped use reports by sampling events in the same month across years (i.e.; for each month, we calculated a grand mean from 3 to 4 sampling events). We also used household survey data on weight of fish (finfish and other aquatic animals) consumed in the household by source (i.e. catch, purchase, gift, and home aquaculture) to evaluate contribution of household catch to total household fish consumption.
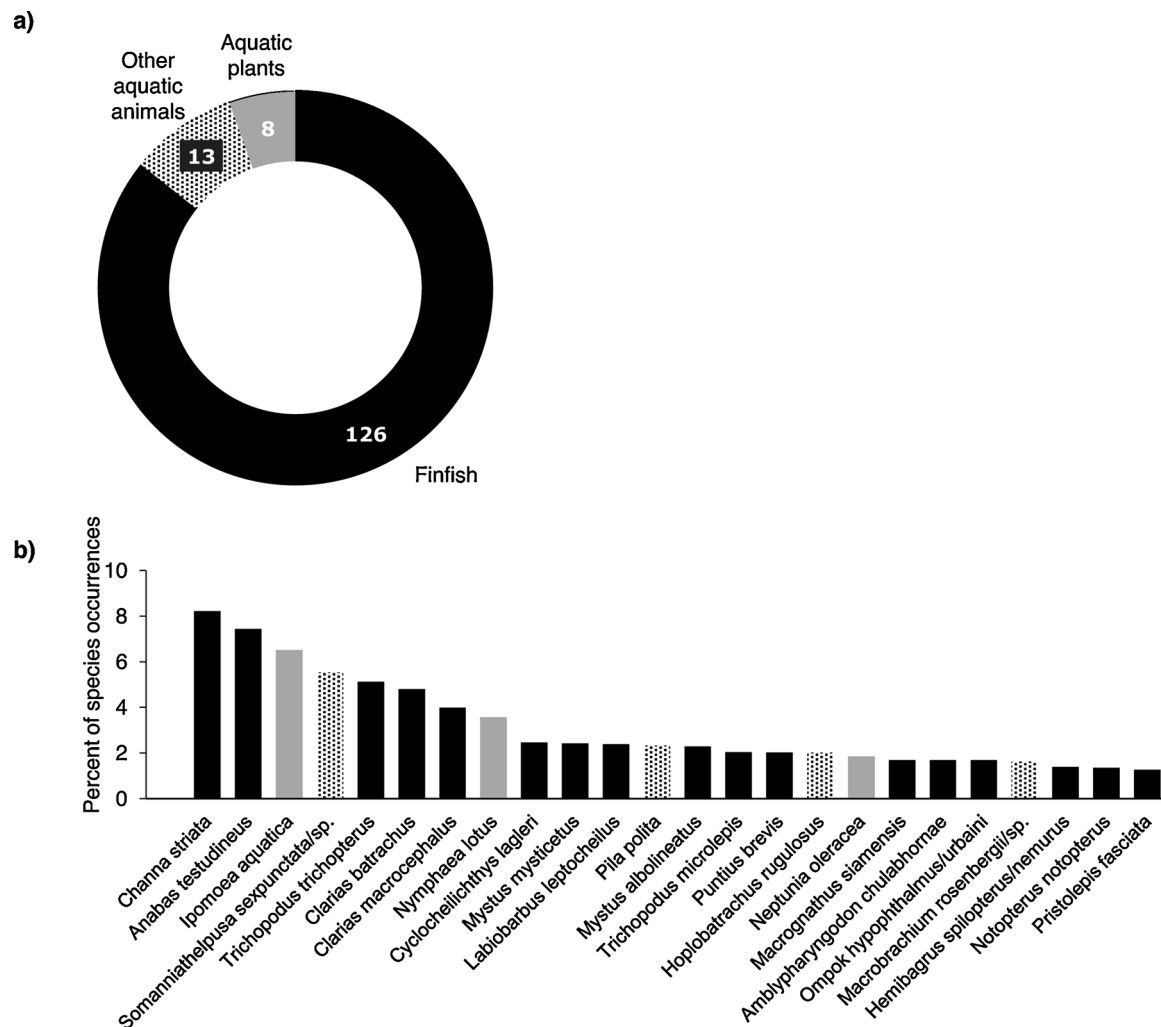
Fig. 2. Species reported in household catch recall surveys as a) number of species of finfish, other aquatic animals, and aquatic plant; b) Percent of all species occurrences in which a species was reported (figure is truncated at 75%, see supplementary Table 1 for full species list).

4. Results

4.1. Wild aquatic species inventory

A total of 147 species were reported in household surveys, comprised of 126 finfish species from 24 families, 13 other aquatic animal species from 10 families, (four species of snake; two species each of frogs, snails, and bivalves; one species each of crab, prawn, and turtle), and eight aquatic plant species from as many families (Fig. 2a). By migratory guild, 23 finfish species were black fish, 84 were grey, 16 were white, and two were unassigned (Supplementary Table 1). An additional 11 species (nine finfish and two snake species) were identified in catch from experimental fishing (Supplementary Table 1).

Twenty-four species (17 finfish species, three aquatic plant species, and four other aquatic animal species) made up 75% of all species occurrences (n = 35,016) in reported household catch (Fig. 2b). The remaining 123 species appeared in 5% or less of household catch reports. The most frequently reported species appeared in 38% of surveys. Fewer species (130) were caught in the dry season than in the flood season (148), but the same six species had the highest occurrences across seasons (although ranked differently), making up 41 and 36% of dry and flood season species occurrences, respectively.

4.2. Fisheries productivity

The 37 fishing grounds used for the calculation of rice field fishery productivity varied in area from 183 ha to 5167 ha (mean area: 1736 ± 1366 ha). A total of 32,458 households resided within the 64,231 ha of fishing grounds. For the 30–74% of surveyed households that fished within the fishing grounds, average weekly fish catch was 7.6 ± 15 kg (median: 3.5 kg). From these data, we estimated an upper bound average yearly total catch of 8853 ± 1494 metric tons (for the lower bound, 4293 ± 685 metric tons). We estimated that rice field fisheries provided $138 ± 23.3$ kg ha^{-1} yr^{-1}, composed of $104 ± 16.0$ kg ha^{-1} yr^{-1} finfish catch and $34 ± 7.7$ kg ha^{-1} yr^{-1} other aquatic animal catch (for the lower bound, $67.8 ± 10.7$ kg ha^{-1} yr^{-1}, $49.7 ± 7.3$ kg ha^{-1} yr^{-1}, and $17.1 ± 3.9$k, kg ha^{-1} yr^{-1}, respectively). Results by year are provided in Supplementary Table 2.

4.3. Fishing practices and habitat and seasonal patterns in fishing effort and catch weights

From household surveys, on average 62 ± 12% (mean ± sd) of sampled households reported fish catch and 39 ± 13% reported aquatic plant catch during the previous seven days. Reported catch came from a median of one habitat (maximum of four habitats), over a median of four person-days (maximum of 35 person-days), by a median of one fisher (maximum of five fishers) per household in a seven-day
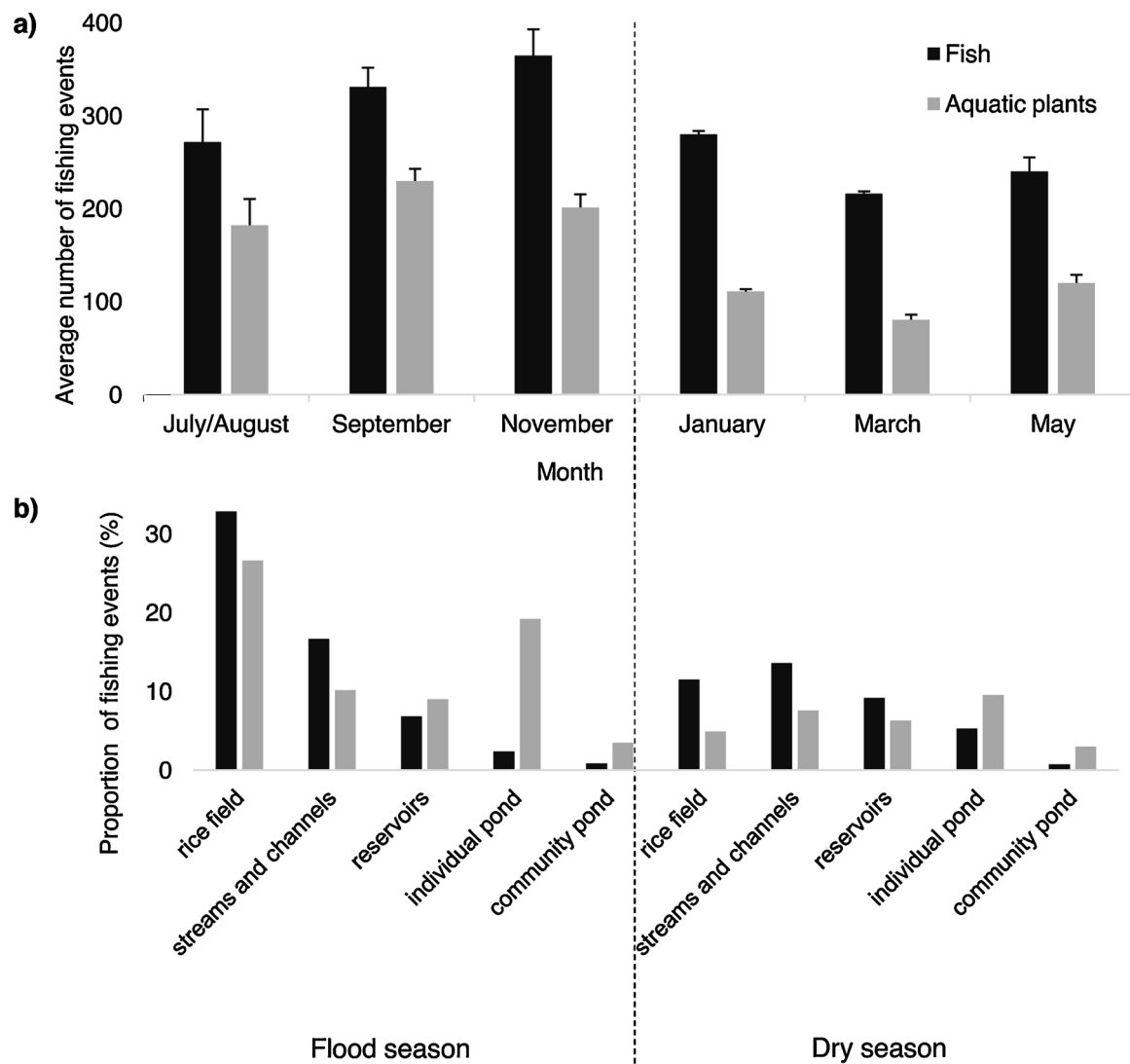
Fig. 3. Fishing effort within rice-field ecosystems as a) average number of weekly household fishing or aquatic plant fishing events each month (n = 400 households in each of 3–4 sampling events); b) proportion of fishing or aquatic plant fishing events by season (flood: July–November; dry: January–May) and habitat.

period. Households caught fish and aquatic plants nearly entirely from the rice field ecosystem in terms of both effort (95 and 91% of fishing events for fish and for aquatic plants, respectively) and catch weight (92% of reported catch weight for both fish and aquatic plants).

From the subsample of surveys in which fisher age and gender were reported, fisher ages ranged from six to 65 and fishers were primarily (77%) males. The majority of males were between 20 and 34 years of age, while the majority of females were between 10 and 24 years of age (57 and 58%, respectively). From gear reports, fishers used traditional gears, most often cast net or gill net for finfish (30 and 24% of all gear reports for finfish catch, respectively) and hand collection for other aquatic animals (51% of all gear reports for other aquatic animal catch).

Fishing effort followed the seasonal flow of water and fish in that effort ramped up as rice fields became flooded (July-Nov), then decreased as flood waters receded (Jan-May; Fig. 3a). Based on 3-year averages, fishing events were more common in flood season (55 ± 4% for fish, 65 ± 4% for aquatic plants) than in dry season (45 ± 4% for fish, 35 ± 4% for aquatic plants). Looking at combined seasonal and habitat patterns of effort for fish, rice fields were the primary habitat in flood season (comprising 33% of total fishing events), while rice fields, streams and channels, and reservoirs were relatively evenly frequented during dry season (comprising 12, 14, and 9% of all fishing events, respectively; Fig. 3b). For aquatic plants, rice fields and individual

ponds were the primary sites of catch during flood season (comprising 27 and 19% of total fishing events, respectively), while all habitats were similarly frequented in dry season (each habitat comprising between 3 and 10% of all fishing events; Fig. 3b).

Seasonal patterns for catch weight were slightly different from those of fishing effort. November (flood season) was the month with highest reported fish catch weight, closely followed by January and March (dry season; Fig. 4a), although fishing effort was lower in dry months when compared to flood months (Fig. 3a). During flood season, rice fields returned the largest total fish catch (32% of total catch weight; Fig. 4b). During dry season, fish catch weights from streams and channels, reservoirs, and individual ponds were higher than those from rice fields (13, 11, 11, and 6% of total catch weight, respectively; Fig. 4b). Other aquatic animals were caught primarily in rice fields and made up a substantial portion of rice field catch (39% during flood season and 63% during dry season; Fig. 4b). Except for community ponds, habitat patterns for catch weight of aquatic plants mirrored patterns for effort. Although community ponds were the least frequented habitats for aquatic plants (Fig. 3b), they provided the third largest proportion of plants by weight (15% during the flood season and 17% overall; Fig. 4b).
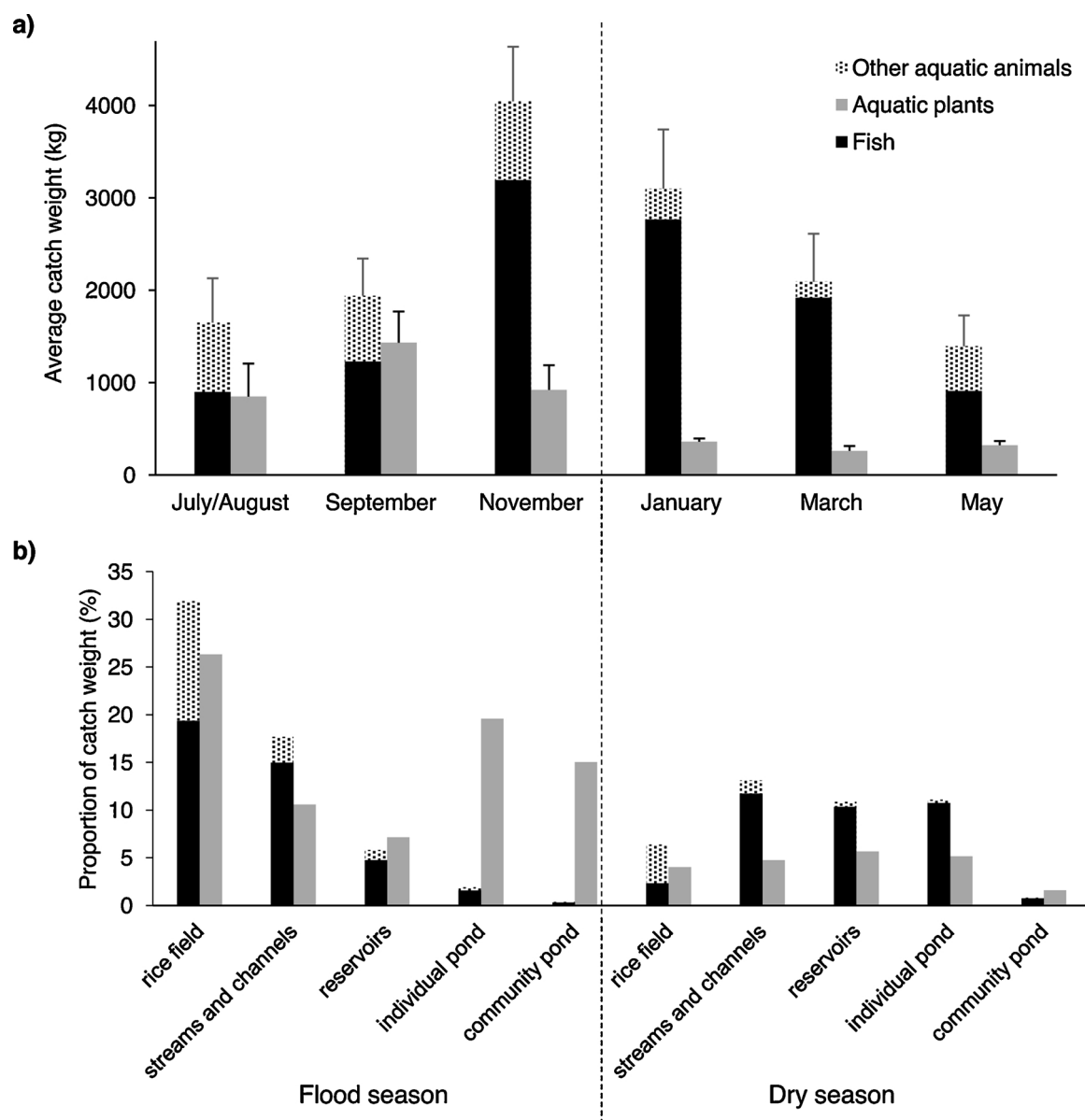
Fig. 4. Catch weights from rice-field ecosystems as a) averages are of monthly total catch weights (n = 400 households in each of 3–4 sampling events); b) proportion of total catch weight by season and habitat.

4.4. Catch use and total household fish consumption

Sampled catch was primarily destined for immediate consumption within the household. Nearly all household catch reports included a portion designated for immediate consumption (99% of finfish and aquatic plant catch reports, 93% of other aquatic animal catch reports; Fig. 5). All surveyed fishing households reported consumption of catch during one or more survey events, while eight percent of households never reported processing their catch and 35% never reported selling.

Weight consumed from fish catch was relatively consistent, while weights destined for sale, processing, or other uses varied greatly by household and season (Fig. 6). Use of fish catch for sale and processing occurred primarily during the peak catch period from November to March (Fig. 6). Processing included drying, fermentation as "prahoc", and other preservation methods for later consumption and/or sale and was more common for finfish than for other aquatic animals or aquatic plants (Fig. 5). "Other" uses for finfish and other aquatic animals primarily meant the catch was kept at the home, but not yet consumed, processed, or sold. A few households used large quantities of aquatic
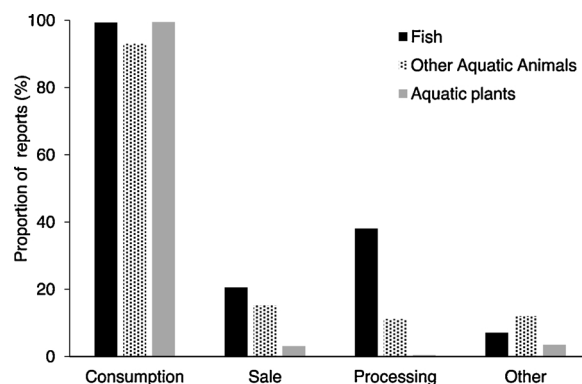

Fig. 5. Reported uses of rice field fishery catch by catch type: proportions of household survey reports designating a portion of catch to consumption, sale, processing, or other uses. As each report could include multiple uses, total number of reported uses is greater than number of reports.
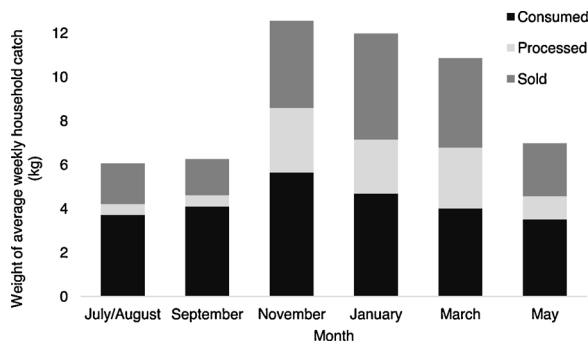
Fig. 6. Use of finfish and other aquatic animal catch. Values are grand means of weekly household catch weights by month.

plants for "other" purposes (Fig. 5), primarily for feeding livestock.

Contribution of fish catch (as fresh or processed, finfish or other aquatic animals) to household fish consumption varied more among households than across seasons and months. Overall, fish catch made up 62% (57% in dry season, 66% in flood season) of average household fish consumption (3.1 ± 1 kg of an average total 5.0 ± 0.8 kg consumed per week). Purchased fish, gift fish, and home aquaculture made up of 34, 4, and 0.2% of average household fish consumption, respectively. Home aquaculture was practiced by only 14 surveyed households and reported as a consumption source only 19 times across the 14 households and 14 sampling events.

5. Discussion

5.1. Wild aquatic species diversity in rice field ecosystems and local catch

This study demonstrated that the diversity of wild aquatic species in rice field ecosystem habitats is much greater than previously documented. In previous studies, the numbers of finfish species found in rice field ecosystems were approximately half or less than the number found in our study (126 in household catch, 135 including experimental fishing): 44 in Laos (Garaway et al., 2013) and at most 70 in Cambodia (Balzer et al., 2005). Three studies found around half or less the number of other aquatic animal species in this study (13 in household catch, 15 including experimental fishing), although not all studies identified to species (Gregory, 1997; Hortle et al., 2008; Shams, 2007). Studies of wild plants (not exclusively aquatic plants) collected from rice field ecosystems found around twice the number of species found in this study (8), but it is unclear how many were aquatic plants (13 species in Kamoshita et al., 2014; 16 species in Shams, 2007). Kamoshita et al. (2014) found more wild plant species (76 in total) through biological sampling in Cambodian rice fields and attributed the presence of these "weeds" (also known as self-recruits or volunteers) to the low use of agrochemicals and natural flooding. It would be of interest to conduct further study on habitat specific species richness in rice field ecosystems, as a study from the Mediterranean region found species differed when comparing rice field and channel habitats (Clavero et al., 2015).

The diversity of wild aquatic species found in this study should not be surprising, given the high diversity within Tonle Sap lake and the speculation that many species from the lake and/or nearby rivers take temporary residence in rice field ecosystems during flooding (e.g., Gregory, 1997; Halls and Kshatriya, 2009). It is likely that the geographical spread, number of sites, and multiple seasons and years in this study contributed to the higher diversity of wild aquatic species recorded than previous studies of catch from rice field ecosystems in Cambodia. Two other factors are likely contributors to the higher diversity in comparison with studies outside Cambodia: the relatively low use of agrochemicals and the diversity of habitats across the rice field ecosystem. Regarding agrochemical use, Kamoshita (2014) found higher plant diversity in rice field habitats where fewer inputs were

used for rice cultivation (specifically, less fertilizer use, direct seeding instead of transplanting, mid-season tillage and weed management). Regarding habitat diversity, it has been demonstrated to contribute to species diversity in rice fields and other agroecosystems (e.g. Kamoshita et al., 2014; Purtauf et al., 2005).

5.2. Fishery prevalence, rice field fisheries productivity, and contribution to national fisheries

This study supports findings from Nasielski et al. (2016) that national census data in Cambodia underrepresents fishers, primarily because fishing-related questions focus on income generation. The most recent national statistics recognize 20–26% of households as involved in fishing as an occupation (MoP, 2015), but do not capture households participating in fisheries for subsistence or as occasional livelihood. The latest agricultural census acknowledges the difficulty of capturing fisher numbers, as a repeat survey found an increase in the number of households reporting fishing as part of their livelihood following a flood season (MoP, 2015). Across three years and 19 sampling events, 35% of households in this study never reported sale of catch, confirming that subsistence fishing is prevalent in rice field ecosystems. National statistics on fishery participation could be improved through modifications to the agricultural census protocol and questions, for example, inclusion of landless households and questions on subsistence-based fishing to better capture actual numbers of fishing households and fishers.

As the largest field study evaluating rice field fisheries productivity, the upper bound estimate for finfish productivity (104 ± 16.0 kg ha^{-1} yr^{-1}) was similar to an estimate (112 kg ha^{-1} yr^{-1}) provided by Chheng et al. (2016). The latter estimate came from previous studies on rain-fed rice field habitats in Cambodia and Thailand that ranged in productivity from 25 to 209 kg ha^{-1} yr^{-1} (Chheng et al., 2016). This study's upper bound estimate for productivity of other aquatic animals (34 ± 7.9 kg ha^{-1} yr^{-1}) was slightly higher than an average from two studies conducted in previous years (25.1 kg ha^{-1} yr^{-1}; Chheng et al., 2016). Our study supports Chheng et al. (2016) estimations that 1) productivity of rice field fisheries is in the mid-range among Cambodia's highly productive and diverse fisheries ecosystems (flooded shrub land, reservoirs, open water, flooded grassland, and flooded forest in Chheng et al., 2016) and 2) Cambodia's expansive area of rice field ecosystems means that rice field fisheries potentially contribute the largest proportion of the nation's annual inland fish catch (around 70% according to Chheng et al., 2016). Official rice field fishery productivity estimates (ranging from 68 to 79 kg ha^{-1} yr^{-1} for fish catch, unpublished data Fisheries Administration, 2014) from the provinces where this study was conducted were closest to the lower bound estimate in this study (66.8 ± 10.7 kg ha^{-1} yr^{-1}).

As annual fisheries productivity differs across sites and years, national estimates would benefit from field studies in other locations and under differing rainfall and hydrological conditions. The productivity estimates presented in this study were produced under counterbalancing conditions. First, the rice field ecosystems included in this study may have higher productivity relative to other rice field ecosystems in Cambodia due to their proximity to Tonle Sap, the relatively good condition of the connected Community Fish Refuges, and project related habitat and management enhancements. Second, the poor rainfall conditions during the years used for the productivity estimate (especially in 2015, a low-rainfall year that led to the worst drought in 50 years) are likely to have reduced the number of active fishing households and fish catch per household relative to "normal" years of rainfall.

5.3. Habitat and seasonal fishing patterns relevant to decision-making on agricultural development

The importance of diverse and interconnected habitats has been previously noted for rice field ecosystems in both Cambodia and Laos

(Kamoshita et al., 2014; Nguyen Khoa et al., 2005; Shams, 2007). The habitat and seasonal fishing patterns found in this study revealed that connectivity and access across rice field ecosystem habitats are essential for wild aquatic species harvests. Rice fields provided the majority of finfish and other aquatic animal catch during flood season (Fig. 4b), made possible by their connectivity to the more perennial habitats for finfish and many other aquatic species. Streams and channels, individual ponds, and reservoirs provided the majority of catch during the dry season, and collectively surpassed catch weight from flood season rice fields (Fig. 4b). Due to the importance of small reservoirs, canals, and individual ponds for dry season catch, we recommend further study to determine whether socioeconomic differences play a role in fishery use of these habitats, and of dry season catch in general.

The Cambodian Ministry of Agriculture, Forestry, and Fisheries recognizes the importance of rice field fisheries and the role of habitat connectivity. Agricultural and fisheries planning documents include targets to maintain natural hydrological features and habitat integrity of rice field ecosystems, thereby increasing rice field fishery productivity (Fisheries Administration, 2011; MAFF, 2014). When considering improvements to new or old irrigation infrastructure, technologies to allow fish passage and water management protocols that allow natural flows from flood pulses are two requirements to ensure habitat connectivity (Gregory et al., 2018). We recommend further research and application of these strategies if irrigation development in Cambodia and the Lower Mekong region is to continue. We also recommend maintaining access to diverse rice field ecosystem habitats for fishery purposes and minimal use of chemical inputs to ensure availability of wild aquatic species.

5.4. Catch use and contribution to household food provisioning and livelihoods

It is widely understood that finfish and other aquatic animals are the predominant sources of animal protein (Arthur and Friend, 2011; Garaway et al., 2013; Halwart, 2006; Jensen, 2001; Shams, 2007) and micronutrients (Golden et al., 2019; Kawarazuka and Béné, 2011; Nam and Bunthang, 2011; Roos et al., 2007) for rural households in the Lower Mekong region. In this study, the overwhelming proportion of catch reports with some portion allocated to household consumption (93–99%; Fig. 5) and the substantial contribution of fish catch to total household fish consumption (62%) provided further evidence of the important role of wild aquatic species in rural food and nutrition security. To continue bringing in catch during the dry season, fishers shifted their efforts across habitats (Fig. 3b) as the overall most frequented location (rice fields) returned less catch. Additionally, study households prioritized consumption of fish catch relative to other uses, as evidenced by relatively consistent average household consumption from catch even as catch amounts declined in late dry season and early wet season (May-September; Fig. 6). Similarly, when comparing results across study sites and wealth status, Shams (2007) also found relatively consistent fish consumption despite differing catch amounts and found fish were much more consumed than pork or beef (by 10 to over 300 fold). As an estimated 49% of households own less than 1 ha of agricultural land and a further 29% are landless nationally (Phann et al., 2014), access to wild aquatic species is essential for rural food security in Cambodia. This has been recognized and included in Cambodia's National Strategy for Food Security and Nutrition (CARD, 2014).

The diversity of wild aquatic species in rice field ecosystems around Tonle Sap also contributed to household livelihoods in other ways. Especially during the peak catch period, excess catch was sold for income or processed to ensure availability for consumption for many months (Fig. 6). Some households depended greatly on catch for income, collecting and selling large quantities. Wild aquatic plants also contributed indirectly to livelihood and food and nutrition security through their use as feed for livestock. Sok et al. (2019) and Teh et al. (2019) have demonstrated that fisheries, as part of a diversified

household livelihood, can enhance household adaptive capacity. The income opportunities from rice field fisheries may be especially important for the most remote households that tend not to be reached by irrigation development or other agricultural intensification schemes.

6. Conclusion

The findings from this study demonstrate the importance of rice field ecosystems for national fishery productivity, biodiversity, and local food provision. These benefits have implications for both national and regional policy and decision-making. First, the recognition of rice field fishery benefits in some of Cambodia's policies on fisheries, agriculture, and food and nutrition security must be extended to water management and irrigation policies, especially as plans for irrigation development are considered. The habitat and seasonal patterns of rice field fisheries that were identified in this study can be especially informative for designing agricultural and irrigation development schemes that maintain aquatic habitat connectivity, natural flooding regimes, fishery access, and low application of agrochemicals for rice cultivation. Second, policy support for maintenance of wild aquatic species in agroecosystems can also support livelihood and development priorities at national and regional levels. Cambodia's recent reduction in extreme poverty leaves a large number of people only just above poverty levels, many of whom still greatly depend upon access to natural resources (Navarro et al., 2016; The World Bank, 2017). Rice field fisheries can support food provisioning and livelihoods in rural households transitioning out of poverty. As rural populations throughout the Lower Mekong region continue to endure persistent poverty and undernourishment despite their nations' growing GDPs (Ingalls et al., 2018; The World Bank, 2017), broader policy and investment support to maintain wild aquatic species in agroecosystems could benefit rural populations throughout the region. Finally, policies supporting the presence of wild aquatic species in agroecosystems can benefit local economies and environments. This is exemplified by the contrast of Cambodia's rice field ecosystems that maintain diverse habitats, biodiversity, and food provisioning in comparison with Vietnam's rice monocultures, where farmers experience ecosystem service loss and financial vulnerability (Berg et al., 2017; Nguyen et al., 2018). Considering the increasingly common challenges of invasive pests, disease, volatile commodity prices, and politically tenuous international trade that agricultural systems face, policies can bolster resilience of the agricultural environment and economy by supporting integration of wild aquatic species and agricultural biodiversity within Cambodia and the Lower Mekong region.

CRediT authorship contribution statement

Sarah Freed: Conceptualization, Formal analysis, Methodology, Writing - original draft. **Yumiko Kura:** Conceptualization, Methodology, Writing - review & editing. **Vichet Sean:** Investigation, Data curation. **Samonn Mith:** Investigation, Data curation. **Philippa Cohen:** Writing - review & editing. **Miratori Kim:** Methodology, Supervision, Data curation. **Somony Thay:** Supervision, Validation. **Savry Chhy:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

associated research; O. Joffre, A. Tilley, and anonymous reviewers for comments on earlier versions of the manuscript; C. Huchery and A. Tilley for assistance with figures.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2020.105615.

References

Ali, A.B., 1990. Some ecological aspects of fish populations in tropical ricefields. Hydrobiologia 190, 215–222. https://doi.org/10.1007/BF00008188.

Amilhat, E., Lorenzen, K., Morales, E.J., Yakupitiyage, A., Little, D.C., 2009. Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS) I. Characterisation of systems. Aquaculture 296, 219–226. https://doi.org/10.1016/j.aquaculture.2009.08.014.

Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N.J., Bauch, S., Börner, J., Smith-Hall, C., Wunder, S., 2014. Environmental income and rural livelihoods: a global-comparative analysis. World Dev. 64, S12–S28. https://doi.org/10.1016/j.worlddev.2014.03.006.

Arias, M.E., Cochrane, T.A., Elliott, V., 2014. Modelling future changes of habitat and fauna in the Tonle Sap wetland of the Mekong. Environ. Conserv. 41, 165–175. https://doi.org/10.1017/S0376892913000283.

Arthur, R.I., Friend, R.M., 2011. Inland capture fisheries in the Mekong and their place and potential within food-led regional development. Glob. Environ. Chang. 21, 219–226. https://doi.org/10.1016/j.gloenvcha.2010.07.014.

Asian Development Bank (ADB), 2015. Operational Plan for Agriculture and Natural Resources: Agriculture & Food Security.

Balzer, P., Balzer, T., Pon, S., 2005. Traditional use and availability of aquatic biodiversity in rice-based ecosystems. 1. Kampong Thom Province, Kingdom of Cambodia. In: Halwart, M., Bartley, D. (Eds.), Recent Initiatives on the Availability and Use of Aquatic Organisms in Rice-Based Farming. FAO, Rome, pp. 1–16.

Baran, E., Starr, P., Kura, Y., 2007. Influence of Built Structures on Tonle Sap Fisheries. Phnom Penh. .

Barnes-mauthe, M., Oleson, K.L.L., Zafindrasilivonona, B., 2013. The total economic value of small-scale fisheries with a characterization of post-landing trends: an application in Madagascar with global relevance. Fish. Res. 147, 175–185. https://doi.org/10.1016/j.fishres.2013.05.011.

Baumgartner, L., Marsden, T., Millar, J., Thorncraft, G., Phonekhampheng, O., Homsombath, K., Singhanouvong, D., Robinson, W., McPherson, J., Martin, K., Boys, C., 2016. Development of Fish Passage Technology to Increase Fisheries Production on Floodplains in the Lower Mekong Basin.

Bayley, P.B., Petrere, M., 1989. Amazon fisheries: assessment methods, current status and management options. Can. Spec. Publ. Fish. Aquat. Sci. 106, 385–398.

Berg, H., Ekman Söderholm, A., Söderström, A.S., Tam, N.T., 2017. Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. Sustain. Sci. 12, 137–154. https://doi.org/10.1007/s11625-016-0409-x.

Bharucha, Z., Pretty, J., 2010. The roles and values of wild foods in agricultural systems. Philos. Trans. R. Soc. B Biol. Sci. 365, 2913–2926. https://doi.org/10.1098/rstb.2010.0123.

Bouman, B.A.M., Humphreys, E., Tuong, T.P., Barker, R., 2007. Rice and water. Adv. Agron. 92, 187–237. https://doi.org/10.1016/S0065-2113(04)92004-4.

Broegaard, R.B., Rasmussen, L.V., Dawson, N., Mertz, O., Vongvisouk, T., Grogan, K., 2017. Wild food collection and nutrition under commercial agriculture expansion in agriculture-forest landscapes. For. Policy Econ. 84, 92–101. https://doi.org/10.1016/j.forpol.2016.12.012.

Brussaard, L., Caron, P., Campbell, B., Lipper, L., Mainka, S., Rabbinge, R., Babin, D., Pulleman, M., 2010. Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. Curr. Opin. Environ. Sustain. 2, 34–42. https://doi.org/10.1016/j.cosust.2010.03.007.

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the earth system exceeding planetary boundaries. Ecol. Soc. 22. https://doi.org/10.5751/ES-09595-220408.

CARD, TWG-SP&FSN, 2014. National strategy for food security and nutrition 2014-2018. In: Council for Agricultural and Rural Development and Technical Working Group for Social Protection and Food Security and Nutrition. Phnom Penh.

Chheng, P., Un, S., Tress, J., Simpson, V., Sieu, C., 2016. Fish Productivity by Aquatic Habitat and Estimated Fish Production in Cambodia. Phnom Penh. .

Clavero, M., López, V., Franch, N., Pou-Rovira, Q., Queral, J.M., 2015. Use of seasonally flooded rice fields by fish and crayfish in a Mediterranean wetland. Agric. Ecosyst. Environ. 213, 39–46. https://doi.org/10.1016/j.agee.2015.07.022.

Cramb, R., Manivong, V., Newby, J.C., Sothorn, K., Sibat, P.S., 2017. Alternatives to land grabbing: exploring conditions for smallholder inclusion in agricultural commodity chains in Southeast Asia. J. Peasant Stud. 44, 939–967.

DeFalco, R.C., 2014. Justice and starvation in Cambodia: the khmer rouge famine. Cambodia Law Policy J. 3, 45–84.

Fisher, W.L., Grambsch, A.E., Eisenhower, D.L., Morganstein, D.R., 1991. Length of recall period and accuracy of estimates from the national survey of fishing, hunting, and wildlife-associated recreation. American Fisheries Society Symposium 367–374.

Fisheries Administration, 2011. Cambodia Strategic Planning Framework for Fisheries 2010–2019. Phnom Penh. .

Frison, E.A., Cherfas, J., Eyzaguirre, P.B., Johns, T., 2006. Biodiversity, nutrition and health: making a difference to hunger and conservation in the developing world. Food Nutr. Bull. 27.

Funge Smith, S., Bennett, A., 2019. A fresh look at inland fisheries and their role in food security and livelihoods. Fish Fish. 1–20. https://doi.org/10.1111/faf.12403.

Garaway, C.J., Photitay, C., Roger, K., Khamsivilay, L., Halwart, M., 2013. Biodiversity and nutrition in rice-based ecosystems; the case of Lao PDR. Hum. Ecol. 41, 547–562. https://doi.org/10.1007/s10745-013-9602-z.

Golden, C.D., Shapero, A., Vaitla, B., Smith, M.R., Myers, S.S., Stebbins, E., Gephart, J.A., 2019. Impacts of mainstream hydropower development on fisheries and human nutrition in the Lower Mekong. Front. Sustain. Food Syst. 3, 1–10. https://doi.org/10.3389/fsufs.2019.00093.

Gotelli, N.J., Colwell, R.K., 2001. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. Ecol. Lett. 4, 379–391.

Gregory, R., 1997. Ricefield Fisheries Handbook. Phnom Penh. .

Gregory, R., Guttman, H., 1996. Capture and culture ricefield fisheries in Cambodia. In: Nesbitt, H.J. (Ed.), Rice Production in Cambodia. University Press, Phnom Penh, pp. 159–173.

Gregory, R., Funge-smith, S., Baumgartner, L., 2018. An Ecosystem Approach to Promote the Integration of Fisheries and Irrigation Systems. Rome. .

Halls, A., Kshatriya, M., 2009. Modelling the Cumulative Barrier and Passage Effects of Mainstream Hydropower Dams on Migratory Fish Populations in the Lower Mekong Basin, MRC Technical Paper. Vientiane. .

Halwart, M., 2006. Biodiversity and nutrition in rice-based aquatic ecosystems. J. Food Compos. Anal. 19, 747–751. https://doi.org/10.1016/j.jfca.2006.03.012.

Heckman, C.W., 1979. Rice Field Ecology in Northeastern Thailand. Springer Science + Business Media Dordrecht.

Hori, M., Ishikawa, S., Kurokura, H., 2011. Small-scale fisheries by farmers around the Tonle Sap Lake of Cambodia. In: Taylor, W.W., Lynch, A.J., Schechter, M.G. (Eds.), Sustainable Fisheries: Multi-Level Approaches to a Global Problem. American Fisheries Society, pp. 185–196.

Hortle, K., Troeung, R., Lieng, S., 2008. Yield and Value of the Wild Fishery of Rice Fields in Battambang Province, Near the Tonle Sap Lake. Cambodia. Vientiane. .

Ingalls, M.L., Diepart, J., Truong, N., Hayward, D., Neil, T., Phomphakdy, C., Bernhard, R., Fogarizzu, S., Epprecht, M., Nanhthavong, V., Vo, D.H., Nguyen, D., Nguyen, P.A., Saphangthong, T., Inthavong, C., Hett, C., Tagliarino, N., 2018. State of Land in the Mekong Region. Bern. Lao PDR, Switzerland and Vientiane.

Jensen, J.G., 2001. Managing fish, flood plains and food security in the Lower Mekong Basin. Water Sci. Technol. 43, 157–164.

Joffre, O., Kosal, M., Kura, Y., Sereywath, P., Thuok, N., 2012. Community Fish Refuges in Cambodia – Lessons Learned. Phnom Penh. .

Johns, T., Powell, B., Maundu, P., Eyzaguirre, P.B., 2013. Agricultural biodiversity as a link between traditional food systems and contemporary development, social integrity and ecological health. J. Sci. Food Agric. 93, 3433–3442. https://doi.org/10.1002/jsfa.6351.

Johnston, R., da Silva, S., Try, T., 2014. Investing in water management to improve productivity of rice-based farming systems in Cambodia. In: Robins, L. (Ed.), A Policy Dialogue on Rice Futures: Rice-Based Farming Systems Research in the Mekong Region. Proceedings No. 142. Australian Centre for International Agricultural Research, Phnom Penh. pp. 116–119.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in River-floodplain systems. Dodge, D.P. (Ed.), Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences 106, 110–127.

Kamoshita, A., Araki, Y., Nguyen, Y.T.B., 2014. Weed biodiversity and rice production during the irrigation rehabilitation process in Cambodia. Agric. Ecosyst. Environ. 194, 1–6. https://doi.org/10.1016/j.agee.2014.05.001.

Kawarazuka, N., Béné, C., 2011. The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. Public Health Nutr. 14, 1927–1938. https://doi.org/10.1017/S1368980011000814.

Kuster, C., Vuki, V.C., Zann, L.P., 2006. Validation of the accuracy of household reporting of subsistence fishing catch and effort: a Fijian case study. Fish. Manag. Ecol. 13, 177–184.

Lawler, S.P., 2001. Rice fields as temporary wetlands: a REVIEW. Isr. J. Zool. 47, 513–528. https://doi.org/10.1560/X7K3-9JG8-MH2J-XGX1.

Liu, Y., Duan, M., Yu, Z., 2013. Agricultural landscapes and biodiversity in China. Agric. Ecosyst. Environ. 166, 46–54. https://doi.org/10.1016/j.agee.2011.05.009.

Lu, J., Li, X., 2006. Review of rice-fish-farming systems in China - one of the globally important ingenious agricultural heritage systems (GIAHS). Aquaculture 260, 106–113. https://doi.org/10.1016/j.aquaculture.2006.05.059.

MAFF, 2014. Cambodia Climate Change Priorities Action Plan for Agriculture, Forestry and Fisheries Sector 2014–2018. Ministry of Agriculture, Forestry, and Fisheries, Phnom Penh.

MAFF, 2017. Annual Report of Agriculture, Forestry and Fisheries 2016–2017 and Directions 2017–2018. Ministry of Agriculture, Forestry, and Fisheries, Phnom Penh.

MAFF, 2018. Annual Report 2017–18 and Directions for 2018–19. Ministry of Agriculture, Forestry, and Fisheries, Phnom Penh.

Mccartney, M.P., Whiting, L., Makin, I., Lankford, B.A., Ringler, C., 2019. Rethinking irrigation modernisation: realising multiple objectives through the integration of fisheries. Mar. Freshw. Res. 70, 1265–1273. https://doi.org/10.1071/MF19161.

Mccluskey, S.M., Lewison, R.L., 2008. Quantifying fishing effort: a synthesis of current methods and their applications. Fish Fish. 9, 188–200.

MoP, 2015. Census of Agriculture in Cambodia 2013. Ministry of Planning, Phnom Penh.

Moreno, C.E., Halffter, G., 2001. On the measure of sampling effort used in species accumulation curves. J. Appl. Ecol. 38, 487–490. https://doi.org/10.1046/j.1365-2664.2001.00589.x.

Nam, S., Bunthang, T., 2011. Fisheries Resources in. Implications for Food Security, Human Nutrition and IFReDI, Cambodia.

Nasielski, J., Kc, K.B., Johnstone, G., Baran, E., 2016. When is a fisher (not) a fisher? Factors that influence the decision to report fishing as an occupation in rural Cambodia. Fish. Manag. Ecol. 23, 478–488. https://doi.org/10.1111/fme.12187.

Navarro, N., Foraci, M., Hang, S., 2016. Building the Foundations for Inclusive and Sustainable Economic Growth in Cambodia [WWW Document]. United Nations Dev. Program. News Cent (Accessed 3 April 2019). http://www.kh.undp.org/content/cambodia/en/home/presscenter/articles/2016/10/19/building-the-foundations-for-inclusive-and-sustainable-economic-growth-in-cambodia.html.

Nguyen, V.K., Dumaresq, D., Pittock, J., 2018. Impacts of rice intensification on rural households in the Mekong Delta: emerging relationships between agricultural production, wild food supply and food consumption. Food Secur. 10, 1615–1629. https://doi.org/10.1007/s12571-018-0848-6.

Nguyen Khoa, S., Lorenzen, K., Garaway, C., Chamsinhg, B., Siebert, D., Randone, M., 2005. Impacts of irrigation on fisheries in rain-fed rice-farming landscapes. J. Appl. Ecol. 42, 892–900. https://doi.org/10.1111/j.1365-2664.2005.01062.x.

Padoch, C., Sunderland, T., 2013. Managing landscapes for food security and livelihoods. Unasylva 64, 3–13.

Pascual, U., Perrings, C., 2007. Developing incentives and economic mechanisms for in situ biodiversity conservation in agricultural landscapes. Agric. Ecosyst. Environ. 121, 256–268. https://doi.org/10.1016/j.agee.2006.12.025.

Phann, D., Phay, S., Tong, K., Pon, D., 2014. Landlessness and Child Labour in Cambodia. Phnom Penh. .

Pimentel, D., Mcnair, M., Buck, L., Pimentel, M., 1997. The value of forests to world food security. Hum. Ecol. 25, 91–120. https://doi.org/10.1023/A.

Powell, B., Sunderland, T., Termote, C., Ickowitz, A., Thilsted, S.H., Herforth, A., 2015. Improving diets with wild and cultivated biodiversity from across the landscape. Food Secur. 7, 535–554. https://doi.org/10.1007/s12571-015-0466-5.

Purtauf, T., Roschewitz, I., Dauber, J., Thies, C., Tscharntke, T., Wolters, V., 2005.

Landscape context of organic and conventional farms: Influences on carabid beetle diversity. Agric. Ecosyst. Environ. 108, 165–174. https://doi.org/10.1016/j.agee.2005.01.005.

Rainboth, W., 1996. Fishes of the Cambodian Mekong. FAO, Rome.

Roos, N., Thorseng, H., Chamnan, C., Larsen, T., Gondolf, U.H., Bukhave, K., Thilsted, S.H., 2007. Iron content in common Cambodian fish species: perspectives for dietary iron intake in poor, rural households. Food Chem. 104, 1226–1235. https://doi.org/10.1016/j.foodchem.2007.01.038.

Sabo, J.L., Ruhi, A., Holtgrieve, G.W., Elliott, V., Arias, M.E., Ngor, P.B., Räsänen, T.A., Nam, S., 2017. Designing river flows to improve food security futures in the Lower Mekong Basin. Science 358 https://doi.org/10.1126/science.aao1053. eaao1053.

Scoones, I., Melnyk, M., Pretty, J.N., 1992. The Hidden Harvest: Wild Foods and Agricultural Systems: A Literature Review and Annotated Bibliography. The Sustainable Agriculture Programme, International Institute for Environment and Development, London.

Shams, N., 2007. Contribution of rice field ecosytems to food security strategies in Northwest Cambodia. J. Sustain. Agric. 29, 109–133. https://doi.org/10.1300/J064v29n04.

Sok, K., Meral, P., Pilot, D., Defossez, S., 2019. Ecosystem services from Tonle Sap Flood Pulse: spatial and economic analysis in Aek Phnom and Sangkae Districts of Battambang Province, Cambodia. In: Stewart, M.A., Coclanis, P.A. (Eds.), Water and Power. Springer International Publishing AG, pp. 123–151. https://doi.org/10.1007/978-3-319-90400-9_8.

Teh, L.S.L., Bond, N., KC, K., Fraser, E., Seng, R., Sumaila, U.R., 2019. The economic impact of global change on fishing and non-fishing households in the Tonle Sap ecosystem, Pursat, Cambodia. Fish. Res. 210, 71–80. https://doi.org/10.1016/j.fishres.2018.10.005.

The World Bank, 2017. Cambodia - Sustaining Strong Growth for the Benefit of All.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biol. Conserv. 151, 53–59. https://doi.org/10.1016/j.biocon.2012.01.068.

Vásquez-Yeomans, L., Vega-Cendejas, M.E., Montero, J.L., Sosa-Cordero, E., 2011. High species richness of early stages of fish in a locality of the Mesoamerican Barrier Reef System: a small-scale survey using different sampling gears. Biodivers. Conserv. 20, 2379–2392. https://doi.org/10.1007/s10531-011-9990-6.

Verhoeven, J.T.A., Setter, T.L., 2010. Agricultural use of wetlands: opportunities and limitations. Ann. Bot. 105, 155–163. https://doi.org/10.1093/aob/mcp172.

Welcomme, R., 2001. Inland Fisheries Ecology and Management. Food and Agriculture Organization of the United Nations and Blackwell Science, Oxford.

Wittman, H., Chappell, M.J., Abson, D.J., Kerr, R.B., Blesh, J., Hanspach, J., Perfecto, I., Fischer, J., 2017. A social–ecological perspective on harmonizing food security and biodiversity conservation. Reg. Environ. Chang. 17, 1291–1301. https://doi.org/10.1007/s10113-016-1045-9.