

## Article

# Conserving Mekong Megafishes: Current Status and Critical Threats in Cambodia

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**Abstract:** Megafishes are important to people and ecosystems worldwide. These fishes attain a maximum body weight of  $\geq 30$  kg. Global population declines highlight the need for more information about megafishes' conservation status to inform management and conservation. The northern Cambodian Mekong River and its major tributaries are considered one of the last refugia for Mekong megafishes. We collected data on population abundance and body size trends for eight megafishes in this region to better understand their conservation statuses. Data were collected in June 2018 using a local ecological knowledge survey of 96 fishers in 12 villages. Fishers reported that, over 20 years, most megafishes changed from common to uncommon, rare, or locally extirpated. The most common and rarest species had mean last capture dates of 4.5 and 95 months before the survey, respectively. All species had declined greatly in body size. Maximum body weights reported by fishers ranged from 11–88% of their recorded maxima. Fishers identified 10 threats to megafishes, seven of which were types of illegal fishing. Electrofishing was the most prevalent. Results confirm that Mekong megafishes are severely endangered. Species Conservation Strategies should be developed and must address pervasive illegal fishing activities, alongside habitat degradation and blocked migrations, to recover declining populations.

**Keywords:** megafauna; biodiversity; freshwater; conservation; body size; abundance; human impact; dams; endangered; local ecological knowledge

## 1. Introduction

Megafishes are some of the most ecologically, economically, and culturally important species in the world. They are also some of the most endangered [1,2]. Based on a threshold established for the broader group of megafauna, we define megafishes as fish species that attain a maximum size of at least 30 kg [2–4]. These fishes are ecologically important in both marine and freshwater systems. Often top predators or voracious herbivores [5–7], megafishes serve as keystone species that structure local species assemblages [8–11]. As long-distance migrants [5,12,13], megafishes are also a key vehicle of nutrient transport between distant habitats [14]. Megafishes can also be used as indicator and flagship species to highlight ecological health, foster ecosystem and biodiversity conservation, and inform conservation measures [3,15]. Economically, these species fetch high sale prices and are a staple of global and local economies [16,17]. Megafishes are also the center of stories

and traditions. Ancient cultures revere and give special protection to local megafish species [18]. These examples highlight the essential roles these fishes play in sustaining the health of species, people, and ecosystems around the world.

Among the world's major river basins, the Mekong in Southeast Asia has the third highest number of freshwater megafauna species, the majority of which are fishes [2]. Until the early 2000s, these megafishes were thought to persist in the Mekong despite centuries of fishing pressure [19]. One Mekong megafish—the Mekong giant catfish *Pangasianodon gigas*—is the largest entirely freshwater fish species in the world [20]. Many fishers in the Mekong Basin regard *P. gigas* and other megafishes, like the giant barb *Catlocarpio siamensis*, which is the Cambodian national fish, as special creatures that must be honored and protected and can bring curses upon their family if they are killed. Many of these species are also highly threatened and thus have harvest and trade restrictions [1]. However, neither superstition nor legal protection has prevented a widespread and often-illegal trade for Mekong megafishes [21]. The perceived risks are outweighed by the opportunity for a lucrative catch since large megafish specimens are among the highest-priced species in the Lower Mekong Basin [21]. This trade is one of many factors that have caused severe declines in Mekong megafish populations to the point that most are now extremely rare and highly endangered [1,2,22].

Megafishes of the Mekong River Basin face ever-increasing anthropogenic threats that push them closer to extinction. Prolonged intense and indiscriminate fishing has led to declines in the abundance and body size of large-bodied fishes [23]. With the advent of cheap nylon mesh and access to new technologies, combined with the open access nature of the fish resources, illegal fishing methods—such as nets with too-small or too-large mesh sizes, electrofishing, poisons, and explosives—are on the rise [24]. These fishing methods not only directly deplete fish stocks, but also destroy habitat and food resources. The rapid proliferation of dams on the Mekong mainstem and its tributaries threaten to disrupt the life cycle of megafishes by restricting them from essential habitats, destroying habitat, removing sediment and nutrients, and modifying vital flow and temperature regimes, among other impacts [4,25–28]. Other threats like pollution, rapid industrialization, urbanization, and habitat modification in the form of deforestation and rapids blasting both degrade and eliminate fish habitats [4,24]. All of these threats are compounded by a lack of effective resource management and enforcement [24], poor education about natural resources and the environment, and high economic incentive to exploit megafishes [21]. Furthermore, these threats are expected to intensify due to a rapidly growing human population that will increase the demand for natural resources and take a heavier toll on the environment [24]. For megafishes, ecological traits such as large body size and late maturity make them especially vulnerable to these pressures [4,29,30], and their poor conservation statuses reflect the impacts [1].

Because of the threats mounting up against them, research is urgently needed to increase understanding of megafish conservation statuses by filling knowledge gaps about their abundance, current distribution, population stability, and basic ecological traits such as habitat requirements and migration patterns [2,22]. Available evidence for Mekong megafishes, mostly in the form of fishers' reports of decreased catches through time—especially of large individuals—suggests that their populations are decreasing [1]. Additionally, a recent study using local ecological knowledge in the Siphandone area of Lao People's Democratic Republic (Lao PDR) revealed high rarity and declining trends in perceived abundance of several megafishes [31]. Fifteen years of catch data from the Tonle Sap River (Cambodia) also showed a decrease in abundance and body size of the largest species, suggesting selection against large-bodied fishes [23]. These works are helpful to highlight declining trends, but more information is needed to improve understanding of megafishes' conservation statuses and create effective Species Conservation Strategies and Species Action Plans [32,33], which are urgently needed if megafishes are to be preserved in the Mekong [3,22].

The purpose of this study was to identify the conservation status and critical conservation needs of megafish species in the northern Cambodian Mekong River and the Sekong, Sesan, and Srepok (3S) Rivers, which are major tributaries to the Mekong. This part of the Mekong River Basin is

thought to be critical habitat for megafishes [34–36]. However, little work has been done to understand their current distributions, abundances, population trends, and threats, all of which are necessary components of Species Conservation Strategies and Action Plans [33]. The stretch of the Mekong River between the towns of Kratie and Stung Treng is arguably the most important deep pool area for many fishes [35,37]. Many fish species, including megafishes, are known to use these pools for dry season refugia and spawning habitat [37,38]. A Ramsar site protects 40 km of river just north of the city of Stung Treng [39]. No mainstem dams have been constructed in this area to date, which means flow alterations should be relatively minimal (compared to sections of river close to large dams) and habitat relatively unaltered. In support of this conclusion, this is also the last known range of the critically endangered Irrawaddy dolphin *Orcaella brevirostris* [37]. Finally, the input of the 3S Rivers at Stung Treng town provide alternative habitat choices that are known to be important to some fishes, including megafish [40]. These characteristics suggest that the main river and large tributaries of the northern Cambodian Mekong constitute prime habitats for megafish and possibly the best opportunity to gather conservation data on these species.

We used local ecological knowledge to collect data on the conservation status and needs of eight megafish species in this area (Figure S1). Because the rarity of megafishes, the vastness of the Mekong system, and limited resources prevent direct sampling (e.g., netting or tagging surveys), a local ecological knowledge survey was deemed the most viable method of collecting initial conservation data on these species. Local ecological knowledge is a proven and effective method for obtaining data on sensitive, threatened, and rare species [41–44]. It involves collecting information from local people who interact with the study species on a regular basis, i.e., “expert” fishers. Because many people in the Mekong River Basin fish every day, it is possible to acquire high-quality local ecological knowledge about megafishes. Although more than eight megafish species are known to occupy this area, time constraints for the interviews limited the number of species that could be investigated. Thus, the study species were selected based on their status as threatened or data-deficient according to the International Union for Conservation of Nature (IUCN) Red List [1] (Table 1). To increase understanding of the conservation status and needs for these species, this study addressed four sub-objectives: (1) assess the rarity of each species in the study area and across three habitat types to identify critical habitats; (2) identify temporal trends in population abundance; (3) assess temporal trends in individual body size; and (4) identify threats to these species from fishers’ perspectives. The outcomes of this work are expected to contribute significantly to the management and preservation of megafishes in the Mekong River Basin by filling knowledge gaps needed for Species Conservation Strategies [33].

**Table 1.** Mekong megafish species investigated in this study. Information was obtained from the FishBase ([www.fishbase.org](http://www.fishbase.org)) and IUCN ([www.iucnredlist.org](http://www.iucnredlist.org)) databases. Some local names were provided by local collaborators. For local names, “Kh” = Khmer language name; “Lao” = Lao language name. Maximum length abbreviations: “SL” = Standard Length; “TL” = Total Length; “WD” = Width. The “Species Abbr” column shows the species name abbreviations used throughout the paper.

Scientific Name/English Name	Local Names	Max Length/Weight	IUCN Status	Species Abbr
<i>Aptosyax grypus</i> Giant salmon carp	Trey pasanak (Kh), Pa sanak, Pa sanak gnai (Lao)	130 cm SL/30 kg	Critically Endangered	agry
<i>Catlocarpio siamensis</i> Giant barb	Trey kolriang (Kh), Pa kaho (Lao)	300 cm TL/300 kg	Critically Endangered	csia
<i>Luciocyprinus striolatus</i>	Trey sroum dao (Kh)	200 cm SL	Endangered	lstr
<i>Pangasianodon gigas</i> Mekong giant catfish	Trey reach (Kh), Pa boeuk (Lao)	300 cm TL/350 kg	Critically Endangered	pgig

Table 1. Cont.

Scientific Name/English Name	Local Names	Max Length/Weight	IUCN Status	Species Abbr
<i>Pangasius sanitwongsei</i> Giant pangasius or dog-eating catfish	Trey po pruy (Kh), Pa leum (Lao)	300 cm SL/300 kg	Critically Endangered	psan
<i>Probarbus jullieni</i> Isok barb	Trey trasak (Kh), Pa eun, Pa eun ta deng (Lao)	150 cm SL/70 kg	Critically Endangered	pjul
<i>Urogymnus polylepis</i> Giant freshwater whipray	Trey bor bel yeak, Trey bawbel (Kh), Pa fa hang, Pa fa lai (Lao)	240 cm WD/600 kg	Endangered	upol
<i>Wallago micropogon</i>	Trey stourk (Kh), Pa khoun (Lao)	154 cm SL/96 kg	Data deficient	wmic

## 2. Materials and Methods

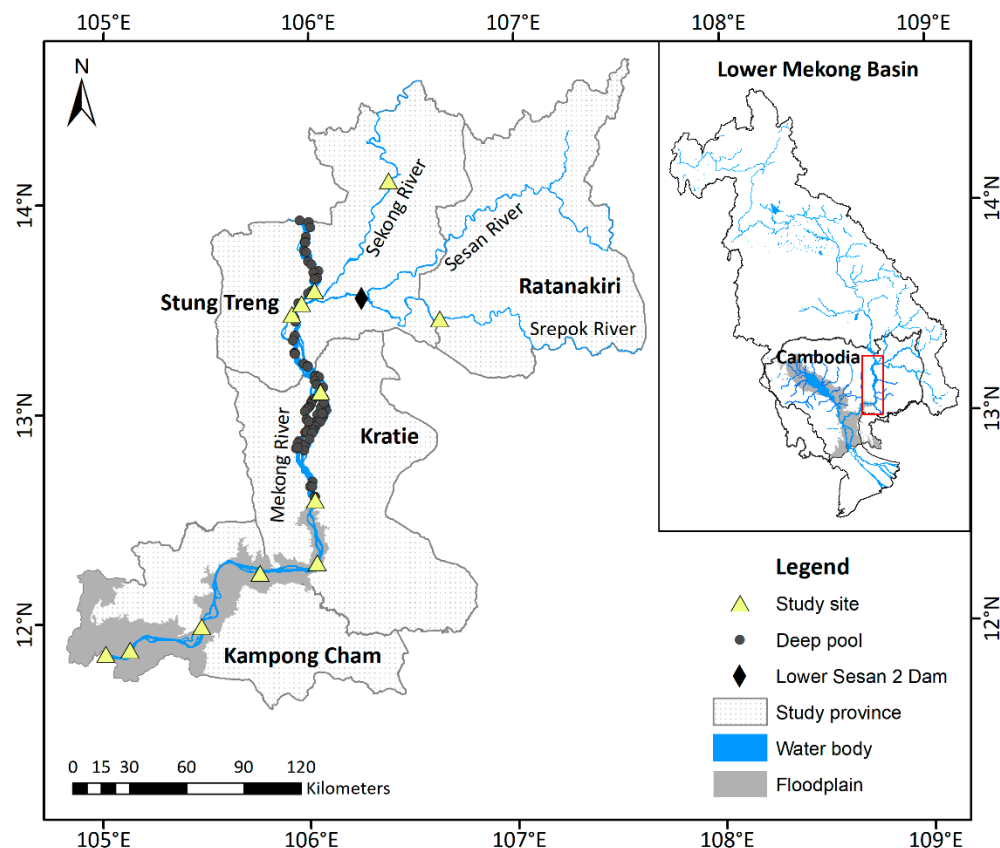
### 2.1. Study Area

This study was conducted in the Mekong River Basin in northern Cambodia (Figure 1). All of the species are known to occur in this area, except for *Aptosyax grypus*, which likely only occurs in the very northern part of the study area, and *Luciocyprinus striolatus*, which likely only occurs in Lao PDR at present [1]. However, because these species are still data-poor and they may have once existed within the study area, we interviewed fishers about them to obtain presence-absence data for northern Cambodia.

Semi-structured interviews with fishers were conducted in fishing villages along the Mekong River from Kampong Cham to Stung Treng provinces. This stretch of river encompasses a variety of habitats thought to be essential for megafish life cycles, including an abundance of floodplain habitats (connected lakes, tributaries, and flooded forests) south of Kampong Cham town and more deepwater (pool) habitats to the north. There are also, as of yet, no mainstem dams in this part of the Mekong. (However, there are plans for two mainstem dams in the study area—one in Stung Treng and one in Sambor, which is near Kratie town). Interviews were also conducted in two villages on major tributaries to the Mekong River—the Sekong and Srepok rivers, which are part of the 3S River System in northeast Cambodia and part of the known range of all of our megafish study species [40,45]. (*Pangasius sanitwongsei*'s presence in the 3S is not well documented, but Poulsen et al. [45] show some occurrence data from local ecological knowledge). The Sekong River is the last of the 3S Rivers to remain undammed for most of its length, whereas the first dam on both the Sesan and Srepok rivers is located between their confluence and the Mekong River (Figure 1). This dam, Lower Sesan 2, began operating fully at the end of 2018 [46]. For this study, the study area was divided into five river sections based on river and province: (1) the Mekong River in Kampong Cham Province, (2) the Mekong River in Kratie Province, (3) the Mekong River in Stung Treng Province, (4) the Sekong River in Stung Treng Province, and (5) the Srepok River in Ratanakiri Province (Figure 1).

The villages where interviews were conducted were selected based on the presence of experienced fishers, which was either known prior to the survey or identified during the survey by asking fish sellers, other local people at ports and markets, and their peer fishers. These villages were also spatially distributed evenly along the Mekong mainstem to provide a relatively even sampling of geographic areas and habitat types (Figure 1). In all, 12 villages were sampled on the Mekong mainstem—four from Kampong Cham Province, three from Kratie Province, and three from Stung Treng Province (Figure 1, Table 2). Two villages were sampled in the 3S Rivers—one in Stung Treng Province on the Sekong River and one in Ratanakiri Province on the Srepok River (Figure 1, Table 2). The number

of fishers interviewed varied among villages and provinces due to limited survey time and because finding expert fishers was easier in some places than in others.



**Figure 1.** Map of the Mekong, Sekong, Sesan, and Srepok rivers within the study area in northern Cambodia. Water bodies indicate permanent rivers and lakes, while the floodplain indicates seasonally-inundated areas. Deep pool depths range from approximately seven to 80 m. Land cover data were provided by the Mekong River Commission (MRC); these data were published in the MRC technical reports [47,48] and were reproduced with permission from the MRC.

Three coarse habitat types were represented in this survey: floodplain, pool, and tributary. These habitat classifications are general representations of the broader riverine area near the villages. The classifications are not suggesting that fishers from these villages only fished in these specific habitat types.

1. Floodplains are known to be essential feeding and rearing habitat for many Mekong migratory fishes [48]. In our study, floodplain habitat was defined as sections of river that had close lateral connectivity with large flooded areas; these river sections also tended to have few to no deep pools in the river channel and a larger web of small streams and ox-bow lakes. The floodplain habitat type occurred in the Mekong River in Kampong Cham Province and the southernmost village sampled in Kratie Province (Figure 1, Table 2).
2. Deep pools are thought to be critical dry season refugia and spawning habitat for many species [37]. Pools are found throughout the Mekong Basin in Cambodia, including Kampong Cham Province and the 3S Rivers, but some are considered more important to fisheries than others [35,47]. The deep pools in the Mekong River in Kratie and Stung Treng provinces (shown in Figure 1) were identified as productive fishing grounds by local fishers; they are also larger, deeper (up to 80 m), and more numerous (95 between Sambor and the Lao border) than pools in other parts of the Cambodian Mekong [35,47]. Thus, for our study, we defined pool habitat as river



sections characterized by numerous deep pools that were identified as important by local fishers. These occurred in Kratie and Stung Treng provinces (Figure 1, Table 2). It is noteworthy that less work has been done to map pools on Mekong tributaries [47].

3. Tributaries are often used by fish species for spawning and migration to other essential habitats, and some species are specialized to tributaries [40,48]. In our study, the tributary habitat was represented by the villages sampled on the 3S Rivers (Figure 1, Table 2).

In total, of the villages sampled in this survey, five were in river sections connected to floodplain habitat, five in deep pool habitat, and two in tributary habitat in the 3S Rivers (Figure 1, Table 2).

## 2.2. Survey Methods

This research was approved by the Institutional Review Board and the Research Integrity Office at the University of Nevada, Reno (IRBNet ID: 1210753-2, 20 March 2018). Data were collected using a local ecological knowledge survey [42]. Local ecological knowledge is defined as “a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment” [49]. Obtaining the local ecological knowledge of natural resource users is an established method of collecting ecological and conservation data on rare and sensitive species [42,44]. It is also currently the most effective way to collect data on threatened megafishes in the Cambodian Mekong River Basin.

Interviews with fishers were conducted using a semi-structured questionnaire in which both closed and open-ended questions were asked to obtain specific information while also allowing fishers to highlight other knowledge from their experience and expertise. The full set of interview questions can be found in the Supplementary Material.

**Table 2.** The number of fishers interviewed in each village. Villages are grouped by river section. Bold numbers in parentheses are the number of fishers interviewed in each river section and are subtotals of the number of fishers interviewed from the villages within the river section. Villages are ordered from downstream to upstream. Habitat indicates the habitat type where the village was located (see text for more details).

Village	Habitat	No. Fishers
<b>Mekong/Kampong Cham (34)</b>		
Svay Leu	Floodplain	7
Prek Koy	Floodplain	10
Prek Toch	Floodplain	10
Roka Knol 3	Floodplain	7
<b>Mekong/Kratie (21)</b>		
Chheu Teal Plous	Floodplain	8
Sambok	Pool	5
Koh Khnhe	Pool	8
<b>Mekong/Stung Treng (21)</b>		
Sma Koh	Pool	5
Ba Chung	Pool	7
Koh Khon Den	Pool	9
<b>Sekong/Stung Treng (10)</b>		
Pha Bang	Tributary	10
<b>Srepok/Ratanakiri (10)</b>		
Sre Angkrong	Tributary	10
<b>Grand Total</b>		<b>96</b>

For this study, our goal was to collect the highest-quality information available on these study species. Therefore, we sought to interview only “expert” fishers [50]. To facilitate this, several survey trials and scouting trips were conducted to find villages with knowledgeable fishers, make contact with village chiefs, and also to refine the questionnaire and methodology. (More detailed information

about survey trials and methods is available in the Supplementary Material). Fishers were considered experts if they were full-time fishers by trade (as opposed to part-time for subsistence), if they had been fishing for more than five years, or if they were referred to by their peers as being very knowledgeable about the fish. Some fishers were also selected because they had specialized experience with one of the study species. Careful fisher selection was very important because the rarity of the study species makes it easy for inexperienced fishers to confuse them with other species that are similar in appearance. Even with our selection process, many interviews had to be discarded due to uncertainty over whether fishers had correctly identified the species. (This quality-control process is described in more detail in the following paragraphs). Therefore, using expert fishers was essential for obtaining good quality data from this survey.

Once fishers were selected to interview, several quality checks were incorporated into the interview to ensure accurate species identification. First, using photographs of both adults and juveniles of each species, the fishers from a village were asked as a group whether they knew the names and had knowledge of the study species. Photographs of closely-related species that were similar in appearance to the study species were also presented to reduce confusion between the study species and close relatives. Species that were not well known by anyone in the group were eliminated and then interviews were conducted about the species that were known. Of the species that were known by the group, if an individual fisher did not know enough about one to provide high-quality information, then that species was skipped so that each fisher was only asked about species with which he was familiar. Interviews were conducted one-on-one as much as possible.

The second set of checks were interview questions about known biological and ecological traits to make certain that the fisher had identified the correct species. For example, fishers were asked to describe the species' physical characteristics, diet, seasonal distribution patterns, and any closely-related species. Based on their responses, the interviewers were able to discern, using prior knowledge of the species, whether the fisher knew the species in question. This made the interviewer's knowledge of the species critically important in assessing the quality of the information given. Thus, we strove to have only experienced fisheries professionals conducting the interviews. At the end of each interview, the interviewer rated the information provided as "poor," "good," or "expert" as an assessment of the quality of the information. An interview was considered "poor" if the fisher had trouble identifying the species or answered some of the quality-control questions (e.g., about basic ecology) incorrectly. An interview was considered "good" if the fisher was able to clearly identify the species and answer the quality-control questions correctly. An interview was considered "expert" if the fisher provided detailed, specialized information about the species. A quality rating was given for each species covered in an interview. (Therefore, one fisher could provide a good interview for one species and a poor interview for another species.) "Good" and "expert" interviews were considered high-quality interviews. The quality ratings were used during data analysis (more on this below).

### 2.3. Analyses

For all analyses, unless otherwise stated, data were only used from high-quality interviews (those rated "good" or "expert"; see above). All analyses were conducted in RStudio Version 1.1.456 or Microsoft Excel 2016. For some analyses, as shown in the results, *Luciocyprinus striolatus* was excluded due to its low sample size of high-quality interviews.

#### 2.3.1. Population Status

**Rarity**—The rarity of megafish species in the study area was assessed following the methods in Gray et al. [31]. Fishers were asked to provide the month and year in which they most recently captured a specimen of each species. Dates of the last capture were converted to the number of months before the survey (June 2018), and the mean and 95% confidence interval (CI) were calculated to evaluate the rarity of each species. If fishers could only provide the year of capture, the date was set as June of that year [31]. Species that were captured a greater mean number of months before the survey

were considered to be rarer than more recently captured species. These analyses were also conducted for the three coarse habitat types within the study area—floodplain, pool, and tributary (explained above)—to see if species rarity varied across habitats.

*Perceived abundance*—Temporal trends in megafish abundance were assessed by asking fishers to provide their perception of the abundance of these species at four time periods: 20, 10, five, and zero years before present (June 2018). Fishers ranked abundance on a scale of: 1-common, 2-uncommon, 3-rare, and 4-extirpated. To evaluate the abundance of each species through time, the mean and 95% CI of the perceived abundance ranking were calculated for each time period.

During the trial surveys, interviewers attempted to put qualifications on perceived abundance rankings based on the number of individuals captured per interval of time (e.g., year, season, month, etc.). However, it proved to be too difficult for fishers to answer the questions with that amount of specificity. When these qualifications were removed, fishers were able to answer with much more ease. Thus, these abundance rankings were open to the subjective perception of the fisher.

### 2.3.2. Body Size

Another important component of conservation status is body size. Fish body size is a critically-important factor of biological and ecological functions [51–54]. Therefore, analyses of fish body size were conducted to find out the size composition of these megafish populations.

Observed fish body size (weight in kg) was evaluated to understand temporal trends and current size composition in relation to the species' maximum size potential (obtained from FishBase, [www.fishbase.org](http://www.fishbase.org)). For each species, fishers were asked for data on the maximum attainable size, the size of their most recently captured specimen, the size of their largest captured specimen, and the average body size in their catches 20, 10, five, and zero years before present (June 2018). The means of these values were calculated and compared to the maximum reported size from FishBase.

The temporal change in the size of the largest individuals in the population was also assessed. For each species, fishers were asked for the size (weight in kg) and date of capture of the largest specimen they ever captured. The size of the largest individuals captured was compared to the time of capture using simple linear regression. The purpose of this analysis was to detect a change in the size of the largest individuals, which has implications for reproductive potential and population stability [51,55,56].

### 2.3.3. Conservation Threats

Fishers were asked, with an open-ended question, to identify the greatest threats to these megafishes. Fishers were allowed to name more than one threat. Because this question was not part of the individual species questions, it did not receive an interview quality rating; thus, all interviews were used in this analysis. To identify geographic variation in the threats to these species, the number of times a threat was named in each of the five river sections was counted and then divided by the total number of fishers interviewed in that section. This gave a measure of the importance of each threat to each area while accounting for sample size.

## 3. Results

### 3.1. Sample Sizes and Assessment of Species' Geographic Distributions

Ninety-six fishers were interviewed from 12 villages in five river sections (Table 2). The number of fishers interviewed in each village ranged from 5–10 (mean  $8 \pm \text{SD } 2$ ). There were 34 fishers interviewed from the Mekong in Kampong Cham, 21 from the Mekong in Kratie, 21 from the Mekong in Stung Treng, 10 from the Sekong in Stung Treng, and 10 from the Srepok in Ratanakiri (Table 2). Fishers' ages ranged from 20–76 years (mean  $46 \pm \text{SD } 13$ ) and their fishing experience ranged from 5–55 years (mean  $23 \pm \text{SD } 10$ ). These fishers were all active fishers at the time of the survey and fished a mean of  $35 \pm \text{SD } 17$  hours per week (range 12–72).



Fishers used a variety of fishing gears. All fishers used gillnets, 75 used hooks, 40 used castnets, and 22 used various types of traps. Gillnet mesh sizes ranged from 2–30 cm (mean  $10 \pm \text{SD } 6$ ). Some fishers mentioned using different mesh sizes in the past; past sizes ranged from 5–40 cm (mean  $23 \pm \text{SD } 8$ ), showing a general decrease in mesh sizes used from past to present. Forty-one percent of fishers reported using gear that was able to capture large specimens (e.g. trawls, large seine nets, and gillnets with mesh greater than 20 cm) at some time in their fishing careers (usually in the past).

From these 96 fishers, we obtained 326 interviews about individual species, including six expert interviews, 202 good interviews, and 118 poor interviews. (The total number of species interviews is greater than the number of fishers interviewed because one fisher provides interviews on multiple species.) The proportion of fishers who provided high-quality (good or expert) interviews (% columns in Table 3) provided insight into how well known a species was in a given area, which could relate to the abundance of the species in that area (although fisher memory and fishers fishing in different locations through time could impact this assumption). For the whole study area, 65% of fishers were able to provide high-quality interviews on *Probarbus jullieni*, making it the best-known study species among fishers (Table 3). High proportions of fishers were knowledgeable of this species in every river section (range = 57–90%), suggesting *Probarbus jullieni* occurs (relatively) commonly throughout the study area (Table 3).

Other megafish species that were well known by fishers were *Catlocarpio siamensis* and *Wallago micropogon* (Table 3). Forty-six and 53% of fishers, respectively, within the whole study area provided high-quality interviews on these species. Higher proportions of fishers knew *Catlocarpio siamensis* in the mainstem Mekong River than in the 3S Rivers, suggesting that this species may prefer the larger river to tributaries. *Wallago micropogon* seemed to be fairly well known (range = 29–90%) throughout the study area, suggesting a fairly even distribution among river sections.

Lower proportions of fishers were able to provide high-quality interviews on *Pangasius sanitwongsei* and *Urogymnus polylepis* (20% and 19%, respectively, for the whole study area; Table 3). Both of these species were best known in the deep pool areas of the mainstem Mekong (Kratie and Stung Treng provinces). *Pangasius sanitwongsei* was also fairly well known in the Srepok River (50%), suggesting that the 3S Basin may be included in the species' range [40]. Based on the low proportion of high-quality interviews in the 3S Rivers (range = 0–10%), *Urogymnus polylepis* seemed to prefer the mainstem Mekong over tributaries.

**Table 3.** Summary of high-quality interviews by river section and species. For the summary by species, “Ct” columns show the count (number) of high-quality interviews for each species in each river section. The “%” columns show the proportion of fishers from each river section who provided a high-quality interview on each species. Thus, a larger value in the “%” column indicates more fishers were knowledgeable about that species than other species. For species abbreviations, see Table 1.

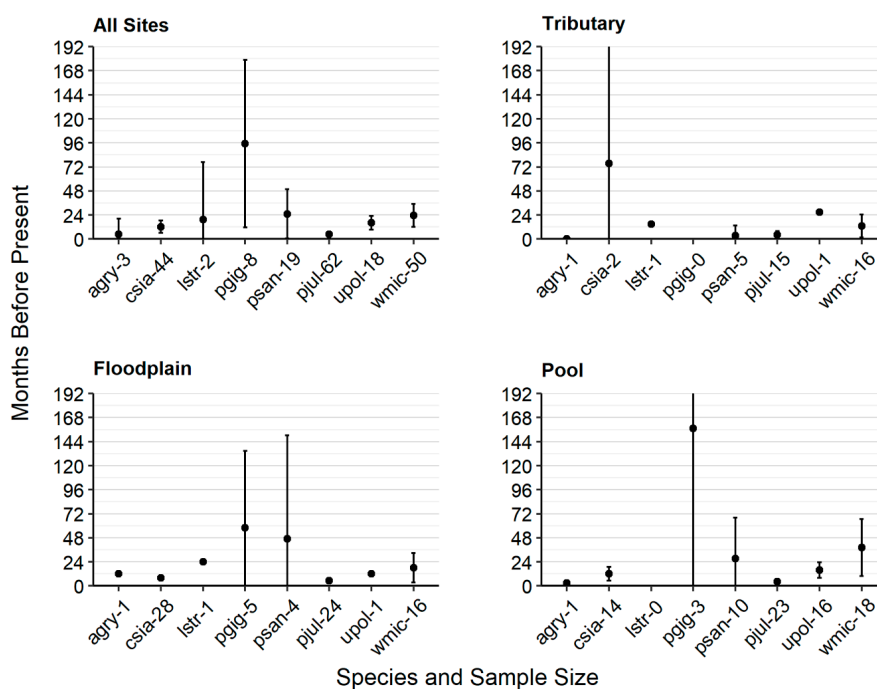
River			Mekong				Sekong		Srepok		TOTAL	
Province	Kampong Cham		Kratie		Stung Treng		Stung Treng		Ratanakiri			
Total Fishers	34		21		21		10		10		96	
Summary of High-Quality Interviews by Species												
Species	Ct	%	Ct	%	Ct	%	Ct	%	Ct	%	Ct	%
agry	0	0	1	5	1	5	1	10	0	0	3	3
csia	21	62	15	71	6	29	1	10	1	10	44	46
lstr	0	0	1	5	0	0	0	0	1	10	2	2
pgig	3	9	6	29	0	0	0	0	0	0	9	9
psan	3	9	7	33	4	19	0	0	5	50	19	20
pjul	20	59	15	71	12	57	6	60	9	90	62	65
upol	0	0	10	48	7	33	0	0	1	10	18	19
wmic	10	29	17	81	8	38	9	90	7	70	51	53

*Pangasianodon gigas* was not well known by fishers in the study area, with only 9% providing high-quality interviews, suggesting it is extremely rare in this part of the Mekong (Table 3). *Pangasianodon gigas* was best known in the southern portion of the study area (Kampong Cham and Kratie provinces of the Mekong River) but was still only given high-quality interviews by 9–29% of fishers in those river sections.

The least known study species were *Aptosyax grypus* and *Luciocyprinus striolatus* (Table 3). Only 3% and 2% of fishers, respectively, in the whole study area were able to provide high-quality interviews on these species. This is not surprising considering the presence of these species within the study area was uncertain [1]. However, the ability of at least a few fishers to provide high-quality information on these species suggests that they may occur in very low numbers in northern Cambodia.

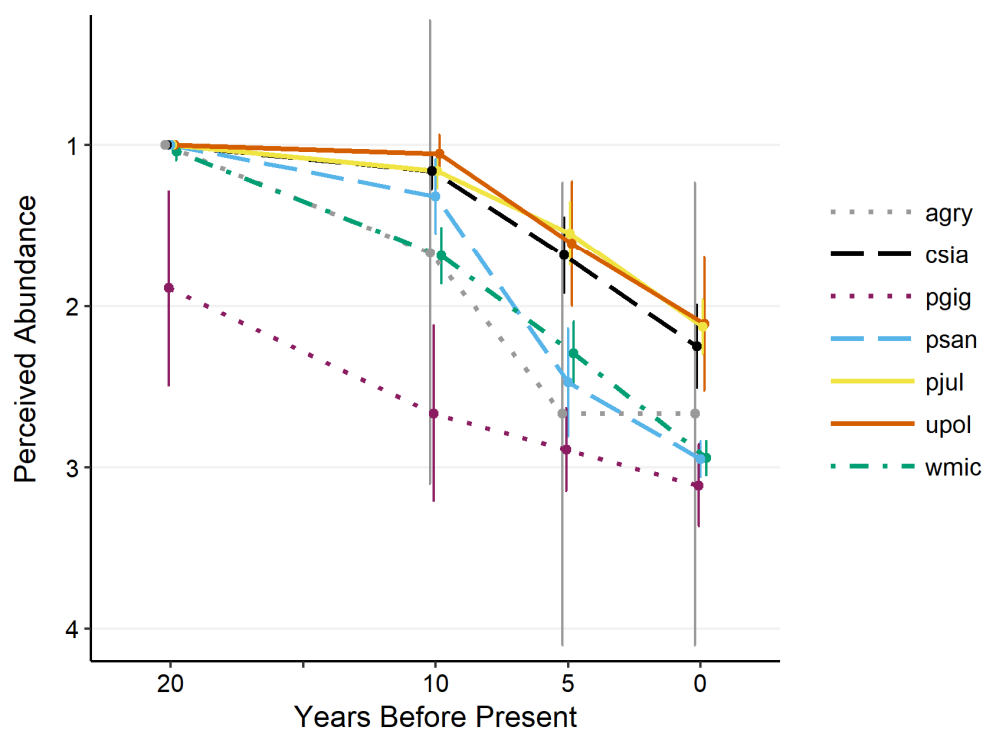
### 3.2. Population Status

Megafishes in northern Cambodia had great variation in reported rarity, but none of them were common (Figure 2). Across all species and sites, the most common species (the one that was generally captured most recently) was *Probarbus jullieni*, which had a mean last capture date of 4.5 months before the survey (Figure 2). *Pangasianodon gigas* was the rarest species, with a mean last capture date approximately 95 months before the survey. *Pangasianodon gigas* also had a large variation in its estimate due to its low sample size, which is another indicator of its rarity. The next rarest species was *Pangasius sanitwongsei*, with a mean last capture date approximately 25 months before the survey. The means of the most recent captures of the other study species ranged between five to 24 months before the survey. Across habitat types (for species with sufficient sample sizes), there was not much variation in the date of the last capture; all were uncommon to very rare (Figure 2).



**Figure 2.** Rarity of Mekong megafishes in northern Cambodia. Species rarity is represented by the amount of time since the most recent capture by fishers in months before present (June 2018). Points and error bars are the means and 95% confidence intervals. Zero months before the present represents a specimen captured within a month of the survey. The number after the species abbreviation on the x-axis is the number of high-quality interviews obtained for that species. “All Sites” = data from all 12 villages where interviews were conducted; “Floodplain” = data from five villages in river sections that have close connectivity with the floodplain; “Pool” = data from five villages in river sections that have nearby deep pool habitat; “Tributary” = data from two villages on the Sekong and Srepok rivers, which are tributaries to the Mekong River. For species abbreviations, see Table 1.

All megafish species were shown to have a decreasing trend in perceived population abundance between 20 years ago and present (Figure 3 and Figure S2). Twenty years ago, most species were ranked as common. The exception was *Pangasianodon gigas*, which was ranked uncommon even 20 years ago. The species with the smallest declines over the last 20 years (other than *Pangasianodon gigas*) were *Urogymnus polylepis*, *Probarbus jullieni*, and *Catlocarpio siamensis*. These species, on average, were ranked uncommon at present. The species with the greatest declines were *Aptosyax grypus*, *Wallago micropogon*, and *Pangasius sanitwongsei*. These species were, on average, ranked rare at present. Although *Pangasianodon gigas* had the smallest magnitude of change in perceived abundance between 20 years ago and present, this species was considered to be the rarest of all, with its present mean abundance ranked between rare and locally extirpated. In general, the largest magnitudes of population decline occurred during the last ten years before the study (Figure 3 and Figure S2). These results contribute to the conclusion that these species are all currently uncommon to rare, and also show that their populations are in a state of decline. Moreover, when fishers were asked which species they thought might become locally extirpated in their fishing area, all eight study species were identified as either already gone or likely to disappear in the near future (Figure S3). Furthermore, all river sections reported multiple species at risk of extirpation, showing that the risk to megafishes is widespread in the study area (Figure S3).

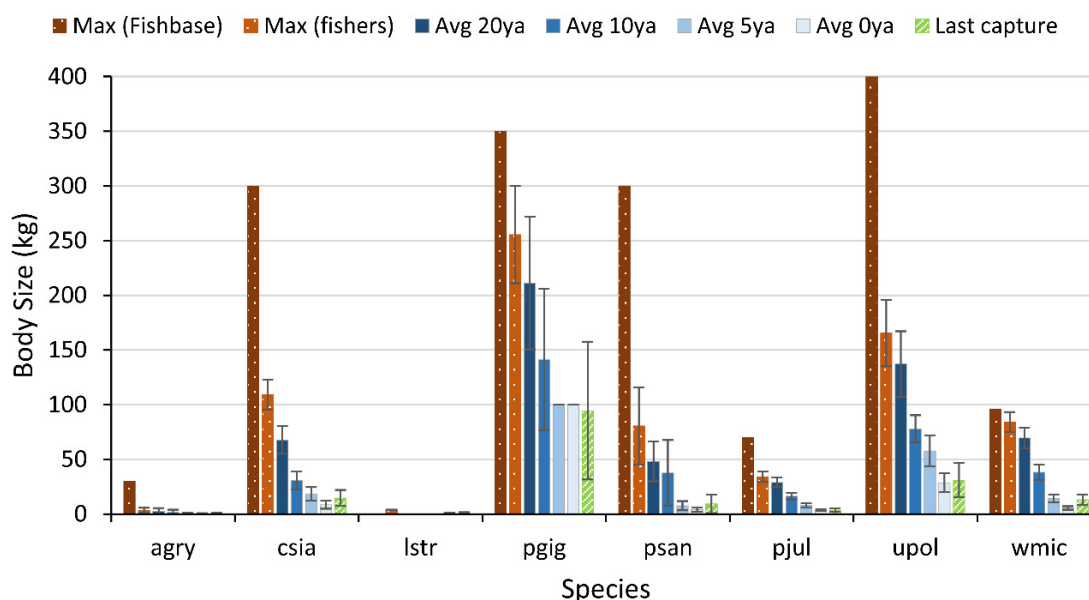


**Figure 3.** Perceived population abundance for Mekong megafishes in northern Cambodia in four discrete time periods over the last 20 years. Zero years before present indicates the time of the survey, June 2018. Data points and error bars represent the means and 95% confidence intervals of fishers' rankings of population abundance. Rankings were: 1-common, 2-uncommon, 3-rare, and 4-extirpated. Sample sizes for each species are the total numbers of high-quality interviews for the whole study area reported in Table 2. For species abbreviations, see Table 1.

### 3.3. Body Size

According to fishers, average body size (weight in kg) decreased for every species in every time interval except for *Pangasianodon gigas* between five years ago and present, when there was reportedly no change in body size (Figure 4 and Figure S4). The means and upper confidence limits of all size categories reported by fishers—including the maximum size—were smaller than the maximum size

reported by FishBase (Figure 4). The mean size of the last capture was always closest to either the average size five years ago or at present and was often more than five times smaller than the maximum size reported by FishBase or by fishers. For many of the study species, the upper 95% confidence limit on the size of the last capture was greater than that for the size at present, showing the influence of large specimens caught in the more distant past (Figure 4). Thus, Mekong megafishes captured by fishers at the time of the survey were usually very small relative to their maximum size potential.

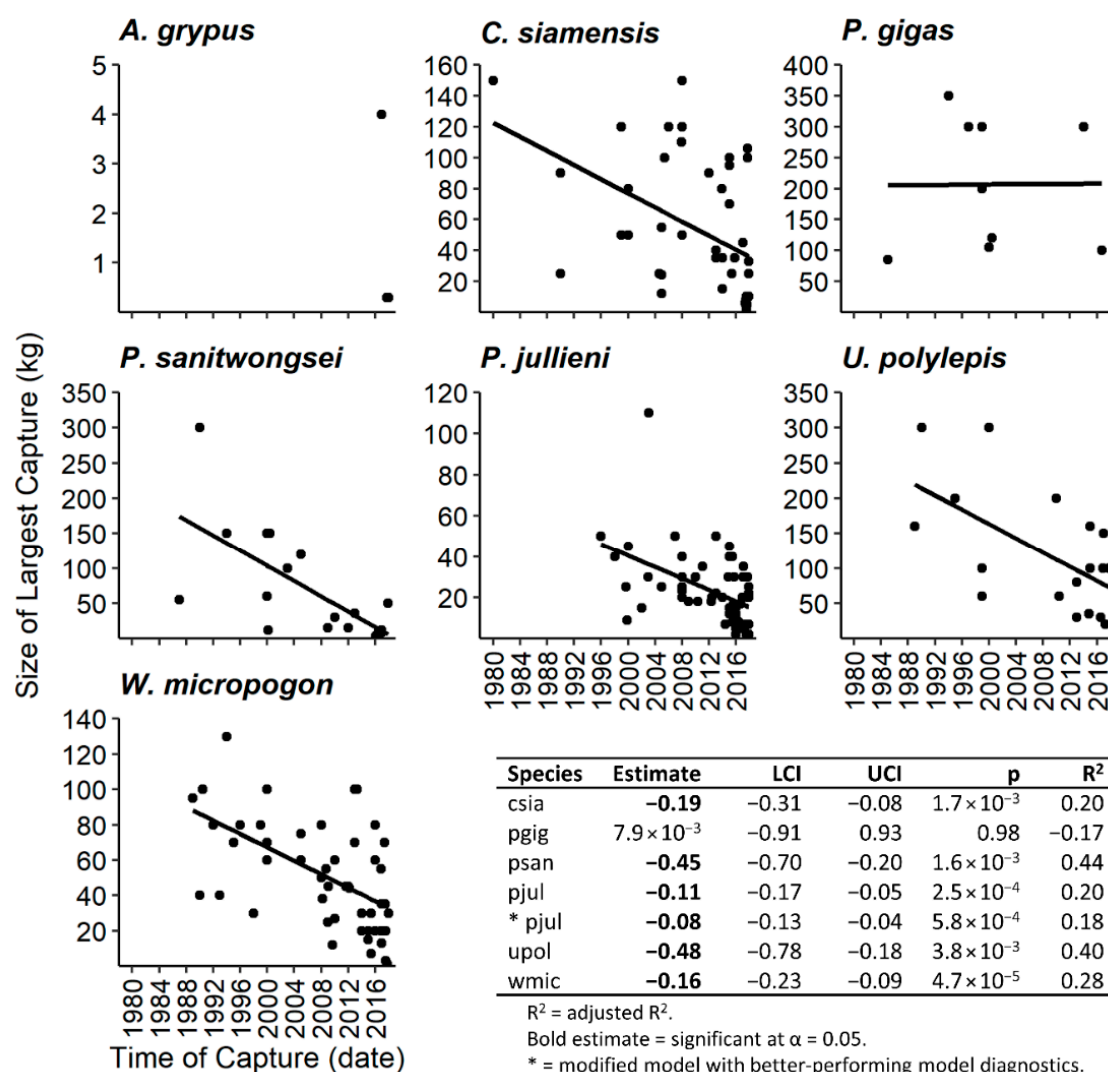


**Figure 4.** Temporal trends in Cambodian megafish body size (kg) with comparisons to maximum size and size of the last capture. Bars with orange-red shades and white speckling show the maximum reported size from FishBase ([www.fishbase.org](http://www.fishbase.org)) and the maximum size known by fishers interviewed during local ecological knowledge surveys. The maximum size from FishBase for *Urogymnus polylepis* is 600 kg and is off the scale for graph clarity. Bars with solid blue shades show the average body size reported by fishers 20, 10, 5, and 0 years before the survey in June 2018 (“ya” = years ago). Green bars with white stripes show the body size of the most recent specimen captured by fishers. Each bar (except for the maximum size from FishBase) shows the mean and 95% confidence intervals calculated from fisher responses across the whole study area. Sample sizes for each species are the total numbers of high-quality interviews for the whole study area reported in Table 2. For species abbreviations, see Table 1.

At the time of the survey, most of the study species were being captured at an average body size between one (*Aptosyax grypus*) and six (*Wallago micropogon*) percent of their maximum size potential reported by FishBase (Table S1). The exception was *Pangasianodon gigas*, which on average was at 29% of its maximum size potential. The maximum body size reported by fishers also was smaller than the maximum size reported by FishBase. For all species, the maximum body size reported by fishers ranged between 11 (*Aptosyax grypus*) and 88 (*Wallago micropogon*) percent of the maximum body size from FishBase. Additionally, the mean size of the last capture and mean size of the largest capture were also a small fraction of the maximum size potential (range = 2–27% and 5–59% respectively across all species; Table S1).

The body size of the largest individuals captured also decreased through time (Figure 5). For species with sufficient sample sizes, all simple regression models showed significant and decreasing trends in body size through time, although some species models had issues with heteroscedastic and non-normal residuals (Figure 5). The largest specimen of *Probarbus jullieni* (110 kg) was determined to probably be a misidentification due to it being larger than the maximum body size reported from FishBase. When this data point was removed from the analysis, the decreasing trend in body size was still significant ( $5.8 \times 10^{-4}$ ), but issues with model residuals remained (Figure 5). The trend

for *Pangasianodon gigas* was not significant ( $p = 0.98$ ) and there were insufficient data to evaluate *Aptosyax grypus* and *Luciocyprinus striolatus* (Figure 5). Only one high-quality interview provided data on the largest specimen captured for *Luciocyprinus striolatus*. This interview was with a master fisherman in Kratie, whose largest specimen was captured in June 2016 at 4 kg.



**Figure 5.** Plots of the size and date of capture of the largest Mekong megafish specimens reported by fishers. Trend lines represent the result of a simple linear regression of body weight and time. The table summarizes regression statistics for the simple linear regression models. (*Aptosyax grypus* was excluded from the table because its sample size was too small to model the relationship between body weight and time). Model diagnostics were run and found to be acceptable for all species with these exceptions: *Pangasianodon gigas* had non-normal residuals; *Pangasius sanitwongsei* had heteroscedastic residuals; *Probarbus jullieni* had non-normal and heteroscedastic residuals and an influential outlier. A second model was run for *Probarbus jullieni* without the outlier (\* pjul), and the model diagnostics were only slightly improved. Sample sizes for each species are the total numbers of high-quality interviews reported for the whole study area in Table 2. Note that all plots have the same x-axis, but different y-axes.

Because of the direct effect that gear size could have on this analysis, some further analyses were conducted to see if an effect of gear size used by fishers could be detected. Some fishers did not fish with gears large enough to catch the biggest of megafish specimens. Therefore, using information that fishers provided on the fishing gears they used, the data on the size of largest capture (Figure 5) were grouped into fishers who said they used large gears and fishers who said they did not use large gears.



Across species, the temporal trend in the size of the largest individuals captured was similar for both groups of fishers and was always decreasing, although fish body sizes tended to be smaller for fishers who did not use large gears (Figure S5).

Furthermore, in 2006, fisheries law was changed and, among other regulations, restricted the size of net mesh used in inland fisheries to 1.5–15 cm [57]. Therefore, these trends were also looked at before and after these regulations were in place (Figure S5). Results varied and were often affected by low sample sizes after 2006, and so it was unclear how the regulations may have affected the size of fish caught by fishers (Figure S5). However, the regulations may have influenced fishers to reduce the size of their gillnets (see discussion of fishing gears used in Section 3.1), which may have reduced the size of fish captured.

### 3.4. Conservation Threats

Fishers identified 10 different threats to Mekong megafish in northern Cambodia (Figure 6). Seven of the 10 threats were different types of fishing methods and practices, all of which are illegal in Cambodia. The threats that fishers identified, in order of importance across all study areas, were: electrofishing, small mesh, dynamite, poison, big mesh, big traps, dams, dry season fishing (in deep pools), human population growth, and high market price for megafish (Figure 6).

“Electrofishing” is the use of electricity to catch fish. It is highly effective and kills aquatic animals indiscriminately across species and sizes.

“Small mesh” usually refers to catching fish with mosquito nets, which capture large quantities of larval fish. This is thought to be detrimental to both common and rare species populations.

“Dynamite” refers to using explosives to catch fish, which kills many fish at once and destroys fish habitat.

“Poison” refers to chemicals used to kill and harvest fish in large quantities.

“Big mesh” indicates gillnets with large mesh sizes used to target the largest-bodied fish, especially during their sedentary period in deep pools in the dry season.

“Big trap” refers to extremely large traps (e.g. fences and bamboo poles with mosquito netting) that are highly efficient at catching large quantities of fish of all sizes.

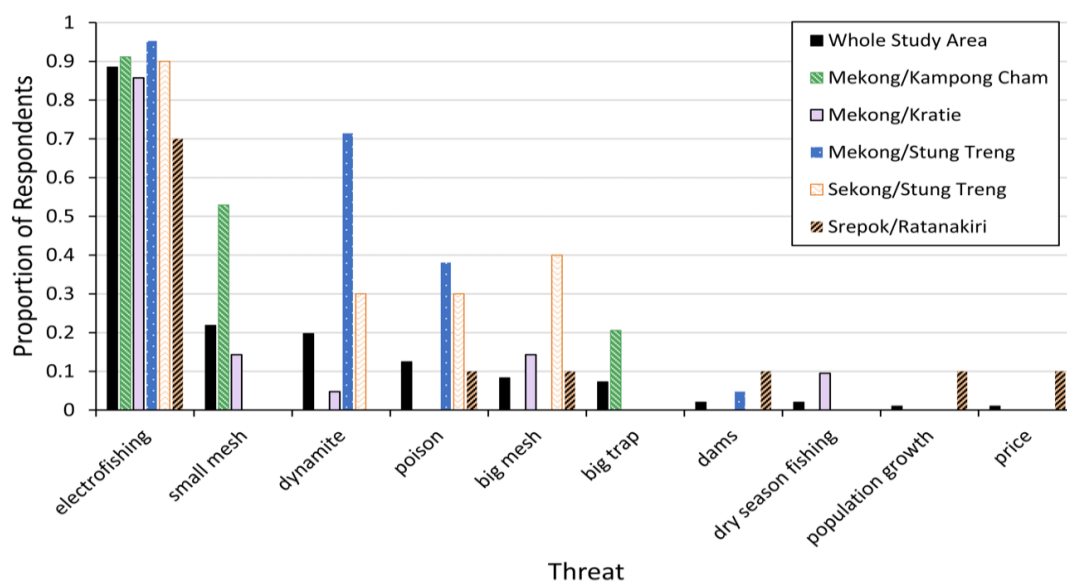
“Dams” refers to the recently-built Lower Sesan II Dam and other dams proposed for, and being built-in, the mainstem of the Mekong River (e.g. Xayaburi and Don Sahong).

One fisher identified “dry season fishing” and was referring specifically to fishing in deep pools (known to be dry-season refugia for megafishes) during the dry season when megafishes are easiest to catch.

“Population growth” refers to the rapidly-growing Cambodian human population.

“Price” indicates the extremely high prices (up to 100 USD/kg) fishers fetch for these species, which encourages capture and trade. It also reflects a high market demand for megafishes.

Across all river sections, electrofishing was the threat most likely to be identified by local fishers, being named by 70–95% of respondents (Figure 6). The importance of other threats varied by region. The use of small mesh and big traps (with very long fences) were the other prominent threats (reported by >20% of fishers) in Kampong Cham Province on the Mekong River, while in Stung Treng Province (Mekong River) the next prominent threats were dynamite and poison. Big mesh, poison, and dynamite all played near-equal secondary roles in the Sekong River (Stung Treng Province). For Kratie Province on the Mekong River and Ratanakiri Province on the Srepok River, there were no other threats reported by greater than 20% of fishers. In all, illegal fishing practices were the most-identified threats across the study area, with other factors—dams, population growth, and sale price—being mentioned in only a subset of river sections and by a small proportion of fishers in those sections (Figure 6).



**Figure 6.** Threats to Mekong megafishes in northern Cambodia identified by local fishers. Bars show the proportion of fishers interviewed from each river section that named a given threat. Sample sizes are the total number of fishers interviewed in each river section in Table 2. Refer to the text for threat definitions. All of the fishing practices listed here are illegal in Cambodia.

#### 4. Discussion

Based on the local knowledge of fishers in northern Cambodia, the megafishes of the Mekong River Basin in this region are experiencing severe declines in population abundance and individual body size that have led to increased rarity and risk of extirpation. Fishers perceived megafishes as currently uncommon, rare, or extirpated in some locales. These conclusions were drawn from both subjective rankings of population status and extirpation risk (Figure 3 and Figure S3) and objective date of last capture data (Figure 2). The current perceived rankings of population abundance (Figure 3) agreed very closely with the date of last capture data (Figure 2, Table S3). Uncommon species (*Urogymnus polylepis*, *Probarbus jullieni*, and *Catlocarpio siamensis*) had a mean last capture date between 4.5 months and two years before present; rare species (*Wallago micropogon* and *Pangasius sanitwongsei*) had a mean last capture date very close to two years before present; the rarest species (*Pangasianodon gigas*) had a mean last capture date of approximately eight years before present. Thus, none of these megafishes are commonly captured in northern Cambodia.

A similar study by Gray et al. [31] in the Siphandone area of Lao PDR (just upstream of our study area) also found that megafish species are now uncommon to rare. However, the estimates of mean dates of the last capture varied between the two studies. Four species were investigated in both studies: *Pangasianodon gigas*, *Pangasius sanitwongsei*, *Probarbus jullieni*, and *Urogymnus polylepis*. Three of these species were caught more recently in northern Cambodia than in the Lao Siphandone. *Pangasius sanitwongsei* was much more common in northern Cambodia, where it was captured, on average, 91 months more recently than in the Lao Siphandone. *Urogymnus polylepis* and *Probarbus jullieni* were caught more recently in northern Cambodia by approximately 9 and 3 months, respectively. Conversely, *Pangasianodon gigas* were rarer in northern Cambodia than in the Siphandone, having been caught approximately 69 months more recently in the Siphandone.

These differences highlight the importance of geography in patterns of species rarity. Due to many differences between the two study areas, such as habitat type and fisheries governance, a more in-depth investigation is necessary to uncover true differences in megafish conservation status in these regions. However, this preliminary comparison suggests that northern Cambodia may have larger populations of several species of megafish. Alternatively, Gray et al. did use a randomized approach to fisher selection that may have impacted their results relative to the findings here. A randomized

sampling method, versus an expert peer referral method, could bias dates of the last capture towards the more distant past because the average fisher is probably less likely to capture rare species than experts. Regardless of the differences between the two studies, both clearly show that megafishes in this part of the Mekong are now very rare.

In northern Cambodia, all study species were identified by fishers as being at risk of extirpation, although the risk level varied by species and geographic area (Figure S3). Interestingly, the order of species fishers considered most at risk of extirpation varied from the order produced by the estimates of rarity and population abundance discussed previously. Such discrepancies in extirpation risk versus rarity reveal the importance of investigating different lines of evidence to understand the conservation status of rare species for which there are very little survey data. They also provide an opportunity for further research to investigate why fishers perceive certain fishes as disappearing. Lastly, the results of all these evaluations of conservation status revealed that these species are at high risk of extirpation, a conclusion which agrees with their IUCN Red List statuses (Table 1).

In further support of this conclusion are the severe declines in population abundance experienced by all of the study species over the last 20 years (Figure 3). The rankings of perceived population abundance in earlier time periods compared to present showed that most species were considered by fishers to be common 20 years ago and, since that time, all of these species' abundances decreased at varying rates. The group of rare species listed above (*Wallago micropogon* and *Pangasius sanitwongsei*) showed the greatest decline between 20 years ago and present, with *Pangasius sanitwongsei* decreasing more than one full abundance ranking (from almost common to between uncommon and rare) in a single time interval (10 to five years ago) (Figure 3). Furthermore, the greatest decreases among all species tended to occur between 10 and five years before present. Gray et al. [31] also found temporal decreases in perceived abundance that were similar to the decreases presented in this study. Therefore, it appears that megafish populations in the Mekong have experienced declines in abundance beginning as far back as the mid-1990s in a broad geographic range and that something occurred to accelerate this decline between 2008 and 2013. During this period, there was a three-fold increase in the cumulative gross storage capacity of hydropower dam reservoirs in the 3S River System [58]. Ngor et al. [58] found that flow alterations caused by these dams led to reduced fish diversity in the 3S, notably in large-bodied, highly migratory cyprinids (Cyprinidae) and catfishes (Pangasiidae and Siluridae), which cover six of our species. Hydropower development in Mekong tributaries is predicted to drive down fish productivity and biodiversity in the Mekong Basin [25] and is likely contributing to the population declines observed in our study.

In addition to high rarity, high extirpation risk, and extensive population declines, multiple lines of evidence from this study convey a story of decreasing body size in Mekong megafishes. This agrees with other size trend data from the region that show a decrease in the body size of large fishes from 2000 to 2015 [23]. Large fishes generally become sexually mature at relatively larger body sizes and older ages, which puts them at high risk of capture before they can reproduce, increasing their populations' vulnerability to fishing and risk of extirpation [30,59]. Currently, captured megafish specimens are almost always in the low end of their size range (Figure 4, Table S1). Our survey found that the size of the average individual has decreased by more than half in the last twenty years (Figure 4). For most species, the size of the largest individuals captured has also decreased greatly through time (Figure 5). Even more alarming is that most fishers today are not even aware of the maximum size potential of most of these fishes (Figure 4 and Table S1). Thus, while most of these megafishes are still found in the study area, albeit infrequently (Figure 2), their body size data suggest that the populations are subject to recruitment overfishing, which is "characterized by a greatly reduced spawning stock, a decreasing proportion of older fish in the catch, and generally very low recruitment year after year" [20]. Although these species are too rare to have measured data on maturation rates, estimates from FishBase's life history tool suggest that most of the specimens currently being captured are unlikely to have reached sexual maturity (Table S2). If nearly all mature adults have been lost, the remaining juveniles/sub-adults are likely the progeny of very few remaining spawning adults. This has

strong implications for decreased future reproductive success, reduced genetic variation, and increased extinction risk [60,61]. If megafish populations are to persist into the future, protections for the largest individuals must be effectively implemented and enforced.

Fishing regulations were created in 2006 that provided protections for large fish [57]. Nevertheless, the results of this study's threats analysis showed that regulations are not effectively enforced. Many illegal fishing practices are widespread in the study area (Figure 6) and in other productive fishing grounds in inland waters countrywide [62]. These practices decimate fish populations and also damage the environment in the case of dynamite and poison [62]. The most-identified threat to megafishes by fishers was electrofishing (Figure 6). This illegal fishing method threatens species throughout the whole study area and the rest of Cambodia [62]. Electrofishing is one of the most convenient and effective means of increasing one's catch at a reasonable investment, leading to its widespread use [63]. Electrofishing targets species indiscriminately and impacts larger-bodied individuals more severely [64]. However, the power outputs used by poachers would probably allow very few fish to escape the current. Another practice identified by fishers—dry season fishing in pools when fish are concentrated there—is likely a more serious cause of population declines than indicated in this analysis. Furthermore, some fishers freely indicated that they continue to use gillnet mesh sizes greater than the legal limit of 15 cm. If Cambodian fisheries management seeks to improve the conservation status of megafishes, and fishes in general, a priority conservation action must be to bring illegal fishing under control. In doing so, socioeconomic conditions need to be addressed as illegal fishing is often the outcome of persistent poverty [62,63].

Other than fishing practices, three other threats to megafishes were identified: dams, human population growth, and high cash value of the fish (Figure 6). Fishers widely perceive reduced fish catches to be partly due to increased fishing pressure caused by the rapidly growing human population in Cambodia. When fishers are struggling to fill their nets and the price of megafishes is high, there is an extremely high incentive for fishers to keep and sell megafishes—even with the risk of fines or imprisonment. These factors reemphasize the need for socioeconomic reforms, in addition to crack downs on the illegal species trade [21], to protect megafish populations. Furthermore, the highly migratory nature of these megafishes, combined with evidence that their populations are declining in other Lower Mekong Basin countries [31], suggest that conservation efforts should be broadened to a regional scale if megafishes are to persist in the Mekong.

Curiously, very few fishers mentioned dams as a threat to megafishes. It is widely known within scientific and management communities that dams are a severe and impending threat to fishes in the Mekong [25,26,65]. All of the fishes studied here, except for *Luciocyprinus striolatus*, are migratory and will be highly affected by dams. However, most of the fishers interviewed for this study live far away from large hydropower dams and they likely have yet to feel the full effects of the dams farther up- and downstream. Furthermore, large hydropower dams are new to the lower Mekong, especially to Cambodia, and fishers may not be aware of the magnitude of short- and long-term impacts on fisheries. It is important to remember that the threats presented in this study are from the perspectives of the fishers, which are limited to their experiences. Thus, this list of threats does not preclude other real and present threats not listed here. What this list of threats does show is that it is critical, in the face of impending hydropower impacts, to not lose sight of the detrimental effect that widespread, intensive, and uncontrolled fishing pressure has on fish populations [66].

We also assessed differences in megafish conservation status across regions and habitat types within the broader study area. Among habitat types, there was not much variation in species rarity (Figure 2). There also was not a consistent pattern in species extirpation risk across regions (Figure S3). However, there was a slight tendency for fish body size to be greater in pool areas than in tributaries or shallower river sections with a close floodplain connection (Figure S6). It makes sense for larger individuals to be found in pools where they have more space than in these other habitats, and pools are known dry-season refugia for adults of these species [37]. However, it is a little unexpected that megafish were considered no more common in pools than in the other habitats. It may be that, while

larger individuals are caught in pools, smaller individuals continue to be caught in or near floodplains and tributaries, which are known to be important feeding, rearing, and spawning habitats for Mekong fishes [40,67]. These results suggest that all of the habitats covered by the study area are important to megafish life cycles and that deep pools are particularly important for adults. Therefore, to protect large individuals, areas with deep pools should be given conservation priority. This is already somewhat in place in Cambodia via fish conservation zones, which often protect deep pools [37,68], but again, the enforcement in those zones must be effective.

To fully understand the data presented in this study, there are a few caveats to these conclusions that should be discussed. Firstly, although local ecological knowledge surveys are currently the most efficient method of collecting data on rare Mekong fishes, there are limitations to this method, including the dependency on human memories to accurately replicate facts from the past.

Secondly, despite extensive efforts to reduce fisher misidentification of species (see methods), there is still the possibility that this occurred, especially when talking about juveniles and the Pangasiid species. At small body sizes, many fishes, and especially Pangasiids (which can also be problematic at large sizes, depending on the species), are very similar in appearance. For example, although not presented in this paper, we interviewed fishers about *Pangasius krempfi*, a Pangasiid catfish with a maximum body weight of 14 kg. Size data collected from fishers on *Pangasius krempfi* indicated that fishers were misidentifying this species because many claimed to have caught specimens of a much greater size than its maximum. Such misidentifications may also occur because some species share the same Khmer name. Additionally, an informal follow-up survey of other fishers about *Aptosyax grypus* showed that fishers tended to confuse this species (at small sizes) with the small cyprinid *Raiamas guttatus*, as noted by Rainboth [69]. Fishers may also confuse *Wallago micropogon* at small sizes with *Ompok* spp. Thus, there is the possibility that fishers were unable to clearly distinguish small juveniles of *Pangasianodon gigas*, *Pangasius sanitwongsei*, *Aptosyax grypus*, *Wallago micropogon*, and possibly *Luciocyprinus striolatus*. However, at large body sizes, these species are much more distinct and easier for fishers to identify. Furthermore, the other study species—*Catlocarpio siamensis*, *Probarbus jullieni*, and *Urogymnus polylepis*—are unique in appearance and fishers are unlikely to mistake them for other species. *Probarbus jullieni* does have a congener—*Probarbus labeamajor*—in the region that is similar in appearance, but fishers accurately described the physical differences between the two *Probarbus* species. Thus, if misidentification were to affect the conclusions of this study, we would expect it to primarily impact the reports of small size classes of a subset of the species. This may bias body size estimates to be lower than reality. It should also bias fishers towards thinking juveniles of these species are more common than in reality, which only strengthens the conclusion that these species are extremely rare and in need of immediate protective actions.

A third consideration of this study is whether fishers trusted us enough to provide information on catching illegal species and knowledge of illegal fishing activities. In many villages, fishers seemed comfortable with us, but in a few they seemed more guarded. Fishers can face steep penalties (including jail and possibly bodily harm) if they are caught for such activities, and there can be suspicion toward unknown people coming to ask questions about these topics. Knowing this, interviewers took every precaution to show that we were only interested in the biological status of the species and not in enforcing laws (see methods for more explanation). However, it seemed as though the greatest asset to facilitating trust between fishers and interviewers was having someone from their community who could vouch for us. One such example was using a contact of one of the interviewers to make introductions with fishers. In communities where we did not have such a contact, it helped to communicate with the village chief ahead of time and thoroughly explain our purposes. Based on this insight, we recommend researchers desiring to conduct work in this area to establish relationships with local people by periodically maintaining contact with them to show reliability and trustworthiness. This will lead to more accurate data collection.

The fourth consideration of these data is changes in fishing regulations over time that potentially impacted fishing behavior and/or reporting of catches. As previously mentioned, it is illegal to use nets



with mesh sizes that target large-bodied fishes (mesh >15 cm) [57]. Thus, there is a high incentive for fishers to under-report catches of very large individuals. Furthermore, those fishing regulations were put into place in 2006 and there could be a tendency for fishers to be less honest about reporting catches of large-bodied fish after 2006. Lastly, some fishers did stop using gears that targeted large-bodied individuals to conform to the law and, therefore, their current gear gives them a lower probability of capturing a large-bodied fish than they had in the past. All of these behaviors would serve to bias trends towards a steeper decrease in body size and less recent dates of the last capture, making these species appear to be smaller and rarer than they are. (However, an alternative explanation is that a true decrease in fish body size is what caused fishers to switch to smaller mesh sizes).

Although this is a significant consideration that may affect the results, pressing further into these issues with the fishers was unwise as it could foster distrust, leading to even less accurate information. A delicate balance had to be struck between obtaining specific information and maintaining a relaxed interview environment. As it was, our analysis of the effect of gear size and regulations on the trends in body size of the largest megafish individuals suggested that neither of these variables impacted the declining trends in body size (Figure S5). This analysis also suggests that fishers were being honest about the size of the largest fish captured and the type of gear they were using because the captures from fishers with smaller gears were generally smaller than the captures from fishers who used larger gears. This declining trend in body size also agrees with results from other studies [23,70]. More detailed investigation into the relationship between gear size and the impact of fishing regulations on reported fish body sizes was beyond the scope of this work. Future investigations would benefit from developing a method to control for gear types used throughout fishers' careers to see how that affects the size of fish captured.

The final limitation of this study was low sample sizes. Two of the species (*Aptosyax grypus* and *Luciocyprinus striolatus*) had too few high-quality interviews to be able to draw any strong conclusions about their populations. *Luciocyprinus striolatus* may not have historically occurred in this study area; the southernmost part of its range in the Mekong River is currently known to be Lao PDR [20]. *Aptosyax grypus* is known from Cambodia, but is considered very rare [20] and is difficult for many fishers to identify. Despite the low sample size, we found *Aptosyax grypus* had a relatively recent mean date of last capture (five months before the survey; Figure 2), which may suggest that it is generally poorly known throughout the study area, but a small number of fishers specialize in catching it and can catch it relatively frequently. Although a little better than those species, *Pangasianodon gigas* also had a low sample size. It is difficult to know if the low sample sizes are a result of the species not being present in those areas or fishers being unable to identify them. However, it could simply be another indicator of the extreme rarity of these species. Another benefit of establishing networks of knowledgeable and reliable fishers for this type of research is that scientists can assist and train fishers in the identification of these rare species, which generates more accurate data.

To conclude, megafishes in the northern Cambodian Mekong Basin are very rare, decreasing in population abundance and body size, at high risk of extirpation, and threatened by multiple anthropogenic pressures. This is especially concerning considering that this region of the Mekong is thought to be one of the last strongholds for these fishes on Earth. Protective management policies and effective enforcement are urgently needed to preserve these species in the wild. We recommend developing Species Conservation Strategies and Species Action Plans, which focus and guide all aspects of species conservation and recovery. The IUCN Species Survival Commission offers specific guidance in developing such plans, which is freely available online [32,33]. The results of this survey can inform the species Status Review, an integral part of any Conservation Strategy or Action Plan. Speedy development and implementation of conservation plans are worthwhile and have the potential to help these species. One encouraging result of this (and other) studies is that individuals in multiple size classes of certain megafishes do still exist, albeit in low numbers, suggesting limited natural reproduction. Furthermore, Cambodia's decision in March 2020 to suspend all mainstem dam-building—two of which were planned for this study area—for ten years [71] offers hope of

maintaining open migration channels and a more natural flood pulse for the megafishes in northern Cambodia. If more conservation actions like this are taken, there may still be hope for preserving Mekong megafishes in the wild.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2073-4441/12/6/1820/s1>, Table S1: Comparison of Mekong megafish body size (weight in kg) reported by fishers to the maximum body size from FishBase ([www.fishbase.org](http://www.fishbase.org)), Table S2: Mekong megafishes' age and length at first maturity, Table S3: Comparison of fishers' mean dates of last capture with their perceived rankings of megafish population abundance, Figure S1: Photographs of the megafish species examined in this study, Figure S2: Annual change in perceived abundance of Mekong megafishes in northern Cambodia, Figure S3: Mekong megafishes identified by local fishers as extirpated or likely to be extirpated in northern Cambodia, Figure S4: Annual change in perceived average body size of Mekong megafishes, Figure S5: Plots of the size and date of capture of the largest Mekong megafish specimens captured by fishers, Figure S6: Distributions of body sizes of the most recent Mekong megafish specimens captured by fishers in northern Cambodia. The survey questionnaire is also available along with a detailed description of the local ecological knowledge survey methods and recommendations.

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