

Implications of Insecticide-Treated Mosquito Net Fishing in Lower Income Countries

David A. Larsen,¹ Joseph Makaure,² Sadie J. Ryan,³ Donald Stewart,² Adrienne Traub,⁴ Rick Welsh,⁴ Deirdre H. Love,⁵ and Joseph H. Bisesi Jr⁵

¹Department of Public Health, Syracuse University, Syracuse, New York, USA

²Department of Environmental and Forest Biology, State University of New York College of Environmental Sciences and Forestry, Syracuse, New York, USA

³Department of Geography, University of Florida, Gainesville, Florida, USA

⁴Department of Nutrition and Food Studies, Syracuse University, Syracuse, New York, USA

⁵Department of Environmental and Global Health and Center for Environmental and Human Toxicology, University of Florida, Gainesville, Florida, USA

INTRODUCTION: Insecticide-treated mosquito nets (ITNs) are highly effective for the control of malaria. Yet widely distributed ITNs have been repurposed as fishing nets throughout the world.

OBJECTIVES: Herein we present a synthesis of the current knowledge of ITN fishing and the toxicity of pyrethroids and discuss the potential implications of widespread fishing with ITNs. We further review effective management strategies in tropical fisheries to explore a framework for managing potential ITN fishing impacts.

DISCUSSION: Pyrethroids are toxic to fish and aquatic environments, and fishing with ITNs may endanger the health of fisheries. Furthermore, although human toxicity to the pyrethroid insecticides that impregnate ITNs is traditionally thought to be low, recent scientific advances have shown that pyrethroid exposure is associated with a host of human health issues, including neurocognitive developmental disorders, diabetes, and cardiovascular disease. Although it is known that ITN fishing is widespread, the implications for both fisheries and human communities is understudied and may be severe. <https://doi.org/10.1289/EHP7001>

Introduction

The insecticide-treated mosquito net (ITN) has saved millions of lives since its development in the 1990s and wide deployment in the 2000s (Bhatt et al. 2015a; Eisele et al. 2012). A person sleeping under an ITN is both protected from a potentially infective bite from a malaria-transmitting mosquito and serves as a lure to bring malaria-transmitting mosquitoes into contact with the insecticide in the net. Thus, not only do ITNs protect those sleeping under them, but the lethal effect of the insecticide in the ITNs provides community-level protection from malaria transmission (Hawley et al. 2003; Larsen et al. 2014), a fact that led world health bodies to consider the ITN a public good similar to vaccines (Curtis et al. 2003). The insecticide in the ITN is most pertinent to malaria control—although untreated bed nets may provide a physical barrier to individuals sleeping under them, without the insecticide, the mosquito survives and the cycle of malaria transmission continues. In other words, without insecticides, the impact of untreated mosquito nets on malaria transmission is minimal. The great reductions seen in malaria transmission since 2000 have been driven by the free distribution of more than two billion ITNs since the mid-2000s (Akinremi 2020; Bhatt et al. 2015b).

Although dismissed by scientists and malaria control personnel for years (Eisele et al. 2011), mounting evidence confirms that ITNs are often used as fishing nets across sub-Saharan Africa. A recent review of literature and a global survey of stakeholders in fisheries, public health, conservation, and development sectors found that mosquito net fishing is widespread worldwide (Short et al. 2018). Numerous case studies have also been

published, documenting frequent use of ITNs for fishing along the upper Zambezi River in Zambia (Larsen et al. 2018), in Lake Tanganyika (McLean et al. 2014), along coastal Kenya (Bush et al. 2017), in Lake Victoria (Minakawa et al. 2008), and in Timor-Leste (Lover et al. 2011).

When examined through the lens of the sustainable livelihoods framework (Bebbington 1999; Scoones 2009), the innovative behavior of fishing with ITNs is understandable and perhaps even predictable. An underlying aspect of the sustainable livelihoods framework is that rural livelihoods are variable as people exploit opportunities to generate income or ensure food security (Ellis 1998). In other words, farmers fish and fishers farm, with activity in either sector or others depending upon the capital available to the household (Figure 1). Although ITNs are intended to be used to reduce malaria and improve health (human capital), ITNs are tools (physical capital) and have also been repurposed to achieve livelihood outcomes such as food security and increased income through fishing.

The value of fish both in terms of food security and as a tradeable commodity reinforce repurposing ITNs for fishing as a livelihood strategy for poor households. Fish represent an important cash crop for subsistence farmers in rural areas (Béné et al. 2009), and fishing as a food-generating or economic activity presents few barriers (Smith et al. 2005). Some have even called fish the “bank in the water” (Béné et al. 2009). Fish are the most commonly traded agricultural product worldwide (Asche et al. 2015), and the natural capital of fisheries can be exploited when effective physical capital (i.e., fishing gear) is available. ITN distributions have provided the physical capital, facilitating the exploitation of the existing natural capital. With limited management of fisheries across most of sub-Saharan Africa (Sumaila et al. 2016), it is understandable that ITNs were and are widely adopted to be used as fishing nets.

Discussion

Fishery Collapse and ITNs

The worldwide collapse of tropical inland freshwater fisheries is well documented and occurred before the scale-up of ITNs (Allan et al. 2005; Hickley et al. 2004; Lyons et al. 1998; van Zwieten et al. 2003). Therefore, the introduction of ITNs in malaria-prone tropical regions likely contributes to, rather than

Address correspondence to David A. Larsen, 430C White Hall, Syracuse University, Syracuse, NY 13244 USA. Telephone: (315) 443-4059. Email: dalarsen@syr.edu

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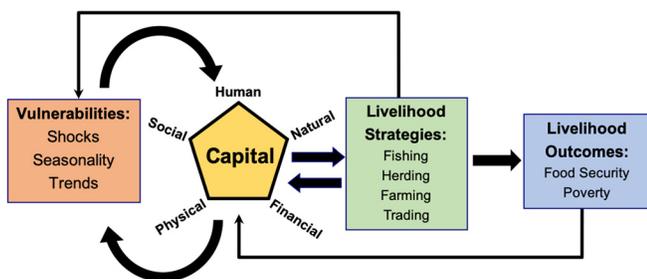


Figure 1. The sustainable livelihoods framework as it pertains to mosquito net fishing. International aid's free distribution of insecticide-treated mosquito nets acts as an injection of physical capital into the system, which then influences livelihood strategies and may lead to a shock. The influence of mosquito net fishing on food security and poverty remains to be seen.

creates, the problem of overfishing and potential fishery collapse. Landings and other information on freshwater fisheries is systematically underreported, particularly in sub-Saharan Africa (Lynch et al. 2017). However numerous scientists agree that inland fisheries may be already overexploited or approaching overexploitation in Africa and Asia (Welcomme et al. 2010), without taking into account potential impacts from fishing with ITNs. It is also important to note that the contribution of inland fisheries to food security in lower income countries is vitally important and underestimated (Fluet-Chouinard et al. 2018; Lynch et al. 2017).

ITNs are essentially a free and readily available type of extremely small mesh net. Small mesh sizes allow the capture of very small-bodied fish species and juveniles of larger-bodied fish species as has been documented in Mozambique (Jones and Unsworth 2020), which can limit the longer-term availability of fish and lead to fishery decline and collapse, depending on the local ecological conditions (Short et al. 2018). ITN availability can act as a recruitment tool for fishers given that the entry cost is almost negligible if the nets are free and the water bodies are open access—as is typical throughout malaria-endemic countries (Allan et al. 2005). Therefore, since the decline of freshwater fishing from overfishing has been documented even prior to the introduction of ITNs, it follows that an increase in the number of potential fishers using effective, indiscriminate, durable, and replaceable gear in an open-access environment can pressure fisheries further (Castello et al. 2013; Larsen et al. 2018). Furthermore, ITNs are often sewn together to form large drag nets, which not only catch fish of all types, sizes, and life stages, but can disrupt critical invertebrate prey populations, habitat, and fish spawning via dragging the weighted nets across the bottom of water bodies (Larsen et al. 2018; Short et al. 2018).

Sustained fishing pressure has led to declining catch rates, changes in fish community structure and composition, and loss of larger and commercially more valuable species (Tweddle et al. 2015). Most often, impoverished fishing communities in these regions follow a predictable pattern of resource exploitation by increasing fishing effort and ultimately using destructive fishing gear to catch the remaining fewer and smaller species, reducing recovery prospects for affected systems in the process (Bernier et al. 2005; Castello et al. 2013). ITN fishing in tropical regions presents an emerging form of fisheries exploitation, which, if left unchecked, can potentially exacerbate the collapse of already vulnerable affected systems.

Environmental Toxicity of Pyrethroid Insecticides, What is Known and What is Not

It has been suggested that pyrethroids may present an even greater environmental risk to aquatic biodiversity than previous-generation

insecticides such as organophosphates and organochlorines (Stehle and Schulz 2015). Although there are currently no published studies that have examined the direct toxicity of pesticides leaching from ITNs during fishing, we consider the bioconcentration (concentration of insecticide from water to fish tissue) and overt toxicity associated with pyrethroid insecticides in aquatic organisms is cause for concern. The octanol-water partition coefficient (K_{ow}) to be one of the values used to qualify a chemical as a persistent organic pollutant because it can be a predictor of bioconcentration potential, according to the Stockholm Convention (Aznar-Alemany and Eljarrat 2020). In cases where bioaccumulation factors (for terrestrial organisms) or bioconcentration factors (for aquatic organisms) are unknown, a chemical with a $\log K_{ow}$ value >5 is generally considered to have the potential to bioaccumulate or bioconcentrate (Aznar-Alemany and Eljarrat 2020). Common pyrethroids used to impregnate ITNs are permethrin, cyfluthrin, and deltamethrin, which have $\log K_{ow}$ values of 6.1, 6, and 4.6, respectively, indicating the potential for bioconcentration in aquatic organisms (Aznar-Alemany and Eljarrat 2020).

The K_{ow} values of pyrethroids indicate that they have the potential to bioconcentrate in aquatic organisms, which has been documented in numerous studies in fish and dolphins (Alonso et al. 2012; Corcellas et al. 2015). In fact, the pyrethroid insecticides deltamethrin and cypermethrin were found to bioconcentrate in the brains, livers, and ovaries of catfish in Jaunpur when compared with a reference site (Vengayil et al. 2011). In rainbow trout, permethrin has a bioconcentration factor of 1,940, whereas deltamethrin has a bioconcentration factor of 502. In fathead minnows, the bioconcentration factor for permethrin is 2,800 (Spehar et al. 1983). Although numerous studies have indicated that the pyrethroids can bioconcentrate, the rapid metabolism and excretion of these compounds in vertebrates and invertebrates indicate that biomagnification is unlikely (López and Fernández-Bolanos 2011). Although it is evident that pyrethroids have a strong potential for uptake and bioaccumulation in aquatic organisms, studies have also indicated that they can be overtly toxic at very low concentrations. For example, spray drift studies with deltamethrin insecticides, a pyrethroid that is commonly used in ITNs, indicated high toxicity to aquatic vertebrates and invertebrates at parts-per-trillion concentrations (Palmquist et al. 2012). Concentrations as low as 0.1 $\mu\text{g/L}$ of the pyrethroid cypermethrin were shown to decrease egg fertilization rates and hormone production in fish (Little et al. 1993). Although these values are concerning, pyrethroids have also been shown to adversely affect crustaceans and plankton (Anderson 1989), and contamination from pesticides such as pyrethroids has been associated with a 42% reduction in the biodiversity of invertebrates in riverine systems (Beketov et al. 2013). It is important to note that toxicity at low concentrations can be expected to impact fisheries at the population level through numerous avenues (Figure 2). Adult fish can be directly harmed by the insecticides, which have been shown to impact behavioral and reproductive success (Palmquist et al. 2012). In addition, larval fish tend to be more sensitive to mortality caused by pyrethroids when compared with adult fish (Palmquist et al. 2012). Finally, the high toxicity of pyrethroid insecticides to invertebrates represents a significant threat to important food sources for fish (Pimentel et al. 1992). We suspect these impacts to ripple upward, which may lead to an overall decline in the productivity of a fishery.

To our knowledge there is currently a complete lack of data to assess the potential risks associated with pyrethroid insecticide leaching from ITNs. Simply put, ITNs were not designed with submergence in mind. Even if pyrethroids do leach from nets once they reach the water, which we suspect they do, there is a question concerning whether the pyrethroid contributions from these nets can reach high enough concentrations to cause toxicity in aquatic

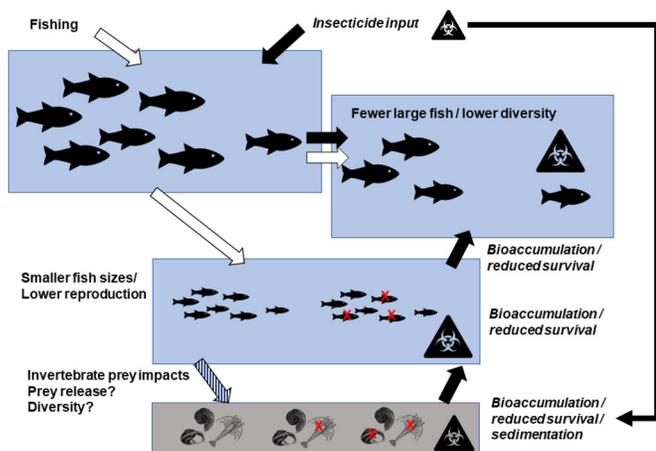


Figure 2. Overview of the combined potential impacts of increased fishing (solid arrows, left pathway) and insecticide inputs (open arrows) due to insecticide-treated mosquito net (ITN) fishing. The direct impact on large fish of increasing ITN fishing can be to reduce their numbers or diversity, pushing the size structure of a fishery to smaller average body sizes and perhaps lowering reproductive output and associated recruitment. That, in turn, may affect small prey fish by releasing selected species from predation, but any such benefits could be countered by overharvest of even the smallest fish with ITNs. Insecticides also may impact all sizes of classes of fish by variously causing direct mortality, with related effects on diversity and species abundances. As fish grow, bioaccumulation of toxins from any combination of water, sediments, and food webs could lead to progressive increases in mortality or sublethal effects, such as compromised reproduction.

organisms. Although the current state of the science on this matter does not provide enough information on the leaching rates of pyrethroids from ITNs to calculate potential concentrations, data from manufacturers and the literature indicate that each net typically contains >1 g of pesticide (Barlow et al. 2001). Although this amount may seem small, when considered in the context of the small pan and oxbow lakes where ITN fishing has been observed (Larsen et al. 2018), concentrations could reach the parts-per-trillion concentrations shown to be toxic to aquatic organisms. Each year the floodplains of the African wetlands drain during the dry season to reveal shallow pan and oxbow lakes that serve as refugia for fish and invertebrates unable to escape in the receding floodwater. These lakes can be as small as 20–50 m in diameter, yielding small-volume lakes that can be easily seined with ITNs to provide easy catches for local fishers (Fynn et al. 2015). Because these lakes are small in volume, a small amount of pesticide from the net could reach concentrations known to cause toxicity in fish.

Of course, there are other factors in play that can influence the potential for bioaccumulation and toxicity of pyrethroids from ITNs. For example, one study has suggested that pyrethroids may adsorb rapidly to organic matter in water, which could help to reduce toxicity (Liu et al. 2004). In addition, another study showed pyrethroids undergoing rapid photodegradation in water (Liu et al. 2010), which also can decrease toxicity in areas where nets are used infrequently. However, frequent use of these nets by multiple fishers may cause a pseudo persistence of these compounds in aquatic systems, effectively negating the impacts of photodegradation and water quality on their aquatic toxicity.

In summary, the pyrethroid insecticides used in ITNs have significant potential to bioaccumulate and cause toxicity in fish. Because fish are an important source of nutrition (Sidhu 2003), we find the potential for bioaccumulation to be alarming, considering the human health effects of pyrethroid exposure that we discuss in the next section. However, there is still much work to be done to determine whether and how much ITN fishing represents a risk to fish and aquatic invertebrates. We recommend that

leaching rates from ITNs be assessed to determine what concentrations are possible, especially in low-volume pan and oxbow lakes where ITN fishing has been observed.

Next-Generation ITNs Combine Pesticides and Synergists

Malaria-transmitting mosquitoes in many areas have developed resistance to the pyrethroid insecticide used in ITNs (Strode et al. 2014). In efforts to preserve the effectiveness of ITNs at killing malaria-transmitting mosquitoes and the gains made to date against malaria transmission, scientists have begun to experiment with combination-treated nets. The ITNs are treated with multiple insecticides to enhance the lethal effect and reduce the probability that resistance to both insecticides develops. Success was reported from the inclusion of a synergist, piperonyl butoxide, which increased mortality from pyrethroids by inhibiting the mixed function oxidases in pyrethroid-resistant mosquito populations (Gleave et al. 2018). Others observed success when adding the growth hormone inhibitor pyriproxyfen, which is typically used to control the aquatic stage of a mosquito's life cycle. A recent study in Burkina Faso showed that adding pyriproxyfen to pyrethroid-treated ITNs reduced the entomological inoculation rate by almost half compared with areas with ITNs treated with pyrethroids alone (Tiono et al. 2018).

We find it likely that combination ITNs will end up in the water ways as fishing nets. In the case of piperonyl butoxide, it is unclear whether the combination of these chemicals in the aquatic environment presents an increased risk to the fisheries and fish therein. Piperonyl butoxide was shown to increase the toxicity of the pyrethroid lambda-cyhalothrin in Nile tilapia (*Oreochromis niloticus*) (Guedegba et al. 2019); however, a different study indicated that the low concentration required to cause synergism of pyrethroids by piperonyl butoxide may limit the potential for increased toxicity in the aquatic environment (Amweg et al. 2006). In the case of pyriproxyfen, the evidence is more clear—the growth hormone inhibitor would likely have severe ramifications. For fish, pyriproxyfen presented developmental challenges in high concentrations (Maharajan et al. 2018), and it may decrease swimming performance at environmentally relevant concentrations (Caixeta et al. 2016). In the cladoceran invertebrate *Daphnia carinata*, exposure to 10- μ g/L pyriproxyfen caused a dramatic 80% decrease in growth (Trayler and Davis 1996) and in crabs, lead to reduced reproductive capacity (Linton et al. 2009).

Pyrethroids and Human Toxicity

Although it is clear that the pyrethroids that are commonly used in ITNs have the potential to bioaccumulate and cause toxicity in fish, it is unclear whether this may lead to toxicity in humans who may consume the fish. Although fish are slower to metabolize these compounds than mammals, which can lead to bioconcentration (Brander et al. 2016), the high toxicity of these chemicals in fish may limit the tissue concentrations of these chemicals given that the fish could die before reaching high levels of bioconcentration. As a result, the levels of pyrethroids in the fish may not reach toxic levels for mammals. However, until we can characterize these exposures, we must consider the potential for toxicity to humans who consume these fish.

Human exposure to pyrethroids is thought to be primarily through ingestion, either dietary ingestion or, in the case of children, the ingestion of pyrethroid-contaminated dust (Morgan 2012). In addition to being found commonly in sediments and waters (Tang et al. 2018), bioaccumulation of pyrethroids has been reported in wild fish (Corcellas et al. 2015) and dolphins (Alonso et al. 2012). Should fishing with ITNs lead to leaching of pyrethroid insecticides, bioaccumulation in exploited fish is likely

(as discussed above), and as a result, human exposure through fish consumption would be expected.

A number of reviews discuss the current state of the science around pyrethroids and human toxicity, including potential links between pyrethroid exposure and neurocognitive development and behavioral problems (Burns and Pastoor 2018; Chrustek et al. 2018; Saillenfait et al. 2015). More recently, exposure to pyrethroids was associated with a three-fold increase in the risk of cardiovascular disease mortality (Bao et al. 2020) and diabetes (Park et al. 2019).

Managing Fisheries

ITN fishing is an example of how communities with fewer alternative livelihood strategies can adapt new methods of seemingly unsustainable resource exploitation. Although we expect ITN distributions will continue given the severity of malaria for human health, we find it unlikely that ITN fishing will be contained given the combination of limited funding, weak enforcement of legislation by state institutions, and free availability of ITNs in most affected areas.

As noted, fisheries in tropical regions play a central role in food security (i.e., providing a dominant protein source), income generation, and improving human livelihoods (Allison 2011; Béné and Heck 2005; McClanahan et al. 2015). Their management therefore requires strategies that consider both the socioeconomic status of local populations and the ecological processes in freshwater habitats. Two divergent fisheries management approaches (i.e., the wealth-based vs. welfare-based approaches) have recently emerged in the fisheries literature (Nunan 2014). Fisheries management can focus on either limiting access and creating wealth for a small section of the society (wealth approach) or maintaining broader access to create employment, development, and welfare of the community (welfare approach) (Nunan 2014). Studies have shown that welfare-based management strategies are more applicable in low-income, tropical countries, where fewer alternative livelihood strategies exist (Béné 2006; Smith et al. 2005).

One potential solution that has found success can be the formation of community-based fisheries management programs in which local fishers and other key stakeholders, such as traditional leaders, scientists, and resource managers, participate in formulating management decisions on fisheries within their area of jurisdiction. Community-based fisheries management programs can focus on different aspects of fish ecology, such as protecting fish spawning areas (Erismann et al. 2017), establishing fish protected areas (Tweddle and Hay 2011), and regulating fishing gear (McClanahan and Mangi 2004). Alternatively, they can protect fisheries by basing regulations on the community's sociocultural norms [e.g., protecting culturally important species (Freitas et al. 2020)] or using community religious beliefs (Lowe et al. 2019).

Stakeholder engagement in fisheries management is an important aspect for sustainable fisheries management (Pita et al. 2010), and factors that promote sustainable fisheries (i.e., management, governance, and ecosystem status) are inextricably linked (Bundy et al. 2017). This system of co-management transfers the responsibility for the fisheries to the local communities that can enforce locally formulated fishing strategies that ensure sustainable fishing practices. With the help of fishery scientists, communities can draft fisheries management plans, detailing how they will control fishing effort, register fishers, restrict destructive and active fishing gear, and, more importantly, monitor adherence and compliance to established guidelines. In our experience, the elimination of open access is invariably a key to success, as is also the regulation of the fishing gear used in water bodies.

Communities may also consider creating fish protected areas (Tweddle and Hay 2011), which are “no-take zones” and serve as a refuge or insurance against unsustainable harvesting in open-access fishing zones. In areas affected by ITN fishing, fish

protected areas could potentially maintain largely pristine habitats with low contamination from pyrethroid leachate, thus providing suitable habitat for spawning and larval development. The success of no-take zones, however, generally requires almost constant vigilance on the part of the community to minimize poaching (Tweddle and Hay 2011). A variation of fish protected areas can be seasonal closures (Halliday 1988), in which fishing activities are temporarily prohibited during peak spawning periods to avoid recruitment failure. As mentioned above, pyrethroids can be degraded in natural systems over short periods of time, so these seasonal closures would likely also help to reduce pyrethroid loads during these crucial spawning seasons.

Overall, fisheries are complex systems that transcend social, economic, political, and ecological realms, and their successful management must include multiple stakeholders, often with different or competing interests (Martin 2001). This is especially true in tropical regions where other challenges such as poor scientific research, poverty, and weak state institutions make sustainable fisheries management more challenging. With proper enforcement of accords, community-based fisheries management programs can provide long-term benefits to individual households, such as reducing fishing effort (Schons et al. 2020). This is particularly important in tropical subsistence communities because it frees up time that can be used for alternative income-generating activities. Creating community-based fisheries management programs can, therefore, be a viable strategy to create win-win solutions for both fishers and aquatic biodiversity in these regions.

Conclusions

Fishing communities in malaria-endemic regions are seemingly caught between competing sustainable development goals (Trisos et al. 2019). As we have summarized, ITNs reduce malaria transmission and save lives—millions since widescale distributions—but are also oftentimes used as fishing nets. Numerous questions remain as to the impacts of fishing with ITNs for the ecosystems affected and the humans who live in them. We consider the following questions to be of greatest importance:

- How do the pyrethroid chemicals in an ITN act once the ITN is used as a fishing net? Do the nets provide a constant contamination source of pyrethroids, or do the pyrethroids leach out quickly into the environment?
- What is the bioaccumulative nature of pyrethroids in aquatic environments?
- Some argue that mosquito net fishing is beneficial to the world's poor (Tilley et al. 2020). Small fish when eaten whole are more nutritious than meat from larger fish (Thilsted 2012), and taking young fish may be less detrimental to some fisheries than taking big old fat fecund females, referred to as BOFFFs (Hixon et al. 2014). But, will the harvest of immature individuals severely inhibit recruitment? In general, how is mosquito net fishing impacting fisheries and food security?
- Pyrethroids have been implicated as a risk factor for a host of human diseases, including neurodevelopmental disorders (Viel et al. 2015; Xue et al. 2013), diabetes (Park et al. 2019), and cardiovascular disease (Bao et al. 2020). Are we seeing bioaccumulation in fish that then exposes humans to pyrethroids, and, if so, is this having a detrimental effect on human health?

Pyrethroids are highly toxic in aquatic environments, and related research suggests there are a host of deleterious effects of pyrethroid ingestion on human health. Given the cash value of fish, the ease of ITN fishing, and limited alternative income generating opportunities, distribution of ITNs into fishing communities without strong fisheries management may present a serious challenge to fishery health, aquatic biodiversity, and perhaps even human health.

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