A Global Perspective on the Influence of the COVID-19 Pandemic on Freshwater Fish Biodiversity

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Abstract

The COVID-19 global pandemic and resulting effects on the economy and society (e.g., sheltering-in-place, alterations in transportation, changes in consumer behaviour, loss of employment) have yielded some benefits and risks to biodiversity. Here, we considered the ways the COVID-19 pandemic has influenced (or may influence) freshwater fish biodiversity (e.g., richness, abundance). In many cases, we could only consider potential impacts using documented examples (often from the media) of likely changes, because anecdotal observations are still emerging and data-driven studies are yet to be completed or even undertaken. We evaluated the potential for the pandemic to either mitigate or amplify widely acknowledged, pre-existing threats to freshwater fish biodiversity (i.e., invasive species, pollution, fragmentation, flow alteration, habitat loss and alteration, climate change, exploitation). Indeed, we identified examples spanning the extremes of positive and negative outcomes for almost all known threats. We also considered the pandemic's impact on freshwater fisheries demand, assessment, research, compliance monitoring, and management interventions (e.g., restoration), with disruptions being experienced in all domains. Importantly, we provide a forward-looking synthesis that considers the potential mechanisms and pathways by which the consequences of the pandemic may positively and negatively impact freshwater fishes over the longer term. We conclude with a candid assessment of the current management and policy responses and the extent to which they ensure freshwater fish populations and biodiversity are conserved for human and aquatic ecosystem benefits in perpetuity.

Introduction

Freshwater biodiversity is widely acknowledged to be in crisis (Harrison et al. 2019), with biodiversity loss in freshwater systems exceeding both terrestrial and marine environments (Ricciardi and Rasmussen 1999; Tickner et al. 2020). Freshwater fishes are the most threatened group of vertebrates, after amphibians (Darwall & Freyhof 2016). Moreover, the global extinction rate of fishes (including marine fish) is believed to exceed that of other vertebrates (Dais et al. 2017). More than 60% of freshwater habitat is classified as moderately or highly threatened by human activity (Vörösmarty et al. 2010) and few free-flowing rivers remain (Grill et al. 2019). The threats to freshwater fishes and their aquatic ecosystems are many and varied, spanning long-standing threats (Dudgeon et al. 2006) as well as emerging ones (e.g. nanoparticles; Reid et al. 2019). Recent efforts have recognized the severity of the conservation crisis in freshwater environments and the need to adopt an emergency action plan to recover biodiversity (Tickner et al. 2020).

The Sars-Cov-2 virus causing COVID-19 and the subsequent global pandemic (hereafter, 'COVID-19') have rapidly and dramatically altered patterns of human behaviour, society, and economies. It has been suggested the pandemic is serving as an unprecedented global human confinement experiment as governments around the world institute 'lockdowns' (Bates et al. 2020). During lockdown periods, large portions of society have been isolated, reducing the regional and global movements of people (Askitas et al. 2020), and altering the trade and distribution of goods (Baldwin and Tomiura 2020). Moreover, the economic status of many individuals and communities has changed rapidly with COVID-19, driving potential changes in human interactions with freshwater fishes and ecosystems (e.g., illegal harvest to ensure food security).

Early thinking about the effects of COVID-19 has suggested a potential benefit to biodiversity (Pearson et al. 2020) and the environment (Zambrano-Monserrate et al. 2020; Mandal 2020), yet others have suggested both benefits and disbenefits depending on context (Corlett et al. 2020). The first examples arising from the freshwater realm, however, have indicated mixed outcomes (Pinder et al. 2020; Stokes et al. 2020). For example, the rivers of India are cleaner because of dramatic reductions in industrial pollution, but imperiled freshwater fish species are increasingly exploited by food insecure peoples in response to the disruption of their normal livelihoods and economic well being (Pinder et al. 2020). In a global snapshot of expert-perceived impacts to inland fisheries, Stokes et al. (2020) found responses to be spatially variable with more negative impacts associated with less developed areas and high provisioning fisheries. Given the connections between freshwater fishes and individuals, people, and the broader society (Welcomme et al. 2010; Cooke et al. 2016), regional, national, and global events are driving changes in the ways humans interact with freshwater fishes and freshwater ecosystems.

Although formal analyses will yield empirical tests of the impact of COVID-19 on biodiversity (Bates et al. 2020), there is also a need to engage in forward-looking syntheses that consider the potential mechanisms and pathways by which both negative and positive effects may be revealed. To that end, we assembled a team of global experts in freshwater fish biodiversity and conservation (the authors) with the objective of considering ways COVID-19 has influenced (or may influence) wild freshwater fish populations (e.g., health, abundance, diversity). We approached this from the perspective that there are many existing and widely acknowledged threats to freshwater fish populations (e.g., pollution, dams, climate change, overexploitation, invasive species; Reid et al. 2019) and the recognition that COVID-19 has the potential to either mitigate or amplify their effects (Figure 1). Thus, our goal was to elucidate the interaction of the societal disruption caused by the COVID-19 pandemic and the background of pre-existing threats to freshwater ecosystems in order to understand the potential outcomes for global freshwater fish diversity. We also consider how COVID-19 has influenced freshwater fish assessments, research, compliance monitoring, and management interventions. We conclude with a candid assessment of the current management and policy responses and the extent to which they have contributed to ensuring that fish populations and biodiversity are conserved and continue to benefit future generations. Where possible, we use documented examples (often from the media) but recognize that often we are only able to consider potential impacts given that anecdotal observations are still emerging and data-driven studies are yet to be completed or even undertaken.

COVID-19's modulating effect on existing threats

Invasive species

Invasive species are considered one of the most significant drivers of freshwater biodiversity decline (Reid et al. 2018 and references therein). COVID-19 has both changed the way that invasive species spread between regions and the way humans are able to control this spread. Human-related pathways of species introductions have been altered due to COVID-19. Dramatic reductions in both local and international travel will likely lead to subsequent reductions in invasive species transport associated with pathways such as ballast water exchange, air transportation, the movement of fresh foods, and recreational activities, among others (Hulme 2009; Early et al. 2016). For example, significant decreases in trade demand have led to reductions in shipping traffic among all global ports. Research prior to COVID-19 forecasted dramatic increases in species invasions associated with mid- 21st Century shipping traffic (e.g., ballast water releases; Sardain et al. 2019), but we expect the economic recovery to COVID-19 may slow the pace of invasions, at least in the short term. As economies rebuild in the coming years, it seems likely that human-related pathways of species introductions may actually accelerate the pace of invasions. Moreover, there remain uncertainties regarding how COVID-19 and other geopolitical issues (e.g., trade wars) may influence trade routes in the coming years and what that may mean for risk of invasive species introductions.

On the other hand, COVID-19 has led to significant budget reductions for controlling the spread of invasive fishes from intentional introductions, aquaculture releases, and unintentional transport. For example, a US$8 million project aimed at stopping the spread of invasive Asian carp in Michigan, USA, was vetoed in order to support the state's response to COVID-19 instead (Boomgaard 2020). Furthermore, reduced monitoring and regulatory measures (e.g., boat inspections; see example from Utah, https://www.sltrib.com/news/environment/2020/04/25/utah-fears-lack-boat/) for invasive species will likely compromise the success of early detection and rapid response of new introductions, leading to greater spread and costs of control in the future. While the public plays an increasing role in the early detection and control of invasive species (e.g., detected range expansion of lionfish (*Pterois* spp – a marine fish) in the northern Gulf of

Mexico, Scyphers et al. 2015; and increased abundance of invasive marine fishes in Turkey, Bodilis et al. 2014), community science programs have largely ceased in response to COVID-19 because of lockdown restrictions, reducing the ability to notice new or track existing invasive species. Similarly, the public remains central to many invasive species control efforts (Crall et al. 2012). For example, sustained public participation is critical to removing invasive lionfish from reef ecosystems (Anderson et al. 2017), but removal events have been cancelled as a result of social distancing. Although those are marine examples, we expect similar reductions in community science in freshwater systems. We also expect that trickle-down effects of reduced community science programs will ultimately decrease science literacy and dampen attitudes towards invasive species in the long-term (Roy et al. 2018). It should be noted however, that COVID-19 may serve as an important example (for outreach and education) of the devastating effects invasive species can have on society. There may also be opportunity for ecologists to learn from the modeling used for COVID-19 to better model invasive species dynamics (Bertelsmeier and Ollier 2020; Nuñez et al. 2020).

Pollution

The COVID-19 pandemic has altered the way that pollutants (i.e., nutrients, pesticides, toxins and contaminants, microplastics, light and noise, and salinity) are influencing freshwater ecosystems. (Reid et al., 2019; Chen et al., 2020). During the pandemic, global lockdowns and temporary closures of many industries have potentially reduced discharge of nutrients, heavy metals, and other chemicals to water bodies and reduced emissions to the atmosphere (Chow 2020). Reduced nitrogen dioxide concentrations observed over Eastern China, Europe, the Northeastern United States, and India have been used as indicators of temporary recovery of urban surface water quality that runs off into waterways (Hallema et al. 2020). In Vembanad Lake, Southern India, an average 15.9% decrease of suspended particulate matter concentration during the lockdown period suggests reduced anthropogenic impacts (Yunus et al., 2020). In China, the percentage of nationwide surface water quality transects at the “good” level increased 6.0% between January to May of 2020 (CMEE, 2020). Noise from shipping traffic on aquatic biota may also be reduced during the pandemic (Zajicek and Wolter, 2019). These reductions in water pollution will have positive effects on aquatic organisms and their habitats.

However, the pandemic has also increased pollution impacts on freshwater fishes. In the UK, disruption to food supply chains has led to dumping wasted food and drink, such as milk, which has entered waterbodies, potentially depleting oxygen levels through eutrophication (Ends report, 2020; Salmon and Trout Conservation, 2020). Elsewhere, altered sewage pollution patterns or collapse of the sewage systems could be a major detriment to aquatic biodiversity (Herbig, 2019; Tortajada & Biswas, 2020). Increased use of disinfectants (e.g., hand sanitizers, cleaning products) has likely increased their presence in freshwater systems through runoff and wastewater discharge (Zhang et al., 2020). In addition, heightened concern for hygiene and disease spread has increased pollution associated with packaging and personal protection equipment (Roberts et al. 2020, van Reenan 2020; Aragaw et al. 2020). Moreover, as single-use plastics are a key source of microplastics in fresh waters (Li et al. 2020), such actions will likely contribute to more plastic pollution entering waterways. Disruption to the monitoring, control, and surveillance of freshwater ecosystems could further increase pollution risks from certain unregulated human activities or fail to detect accidental pollution events altogether.

Fragmentation

Fragmentation of freshwater systems is a major threat to freshwater biodiversity, particularly migratory fishes (Dudgeon et al. 2006; Nilsson et al. 2005). The construction of dams is currently the greatest source of increased fragmentation in freshwater ecosystems as free-flowing rivers are obstructed (Zarfl et al. 2015). The slowdown of industrial development and construction activities during the pandemic has also slowed hydropower projects, particularly in Asia (Bangladesh, China, Nepal, Indonesia, India and Myanmar; Cox 2020), and temporarily suspended further fragmentation of freshwater ecosystems. How long this will persist is unknown, given global changes in energy demand due to COVID-19.

However, as regions prioritise economic recovery post-pandemic, there is evidence that environmental legislation and assessment processes are being side-stepped (Diele-Vegas and Pereira 2020; Canadian Environmental Law Association 2020). It is possible proponents of development projects will attempt to take advantage of a swamped news-cycle, decreased environmental assessment capacity, and a need for economic growth following the lockdown to push forward controversial projects. For example, the Government of India is considering a controversial 3097 MW dam (Dibang Valley Hydropower project) in the Himalayan Biodiversity Hotspot (Chandrashekhar 2020). While many regions of the world are building dams, other regions are removing them (Ding et al. 2019) or constructing fishways to provide passage over such barriers. Funding for such restoration projects may be restricted or diverted during the economic recession to benefit human health and employment security (discussed in Corlett et al. 2020), but to the detriment of river fishes.

Flow alteration (hydropower and water extraction)

Flow regimes in rivers have been modified to accommodate societal needs, leading to changes in hydrogeomorphological processes and ecosystem functioning (Anderson et al. 2019). Agricultural water use accounts for about 70% of water withdrawals from aquatic ecosystems, and associated irrigation and drainage infrastructure also contributes greatly to fragmentation of aquatic habitats (Wisser et al. 2008; Vörösmarty et al. 2010). Changes in irrigation demand and management has major impacts on fish biodiversity and fisheries (Nguyen Khoa et al. 2005; Lorenzen et al. 2007). Along with other sectors, agricultural water demand initially decreased during the COVID-19 crisis, due to impacts on supply and trade systems and the reduced availability of agricultural labor (with irrigated agriculture being more dependent on all of these factors than traditional rainfed farming systems). However, a need to re-invigorate irrigated agriculture quickly to avert food shortages and stabilize the world food system is widely recognized. While the net effect of these shifts in demand and technology are difficult to predict, such changes will affect aquatic ecosystems in multiple ways, including the disconnection of irrigated areas and altered flooding patterns.

Water use and energy demand during the pandemic has varied across spatial scales based on pre-existing usage. In the United States, estimated residential water-demand increased by 21% in April compared to February when the lockdown first began (as per smart-water monitoring company ‘Phyn’; Mendoza 2020). In Turkey, consumption of potable water increased by 60%, compounding the impact of regional drought and concerns for water availability (Daily Sabah 2020). Conversely, non-residential uses of water have decreased. While it is unclear how net water demand has been affected, it appears water bodies near large metropolitan areas would have experienced reductions in water extraction, while water bodies sourcing primarily residential areas have experienced moderate increases in water extraction (Cooley 2020). Disruption to global food production and trade has raised food security fears, and countries are considering increasing their domestic production, including irrigated agriculture (Cambodia New Vision 2020). Increased water use will likely compound existing changes in flow regimes, with associated impacts on fishes and aquatic biota, such as loss of productivity, increased risk of poor water quality and fish kills, and reduced cues for spawning, recruitment and movements. Likewise, with the onset of lockdown measures during COVID-19, global energy demand dropped precipitously, with less industrial production (International Energy Agency 2020). The International Energy Agency estimated overall energy demand contracted by 6%, with a concurrent reduction in the use of fossil fuels and a shift towards renewable energy sources, inclusive of hydropower. As a consequence, hydropower production appears to have changed little during the crisis and thus regulated flow patterns have been sustained. Consequently, little relief from the impact of hydropower operations on freshwater fish populations and biodiversity is expected.

Habitat loss and alteration

Hydropower dams, aggregate mining, pollution, and land-use change have all been implicated in the extensive degradation and loss of freshwater habitats (Dudgeon 2019). Depending on geographical region, key anthropogenic stressors of freshwater habitats have both declined as well as increased under COVID-19. In India, the combined effects of reductions in pollution and commercial activity are predicted to improve habitat quality in the Ganges, facilitating/improving spawning migrations of the anadromous hilsa (*Tenualosa ilisha*; Anon, 2020). Despite some evidence of improvements in habitat quality, it is uncertain whether these reduced impacts will continue and help rejuvenate these systems, or whether efforts to kick-start economies during pandemic recovery will aggravate threats and intensify habitat loss.

Indeed, many examples exist where habitats and entire ecosystems have suffered greater damage during COVID-19. In India, sand mining, an emerging threat to freshwater ecosystems (Koehnken et al., 2020), increased due to reduced enforcement mechanisms (Kannan, 2020), but was considerably reduced in other parts of South Asia (e.g., Sri Lanka and Bangladesh) due to lockdown and associated mobility issues (S. Lockett Pers. Comm.). In the Amazon, deforestation rates increased by 55% from January to April 2020, compared with the same period in 2019 (Brown, 2020) due to reduced enforcement (Schwarts et al., 2020). This is intensifying pressures on the already vulnerable freshwater ecosystems of the region (Castello et al., 2013).

Climate change

Climate change is a widely recognized threat to freshwater fish populations (Lynch et al., 2016a). COVID-19 and associated changes in global emissions could reduce climate impacts over the short term, indirectly benefitting freshwater fishes. Global travel restrictions and reduced industrial activity have dramatically decreased fossil fuel consumption worldwide

(Gössling et al. 2020). These large-scale changes have resulted in a temporary reduction in CO_2 emissions during lockdown (average reduction of 26%, Le Quere et al., 2020). The timescale of these reductions is likely too short to affect long-term climate change trends or freshwater habitat conditions, yet these temporary shifts could translate to longer term change depending on societal responses, i.e., whether economic recovery efforts follow a return to 'business as usual,' or instead, embrace the implementation of new climate policies that drive further reductions in energy use and shifts to clean energy. A shift towards working from home could be a significant longer-term change that reduces emissions (Hern 2020). Perhaps the most important long-term consequence of COVID-19 on climate change is the unplanned global experiment revealing that dramatic reductions in carbon emissions are possible if societal and political will exist. Whether this realisation, together with a renewed public exposure to scientific evidence as a result of COVID-19 media coverage, will alter societal willingness to address climate change is unknown.

While there have been some short-term wins for the environment due to the pandemic, they may be counterbalanced by other losses. In Brazil, decreased emissions related to fossil fuels were offset by increased deforestation in the Amazon (SEEG, 2020). Similarly, electricity consumption has generally decreased in response to lockdowns, largely due to reduced demand from commercial and industrial users (e.g., forecasted decline of 4.2% in the US in 2020, US EIA, Short-term energy outlook July 2020). Additionally, some environmental regulations have already been rolled back. In California, USA, for example, a law passed in 2016 banning restaurants and grocery stores from providing single-use plastics to customers was suspended in April-2020 by Executive Order N-54-20 due to health concerns. Plastics have a large carbon footprint (Zheng and Suh, 2019); they are energy-intensive to produce and transport, and contribute substantially to greenhouse gas emissions when incinerated. Importantly, there is a risk that COVID-19 has taken attention away from climate change as a preeminent world 'crisis.' Given the manifold effects of climate change on freshwater fish, diversion of attention from climate change may harm fish populations and the fisheries and communities that rely on them.

Exploitation

Overexploitation of freshwater fishes is another major driver of freshwater biodiversity loss (Reid et al. 2018 and references therein). The immediate impact of COVID-19 on freshwater fisheries differs regionally and between sectors and is closely tied to market demands and consumer behaviour. Small-scale freshwater fisheries were impacted by reduced demand during the initial phases of the pandemic, resulting in reduced harvest. In Maine (USA), the reduced demand for juvenile eels (*Anguilla rostrate*) resulted in a 75% reduction in market price (Chase, 2020a) and in Ontario, Canada, the closure of restaurants and supermarket fish counters delayed the start of the fishing season on Lake Erie (Chase, 2020b). Similar economic conditions combined with movement restrictions has reduced pressure on freshwater fisheries in Brazil, Namibia, India, and China (Stokes et al. 2020). In Kenya, flood conditions coincided with COVID-19 which collectively led to reductions in fish harvest in inland waters (Auru et al., 2020). Challenges in data collection of diffuse, small-scale fishing activities limit analysis of the pandemic on exploitation at this point in time. However, observed changes potentially impacting exploitation include changes in preference for local fishes (OECD 2020), export bans on fish products (Pisei 2020), and altered fisher behaviour (Indian Council of Agricultural Research 2020a, 2020b). There were also extensive restrictions on recreational fisheries in some regions (e.g., across much of North America; reviewed in Paradis et al., In Press; and in South Africa). Some recreational fisheries closures or other restrictions that limit access and reduce effort may reduce fishing mortality (i.e., harvest or catch-and-release mortality) but we are unaware of any data to support that idea.

Over the longer term, however, the impacts of COVID-19 can be expected to amplify exploitation and unsustainable fishing practices. Freshwater fisheries make important contributions to the food, nutritional, and income security of rural people in the developing world. Even under normal conditions, many rural people fish as part of diversified livelihood strategies, and in times of crisis when other options are reduced, fishing has a well-documented safety net function (Smith et al. 2005; Martin et al. 2013). Job losses in urban areas and the return of migrant workers to their rural homes (Mukhra et al., 2020) will increase fishing effort and may lead to fishing practices that will impact negatively on imperilled fishes, such as the Critically Endangered hump-backed mahseer (*Tor remadevii*; Pinder et al., 2020). This is coupled with evidence of increased illegal fishing activities because of reduced surveillance and enforcement activities.

Increased effort and exploitation have also been documented in many recreational fisheries around the world as many people have sought outdoor spaces while under lockdown and many countries have incentivized recreational fishing as a socially-distanced activity (e.g., free fishing days). Many areas are seeing an increase in the sales of fishing licenses relative to the same periods in 2019, including Texas, USA (39 % increase; CBS Local 2020), Vermont, USA (resident license have increased 50%, Gribkoff and Trombly, 2020), England (increase of 120% in rod licenses; Cuff, 2020), among many other fisheries worldwide. In some areas, restrictions have affected international travel for recreational fishing and related tourism (Gössling et al. 2020), which is likely to reduce local income and compromise co-management agreements aimed at maintaining high abundances of large-bodied freshwater fishes for recreational anglers. Examples include conservancies for tigerfish (*Hydrocynus vittatus*) in Namibia (Cooke et al., 2016), *Arapaima* spp. in Guyana (Lynch et al., 2016b), and mahseer (*Tor* spp.) in India (Pinder and Raghavan, 2013). In northern Thailand, despite no restrictions on in-country travel, several communities temporarily blocked access to self-governed fish reserves by even compatriot anglers out of fear of introducing COVID-19 locally, forgoing important revenues during the tourism season. For many, the lost income from decreased fishing tourism might be replaced by an increase in fishing effort to supplement food sources and income.

COVID-19's modulating effect on conservation/management

Enforcement and policy compliance

Strong regulation and policies are important for arresting the global decline in freshwater biodiversity (Dudgeon et al., 2006; Reid et al., 2019). Enforcement measures are often supported by high levels of regulatory surveillance that encourage user compliance (Eggert and Lokina, 2010) but during COVID-19 lockdown periods these efforts were often restricted (See Figure 2). For instance, some Canadian fisheries and conservation enforcement officers were reassigned to enforce border travel restrictions (Verenca 2020). In China, enforcement has struggled to address increased illegal fishing activities, which usually occur in the winter-spring transition period (e.g., January through March) during the lockdown period. There is evidence that decreased policy compliance of freshwater biodiversity regulations has compromised the protection of some threatened species. For example, Pinder et al. (2020) suggested poaching pressure on large-bodied, threatened fishes, such as mahseers, increased in many developing countries during lockdown, especially in areas where food supply chains and employment levels had collapsed. Indeed, many of the increased exploitation pressures on freshwater fishes during lockdown likely relate to reduced compliance with harvest policies. Food insecurity and reduced enforcement have been suggested as dual causes of increased subsistence fishing (some of which may be illegal) in many regions, including the Mekong, Zambezi system (D. Tweddle pers. comm.), and across South Asia and South America.

In some regions of the world, surveillance for some species and regions, such as in many national parks and protected areas, was maintained (Corlett et al., 2020). Aspects of this were evident in England, where enforcement controls were maintained for conservation priority species (e.g., Atlantic salmon, *Salmo salar*; European eel, *Anguilla anguilla*), despite population monitoring programmes being halted (e.g., Anglers Mail, 2020). Elsewhere, reduced travel has increased policy compliance. For example, the closure of South African nature reserves and national parks increased regulatory compliance as fewer people had access to these areas of conservation importance.

Restoration activities

Every year, considerable effort is devoted to the restoration of aquatic biodiversity focusing on habitat (e.g., wetland creation, stream enhancement) and populations (e.g., conservation hatcheries), with such activities expected to intensify (prior to COVID-19) as we enter the UN Decade for Ecosystem Restoration (Young and Schwartz, 2019). Although restoration remains an imperfect science (Cooke et al., 2019), it is one of the primary ways to mitigate threats to freshwater fishes. For some recently implemented conservation and restoration activities, the reduction in human mobility has allowed for greater success of existing restoration actions (e.g., year-classes of fish protected from angling activity, new habitat not impacted by foot traffic). Many planned or ongoing restoration activities, however, have been reduced or postponed because of COVID-19, particularly those projects involving multiple countries or jurisdictions where international travel/work is necessary (e.g., international research, monitoring projects). Also, many activities involving volunteer groups have been suspended due to concerns about assembling large groups and because many such initiatives rely on volunteers in vulnerable age groups. Where restoration has been undertaken, it has purposefully reduced involvement of local communities who normally provide volunteer labour (e.g., community organizations, students, outdoor clubs). In the Yangtze River Basin, many shoreline restoration projects ceased during the lockdown and in northern China, the largest freshwater restoration initiative in Baiyangdian Lake was stopped because of the lockdown (Y. Chen, Personal Observation). In South Africa, the Working for Water programme, a public works initiative which has a strong focus on removal of alien plants (see van Wilgen et al., 2020), was halted over the lockdown. In the longer term, the need to provide employment in rural areas following the economic impact of COVID-19 may provide for new opportunities to link public-works programmes to well designed and effectively implemented aquatic ecosystem restoration programs.

Public aquaria play an important role in freshwater biodiversity conservation through activities including, but not limited to species reintroduction programs, habitat restoration and ex-situ research programs (see Murchie et al. 2018). The global pandemic has had serious financial implications for numerous nonprofit institutions such as public aquariums, that rely heavily on ticket and membership sales, along with donations to operate (AZA 2020, WAZA 2020, WCS 2020). Indeed, numerous NGOs that play a critical role in public communication of freshwater biodiversity issues and inspire the public to action are currently at risk of losing capacity to maintain the level of engagement that is urgently needed to reverse species loss and restore degraded habitats. However, there have been instances where online engagement has been highly successful. For instance, the biennial World Fish Migration Day reached a greater number of people in 2020 than in its previous three years (Twardek et al. 2020). COVID-19 has also impacted government finances but in some regions there may be federally based stimulus funding, at least over the short-term, to help kick-start economies. NGOs are working to ensure these actions are “green,” including large-scale restoration initiatives (e.g., Carlson and Roe, 2020). Given the urgent need to reverse the decline of biodiversity loss and restore degraded habitats (Tickner et al., 2020), postponing restoration activities (e.g. lack of dam removals, water quality restoration) could have devastating effects on aquatic ecosystems over the longer-term.

Regulations

Fishing, habitat restoration, assessment and enforcement activities were strongly impacted by COVID-19-related restrictions on travel and social distancing guidelines. During full lockdowns, recreational fishing was often initially classified as a non-essential activity while commercial and subsistence fishing was generally permitted as essential. Lobbying efforts by recreational fishing organizations resulted in recreational fishing being given essential status in some jurisdictions in the USA within weeks of initial lockdowns (see Paradis et al., In Press). Outside of strict lockdowns, restrictions persisted with respect to travel distances, congregation at boat ramps and on the water, and the number of people allowed on recreational vessels (Game and Fish, 2020). These restrictions are likely to have resulted in a net reduction and spatial redistribution of recreational fishing effort in the early stages of the pandemic. However, there is also evidence that widespread reductions in working hours and working from home arrangements may have increased the overall level of fishing activity (see above). Due to the suspension of many routine creel surveys and other assessment methods, precise estimates may be difficult to attain, but fishing license sales appear to have increased in many jurisdictions world-wide.

Concurrently, enforcement of fishing and environmental regulations has generally declined during the pandemic due to restrictions on travel and face-to-face interactions by enforcement personnel. Many agencies such as the USA Environmental Protection Agency have explicitly and temporarily relaxed certain reporting requirements and enforcement actions, but not the regulations being enforced (Beitsch 2020). Such actions have fueled widespread speculation in many countries, including the USA and South Africa, that there will be a push to relax environmental regulations to aid economic recovery from COVID-19. There may also be efforts to push through deregulation efforts at times when press coverage is focused on COVID-19 issues. On the other hand, government programs to promote recovery may fast-track modernization of certain industries, for example adoption of ‘smart irrigation’ technologies in agriculture, which may result in an overall reduction of agricultural water withdrawals and in

South Africa, the Inland Fisheries Policy may be fast-tracked to help deal with COVID-19 impacts.

Monitoring and stock assessment

The COVID-19 crisis has resulted in disruptions to routine environmental monitoring (Cheval et al., 2020) and impacted fisheries management and stock assessment practice (FAO, 2020) across the globe. Government-mandated suspension of environmental assessments and protections for freshwater ecosystems have been reported for Canada (Paterson et al., 2020), the USA (Beitsch, 2020), India (Chandrashekhar, 2020), and Brazil (Spring, 2020), and mobility restrictions for environmental managers have meant reductions in the monitoring of populations, watersheds, and fishery landing sites (FAO, 2020). In the UK, monitoring and stock assessment were suspended during lockdown. For anadromous fishes that are only present in UK rivers in spring (e.g., European shads, *Alosa* spp.; sea lamprey, *Petromyzon marinus*), the opportunity to collect data on their 2020 migrations has been lost, and as lockdowns persist and are reinstated, information on other migratory species like Atlantic salmon and sea trout (*Salmo trutta*) will be missed. In China, complete lockdown of Hubei Province and the city of Wuhan – China's epicentre of freshwater fisheries research – has resulted in major reductions in fish monitoring activities. In Brazil, many fish monitoring projects have been paralyzed during the pandemic resulting in large data gaps.

Although closures of formal fisheries in many regions during lockdown have caused temporary reductions in usual harvest pressures (FAO 2020b), interruptions to other food production sectors have led many local communities to rely on freshwater fisheries as an emergency food source (Pinder et al., 2020). An influx of inexperienced fishers and introduction of more damaging gear types might lead to increased risk of overexploitation to nearshore stocks as fishers target these more accessible habitats. Although reductions in monitoring capacity were initially predicted to be short-term (Cheval et al., 2020), in several cases suspensions have extended throughout 2020 and will presumably extend into 2021. As lockdowns are lifted, there will be a critical need to undertake rigorous assessments to understand the longer-term responses of fish biodiversity impacts and their recovery. However, such increased monitoring might not be adequately funded. A potential positive outcome of COVID-19 is that, in some regions, the restriction of human activity represents a major change from the norm and thus is an opportunity to study the effects of humans on freshwater ecosystems (e.g., Bates et al. 2020). Of course, this will only be possible in instances where stock assessment and monitoring occurred during the pandemic lockdown.

Research on freshwater fish biodiversity

Shelter-in-place policies enforced by governments and research institutions have resulted in suspensions and cancellations to both laboratory and field-based research (Corlett et al., 2020, Wilson, 2020). In many countries (e.g., Canada, USA, UK, Germany), freshwater biodiversity research has been suspended for much of 2020 (Bath, 2020; Wilson, 2020; Bunk, 2020). Research activities that have been maintained are primarily maintenance-related (i.e., caring for populations of live fish, upkeep of sensitive battery-powered monitoring equipment) and ensuring long-term monitoring activities in only limited situations. In southern Africa, research on the upper Zambezi floodplains has been suspended despite one of the largest flood years on record. In Asia, major international research initiatives on the Mekong River have been delayed, and in India all freshwater studies, including laboratory and field-based work, were suspended for at least two months. For some research programs, the height of the lockdown coincided with key monitoring months. In India, for example, research on subterranean (e.g., cave, aquifer) aquatic biodiversity during summer months (i.e., May through August) is facilitated by low water levels, and even short lockdowns during that timeframe have resulted in an entire year of research on these species being lost. The consequence of suspended or cancelled research on aquatic biota is that the status of populations, stocks, and migrations are not being appraised. This is of particular concern for endangered fishes and sensitive, threatened freshwater ecosystems. Furthermore, halting research – especially in the long term – could result in overlooking conservation priorities or opportunities to protect freshwater resources (Corlett et al., 2020). In most cases, research is expected to resume as pandemic restrictions are lifted, but there is concern that the economic consequences of lockdowns will limit research funds, typically available from governments and conservation foundations. Reductions in funding could permanently halt or diminish conservation programs around the globe (Corlett et al., 2020).

A silver lining for some researchers unable to conduct field research is the increased time for the analysis and publication of pre-existing data. Yet, not all researchers have benefitted equally and long-lasting productivity disparities are emerging (see Viglione, 2020). For example, journal submission rates during the pandemic have increased for male researchers but decreased for female researchers, a result with high potential to exacerbate existing gender-based inequalities in publishing and pay rates through reductions in women being granted tenure (Collins, 2020). It is unclear how this will influence those working in the realm of freshwater fish biodiversity.

Training and capacity building

Freshwater fisheries science and management is inherently hands on – whether setting nets, identifying fish species in local markets, or conducting door-to-door harvest studies in rural communities. These activities (as well as the examples related to restoration, research, etc outlined above) all depend largely on trained fisheries professionals. COVID-19 has changed college and university education in many ways with cancellation of field-based internships and rapid transition to online instruction (Bao, 2020). Some aspects of fisheries science training can be adapted to online formats with relative ease (e.g., quantitative stock assessment) yet we require fisheries practitioners to interact directly with fish, habitats, and people (Hard, 1995). Consequently, there is concern that there is a cohort of trainees that are currently moving through the system that may not have hands on training experiences needed to engage in various activities that span and integrate the natural sciences, health, humanities and social sciences. Graduate students that are conducting their research in 2020 may be delayed and mental health issues among this cohort are on the rise (Langin 2020). Due to the financial constraints facing doctoral students, the proportion expecting they will drop out has increased greatly (Johnson et al. 2020). In the Anthropocene, we are in desperate need for the next generation of environmental professionals to be well equipped for solving complex problems (Jeanson et al., 2020) and that will be impeded if training is incomplete and limited to text books and videos. Similarly, freshwater fisheries practitioners around the world routinely participate in professional development (continuing education) training courses to improve their skills and proficiency

(Rassam and Eisler, 2001). In some regions where freshwater fisheries science and management capacity is lacking, efforts focused on capacity building are crucial to enable effective local governance and science-based fisheries management (Espinoza-Tenorio et al., 2011). Both professional development and capacity building have been severely hampered by COVID-19. As educators and trainers adapt their curricula, pedagogy, and delivery to COVID-19 realities (see Singh et al. 2020 for example of how medical school has adapted), there is certainly need for creativity to ensure that learners are provided with opportunities to learn through experiential means. There is also uncertainty regarding how COVID-19 may alter enrollment in fisheries-relevant programs. If students perceive such programs to be less desirable given lack of opportunity for experiential education, they could be declines in enrollment which could have consequences for the profession and freshwater ecosystems.

The rapid transition to online formats for many facets of work also creates opportunities to normalize virtual conferences and even participating remotely once in-person opportunities resume. Online formats have low barriers to participate and can increase engagement for those typically unable to travel due to financial burdens, other obligations, or both. Subsidies for international participation (particularly from Low and Middle Income Countries) and on-demand formats can accommodate asynchronous participation across time zones.

Beneficial outcomes and opportunities for freshwater fish biodiversity stemming from COVID-19

Turning short-term benefits to aquatic ecosystems into long-term opportunities for freshwater fish conservation will involve harnessing newly found environmental stewardship. Increased participation in freshwater fisheries activities during the COVID-19 crisis is evident globally, be it in response to food or income security or for recreation. The crisis has highlighted important benefits of inland fisheries, their contributions to social and economic resilience, and the need to conserve and restore the ecosystems upon which they depend. Importantly, these benefits and needs transcend socio-economic strata and geographical boundaries. Increased angling licence sales can contribute to funding increases for fisheries management and potentially greater freshwater fish biodiversity conservation through increased stakeholders and advocates. New and more energized stakeholders can push for broader policies for improved water quality and restoration of freshwater ecosystems. However, we are unaware of any evidence showing that increases in angling interest yield improvements in stewardship. An important step forward is the recent EU strategy on biodiversity for 2030 (released in May 2020) that provides substantial funding to restore connectivity in European rivers. In pandemic recovery mode, as public work programmes are used to rebuild national economies (e.g., Subbarao et al., 2012), conservation initiatives may serve as a foundation for efforts, especially in rural areas. South Africa's Working for Water programme, which pursues conservation, employment, and development (Turpie et al., 2008), could be a model for other public works initiatives.

COVID-19 may also expand certain horizons for freshwater fish biodiversity research. Agricultural frontiers in Brazil, for example, have been linked to infectious diseases leading to calls for more research and conservation (Zimmer, 2019). As there will be greater interest in and funding availability for zoonotic diseases such as COVID-19, 'One Health' approaches that integrate human, animal, and ecosystem health through transdisciplinary research (Osofsky et al., 2005; Zinsstag et al., 2011; Nunez et al., 2020) will be essential components of research portfolios to optimize outcomes for both people and aquatic environments. There is also an opportunity to push for holistic public health systems that recognize the importance of ecosystem health (including fish and aquatic resources) in human health.

Management and policy needs to mitigate negative impacts of COVID-19 on freshwater fish and fisheries and make them resilient to future pandemics

Although we identified a number of benefits for freshwater fish biodiversity arising from COVID-19, there were also a number of negative outcomes or issues identified that will require management or policy actions (Figure 3). Relaxation of regulations in several countries during the pandemic (where environmental issues were already considered as a low priority) is a major concern for freshwater biodiversity (Kavousi et al., 2020). The same scenario will likely continue, and may even be exacerbated, as countries rebuild their economies and bureaucratic hurdles (environmental safeguards) are removed. To ensure biodiversity is not overlooked, it will be essential to link fish biodiversity and environmental integrity to the many other benefits for humanity (e.g., livelihoods, health, well-being), as well as to ensure sustainable fisheries are available into the future (Brooks et al., 2016).

Adequate environmental policies depend on the active participation of the scientific community (Azevedo-Santos et al., 2017), and on the collection of robust data to support management actions (Brooks et al., 2016, Radinger et al., 2019). Both aspects were directly affected by COVID-19, and the related consequences deserve to be evaluated and monitored. The lack of detection and measurement of the direction of possible changes in freshwater fish populations during the pandemic period is a major concern. There is a need for increasing monitoring, control, and surveillance in the short term, and large-scale restoration projects should be resumed as soon as the pandemic returns to a relatively stable situation. While the mobilization of organized civil society, including academia, is necessary to avoid environmental setbacks and their effects on aquatic biodiversity, different measures can be taken to alleviate potential negative consequences on freshwater fish and fisheries during future pandemics or lockdowns. These measures include investing in more contingency planning for research and management, and maintaining necessary management and monitoring programs instead of complete lockdown. The need to stimulate depressed economies provides an opportunity for employment in conservation and restoration programs (similar to the Civilian Conservation Corps in the U.S. during the Great Depression).

1-2 Years from 2020

The potential state of freshwater fish biodiversity in the short-term (i.e., one to two years from now) will depend on the state of the pandemic and how society responds in the post-pandemic recovery phase. If the pandemic is ongoing, a possibility given the current increasing global trend in case numbers, then many of the impacts described above are likely to remain relevant. The state of fish populations under the pandemic recovery scenario will be varied across regions and jurisdictions, primarily determined by localised activities, circumstances, and responses.

One to two years from now, we anticipate freshwater fish biodiversity at the global scale will be in a similar or improved condition relative to if the pandemic had not occurred. Improvements to freshwater habitat quality resulting from the global 'pause' in economic development and declines in human disturbance, adapted fishing activities, and reduced pollution all have the potential to benefit fish populations (Rutz et al. 2020). However, the relatively short-time scale of the lock-down period means freshwater fishes are unlikely to exhibit substantial long-term changes.

However, in some regions of the world, freshwater biodiversity may be in a worse state immediately after the pandemic relative to how things would have been otherwise. Aquatic ecosystems, specifically in and around urban areas, may be degraded by COVID-19-related products (e.g., masks, disinfectants, hand-sanitizers, and other pharmaceutical chemicals; Aragaw 2020). Trade disruptions and loss of income will likely increase exploitation of more accessible and lower value freshwater fisheries, some of which may be already threatened (e.g., Pinder et al. 2020). Increased water use for irrigated agriculture may compound pre-existing threats to freshwater fishes, especially in semi-arid regions.

The pandemic has revealed serious flaws in the global food and public health system, which is far from sustainable or equitable (FAO 2018). The pandemic has also heightened political tensions both within and among countries; global trade has been impacted and this may extend to fish and fish products. Indeed, there are already disputed news articles about COVID-19 being spread by salmon and shrimp (Bloomberg 2020). Freshwater fishes in many areas play an important, but largely undocumented, role in local and regional food and nutrition security, trade, and commerce. It is unclear what the impacts of COVID-19 will be for local communities, freshwater fisheries, and biodiversity, but more intense fishing, increased illegal, unreported, and unregulated (IUU) fishing (albeit this is relatively uncommon in freshwater given that fishing is usually smaller-scale subsistence fishing), and decreased fish availability are likely outcomes. Given the food security implications of COVID-19, these impacts could be immediate in many parts of the world.

5 Years from 2020

On a longer-time scale (i.e., five years), the future state of freshwater fisheries is very likely to be worse than if the pandemic had not occurred. Society's prioritisation of economic and societal recovery in the post-pandemic phase may pause or demote environmental concerns and expenditure on restoration programs. Indeed, India has already given the green light to controversial development projects during the COVID-19 lockdown period (following relaxed environmental assessment processes; Kaggere and Bengaluru 2020) and the impacts on wildlife will be felt in this later period. Eagerness to return to economic growth may lead to a rebounding period that ultimately accelerates and compounds threats to freshwater fishes existing prior to the pandemic. This dynamic may play out to a greater extent in developing regions because of increased prevalence of food insecurity caused by the pandemic.

Some of the longer-term negative impacts on freshwater fisheries will be caused by actions taken during the pandemic period. Disruptions in monitoring and interrupted education and training create data and knowledge gaps that will compromise the ability to make robust sustainable fisheries and conservation decisions. Economic impacts, including the evolving recession and the necessary redirection of funding to human health and other priorities, could greatly compromise important resource management and conservation activities, such as the IUCN Red-List assessment. Indeed, the systems most at risk, and thus heavily reliant on management interventions, will be those impacted greatest by the weakening of fish conservation activities.

The importance of strong environmental policy to protect biodiversity will be emphasised by this pandemic. For example, adoption of the EU Water Framework Directive and Biodiversity Strategy will likely mitigate many of the threats caused by the pandemic to freshwater fishes in Europe. Moreover, an opportunity exists in the creation of new societal behaviors from the global ‘pause,’ and this could manifest as new policy more adept in protecting biological diversity, including freshwater fishes, across the world (Bates et al. 2020). This pandemic provides a global wake-up call to recognise the need to invest in science and policy agendas that allow for preparedness to confront such a crisis. The impacts on freshwater fish populations and biodiversity that result from COVID-19 will largely compound existing stressors that are well known. While supporting science and understanding of these issues are well-established (FAO SOIFR 2019, Beard et al. 2011, Reid et al. 2019), it is a commitment to continued funding and implementation of remedial interventions that is needed to ensure the sustainability of freshwater fish biodiversity, fisheries, and their ecosystems into the post-pandemic future.

Figure Captions

Figure 1. COVID-19 impacts to existing threats on freshwater fish, where positive (+) impacts mitigate and negative (-) amplify threats.

Figure 2. COVID-19 impacts to conservation and management of freshwater fish, where positive (+) impacts mitigate and negative (-) amplify threats.

Figure 3. COVID-19 effects and management needs to alleviate potential negative consequences on freshwater fish and fisheries during future pandemics.

Figure 1.

COVID-19 Impacts to Existing Threats on Freshwater Fish
Positive
Negative
Invasive Species
• Reductions in invasive species movements associated with reduced global trade and travel.
• Constraints on citizen science programs focused on invasive species.
Pollution
• Reductions in industrial pollution due to plant shutdowns.
• Increases in home sewage production and food waste with shelter-in-place orders.
Fragmentation
• Slowed hydropower development in some regions.
• Relaxation of environmental regulations to expedite economic recovery.
Flow Regulation
• Initial reductions in irrigation and industrial water use during lock downs.
• Increased pressure on water sources serving residential areas.
Habitat Loss
• Delayed industrial development in some regions.
• Proliferation of illegal activities that harm fish habitat under reduced environmental enforcement.
Climate Change
• Opportunities to transition to greener infrastructure with reductions in greenhouse gas emissions.
• Diversion of public and political attention from climate change issues.
Exploitation
• Reductions in fishing effort and harvest during early phases of lock down.
• Increased fishing effort and harvest with prolonged lock downs, loss of income, need for food, and time for recreation.

Figure 2.

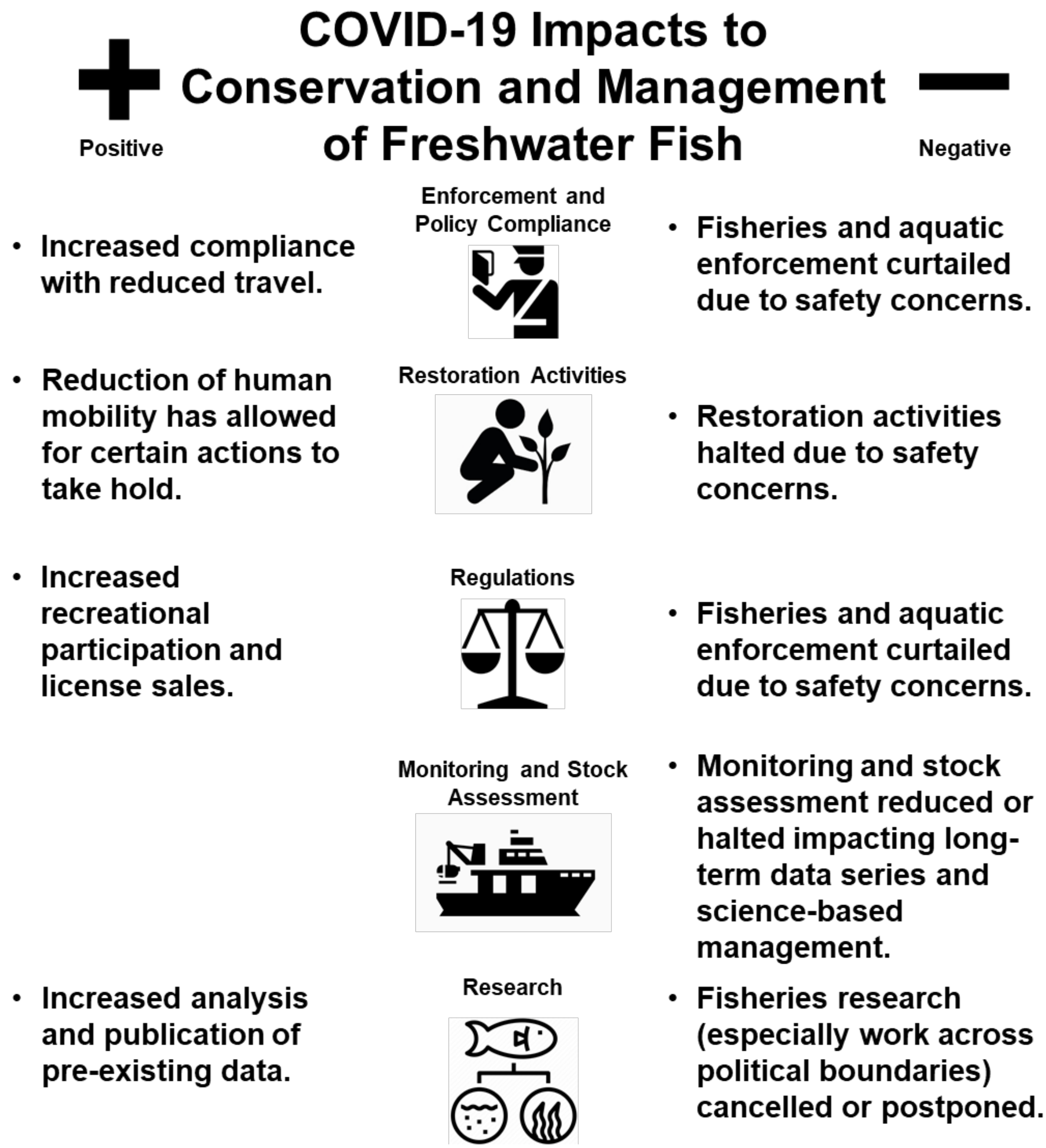
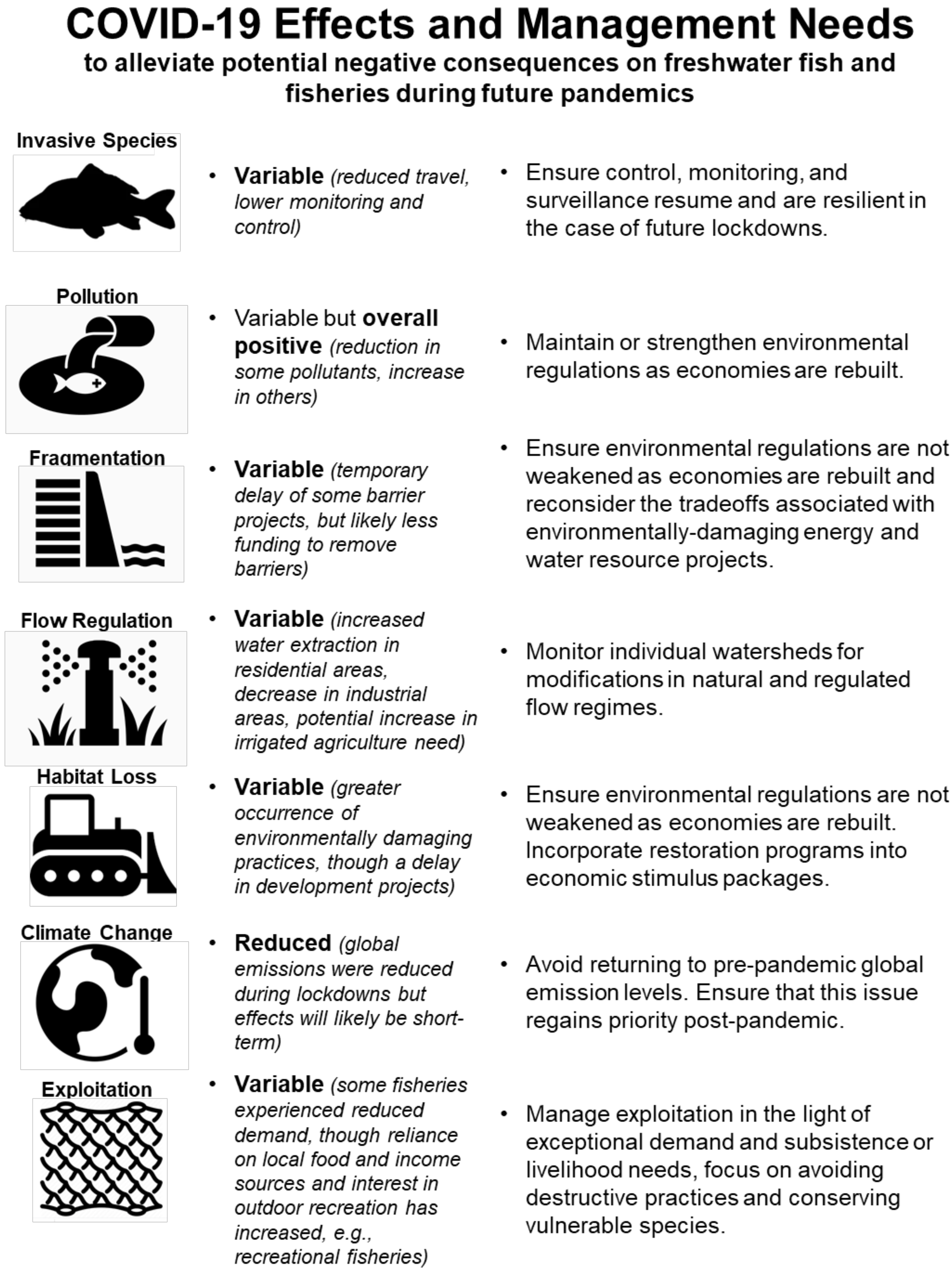

COVID-19 Impacts to Conservation and Management of Freshwater Fish
Positive
Negative
Enforcement and Policy Compliance
• Increased compliance with reduced travel.
• Fisheries and aquatic enforcement curtailed due to safety concerns.
Restoration Activities
• Reduction of human mobility has allowed for certain actions to take hold.
• Restoration activities halted due to safety concerns.
Regulations
• Increased recreational participation and license sales.
• Fisheries and aquatic enforcement curtailed due to safety concerns.
Monitoring and Stock Assessment
• Monitoring and stock assessment reduced or halted impacting long-term data series and science-based management.
Research
• Increased analysis and publication of pre-existing data.
• Fisheries research (especially work across political boundaries) cancelled or postponed.

Figure 3.


COVID-19 Effects and Management Needs
to alleviate potential negative consequences on freshwater fish and fisheries during future pandemics
Invasive Species
• Variable (reduced travel, lower monitoring and control)
• Ensure control, monitoring, and surveillance resume and are resilient in the case of future lockdowns.
Pollution
• Variable but overall positive (reduction in some pollutants, increase in others)
• Maintain or strengthen environmental regulations as economies are rebuilt.
Fragmentation
• Variable (temporary delay of some barrier projects, but likely less funding to remove barriers)
• Ensure environmental regulations are not weakened as economies are rebuilt and reconsider the tradeoffs associated with environmentally-damaging energy and water resource projects.
Flow Regulation
• Variable (increased water extraction in residential areas, decrease in industrial areas, potential increase in irrigated agriculture need)
• Monitor individual watersheds for modifications in natural and regulated flow regimes.
Habitat Loss
• Variable (greater occurrence of environmentally damaging practices, though a delay in development projects)
• Ensure environmental regulations are not weakened as economies are rebuilt. Incorporate restoration programs into economic stimulus packages.
Climate Change
• Reduced (global emissions were reduced during lockdowns but effects will likely be short-term)
• Avoid returning to pre-pandemic global emission levels. Ensure that this issue regains priority post-pandemic.
Exploitation
• Variable (some fisheries experienced reduced demand, though reliance on local food and income sources and interest in outdoor recreation has increased, e.g., recreational fisheries)
• Manage exploitation in the light of exceptional demand and subsistence or livelihood needs, focus on avoiding destructive practices and conserving vulnerable species.

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