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PERSPECTIVE

Scientists' warning to humanity on the freshwater biodiversity crisis

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Abstract Freshwater ecosystems provide irreplaceable services for both nature and society. The quality and quantity of freshwater affect biogeochemical processes and ecological dynamics that determine biodiversity, ecosystem productivity, and human health and welfare at local, regional and global scales. Freshwater ecosystems and their associated riparian habitats are amongst the most biologically diverse on Earth, and have inestimable economic, health, cultural, scientific and educational values. Yet human impacts to lakes, rivers, streams, wetlands and groundwater are dramatically reducing biodiversity and robbing critical natural resources and services from current and future generations. Freshwater biodiversity is declining rapidly on every continent and in every major river basin on Earth, and this degradation is occurring more rapidly than in terrestrial ecosystems. Currently, about one third of all global freshwater discharges pass through human agricultural, industrial or urban infrastructure. About one fifth of the Earth's arable land is now already equipped for irrigation, including all the most productive lands, and this proportion is projected to surpass one third by midcentury to feed the rapidly expanding populations of humans and commensal species, especially poultry and ruminant livestock. Less than one fifth of the world's preindustrial freshwater wetlands remain, and this proportion is projected to decline to under one tenth by midcentury, with imminent threats from water transfer megaprojects in Brazil and India, and coastal wetland drainage megaprojects in China. The Living Planet Index for freshwater vertebrate populations has declined to just one third that of 1970, and is projected to sink below one fifth by midcentury. A linear model of global economic expansion yields the chilling prediction that human utilization of critical freshwater resources will approach one half of the Earth's total capacity by midcentury. Although the magnitude and growth of the human freshwater footprint are greater than is generally understood by policy makers, the news media, or the general public, slowing and reversing dramatic losses of freshwater species and ecosystems is still possible. We recommend a set of urgent policy actions that promote clean water, conserve watershed services, and restore freshwater ecosystems and their vital services. Effective management of freshwater resources and ecosystems must be ranked amongst humanity's highest priorities.

Keywords Aquatic biodiversity · Conservation · Ecosystem services · Freshwater · Groundwater · Wetlands

THE HUMAN FRESHWATER FOOTPRINT

Global civilization is reaching important boundaries of what the Earth's biosphere can support (Steffen et al. 2015). Human activities are altering the distribution and flows of surface, subsurface and atmospheric waters at regional scales, undermining the resilience of aquatic, riparian and coastal ecosystems (Rodell et al. 2018). In clarion calls published over the past quarter century (see Ripple et al. 2017, 2019) the world community of scientists has identified eight global and overlapping trends of environmental deterioration, all of immediate concern for human happiness and prosperity (Heino et al. 2009; Vörösmarty et al. 2010). Freshwater ecosystems are central to five of these trends: declining freshwater availability, forest

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loss, dwindling biodiversity, climate change, and human population growth. Although the profound consequences of anthropogenic activities on the biosphere are widely appreciated, freshwaters are often missing from the discussion (e.g., Lenton et al. 2019).

Freshwater (< 500 ppm dissolved salts) is a renewable, but effectively finite, natural resource. Well-managed watersheds and waterbodies provide critical ecosystem services that maintain local and regional hydro-climatic regimes, and support human food and energy production, waste disposal and remediation, transportation, and recreation (Aldaya et al. 2012; Hoekstra and Mekonnen 2012). Freshwater ecosystems are also among the most diverse per unit habitat volume on Earth, with more than 140 000 species (i.e., fungi, plants, invertebrates, and vertebrates; c. 12% of all described species) compressed into just ∼ 2% of the world's surface area, and a minute ∼ 0.007% of the total planetary water supply (Reid et al. 2019). Freshwater species and ecosystems are increasingly threatened by many human activities, including habitat alteration, water pollution, overfishing, exotic species introduction, river diversions, fragmentation and flow regulation, expansion of agricultural and urban landscapes, climate change, rising sea levels and altered precipitation regimes (Dudgeon 2019; Grill et al. 2019; IPBES 2019).

Withdrawals and diversions (Jaramillo and Destouni 2015) as well as agricultural expansion and intensification (Destouni et al. 2013) are main threats to freshwater availability and quality (Destouni and Jarsjö 2018), while fragmentation and flow regulation (Winemiller et al. 2016) are main threats to freshwater biodiversity by altering rivers, floodplain lakes, wetlands and estuaries. Dams transform river basins by creating artificial lakes locally, fragmenting river networks, and greatly distorting natural patterns of sediment transport and seasonal variations in water temperatures and flows (Latrubesse et al. 2017). Altered flow seasonality in rivers has led to less diverse fish assemblages, decreased inland fisheries production, less stable bird populations and lower riparian forest production (Jardine et al. 2015; Kingsford et al. 2017; Sabo et al. 2017). Sediment retention by dams leads to delta recession (Luo et al. 2017) and degraded coastal fisheries and tropical mangrove forests, indirectly affecting carbon storage that reduces greenhouse gas emissions in the latter case (Atwood et al. 2017). Dams also prevent upstream–downstream movement of freshwater animals, facilitate settlement of non-native species, cause local species extirpations and replacements and increase risk of waterborne diseases in reservoirs and highly altered environments by modifying productivity (Fenwick 2006; Poff and Schmidt 2016). The fragmentation of river corridors also reduces population sizes and gene flows of aquatic species, increasing species extinction risks (Cohen et al. 2016a, b; Dias et al. 2017).

At present humans divert > 10 000 km^3 of freshwater per year for agriculture, industry and domestic uses, an amount that represents about 30% the average flow of all continental waters discharging to the sea or to recharge aquifers. The proportion of river discharge diverted for human activities exceeds 50% in the most densely populated areas of Eurasia. Water withdrawals and diversions currently cause about one-quarter of the world's rivers to run dry before reaching the ocean, and have drained major inland water bodies like the Aral Sea in Central Asia (Destouni et al. 2013) and Lake Urmia in Iran (Khazaei et al. 2019). Worldwide, agriculture accounts for about 70% of all freshwater usage, compared to 20% for industry and 10% for domestic uses (FAO 2016). Human-made dams and irrigation canals are associated with 12-16% of global food production and provide 19% of the world's electricity supply. The volume of water used by the energy sector alone represents about 15% of global freshwater withdrawals, and extracting and processing freshwater represents about 19% of total usage by the energy sector (Fricko et al. 2016). The amount of freshwater withdrawal varies substantially among regions, from < 10% of total runoff in some counties at high latitudes with cold climates or in tropical regions with high rainfall, to > 75% in arid areas of northern Africa, the Middle East and Australia (FAO 2016). Overall, the human freshwater withdrawals and diversions are now altering the distribution of water in the hydrosphere at regional scales. Damages are seen in the total area of anthropogenic (urban and agricultural) modified landscapes worldwide, wetlands reduction, and amount of surface and subsurface flows that have been diminished or degraded (Gleeson et al. 2016). The changes in water use, distribution and flows are combined with changes in climate and human population and land use, to impact biodiversity and ecosystem services (Elmhagen et al. 2015).

With regard to agriculture, just over 3 million km^2 are currently under cultivation worldwide, representing 22% of the total land area that is theoretically available for cultivation, with the most productive lands already long since under irrigation in most countries. Agricultural expansion and intensification in the landscapes increase evapotranspiration (Destouni et al. 2013) and thereby decrease the amount of freshwater runoff and aquifer recharge worldwide (Ceballos et al. 2015). Agricultural practices also degrade the quality and ecological status of the freshwater ecosystems, with status improvements remaining slow and difficult long after environmental regulations have been put in place requiring such improvements (Destouni et al. 2017).

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Due to unprecedented socio-economic advances and demographic shifts over the past 50 years (Crist et al. 2017), human and livestock population and economic growth are driving an ever expanding freshwater footprint (Fig. 1). Freshwater withdrawal and diversions for human uses have more than tripled since the middle of the 20th century, reducing the volume of river flow in more than half of the world's largest rivers. Increased human population and socio-economic activities also increase the pollutant and nutrient loads that deteriorate water quality and ecosystem status across different regions and countries around the world (Destouni and Jarsjö 2018; Levi et al. 2018).

Analysis of historical trends globally provided here shows that freshwaters are being depleted, and ecosystems degraded, even more rapidly than their terrestrial counterparts (Fig. 1; Table 1). Measures of global freshwater withdrawals and total land area equipped for irrigation are rising faster than the human use of terrestrial ecological productivity (Fig. 1a). Similarly, rates of biodiversity loss are greater in freshwater than terrestrial ecosystems (Turak et al. 2017), and freshwater vertebrates (fishes and amphibians) are the most threatened group of vertebrates (Reid et al. 2019). Rates in the decline of both freshwater and terrestrial groups are also closely associated with extent of wetland loss (Fig. 1b). The more rapid increase in threats to freshwater than terrestrial ecosystems arises from the minute total volume of liquid freshwater on the Earth's surface, and from the critical roles that freshwaters serve in human economic systems (Barbier 2017).

Freshwater biodiversity is in sharp decline at many scales. Since 2000, abundances of freshwater insect (Sánchez-Bayo and Wyckhuys 2019; Wagner 2019) and fish populations organisms have become dramatically reduced, at local scales in both temperate (Freyhof and Brooks 2017) and tropical (Cohen et al. 2016a; Pelicice et al. 2017) latitudes, and in different climate zones (Ngor et al. 2018). From 1970 to 2012 populations of vertebrate freshwater

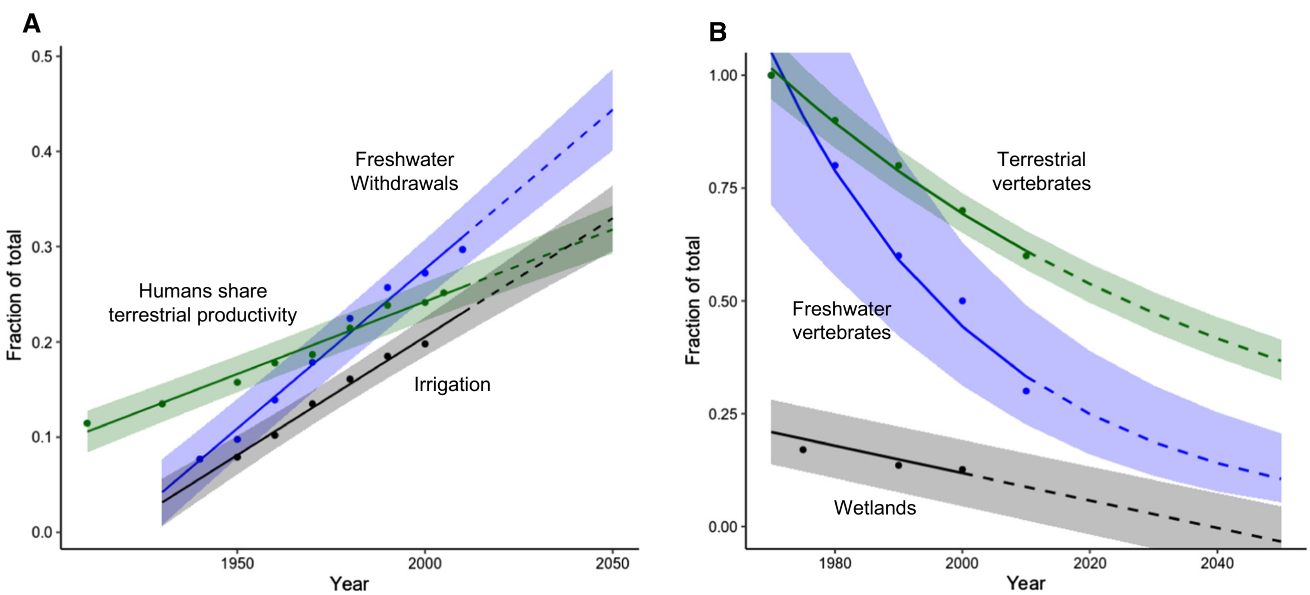

Fig. 1 The expanding human freshwater footprint. **a** Trends in global freshwater resources, assessed as Global Freshwater Withdrawals (blue) and Global Area Equipped for Irrigation (gray). Trend in terrestrial resources assessed as Human Appropriation of Terrestrial Net Primary Productivity (green). Note freshwater utilization is now a stronger limiting factor on human populations than terrestrial utilization. **b** Trends in global biodiversity from a 1970 baseline. Living Planet Index for freshwater vertebrate populations (blue), for terrestrial vertebrate populations (green), and Global Wetland Loss (gray). Global Wetland Loss model fitted to data from 1700 to 2000 and plotted from 1970 to 2050 for compatibility with Living Planet Index datasets. Note rate of biodiversity decline is faster in freshwater than terrestrial systems, and occurring alongside reductions in Global Wetland Loss. The linear model projects global wetlands to disappear entirely by midcentury. Historical estimates as solid curves with 95% prediction intervals. Data as cumulative proportions of global totals. See footnote for methods. Methods for model specifications used to generate future projections (dashed curves) and literature references. Global Freshwater Withdrawals for human use as percentage of total annual river discharge to the sea (c. 36 000 km^3) (Milliman and Farnsworth 2013; van Vliet et al. 2013). Historical estimates from (Shiklomanov and Rodda 2004; Scanlon et al. 2007) adjusted to match the revised human-withdrawal estimate for 2010 of 10 688 km^3 $year^1$ (Jaramillo and Destouni 2015). Irrigation as global area equipped for irrigation or land ready for cultivation as a percentage of total global arable land (*c.* 14 million km^2). Historical estimates from (Scanlon et al. 2007; Ellis et al. 2010; Siebert et al. 2015). Historical estimates of human share of terrestrial net primary productivity from (Krausmann et al. 2013). Population trends as estimated from the Living Planet Index (LP1 from Loh et al. 2005; WWF 2016) evaluated against a 1970 baseline. LPI measures trends in the geometric mean of population abundances. LPI-FW estimates from 3324 monitored freshwater populations representing 881 species (darker curve with circles), and LPI-T for 4658 terrestrial populations of 1678 species (lighter curve with triangles). Note freshwater populations declined an estimated 81% from 1970 to 2012. Wetlands as percentage of pre-industrial total global wetland area at 1700. Historical estimates from (Davidson 2014)

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Table 1 Summary of models used to generate curves in Fig. 1. Note that the historical data abstracted from literature reports used to fit these models do not include estimates of the variability for values at each data point. Therefore, the R^2 and *p*-values have limited utility as estimates of the fit between the models and the data used to generate the models, and the prediction intervals underestimate the true values of future uncertainty. *Abbreviations* GWW, Global water withdrawals; HANPP, Human Appropriation of (terrestrial) Net Primary Productivity; GAEI, Global Area Equipped for Irrigation; LPI-FW, Living Planet Index-Freshwater; LPI-T, Living Planet Index-Terrestrial; GWL, Global Wetland Loss

Trend	Model	R^2	*p*
GWW[a]	− 6.41 + 0.0033 year	0.98	1.20E−06
HANPP[b]	− 2.78 + 0.0015 year	0.98	3.90E−07
GAEI[c]	− 4.77 + 0.0025 year	0.98	6.20E−05
ln(LPI-FW)[d]	56.7 − 0.029 year	0.97	0.0025
LPI-FW[d]	4.2e24e − 0.029 year	0.97	0.0025
ln(LPI-T)[e]	25.1 − 0.013 year	0.99	0.00018
LPI-FW[e]	8.0e10e − 0.013 year	0.99	0.00018
GWL[f]	6.19 − 0.003 year	0.99	4.90E−07

[a]Global water withdrawals (GWW) for human use as percentage of total annual river discharge to the sea (*c.* 36 000 km^3) (Milliman and Farnsworth 2013; van Vliet et al. 2013). Historical estimates from (Shiklomanov and Rodda 2004; Scanlon et al. 2007) adjusted to match the revised human-withdrawal estimate for 2010 of 10 688 km^3 $year^1$ (Jaramillo and Destouni 2015).

[b]Historical estimates of Human Appropriation of (terrestrial) Net Primary Productivity (HANPP) from (Krausmann et al. 2013). Population trends as estimated from the Living Planet Index (Loh et al. 2005; WWF 2016) evaluated against a 1970 baseline.

[c]Global Area Equipped for Irrigation or land ready for cultivation as a percentage of total global arable land (*c.* 14 million km^2). Historical estimates from (Scanlon et al. 2007; Ellis et al. 2010; Siebert et al. 2015).

[d]LPI measures trends in the geometric mean of population abundances. LPI-FW estimates from 3324 monitored freshwater populations representing 881 species. Note freshwater populations declined an estimated 81% from 1970 to 2012.

[e]LPI-T estimates 4658 terrestrial populations of 1678 species.

[f]Global Wetland Loss (GWL) as percentage of pre-industrial total global wetland area at 1700. Historical estimates from (Davidson 2014)

megafauna (defined as fishes, amphibians, reptiles and mammals ≥ 30 kg adult body weight) declined by 88%, with mega-fishes undergoing the largest declines (− 94%, Carrizo et al. 2017; He et al. 2019). The Yangtze basin is among the most impacted of any large river on Earth, with the last citings of two species occurring in the 2000s; i.e., the Yangtze river dolphin †*Lipotes vexillifer* (Turvey et al. 2007), and the Yangtze paddlefish †*Psephurus gladius* (Zhang et al. 2009). The Yangtze paddlefish was the last surviving species of a lineage that originated in the super-greenhouse world of the Mesozoic, with fossils from the Upper Cretaceous about 75 million years ago. Examples of these and several other critically endangered freshwater megafauna species are illustrated in Fig. 2.

The levels of freshwater withdrawal and quality deterioration are well beyond levels that can support existing biodiversity, requisite ecological processes or good ecological status, e.g., as required by the EU Water Framework Directive (Destouni et al. 2017). The largest imminent threats come from megaprojects designed to transfer water among river basins in Brazil and India (Shumilova et al. 2018), and to drain coastal wetlands in China (Cui et al. 2016). The total volume of water planned for near-future diversion megaprojects is projected to exceed 1900 km^3 per year, representing an additional ~ 5% of total global surface freshwater flow (Shumilova et al. 2018). As of this writing ~ 4.0 thousand millions people, or about two-thirds of the world population, experiences severe water scarcity, during at least part of the year (Mekonnen and Hoekstra 2016), and more than one-third of major urban areas globally (those with more than 3 million people) are experiencing high or extremely-high water stress (Sengupta and Cai 2019). Day Zero, the date when a city's water taps go dry, has been narrowly averted recently in São Paulo (Brazil), Chennai (India), Cape Town (South Africa), and Mexico City (Mexico).

The rapid rise of human populations and associated food production (e.g., crops and livestock) is increasing pressures on freshwater resources in many regions of the world. The total biomass of all humans alive today constitutes approximately 60 million metric tons of carbon, which is slightly more than 10 times that of all the remaining wild mammals of the world (Smil 2011). An unsustainable amount of freshwater is used to produce animal livestock. Global populations of domestic ruminants (cattle, sheep, and goats) (Ripple et al. 2013) poultry, and pigs (Bennett et al. 2018) used to feed the growing human population now exceed 100 million tons of carbon (Bar-On et al. 2018), and livestock populations are growing rapidly. Beef production alone consumes about 10 times more resources than other forms of animal protein. Domestic ruminant livestock (~ 4 thousand millions globally) contribute 14.5% of all anthropogenic greenhouse gas emission, especially through the enteric fermentation by ruminants producing methane (Ripple et al. 2013). Ruminant livestock grazing is a direct cause of stream and wetland degradation in many areas (Beschta et al. 2013). Lowering the number of ruminant livestock would have the co-benefits of improving freshwater conditions and mitigating climate change.

The human utilization of both global freshwater and terrestrial resources shows persistent and linear increases over the past half century. A linear "business-as-usual" model is a significantly better fit to the historical data than models with curvilinear asymptotic growth (Fig. 1,

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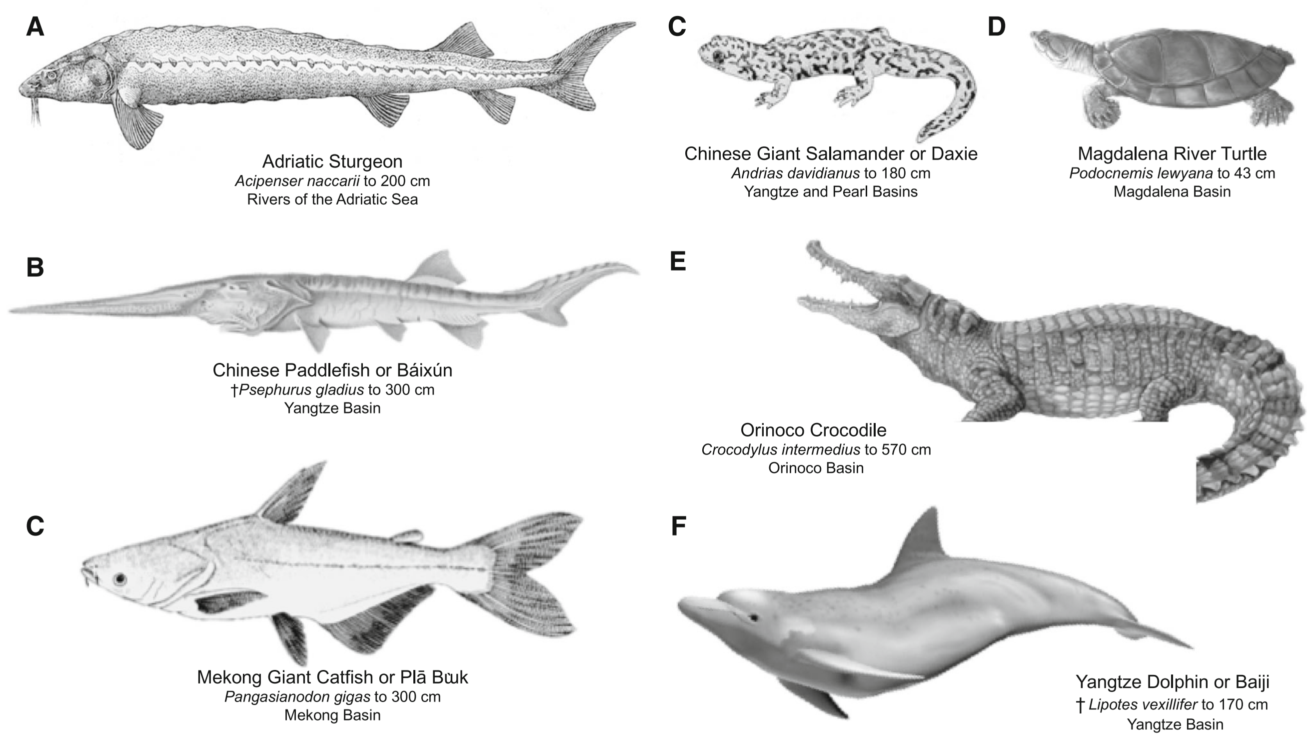

Fig. 2 Examples of critically endangered or recently extinct (†) freshwater megafauna (≥ 30 kg). Freshwater animals with large adult body sizes have higher extinction risk due to complex habitat requirements and slow life-history strategies (e.g., long life span and late maturity). The main conservation threats to these species come from human activities, including overharvesting, pollution, introducing invasive species, and habitat modifications (e.g., water diversions, land-use changes, climate change). The species illustrated roughly represent the proportions of endangered freshwater vertebrates, with greater threats to fishes (**a**–**c**) than to tetrapods (**c**–**f**), and to Eurasian (**a**–**c**, **f**) than non-Eurasian (**d**–**e**) species Image sources: *Acipenser naccarii,* †*Psephurus gladius, Andrias davidianus* from Wikimedia Commons; *Crocodylus intermedius* and *Podocnemis lewyana* from Threatened Reptiles of Colombia (http://reporte.humboldt.org.co/biodiversidad/); *Pangasianodon gigas* from PGNGuru (http://www.pngguru.com/), †*Lipotes vexillifer* from PNGGuru (http://www.pngguru.com/)

Table 1). Such a linear model of global economic expansion yields the chilling prediction that human utilization of critical freshwater resources will approach and even exceed 50% of the Earth's natural supply by midcentury. It is possible for the human freshwater footprint to exceed the Earth's total freshwater capacity, at least transiently, through new technologically-mediated supplements; e.g., desalinated sea water for irrigation, transfer of marine productivity to fertilize terrestrial agroecosystems. Therefore, a linear growth model may be able to persist well into this century, despite the obvious crises that would follow as we reach or surpass the Earth's freshwater capacity.

Demands on global freshwaters continue to grow rapidly, with efforts to expand global food production by 50–70% before 2050 (Molden 2007; FAO 2011). In the twentieth century, the human population grew fourfold and human appropriation of energy from the biosphere about doubled from 13 to 25% (Krausmann et al. 2013). The global human population is projected to reach 9.6–12.3 thousand millions people by the year 2100, and the human appropriation of (terrestrial) net primary productivity (HANPP) to reach 40–60% (Krausmann et al. 2013). Therefore, by the time our grandchildren have grown up they must share the Earths' limited freshwater resources with 1.9–4.6 thousand millions more people, or 25–60% more than the 7.7 thousand millions people who live in the world today. The world that our grandchildren will inherit will be thirsty.

RECOMMENDED ACTIONS FOR FRESHWATER BIODIVERSITY

Slowing and reversing the dramatic losses of freshwater species and ecosystems is still possible. The most effective conservation management coordinates actions at local to regional and national to international levels of organization (Ceballos et al. 2015), commensurate with the geographic

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distributions of species and ecosystems (Magurran 2016). Because many watersheds and all climate zones cross national boundaries, many environmental actions must be designed within international frameworks, and within the socio-economic and ecological contexts of temperate (Elmgren et al. 2015; Udall 2017; Allan and Watts 2018) and tropical (Campos-Silva and Peres 2016; Cooke et al. 2016; Irvine et al. 2016) climates. Table S1 provides a list of major wetland and other freshwater management units for which effective conservation, preservation and restoration actions have been proposed or enacted. These management units represent freshwater ecosystems on all Earth's continents and climate zones, and most of the major continental-scale river drainage basins.

The following summary of policy recommendations therefore includes actions at the local and community scales, and also calls for actions at national and international scales (Poff et al. 2016; Sterner et al. 2019). These actions are critical to maintaining vital global freshwater ecosystem services, avoid water stress and scarcity, and improve human quality of life metrics.

The most effective measures to reduce freshwater degradation and promote watershed conservation need to motivate stakeholders at the local level, including farmers, consumers, municipalities and corporations, using a combination of market-based and regulatory incentives together with technological innovation (Barbier 2017). These actions will require more effective public education (see examples in Cooke et al. 2013) as well as better documentation of: (1) changes in species abundances and geographic distributions, (2) how changes in species composition affect ecosystem processes, and (3) biodiversity in the earth's few remaining unimpacted ecosystems as references for future restoration (Magurran 2016).

At the regional level actions must be prioritized in the interrelated areas of water use, energy use, and biodiversity conservation (D'Odorico et al. 2018). Regional freshwater priorities include: (1) setting limits for sustainable freshwater withdrawals and diversions for river basins and coastal aquifers (Aldaya et al. 2012), (2) halting expansion of water-transfer megaprojects (Shumilova et al. 2018), (3) converting agroecosystems to crops suitable for regional precipitation regimes, (4) halting peatlands draining to protect their specific biodiversity and to avoid their transformation from greenhouse gas sinks to sources, (5) requiring environmental impacts of freshwater appropriations and diversions in regional estimates of human impacts use of net primary productivity, (6) integrating vegetative land-surface cover with surface water and groundwater flows into of hydrological assessments on the impacts of freshwater appropriations, diversions and nutrient/pollutant inputs, (7) reverse osmosis desalination of sea water using new technologies with reduced carbon and thermal footprints (e.g., Gude 2016), and (8) regulation of the use of streams and wetlands by livestock.

Regional energy sector priorities include: (1) phasing out intensive use of freshwater for natural gas extraction and processing, once-through cooling freshwater systems for nuclear, carbon capture and storage, and concentrating solar power technologies, and converting these systems to air and sea-water cooling, (2) investing in an alternative energy matrix including solar, tidal and wind energy, (3) evaluating hydroelectric power and biofuel production and their water impacts across different scales, locally, nationally and globally (Engström et al. 2019), and (4) requiring regional and basin-wide planning for dam placement to more effectively balance conflicting energy and biodiversity interests, removing inefficient dams near the end of their "lifespans" or that were ill-conceived in the first place, and systematically designing technical solutions to maintain the fluvial system connectivity for dams of all sizes (Winemiller et al. 2016).

Regional biodiversity priorities include: (1) designing protected areas for the particular spatial and temporal complexities of freshwater ecosystems (Juffe-Bignoli et al. 2016; Finlayson et al. 2018), (2) improving adaptive management practices to rural economies in developing countries with proactive strategies involving local communities for managing inland fisheries (Fluet-Chouinard et al. 2018), (3) enhancing long-term biodiversity and water quality monitoring programs (Destouni et al. 2017), (4) promoting restoration practices that increase the extent of protected freshwater wetlands and headwater streams, (5) adapting management design to continental aquatic ecosystems (Petts 2018) implementing conservation agriculture policies that increase the proportion of plant products relative to animal products in human food production chains (Hobbs et al. 2011), and (6) accelerating research into water treatment technologies that improve water quality and reduce pollution from domestic and industrial point sources and from diffuse agricultural (Brack et al. 2015) and legacy sources (Destouni and Jarsjö 2018).

Research agencies must increase investments to document freshwater biodiversity through field inventories and long-term support for natural history museums. We must improve incentives for biodiversity assessment and monitoring, coordinate data into searchable online databases, quantify biodiversity trends across space and time, and document the distribution and abundance of invasive taxa. We must establish standardized criteria for assessing freshwater ecosystem health and sustainability, the taxonomic, functional, phylogenetic and population genetic aspects of biodiversity, preventing introductions of non-native aquatic species and infectious diseases. Finally, we must document shifting baselines in conservation management and develop reliable metrics to assess community

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perceptions of what constitutes healthy freshwater ecosystems.

Swift action is needed at every level to limit further expansion of freshwater withdrawals and pollution, and river fragmentation and flow regulation. First and foremost, we must stabilize the global climate and human population growth (Steffen et al. 2015). The international community must work together to limit 21st century global warming to < 2°C, and further return the global temperature anomaly to < 1.5°C above pre-industrial levels (UNFCCC 2015; Schleussner et al. 2016; Rogelj et al. 2018). Slowing and reversing global climate change will require an historical transition to a post-carbon global economy through a combination of regulatory and market-based mechanisms. Among the most effective methods for stabilizing human population growth are to provide primary and secondary education for girls, and voluntary family planning education for women in developing countries (Leigh and Blakely 2017).

International actions with the greatest potential for rapidly reducing freshwater withdrawals and pollution include developing trans-boundary water-sharing and pollution mitigation agreements, and transferring efficient irrigation and water treatment technologies to developing countries in tropical regions. These countries expect the greatest increases in human density and per-capita water consumption in the next 50 years. However, we must not relocate agricultural and bioenergy production from high-income to low-income tropical regions, which will further threaten species-rich tropical aquatic ecosystems.

CONCLUSION

Conservation actions are most effective when they are implemented with full recognition of the genuine fragility of ecosystems. An ounce of conservation prevention is worth a pound of technological cures (Damania et al. 2019). We must realize that some changes are irreversible, such as species extinctions and ecosystem regime shifts (Hughes et al. 2013). We currently have technologies to manage and ameliorate many aspects of the freshwater biodiversity crisis—what we lack is political will. Political will by our policy makers, which in democratic societies means political will by the people who elect the policy makers; i.e., the citizens. A world with diminished freshwaters will impoverish many aspects of human welfare, and we risk further damaging these essential life-support systems at our peril. The time to act is now.

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REFERENCES

Aldaya, M.M., A.K. Chapagain, A.Y. Hoekstra, and M.M. Mekonnen. 2012. *The water footprint assessment manual: Setting the global standard*. London: Routledge.

Allan, C., and R.J. Watts. 2018. Revealing adaptive management of environmental flows. *Environmental Management* 61: 520–533.

Atwood, T.B., R.M. Connolly, H. Almahasheer, P.E. Carnell, C.M. Duarte, C.J.E. Lewis, X. Irigoien, J.J. Kelleway, et al. 2017. Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change* 7: 523–528.

Bar-On, Y.M., R. Phillips, and R. Milo. 2018. The biomass distribution on Earth. *Proceedings of the National academy of Sciences of the United States of America* 115 (25): 6506–6511.

Barbier, E.B. 2017. The economics of aquatic ecosystems: An introduction to the special issue. *Water Economics and Policy* 3: 1202002.

Bennett, C.E., R. Thomas, M. Williams, J. Zalasiewicz, M. Edgeworth, H. Miller, B. Coles, A. Foster, et al. 2018. The broiler chicken as a signal of a human reconfigured biosphere. *Royal Society Open Science* 5: 180325.

Beschta, R.L., D.L. Donahue, D.A. DellaSala, J.J. Rhodes, J.R. Karr, M.H. O'Brien, T.L. Fleischner, and C.D. Williams. 2013. Adapting to climate change on western public lands: Addressing the ecological effects of domestic, wild, and feral ungulates. *Environmental Management* 51: 474–491.

Brack, W., R. Altenburger, G. Schüürmann, M. Krauss, D.L. van Herráez, J. Gils, J. Slobodnik, J. Munthe, et al. 2015. The SOLUTIONS project: Challenges and responses for present and future emerging pollutants in land and water resources management. *Science of the Total Environment* 503: 22–31.

Campos-Silva, J.V., and C.A. Peres. 2016. Community-based management induces rapid recovery of a high-value tropical freshwater fishery. *Scientific Reports* 6: 34745.

Carrizo, S.F., S.C. Jähnig, V. Bremerich, J. Freyhof, I. Harrison, F. He, S.D. Langhans, K. Tockner, et al. 2017. Freshwater megafauna: Flagships for freshwater biodiversity under threat. *BioScience* 67: 919–927.

Ceballos, G., P.R. Ehrlich, A.D. Barnosky, A. García, R.M. Pringle, and T.M. Palmer. 2015. Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Science Advances* 1: e1400253.

Cohen, A.S., E.L. Gergurich, B.M. Kraemer, M.M. McGlue, P.B. McIntyre, J.M. Russell, J.D. Simmons, and P.W. Swarzenski. 2016a. Climate warming reduces fish production and benthic habitat in Lake Tanganyika, one of the most biodiverse freshwater ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* 113: 9563–9568.

Cohen, M.J., I.F. Creed, L. Alexander, N.B. Basu, A.J. Calhoun, C. Craft, E. D'Amico, E. DeKeyser, et al. 2016b. Do geographically isolated wetlands influence landscape functions? *Proceeding of the National Academy of Sciences of the United States of America* 113: 1978–1986.

Cooke, S.J., N.W.R. Lapointe, E.G. Martins, J.D. Thiem, G.D. Raby, M.K. Taylor, T.D. Beard, and I.G. Cowx. 2013. Failure to engage the public in issues related to inland fishes and fisheries: Strategies for building public and political will to promote meaningful conservation. *Journal of Fish Biology* 83: 997–1018.

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Cooke, S.J., E.G. Martins, D.P. Struthers, L.F. Gutowsky, M. Power, S. Doka, and C.C. Krueger. 2016. A moving target—Incorporating knowledge of the spatial ecology of fish into the assessment and management of freshwater fish populations. *Environmental Monitoring and Assessment* 188: 239. https://doi.org/10.1007/s10661-016-5228-0.

Crist, E., C. Mora, and R. Engelman. 2017. The interaction of human population, food production, and biodiversity protection. *Science* 356: 260–264.

Cui, B., Q. He, B. Gu, J. Bai, and X. Liu. 2016. China's coastal wetlands: Understanding environmental changes and human impacts for management and conservation. *Wetlands* 36: 1–9.

Damania, R., S. Desbureaux, A.-S. Rodella, J. Russ, and E. Zaveri. 2019. *Quality unknown: The invisible water crisis*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1459-4.

Davidson, N.C. 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine & Freshwater Research* 65: 934–941.

Destouni, G., and J. Jarsjö. 2018. Zones of untreatable water pollution call for better appreciation of mitigation limits and opportunities. *Wiley Interdisciplinary Reviews: Water* 5: e1312.

Destouni, G., I. Fischer, and C. Prieto. 2017. Water quality and ecosystem management: Data-driven reality check of effects in streams and lakes. *Water Resources Research* 53: 6395–6406.

Destouni, G., F. Jaramillo, and C. Prieto. 2013. Hydroclimatic shifts driven by human water use for food and energy production. *Nature Climate Change* 3: 213.

Dias, M.S., P.A. Tedesco, B. Hugueny, C. Jézéquel, O. Beauchard, S. Brosse, and T. Oberdorff. 2017. Anthropogenic stressors and riverine fish extinctions. *Ecological Indicators* 79: 37–46.

D'Odorico, P., K.F. Davis, L. Rosa, J.A. Carr, D. Chiarelli, J. Dell'Angelo, J. Gephart, G.K. MacDonald, et al. 2018. The global food-energy-water nexus. *Reviews of Geophysics* 56: 456–531.

Dudgeon, D. 2019. Multiple threats imperil freshwater biodiversity in the Anthropocene. *Current Biology* 29: R960–R967.

Ellis, E.C., K. Klein-Goldewijk, S. Siebert, D. Lightman, and N. Ramankutty. 2010. Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography* 19: 589–606.

Elmgren, R., T. Blenckner, and A. Andersson. 2015. Baltic Sea management: Successes and failures. *Ambio* 44: 335–344.

Elmhagen, B., G. Destouni, A. Angerbjörn, S. Borgström, E. Boyd, S.A. Cousins, L. Dalén, J. Ehrlén, et al. 2015. Interacting effects of change in climate, human population, land use, and water use on biodiversity and ecosystem services. *Ecology and Society* 20: 23.

Engström, R.E., G. Destouni, M. Howells, V. Ramaswamy, H. Rogner, and M. Bazilian. 2019. Cross-scale water and land impacts of local climate and energy policy—A local Swedish analysis of selected SDG interactions. *Sustainability* 11: 1847.

FAO. 2011. *The state of the world's land and water resources for food and agriculture (SOLAW)—Managing systems at risk*. Quebec: Food and Agriculture Organization of the United Nations.

FAO. 2016. *AQUASTAT database*. http://www.fao.org/nr/water/aquastat/data/.

Fenwick, A. 2006. Waterborne infectious diseases: Could they be consigned to history? *Science* 313: 1077–1081.

Finlayson, C. M. Arthington, A. H. and Pittock, J. (Eds.). 2018. *Freshwater ecosystems in protected areas: Conservation and management*. London: Routledge.

Fluet-Chouinard, E., S. Funge-Smith, and P.B. McIntyre. 2018. Global hidden harvest of freshwater fish revealed by household surveys. *Proceedings of the National academy of Sciences of the United States of America* 115: 7623–7628.

Freyhof, J., and E. Brooks. 2017. *European red list of freshwater fishes*. Luxembourg: Publications Office of the European Union.

Fricko, O., S.C. Parkinson, N. Johnson, M. van Strubegger, M.T. Vliet, and K. Riahi. 2016. Energy sector water use implications of a 2 C climate policy. *Environmental Research Letters* 11: 034011.

Gleeson, T., K.M. Befus, S. Jasechko, E. Luijendijk, and M.B. Cardenas. 2016. The global volume and distribution of modern groundwater. *Nature Geoscience* 9: 161.

Grill, G., B. Lehner, M. Thieme, B. Geenen, D. Tickner, F. Antonelli, S. Babu, P. Borrelli, et al. 2019. Mapping the world's free-flowing rivers. *Nature* 569: 215.

Gude, V.G. 2016. Desalination and sustainability—An appraisal and current perspective. *Water Research* 89: 87–106.

He, F., C. Zarfl, V. Bremerich, J.N. David, Z. Hogan, G. Kalinkat, K. Tockner, and S.C. Jähnig. 2019. The global decline of freshwater megafauna. *Global Change Biology* 25: 3883–3892.

Heino, J., R. Virkkala, and H. Toivonen. 2009. Climate change and freshwater biodiversity: Detected patterns, future trends and adaptations in northern regions. *Biological Reviews* 84: 39–54.

Hobbs, R.J., P.R. Ehrlich, and H.A. Mooney. 2011. Intervention ecology: Applying ecological science in the twenty-first century. *BioScience* 61: 442–450.

Hoekstra, A.Y., and M.M. Mekonnen. 2012. The water footprint of humanity. *Proceedings of the National academy of Sciences of the United States of America* 109: 3232–3237.

Hughes, T.P., S. Carpenter, J. Rockström, M. Scheffer, and B. Walker. 2013. Multiscale regime shifts and planetary boundaries. *Trends in Ecology & Evolution* 28: 389–395.

IPBES (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, eds. S. Díaz, J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, et al., 56 pp. IPBES secretariat, Bonn. https://doi.org/10.5281/zenodo.3553579.

Irvine, K., L. Castello, A. Junqueira, and T. Moulton. 2016. Linking ecology with social development for tropical aquatic conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems* 26: 917–941.

Jaramillo, F., and G. Destouni. 2015. Local flow regulation and irrigation raise global human water consumption and footprint. *Science* 350: 1248–1251.

Jardine, T.D., N.R. Bond, M.A. Burford, M.J. Kennard, D.P. Ward, P. Bayliss, P.M. Davies, M.M. Dougals, et al. 2015. Does flood rhythm drive ecosystem responses in tropical riverscapes? *Ecology* 96: 684–692.

Juffe-Bignoli, D., I. Harrison, S.H. Butchart, R. Flitcroft, V. Hermoso, H. Jonas, A. Lukasiewicz, M. Thieme, et al. 2016. Achieving Aichi Biodiversity Target 11 to improve the performance of protected areas and conserve freshwater biodiversity. *Aquatic Conservation: Marine and Freshwater Ecosystems* 26: 133–151.

Khazaei, B., S. Khatami, S.H. Alemohammad, L. Rashidi, C. Wu, K. Madani, Z. Kalantari, G. Destouni, et al. 2019. Climatic or regionally induced by humans? Tracing hydro-climatic and land-use changes to better understand the Lake Urmia tragedy. *Journal of Hydrology* 569: 203–217.

Kingsford, R.T., G. Bino, and J.L. Porter. 2017. Continental impacts of water development on waterbirds, contrasting two Australian river basins: Global implications for sustainable water use. *Global Change Biology*. https://doi.org/10.1111/gcb.13743.

Krausmann, F., K.H. Erb, S. Gingrich, H. Haberl, A. Bondeau, V. Gaube, C. Lauk, C. Plutzar, et al. 2013. Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National academy of Sciences of the United States of America* 110: 10324–10329.

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www.kva.se/en

Latrubesse, E.M., E.Y. Arima, T. Dunne, E. Park, V.R. Baker, F.M. d'Horta, C. Wight, F. Wittmann, et al. 2017. Damming the rivers of the Amazon basin. *Nature* 546: 363–369.

Leigh, N.G. and Blakely, E.J. 2017. *Planning local economic development: Theory and practice*. SAGE publications.

Lenton, T.M., J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, and H.J. Schellnhuber. 2019. Climate tipping points—Too risky to bet against. *Nature* 57: 592–595. https://doi.org/10.1038/d41586-019-03595-0.

Levi, L., V. Cvetkovic, and G. Destouni. 2018. Data-driven analysis of nutrient inputs and transfers through nested catchments. *Science of the Total Environment* 610: 482–494.

Loh, J., R.E. Green, T. Ricketts, J. Lamoreux, M. Jenkins, V. Kapos, and J. Randers. 2005. The Living Planet Index: Using species population time series to track trends in biodiversity. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 360: 289–295.

Luo, X.X., S.L. Yang, R.S. Wang, C.Y. Zhang, and P. Li. 2017. New evidence of the Yangtze delta recession after closing the Three Gorges dam. *Scientific Reports*. https://doi.org/10.1038/srep41735.

Magurran, A.E. 2016. How ecosystems change. *Science* 351: 448–449.

Mekonnen, M.M., and A.Y. Hoekstra. 2016. Four billion people facing water scarcity. *Science Advances* 2: e1500323.

Milliman, J.D., and K.L. Farnsworth. 2013. *River discharge to the coastal ocean: A global synthesis*. Cambridge: Cambridge University Press.

Molden, D. 2007. Water for food, water for life: A comprehensive assessment of water management in agriculture. In *Comprehensive assessment of water management in agriculture*, ed. D. Molden. London: Earthscan and International Water Management Institute.

Ngor, P.B., K.S. McCann, G. Grenouillet, N. So, B.C. McMeans, E. Fraser, and S. Lek. 2018. Evidence of indiscriminate fishing effects in one of the world's largest inland fisheries. *Scientific Reports* 8: 8947.

Pelicice, F.M., V.M. Azevedo-Santos, J.R. Vitule, M.L. Orsi, D.P. Lima Junior, A.L. Magalhães, P.S. Pompeu, M. Petrere Jr., et al. 2017. *Fish and Fisheries* 18: 1119–1133.

Petts, G.E. 2018. *Perspectives for ecological management of regulated rivers. Alternatives in regulated river management*, 13–34. Boca Raton: CRC Press.

Poff, N.L., and J.C. Schmidt. 2016. How dams can go with the flow. *Science* 353: 1099–1100.

Poff, N.L., C.M. Brown, T.E. Grantham, J.H. Matthews, M.A. Palmer, C.M. Spence, R.L. Wilby, M. Haasnoot, et al. 2016. Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change* 6: 25.

Reid, A.J., A.K. Carlson, I.F. Creed, E.J. Eliason, P.A. Gell, P.T. Johnson, K.A. Kidd, T.J. MacCormack, et al. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews* 94: 849–873.

Ripple, W.J., P. Smith, H. Haberl, S.A. Montzka, C. McAlpine, and D.H. Boucher. 2013. Ruminants, climate change and climate policy. *Nature Climate Change* 4: 2–5.

Ripple, W.J., C. Wolf, T.M. Newsome, P. Barnard, and W.R. Moomaw. 2019. World Scientists' warning of a climate emergency. *BioScience*. https://doi.org/10.1093/biosci/biz088.

Ripple, W.J., C. Wolf, T.M. Newsome, M. Galetti, M. Alamgir, E. Crist, M.I. Mahmoud, W.F. Laurance, et al. 2017. World scientists' warning to humanity: A second notice. *BioScience* 67: 1026–1028.

Rodell, M., J.S. Famiglietti, D.N. Wiese, J.T. Reager, H.K. Beaudoing, F.W. Landerer, and M.H. Lo. 2018. Emerging trends in global freshwater availability. *Nature* 557: 651–659.

Rogelj, J., A. Popp, K.V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, et al. 2018. Scenarios towards limiting global mean temperature increase below 1.5 C. *Nature Climate Change* 8: 325–332.

Sabo, J.L., A. Ruhi, G.W. Holtgrieve, V. Elliott, M.E. Arias, P.B. Ngor, T.A. Räsänen, and S. Nam. 2017. Designing river flows to improve food security futures in the Lower Mekong Basin. *Science* 358: 1053.

Sánchez-Bayo, F., and K.A. Wyckhuys. 2019. Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation* 232: 8–27.

Scanlon, B.R., I. Jolly, M. Sophocleous, and L. Zhang. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resources Research* 43: 3. https://doi.org/10.1029/2006WR005486.

Schleussner, C.F., T.K. Lissner, E.M. Fischer, J. Wohland, M. Perrette, A. Golly, J. Rogelj, K. Childers, et al. 2016. Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth System Dynamics* 7: 327–351.

Sengupta, S., and W. Cai. 2019. A quarter of humanity faces looming water crises. *New York Times. Aug.* 6: 2019.

Shiklomanov, I.A., and J.C. Rodda. 2004. *World water resources at the beginning of the twenty-first century*. Cambridge: Cambridge University Press.

Shumilova, O., K. Tockner, M. Thieme, A. Koska, and C. Zarfl. 2018. Global water transfer megaprojects: A potential solution for the water-food-energy nexus? *Frontiers in Environmental Science* 6: 150. https://doi.org/10.3389/fenvs.2018.00150.

Siebert, S., M. Kummu, M. Porkka, P. Döll, N. Ramankutty, and B.R. Scanlon. 2015. A global data set of the extent of irrigated land from 1900 to 2005. *Hydrology and Earth System Sciences* 19: 1521–1545.

Smil, V. 2011. Harvesting the biosphere: The human impact. *Population and Development Review* 37: 613–636.

Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R.De Carpenter, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347: 1259855.

Sterner, T., E.B. Barbier, I. van den Bateman, I. Bijgaart, A.S. Crépin, O. Edenhofer, C. Fischer, W. Habla, et al. 2019. Policy design for the Anthropocene. *Nature Sustainability* 2: 14–21.

Turak, E., I. Harrison, D. Dudgeon, R. Abell, A. Bush, W. Darwall, C.M. Finlayson, S. Ferrier, et al. 2017. Essential Biodiversity Variables for measuring change in global freshwater biodiversity. *Biological Conservation* 213: 272–279.

Turvey, S.T., R.L. Pitman, B.L. Taylor, J. Barlow, T. Akamatsu, L.A. Barrett, X. Zhao, R.R. Reeves, et al. 2007. First human-caused extinction of a cetacean species? *Biology Letters* 3: 537–540.

Udall, S.L. 2017. *Battle against extinction: Native fish management in the American West*. Tucson: University of Arizona Press.

UNFCCC. 2015. *United Nations Framework Convention on Climate Change*. Adoption of the Paris Agreement FCCC/CP/2015/L.9/Rev.1. http://www.unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

van Vliet, M.T., W.H. Franssen, J.R. Yearsley, F. Ludwig, I. Haddeland, D.P. Lettenmaier, and P. Kabat. 2013. Global river discharge and water temperature under climate change. *Global Environmental Change* 23: 450–464.

Vörösmarty, C.J., P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, et al. 2010. Global threats to human water security and river biodiversity. *Nature* 467: 555–561.

Wagner, D.L. 2019. Insect declines in the Anthropocene. *Annual Review of Entomology*. https://doi.org/10.1146/annurev-ento-011019-025151.

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Winemiller, K.O., P.B. McIntyre, L. Castello, E. Fluet-Chouinard, T. Giarrizzo, S. Nam, I.G. Baird, W. Darwall, et al. 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* 351: 128–129.

WWF. 2016. *Living planet: Report 2016: Risk and resilience in a new era*. Gland: World Wide Fund for Nature.

Zhang, H., Q.W. Wei, H. Du, L. Shen, Y.H. Li, and Y. Zhao. 2009. Is there evidence that the Chinese paddlefish (*Psephurus gladius*) still survives in the upper Yangtze River? Concerns inferred from hydroacoustic and capture surveys, 2006–2008. *Journal of Applied Ichthyology* 25: 95–99.

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