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Future success and ways forward for scientific approaches on the African Great Lakes

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ABSTRACT

The seven African Great Lakes are some of the most critical freshwater, large-lake systems in the world, providing essential services, food, drinking water, and other livelihood support to over 62 million people. Like most freshwater systems around the world, these lakes are strained by anthropogenic stressors, leading to degradation of these biologically important, and human-dependent resources. Despite their importance, these lakes suffer from insufficient research approaches which are short-term, disparate, and unharmonized. Further, a lack of monitoring, data and information exchange, education and training, and gender balance in research, all lead to insufficient knowledge on which to better manage and protect these lakes. While past efforts have resulted in some knowledge accumulation, there is a need for new approaches to understanding and managing these lakes: bottom-up, harmonized, and long-term processes. This paper, and those within this special section of the *Journal of Great Lakes Research*, highlight new, highly collaborative efforts of freshwater experts representing each riparian country of each African Great Lake through formal advisory groups. These papers are the result of harmonized efforts and collegial agreements as to what issues need to be addressed foremost, written by those on the ground. While each lake has specific, prioritized lists of issues, five overarching issues must be addressed to achieve success on these lakes: providing agency and coordination of African freshwater scientists; increase long-term monitoring; strengthen education and training of existing and future experts; enhance information and data exchange; and ensure stronger gender balance in science and leadership positions.

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1. Introduction

The seven African Great Lakes (AGL; Lakes Albert, Edward, Kivu, Malawi/Niassa/Nyasa, Tanganyika, Turkana, and Victoria) are some of the most critical freshwater, large-lake systems in the world. They harbor over 25 % of the world's unfrozen surface freshwater, providing essential services, food and nutrition security (Loiselle et al., 2014) through animal protein, drinking water, employment, transportation, and livelihood support to over 62 million people. Fisheries and aquaculture activities, support an estimated 4 % of the regions Gross Domestic Product (GDP) and 9 % of agricultural GDP (Chimatiro et al., 2021). The lakes are the most species-rich freshwater systems on the planet, harboring thousands of endemic fish species, and hundreds of other aquatic and terrestrial species.

Like most freshwater systems around the world, these lakes have changed dramatically since the start of the 20th century due to opportunities and challenges associated with open-access, common-property resources, leading to habitat loss and degradation, introduction of exotic species, oil and gas exploration, agricultural runoff and subsequent eutrophication, industrial and urban pollution and waste, overuse, and a host of other issues. Exacerbating the stresses on these freshwater resources from varying effects is climate change, which causes erratic rains, leading to poor soils and crop failures with animal husbandry becoming less effective or impossible, forcing a general human migration towards the relatively easily accessible resources of these lakes (Lawrence, 2015). As populations move from water-scarce areas, migration and the subsequent anthropogenic activities from these large populations, stress these resources to a degree that does not allow the millions who depend on them do so reliably. There is, thus, a critical need to conduct thorough climate change vulnerability studies to determine potential impacts of climate change on the AGL and their resources (particularly fisheries) to develop adaptation strategies for ensuring the sustainable management of these lakes.

Another major challenge of understanding, researching, and creating policy and management decisions on these lakes stems from their multinational nature. The need for collaborative and harmonized approaches to research and monitoring is necessary to understand the lakes, especially regarding fish populations, as these important resources are mobile and do not acknowledge international geo-political lines. Due to parochial and country-specific desires of resource use, collaboration on how to develop management and policy is also of utmost importance; the riparian governments of these resources often have limited enforcement capacity and resource extraction is conducted in a tragedy-of-the-commons-type approach. Thus, both research and management must be done in a coordinated and harmonized manner.

Increasing all of the above-mentioned challenges is the fact that the AGL are some of the least-studied freshwater large lakes globally (Fig. 1) especially compared to other large-lake systems such as the North American Laurentian Great Lakes, Lake Baikal, and others (Hecky, 2003). Despite calls for action on the AGL since the 1920s, when Graham (1929) observed fish populations decreasing and recommended monitoring fish populations, we still find ourselves calling for action. Though action on all of the AGL is needed, a prime example of this is Lake Edward (see Fig. 1) and its associated system (the Kazinga Channel and Lake George). The dearth of publications is representative of the lack of attention this system has received and thus suffers from a lack of comprehensive understanding of the ecological makeup.

There are two differences between past efforts and the current one in this special section:

1) The papers herein are written by a collaboration of experts, groups that represent each riparian country of each African Great Lake through formal advisory groups (Electronic Supplementary Material (ESM) Appendix S1). The advisory groups and consulted

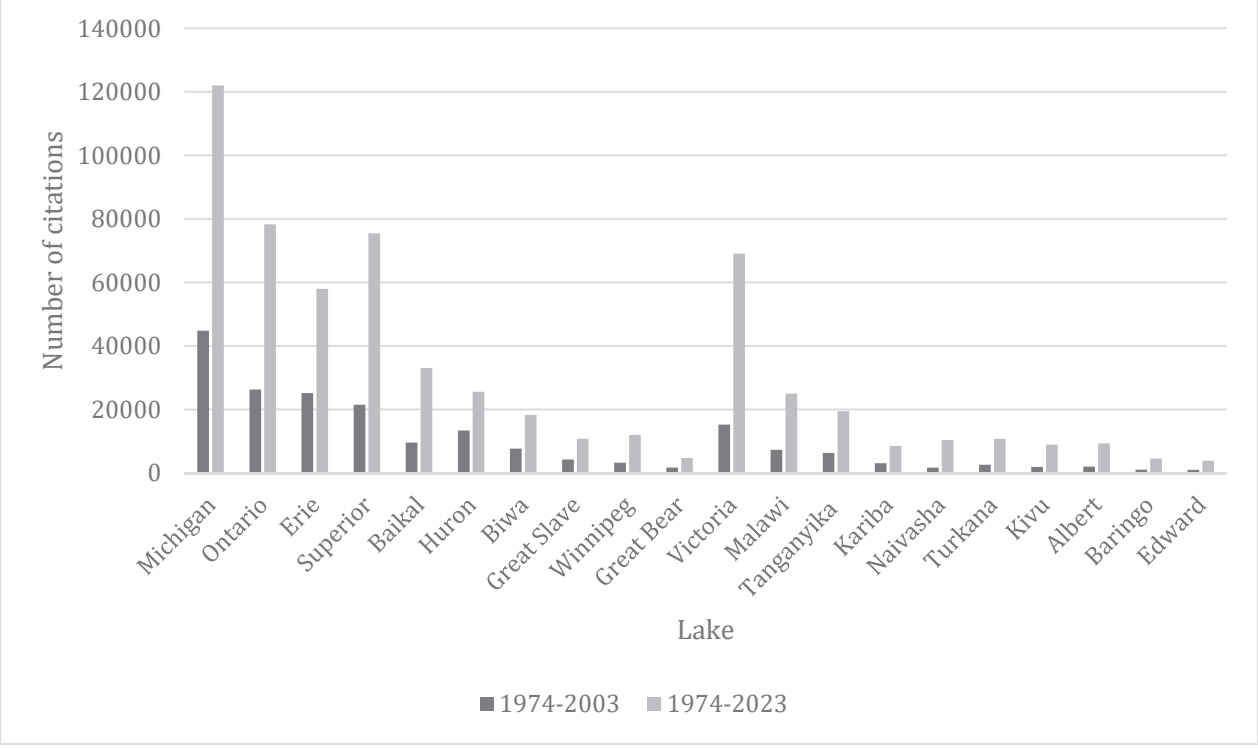

Fig. 1. Comparison of citations, using Google Scholar, between large lakes using two time periods 1974–2003 and 1974–2023, demonstrating the dearth of focus on the critically important African Great Lakes. The first time period follows Hecky's (2003) – "Fig. 1. Numbers of citations per Northern versus African Great Lake, based on citations available on the Web of Science" 1974–2003. The search criteria are meant to reflect the past 20 years of publications. Trends have stayed the same except for a noticeable increase in publications on Lake Victoria, likely due to the international focus on the Nile Perch invasion and surrounding issues and the creation of the Lake Victoria Fisheries Organization.

stakeholders constitute a network of African expertise (ESM Figure S1) . These papers are the result of coordinated efforts, agreements, harmonization as to what issues need to be addressed foremost, written by those on the ground; and,

2) There have been few to no coordinated, lake-wide efforts to address such issues in a harmonized manner, with some exceptions.

2. Challenges on the African Great Lakes

2.1. The upside-down: Parachute science

A lot of good research has been conducted through international collaborations. Trainings, equipment, extra funding, and especially support for masters and Ph.D. educations have come through such projects (see section "On Education and Training" below). In fact, international involvement in research is needed and desired. Without global collaborations to natural resource challenges, we argue that many of our efforts will not succeed, or have not succeeded: Indeed, *it takes more than a village*.

"Parachute" or "colonial" science, however, is where researchers from the "developed world" identify research needs, design projects, and establish funding for issues based on their own assumptions, motives, and personal needs (de Vos, 2020) and may have a detrimental impact on science and those who conduct science in Africa. Some challenges of knowledge accumulation and research on the AGL stem from past systemic, colonial-type approaches to addressing economic and social development. Stein (2008) describes at length how international neoliberal development approaches have created a system of reliance and perverse incentives regarding infrastructural and economic development in Africa, essentially, "aid with strings attached" (Genda et al., 2022). This approach seems to have been transferred, in some form, to research.

When external intervention takes place, research priorities originate from outside the region (Table 1) and often differ widely from priorities identified by the experts of the countries they are entering (de Vos, 2020). While those best placed to identify and address the challenges of the resources around the AGL are the experts of those lakes' riparian nations, these experts are often hampered by lack of financial, research, and academic resources. The financial power lies with these external entities, thus their unintended control of research priorities (for good or bad). Further, such interventions are often short-term, conducted in 2–5 year chunks, are most often parochial, and do not follow coordinated or consistent metrics, thus becoming incomparable to other similar studies on the same resources (Obiero et al., 2020). If local talent is used, they are often not trained to the extent or capacity to continue further work. When data are collected, those who paid depart the study region with the data and information, primarily benefiting external partners as the data most often end up as proprietary or behind pay walls. Open access is beneficial, but these also have costs for the institutions who can pay, but then one has to be a member of that institution to have access.

This top-down approach is notable on all of the AGL, creating an unfavorable power imbalance between those who have the financial resources and relegating the experts in Africa as disadvantaged and powerless. To reject research opportunities is to reject job security, potential lab equipment or other gear or equipment, and most importantly, some semblance of data or information (if it is available).

To address the detrimental and myriad problems with top-down science (Table 1), a long-term system of on-the-ground, highly collaborative scientific network of African freshwater experts has been created (see Section II: The Vision and Ways Forward for the African Great Lakes) to lead us towards a future where the scientists on the African Great Lakes have more agency and influence on how science is conducted and to manage the financial and research resources that are necessary to address the issues on the African Great Lakes.

Table 1
Summary of detrimental effects of current, top-down, "colonial" scientific approaches on the AGL.

- Disenfranchisement: Research is not informed by the experts on the ground, which:
  - o Reduces leadership and agency of African scientists, largely on funding
  - o Does not acknowledge the importance of the local expertise
  - o Undermines current scientific infrastructure in Africa
  - o Excludes collaborations and partnerships
  - o Can create an approach lacking expertise collaboration, reducing training and advancement of on-the-ground experts
  - o Fosters disconnected, repeating research, and/or research that cannot be compared to other data
- Information and Data: Rarely is data collection comprehensive enough to provide meaningful direction for decision-makers which means:
  - o Research or other projects are almost always short-term (2–5 years)
  - o Full-lake studies are infrequent, which is detrimental for multi-national common-property resources
  - o Data often leaves the continent, becoming locked up behind paywalls, is protected, collaboration ceases
  - o Sporadic and short-term data gives a skewed understanding and unclear picture of what is occurring
  - o Infrequent and inconsistent data often doesn't allow for comparative analysis
  - o Inadequate funding for long-term, time-series data curtails full

2.2. On monitoring

One of the biggest challenges on the AGL is that long-term, consistent, and comprehensive monitoring is not being conducted. Quite incredibly, calls for consistent, systematic recording of fishery statistics first occurred almost 100 years ago by Graham (1929) and Worthington (1929). To collect such data in "this way from the first, will be of the greatest possible assistance in following the progress of the lake fisheries, and will make any future work, which is sure to become necessary if the fisheries are to be exploited to their best advantage, a matter of much greater value." (Worthington, 1929). Seventy-four years later, Hecky (2003) wrote in "What does the future hold for the African Great Lakes?" that "long-term monitoring, in service to management objectives, is in its infancy". Unfortunately, it appears that the monitoring infant is still only a toddler as highlighted in Plisnier et al. (2023a) with sporadic, project-oriented, or no monitoring taking place on each of the seven AGL. Nicholson (2023) extends these concerns, highlighting that monitoring needs to be carefully implemented, with the observations from satellite data that rain-fall patterns take place over many of the AGL-proper, and not in the catchment where rain gauges are typically stationed. Sporadic, inaccurate, or no monitoring, leaves scientists with missing variables and sporadic and disparate snapshots of information that do not give enough information to make good decisions. Plisnier et al. (2023b) is a stellar, current example of this problem, as the authors highlight the necessity to combine a 12 year period of combined information from various local knowledge, historical observations, in situ sampling, and remote sensing sources due to inadequate temporal and spatial coverage. These realizations are not new, and in fact were expressed by Graham and Worthington as they pointed out the difficulties of characterising the state of the fisheries in the absence of statistical data. While this, and the other papers in this special section, highlight numerous critical needs and activities that must take place on the AGL for their future health, it is surprising that long-term and consistent monitoring still does not take place on these lakes. It is akin to measuring a rain gauge once a year in the dry season and concluding that it does not rain in that location, then making a policy of water conservation. For most natural resources, it is necessary to collect as much data as possible to ensure we have a comprehensive understanding to make informed decisions on what might be best for the health of the resources and the people who depend on them. We see, again, the importance of more comprehensive knowledge as Plisnier et al. (2023b) show the complex relationship of seasonal wind variations and other aspects to better understand the hydrodynamics of Lake Tanganyika

which potentially better explain seasonal algal blooms, fish die-offs, and other aspects.

The solutions lie in both Plisnier et al. (2023a) and in this paper: Section II: The Vision and Ways Forward for the African Great Lakes.

2.3. On education and training

Education and training in freshwater science within the AGL region have many challenges and hindrances that affect the quality of research leading to poor policy regulation and implementation for conservation and management of the AGL ecosystems and resources. A study on academic institutions that offer freshwater science (including physical, chemical, and biological aspects) and also publish on the status of these lakes showed that many institutions of higher learning rarely offer this in-depth knowledge to graduate and postgraduate levels, hence there is limited human resource and capacity to inform their governance and sustainable utilization resulting in the observed level of degradation (Achieng et al., 2023). The study registered a range of challenges including limited specialized academic programs, low uptake of academic programs, lack of timely information access, low awareness and career guidance, limited skilled human resources, infrastructure, funding, governance and inadequate research in the region. Because these freshwater resources and ecosystems have global and regional importance, with significant economic contribution from their fisheries and rich biodiversity, but with immense study gaps and critical levels of degradation, the need for strengthening experts in freshwater science within the region is paramount. Institutions from abroad have been instrumental in strengthening capacity in the region through postgraduate programs and research collaborations. Some international partnerships also fund highly motivated candidates to pursue postgraduate studies abroad and mobility schemes to improve the quality of research, governance, policy formulation and implementation in conservation and management in the region. However, it is essential that regional institutions play lead roles in the concerted efforts to overcome the myriad governance, infrastructure, institutional and financial challenges to achieve sustainable utilization, conservation, and transboundary management of the AGL.

The lack of education and training of African experts in freshwater and large-lake studies can cause a negative loop cycle for the region. Without properly trained members of these resources, “outside” researchers (those often coming from the global north), “parachute” into the region to conduct research, bringing and taking their equipment and their data, and leaving with little to no benefit to the experts on the ground or those who depend on the resources (see The Upside-down: Parachute Science section above).

The way forward is, once again, harmonizing efforts (see Section II: The Vision and Ways Forward for the African Great Lakes) in education and training on a level that empowers the African freshwater scientific community.

2.4. On information exchange and sharing

Information (data, publications, reports) is critical in understanding our natural resources, their status, how they are used and function, and how human use impacts them as they are relied upon for livelihoods and other ecosystem functions. Formal research has been conducted on these lakes for over a hundred years (e.g., Graham, 1929; Worthington, 1929). Prior to the computer age, reports, publications, and data sets were stored in various places, including desks, dusty bookshelves, or other forgotten repositories. Older electronic databases (think floppy disks and old computers) hold valuable information that is being lost due to deteriorating electronics, abandoned databases, inadequate storage, or non-user-friendly formats. Further, much of the information is scattered in various institutions in and outside the region; large numbers of data are in paper-based format or stored individually as soft copies in different formats, resulting in inefficient viewing, accessing, transferring, and difficulty with integration with electronic datasets. This is a hindrance to efficient data and information sharing since this process requires an identifiable, retrievable, interoperable, and in consistent format. This lack of adequate records and information management results in the absence of standards for the recording, classifying, storing, and managing information. Additionally, most of the data and information in the region have inconsistent formats and lack metadata due to inadequate information management, thus making it difficult for a third-party user to assess the data.

Data and information management is a big issue for the AGL and is highlighted by the Lake Turkana experts as a barrier to understanding the lake and its resources (Obiero et al., 2023). For all of the lakes, there is no central repository of information, much of it is still in various places, whether in journals globally, on individuals’ or organizations’ computers, or behind pay walls. If scientists do not know information exists, or cannot access it, how can we, as the scientific community, accumulate a comprehensive view on the resources, understand them, and make decisions without guessing?

While finding information and highlighting that it simply exists is the first challenge, the absence of national, regional, and international policies governing the sharing of data and information results in uncertainty in the procedures to follow when sharing data, the type of data to be shared, and the responsibility of the custodian and the users, especially decision-makers. This results in duplication of effort and resources resulting in difficulties for informed policy and management decisions on fisheries and aquaculture matters. More importantly, the lack of data sharing policies, especially when external collaborators are concerned, can cause displeasure among national institutions that cannot get a clear picture of the benefits to the region (see The Upside-down: Parachute Science section above).

Finding and making these past pieces of information available and in consistent formats will help advance science in numerous ways, including piecing together information for more long-term, time-series data; recalling, to some degree, base-line information to determine some of the changes that have taken place in recent history; and ensuring that either research is not duplicated, or that it is done so with similar metrics for comparative analysis.

2.5. On women in science

Women bring necessary perspectives and ideas to research and scientific development and execution. The ideas and innovations that women bring to the sciences focus on their unique understanding of societal, economic, and environmental challenges and solutions (Bert, 2018). When these perspectives are driving scientific questions and studies, there is a more holistic approach to guide research which results in valuable outcomes and findings to solve the problems we face globally; making scientific research more accurate and impactful (Bert, 2018). Some of the world’s biggest challenges cannot be solved if the sciences are led only by those who represent 50 % of the world’s brainpower. Yet, men comprise a greater number of scientists, thus more scientific research has been focused on men and their questions and hypotheses. Many research projects have not included gender distinctions, frequently resulting in assumptions and results made by men and applied to both men and women.

While women’s perspectives are necessary, historically, women have been disenfranchised from scientific leadership and economic empowerment. The number of women in science and engineering in Africa is below 20 %, even though women make up over 50 % of the population and form the majority of the workforce in most countries. The percentage of women in science and engineering leadership positions and graduate-level academic programs, is reduced further (AWSE, 2023). Societal-scale problems that prevent women from equally entering the workforce include: women being disproportionately affected by poverty, discrimination, and exploitation (UNESCO, 2017); stereotypes that women are not as effective and efficient as their male peers; unequal

opportunities of employment compared to men with equivalent education (African Development Bank, 2016); and, societal expectations related to familial obligations. When women in sub-Saharan Africa do achieve a place in the workforce, they are still at a disadvantage despite working longer hours on average, earning less than men, often because many of these hours aren't compensated (Saito et al., 1994). Women who overcome these societal barriers and enter into the scientific field often find themselves among mostly male colleagues and supervisors, with few female peers to share their experience with and even fewer female supervisors and role models to provide guidance and mentorship, a key support structure within the early years as a scientist.

The solutions to the inequity of gender inclusion include creating opportunities and breaking down historical barriers for women to enter into, and advance, in the sciences and leadership positions. This cannot be seen as token inclusion, it is critical that women's voices and perspectives are integrated into the sciences, and that they influence, guide, and lead scientific research and conversations. To this end, programs (such as the African Women in Science developed by the African Center for Aquatic Research and Education) can assist in inculcating women into the sciences through targeted training and education, information exchange, mentorship, and programming to strengthen the skills and professional networks of early career African women scientists. This includes strengthening their capacity and perspectives as scientists through means not typically offered, or catered to, women. While skills-based instruction is necessary, women's advancement into the broader freshwater scientific network is also necessary, involving them in the organizations working on freshwater, active advisory groups, networking events, and alumni networks. Women scientists need to stay connected with each other, share opportunities, and help each other advance on an ongoing basis.

3. Conclusion: the vision and ways forward for the African Great Lakes

As transboundary lakes, it is critical to address the challenges of lake and catchment management benefits from national, regional, and international collaborations. This calls for the mobilization of resources, drawing on the support of the global freshwater community and partners to help make this happen. The specific process that the African Center for Aquatic Research and Education (ACARE) engages in follows, but modifies, that of the successful North American Great Lakes Lake Committee system. One major component is to ensure that representatives from each jurisdiction of these multi-national lakes meet in-person at least once a year with an action-oriented agenda, and to hold regularly scheduled, facilitated meetings with a structured agenda virtually throughout the year. Such a process of meetings has proven to be a mechanism in building trust among and between members of each country's scientific community. This results in more effective information exchange, ensures more holistic research is conducted on the lakes (as opposed to one portion of a lake); and draws international attention to the most urgent research needs by giving the experts on the lake a more legitimate platform of strength in numbers. While we use approaches and consult with experts from the global north, including those from the North American Great Lakes, we heed Hecky's (2003) observations that the same challenges that face each of the systems, are expressed in quite different intensities and driven by different socio-economic, cultural, and political pressures. But the need to share perspectives, approaches, and resources (especially financial) are critical in ensuring a healthy and functioning community of African freshwater experts continue to address these issues today and long into the future (Hecky 2003).

This collection of papers represents a larger coordinated effort that answers the call-to-action that has been taking place since the 1970s to "collaborate". The authors represented in this special section are taking the reins and ensuring that collaboration takes place, both among nations sharing each lake, and also among lakes within the AGL region. It is time to seriously invest in these lakes, as an international community, to comprehensively address the challenges and change the system by which we approach the lifeblood of millions of people.

The issues identified in each of these lake-specific papers were developed by scientists from each riparian country of each of the AGL (Table 2) There should be little to no question as to the direction that future research efforts and funding and development should go towards based on this special section. All of the papers reflect the need to continue to harmonize efforts, monitor various aspects of the lakes' parameters, enhance information exchange, increase education and training, and strengthen the voices of women. The differences in each paper are the specific issues that the scientists prioritize, with fisheries being critical for Lake Albert (Nakiyende et al., 2023), Lake Malawi/Niassa/Nyasa (Chavula et al., 2023), and Lake Victoria (Nyamweya et al., 2023) and second only to biodiversity and land use and habitat destruction for Lake Turkana (Obiero et al., 2023) and Lake Tanganyika (Phiri et al., 2023) respectively. On Lake Kivu, Muvundja et al. (2023) state that solid waste pollution and soil erosion are the biggest issues (which also negatively affect fisheries) with the need for increased monitoring, community engagement, and management plans. While these issues are highlighted as the most important, each paper delves into a suite of issues from climate change, invasive species, aquaculture issues, and more. All of them follow the five major themes of this introductory paper: cooperation, monitoring, information exchange, education and training, and gender balance. Without these five major tenets, we, in 20 years, will be writing papers similar to these, asking why we are still stagnant in our progression.

These papers are also a call to action for the larger, global freshwater scientific community to address the issues outlined in this collection of papers. These papers are guidelines on how to safely, sustainably, and effectively conduct research, invest in research and development, and strengthen science on the African Great Lakes. The intent of our efforts is to collect comprehensive information on each of the issues on each of the lakes, make it available to the larger scientific community, and transfer that knowledge along with policy and management suggestions, to make these resources healthier for the millions of people who depend on them and for the overall health of the economies of the countries that these resources support.

To this end, the authors of this special section recommend two major changes to addressing the AGL natural resources: First, the governments of each of the riparian countries of the African Great Lakes (Burundi, Democratic Republic of Congo, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda, and Zambia) must invest in proper research and solutions based on these papers. Second, global, western researchers need to work with the African experts on these lakes to design, develop, and invest, for research and solutions. The time for disparate and short-term efforts is over. We, collectively, cannot afford to look at these lakes with inadequately funded efforts, nor misguided approaches from well-intended but misplaced research. To do so is a disservice to the resources, to the experts who work on these resources, and to the millions of people who depend on them for their livelihoods.

While experts on each of the AGL have specific priorities and actions for the needs of their specific lakes, there are five broader goals that are common threads between and among all of the lakes that must be addressed more comprehensively during the next ten years:

- Continue to meet as cohesive expert scientific groups to enhance the reputation, prominence, and leadership of African scientists, giving them agency over the direction of research and solutions on the AGL;

Table 2
A matrix summary of issues and threats across each of the African Great Lakes (AGL) basins with suggested strategic management recommendations for sustainable use of the resources.

Thematic Area	Critical driving forces and pressures	Strategic management recommendations
Lake Edward and Albert Basin		
Biodiversity	Overuse of resources; declines of fish catch, loss of biodiversity.	Comprehensive assessment and inventory of existing biodiversity; Studies on commercial fish species spawning; guide to setting management measures.
Skills and knowledge	Inadequate scientific information.	Match freshwater issues in curricula to match practical components; conduct field trainings. Develop dedicated master's programs. Climate change added to curricula.
Climate change	Rising water levels displacing fisher communities.	Develop early warning signs and mechanisms for resilience and adaptation for affected communities and fisheries. Install weather stations to monitor water levels – help make predictions for better decision making.
Invasive species	Invasive species, Kariba weed and water hyacinth threated the Lake Albert biodiversity and ecosystem.	Use of biological control agents (e.g., weevils), mechanical removal, and the use of herbicides.
Oil and gas exploration	Oil and gas activities raise environmental concerns, e.g., potential for oil spillage into the lake and the resulting impacts to aquatic fauna and flora.	Conduct research on impact of oil spills on fish species and other aquatic life. Establish Oil spill avoidance strategies.
Land use	Poor land use practices leading to loss of vegetation cover, terrestrial and aquatic pollution, riverbank degradation, landslides, flooding, loss of wetland functionality, soil erosion, loss of soil fertility and decline in fish diversity in this basin.	There is need for a baseline study and continuous monitoring of the physicochemical and microbiological quality of the lake waters.
Lake Kivu Basin		
Pollution	Physical and chemical water pollution due to intense land use and high population density and urban development.	Monitor all potential pollution sources; Raise awareness of the local population on domestic waste management and reforestation to reverse the trend of lake pollution.
Soil erosion	Deforestation and agricultural practices generates high turbidity in rivers and in the lacustrine littoral zone.	Develop an integrated lake watershed management plan to maintain the ecological functions and support livelihoods from the lake.
Fisheries & Aquaculture	Fish habitat destruction and cage aquaculture potentially release nutrients, other chemicals, and invasive species into the lake.	Review and update fisheries and aquaculture policies and regulations; Harmonize fish and aquaculture regulations between Rwanda and DRC; Invasive species prevention/control; Fishery and aquaculture value chain development.
Biodiversity	Biodiversity under threat from natural (volcanism and tectonism) and human induced (pollution, erosion and habitat destruction and fragmentation) activities.	Assess the diversity and distribution patters of macroinvertebrates of all biota groups; Create comprehensive lake monitoring program in Rwanda and DRC for sustainable management of Lake Kivu.
Skills and knowledge	Lack of sufficient knowledge and basic infrastructure and equipment, weak technical and operational capacity by local research bodies.	Increase freshwater science training programs at masters and PhD levels to ensure future qualified local expertise.
Conflicts	Conflicts have been experienced between riparian countries.	Enhance security and safety on the lake.
Lake Malawi/Niassa/Nyasa Basin		
Fisheries resources	Post-harvest fish losses resulting in low levels of per capita and increase in demand, promoting overfishing. Siltation is destroying fish habitat and causing nutrient loading. Non-compliance to fisheries rules.	Increase fishing enforcing rules; Enhance and embrace co-management; Install a vessel monitoring system (VMS) on trawling boats; capacity-building to address issues of fish postharvest losses, targeting the fishermen, fish processors, fish distributors and fish marketers.
Invasive Species	Introduction of the piscivorous *Oncorhynchus mykiss* in Nyika plateau and *Protopterus annectens* in LMNN seasonal wetlands near Salima. *Melanoides tuberculata*, an invasive gastropod, introduced in LMNN, becoming dominant shallow waters. Water hyacinth has terrorised the Shire River.	Develop measures to control introduction of invasive species; Development of Infrastructure to Control Invasive Plants e.g water hyacinth.
Climate change	Studies reported a long-term temperature increase leading to a decline in fish catches, amd negatively affecting the livelihoods of fishing communities. Shifting composition of fish species, with some species becoming more dominant while others declining.	Develop climate change mitigation measure to reduce the impacts; Adoption of Climate-Resilient Fisheries Management.
Lake Tanganyika Basin		
Land use and habitat destruction	Increased population and subsequent anthropogenic land use have negatively impacted the environment and ecosystems.	Establishing protected areas to minimize habitat disruptions in the lake basin; Conduct monitoring of the land use changes within the basin; Develop a comprehensive land use map for the Lake Tanganyika basin.
Fisheries resources	Declining fish stocks due to unplanned settlements; use of inappropriate fishing techniques and gear in prohibited sites; post-harvest losses; and outdated regulations and their weak application.	Mesh-size restrictions, closed areas and seasons, observation of lunar breaks, licensing, and assessment of catches; Consistent and harmonized data collection system in order to inform strategic interventions.
Erosion and sedimentation	Deforestation has increased erosion rates, leading to loss of nutrient-rich topsoil and sedimentation. Eroded sediments accumulate in the near-shore where habitats are altered and primary production is disturbed, negatively affecting aquatic species richness, densities, and ecology.	Manage tree cutting, initiate reforestation; Practice terraced farming on sloping lands; Reduce or prevent stream bank cultivation. Find alternatives to charcoal as a source of energy; Impose stricter building regulations designed to reduce erosion by establishing minimum vegetation buffer zones (need for harmonization of legislations around the lake)_.
Water Pollution	Surface waters polluted by harmful contaminants from diverse sources, such as domestic wastewater, rapid industrialization, use of chemical pesticides and fertilizers in agriculture, and erosion and sedimentation. Pollution by plastics, mainly mineral water bottles and plastic bags.	Detailed studies are needed regarding pollution origins and effects on the lake; Recycling and/or collection (reuse) of non-biodegradable wastes.
Biological invasions	Populations of Oreochromis korogwe from southern Tanzania are threatened by hybridization with the larger invasive Oreochromis niloticus; Water hyacinth in Burundi and DRC (Uvira) may result in the loss of critical fish habitats, reducing productivity in the littoral zone.	A comprehensive mapping of high-risk areas prone to alien species' invasions in the Lake Tanganyika basin to identify potential hot spots and thus create an effective early warning system is a necessity.

(*continued on next page*)

Table 2 (*continued*)

Thematic Area	Critical driving forces and pressures	Strategic management recommendations
Biodiversity decline and habitat modification	Soil erosion, sediment transport and runoff of pesticides used for agriculture are sources of pollution that may affect the lake's biodiversity due to conversion of forests to agricultural land.	Conduct an inventory of the terrestrial and aquatic flora and fauna and design a monitoring programme to establish their relationship with the anthropogenic activities and the variable climatic conditions.
Climate change	Lake Tanganyika has warmed in response to climate change, which has resulted in an increase in the average air temperature.	Long-term monitoring observations are essential to guide management measures to adapt to climate change and decrease, whenever possible, unfavourable human impact on the Lake Tanganyika environment.
Lake Turkana Basin		
Biodiversity and Ecosystem Status	Studies and publications are limited, outdated, or scarce on biological diversity and fisheries, potamodromous fish species migration and fish ecology, other flora and fauna, basic ecosystem functions; hydrological and environmental changes.	Need updated: baseline biodiversity survey and long-term monitoring, understanding of the lake's fauna behaviors, ecosystem models for socioeconomic and environmental change, monitoring of climate change variables, cooperation between Kenyan and Ethiopian scientists, awareness by the international community, research facilities, training of personnel, local community involvement, sustainable funding.
Fisheries Resources	Lack of consistent monitoring for fish stocks; Unreliable and inaccessible fisheries and lake productivity data, unregulated fishing gear, high post-harvest losses, conflicts between Ethiopian and Kenyan fishers over management measures.	Need to: develop indicators of fish stock status and productivity, value, and composition; minimize conflict; monitor contaminants, socio-economic variables, and water quality, among others; ensure Kenyan and Ethiopian experts and institutions harmonize efforts; acquire sustainable financing for research, monitoring, and management.
Limnology and Ecohydrology	High salinity and alkalinity, limiting the lake's water for drinking, irrigation, and biodiversity; Climatic fluctuations causing disruptive rainfall, resulting in floods and causing changes in inflows from the Omo River.	Need regular monitoring of environmental conditions; modeling of potential future environmental states; improved communication between scientists, policy makers and the general public; strengthen funding arrangements for long-term monitoring, research, and management.
Land Use	Increased land-use development from water abstraction, wetland and farming shifts, oil exploration, wind and hydropower productions, and a resort city resulting in sedimentation and species loss; concerns over indigenous land rights and access to resources; fisher-conservationist conflict.	Need conflict resolution measures; monitoring and research on various land-use, climate change, dam construction, population growth, and ecological and limnological variables. Prioritize local population welfare, ecosystem research and management in awareness raising.
Lake Victoria Basin		
Fisheries resources	Dwindling catch rates due to overfishing.	Enforce fishery regulations for sustainability of the Nile perch fishery; Finance fish stock assessment, synthesis, and dissemination.
Biodiversity	Biodiversity decline (e.g., haplochromine cichlids).	Identify Key Biodiversity Areas (KBAs) for future conservation.
Pollution	Nutrient loading from domestic, industrial, and agricultural activities and increased sediment runoff leading to anoxic conditions in the lake.	Create policies to reduce pollution; Prioritize research to identify main pollution agents; Establish databases and information systems for better decision making.
Invasive species	Water hyacinth clog waterways, imped water flow, increase the rate of siltation, and deplete dissolved oxygen levels.	Use of biological control agents (e.g., weevils), mechanical removal, and the use of herbicides.
Aquaculture	Tilapia cage farming raise concerns over loss of biodiversity, the introduction of fish pathogens, safety of products, and pollution.	Biosecurity and biosafety policies for aquaculture should be implemented to ensure sustainable growth of the sub-sector.
Human population growth and Socio-economics	Increased human population results in unsustainable agricultural practices, deforestation and encroachment into wetlands, riverbanks, and lake shore.	An in-depth evaluation of population structure, dynamics, and trends, including gender considerations.
Land use and land cover changes	Increased agriculture, grazing land, urbanization, rural and urban settlements due to population pressure which have had implications for water quality and a reduction in the quality of ecosystem services.	Adopt land use mitigation strategies; Monitor chemical, physical, and biological conditions to understand lake changes; Monitor land use with remote sensing and in situ to measure key parameters in the rivers; Data on the use of soils, fertilizer and pesticide application are also needed.
Habitat degradation	Riparian deforestation; Nutrient input and eutrophication has resulted in water quality and quantity changes, organic matter and nutrient inputs, and the diversity and composition of aquatic communities.	Restoration and maintenance of indigenous riparian forests; Maintenance of buffer strips along riverbanks to prevent sediment erosion from agricultural hillslopes and to stabilize river flows especially during the wet periods.
Climate change	Unpredictable rainfall has negatively affected food production.	Increase research to addresses impacts of climate and weather extremes
Skills and knowledge	The Lake Victoria region lacks enough trained human resources in the modeling and the ecosystem approach to aquatic ecosystem conservation and management; fish processing and fishing gear technology; and well-trained specialists in DNA barcoding, genomics, and aquatic organism sequencing.	More people should be trained in these disciplines to understand the complex ecosystem processes, structure, and function and link them with the increasing state of perturbation from the catchments to the lake.

- Create comprehensive, harmonized, long-term monitoring programs to collect time-series data on each of the AGL, and in a manner that lakes can compare data sets;
- Ensure publications, data, and other relevant information are known, available, and accessible to those who need it to address the issues on these lakes;
- Enhance education and training efforts for the current and next generation of African freshwater researchers and decision-makers on these lakes;
- Increase the voice of women in science and leadership, representing 50 % of the world's population and equal stakeholders in AGL resource use.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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