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Key Points:

- Environmental and occupational health challenges remain significant throughout Eastern Africa
- The Eastern Africa GEOHealth Hub is well positioned to build its research and dissemination activities
- The Hub serves as a model for other large, international research collaborations

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The GEOHealth Hub for Eastern Africa: Contributions and Lessons Learned

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Abstract Externalities, such as air pollution and increased occupational hazards, resulting from global trends in climate change, rapid industrialization, and rapidly increasing populations are raising global concerns about the associated health risks. The Global Environmental and Occupational Health Hub for Eastern Africa was established to address some of these problems at national and regional levels through focused training and applied research that would yield evidence supporting policies and investments to mitigate risks of increasing environmental threats throughout the Eastern African region. Emphasis has been placed on air pollution, a leading risk factor for global mortality, accounting for over 7 million premature deaths or 8.7% of the 2017 global mortality burden. Despite the enormous disease burden that air pollution causes, global investment in air pollution monitoring and research capacity building in low-middle and middle-income countries have been inadequate. This study outlines the activities the Hub has undertaken in planning for and carrying out its initial capacity building and building its primary research programs and identifies central lessons that can inform other large global research partnerships.

Plain Language Summary Air pollution and increased occupational hazards resulting from climate change and rapid industrialization are damaging health. The Global Environmental and Occupational Health (GEOHealth) Hub for Eastern Africa was established to address some of these problems at national and regional levels through training and applied research. This paper describes the activities the Hub has undertaken during its first five years and identifies central lessons that can inform other large global research partnerships.

1. Introduction

Environment-related illnesses, such as indoor air pollution from cooking fires, outdoor air pollution from vehicular and industrial emissions, pesticides, radiation, unsafe water, and climate change, contribute to nearly a quarter of the total global burden of disease (Prüss & Corvalan, 2016). Air pollution alone is a leading risk factor for global mortality, accounting for ~7 million deaths annually (Stanaway et al., 2018; World Health Organization, 2021). Climate change, already having adverse consequences for countries worldwide, will further increase the burden of environmental illnesses and exacerbate global inequities. While environmental health risks affect all regions of the world, populations in low- and middle-income countries (LMICs) are the most severely affected (World Health Organization, 2018). According to the World Health Organization (WHO), few cities in LMIC countries with more than 100,000 inhabitants meet WHO Air Quality Guidelines, as compared to most higher-income countries where air quality control regulations and initiatives have been successfully implemented and in place for decades (World Health Organization, 2016). In addition, workers in LMICs face a disproportionate risk of injuries and contact with hazardous conditions while at work (Abdalla et al., 2017).

While harmful environmental and occupational exposures play a substantial role in the initiation and/or progression of many infectious and chronic noncommunicable diseases, especially in LMICs, there are substantial gaps in understanding this in the proper context. There has been little investment in research to inform evidence-based policy, and capacity is limited to carry out research and to translate findings into

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action. For example, the European Commission, the US Agency for International Development, the Canadian International Development Research Center (IDRC), and other bilateral development agencies have directed very little foreign aid to addressing environmental pollution from industrial, automotive, and chemical sources (Greenberg et al., 2016; Landrigan et al., 2018). In 2018, WHO hosted its first Global Conference on Air Pollution and Health (World Health Organization, 2018). Consequently, environmental and occupational health monitoring and research capacity in most low-income countries trail far behind higher-income peers, as does political attention to regulatory weaknesses.

In an effort to respond to these challenges, the Fogarty International Center at the US National Institute of Health, in partnership with the International Development Research Centre (IDRC) of Canada, the National Institute of Environmental Health Sciences (NIEHS), and the Centers for Disease Control and Prevention's (CDC) National Institute for Occupational Safety and Health, launched the Global Environmental and Occupational Health (GEOHealth) program in 2012. The program eventually funded seven GEOHealth Hubs to support collaborative training and research initiatives around high-priority local, national, and regional environmental and occupational health threats. Included among these seven Hubs is the GEOHealth Hub for Eastern Africa (hereafter referred to the Eastern Africa Hub), a training and research collaboration between the University of Southern California (USC), USA; Colorado School of Public Health, USA; Columbia University, USA; University of Wisconsin—Madison, USA; South Coast Air Quality Management District, USA; Addis Ababa University (AAU), Ethiopia; Makerere University (MU) Uganda; University of Nairobi (UoN), Kenya; and University of Rwanda (UR), Rwanda (Eastern Africa GEOHealth Hub). This manuscript outlines these activities and summarizes the "lessons learned" from the Eastern Africa Hub's achieved successes and challenges encountered over nearly a decade, which can be used to inform and improve the next cycles of the Eastern Africa Hub and other global environmental and occupational health research and capacity building efforts.

2. Background

The Eastern Africa Hub was launched in 2015 following a funded 3-year data gathering and planning phase. In planning for the establishment of the Eastern African Hub, four coordinated and comprehensive reviews of the current state of environmental, occupational, and climate-related health issues were carried out by investigators in the four participating countries in the region; Ethiopia, Kenya, Rwanda, and Uganda (Table 1), in close collaboration with US-based partners. These reviews were framed as a Situational Analysis and Needs Assessment (SANA) in each country to: (a) assess the situational profile in each country on occupational health and safety (OSH), air pollution and health, and climate change and health, including assessing relevant governmental and policy capacities; (b) identify gaps and needs related to tracking data, research evidence, and capacity, and (c) determine possible interventions to remedy the shared needs identified across the countries and that could be addressed through the Eastern African Hub. In each country, the SANA included a systematic review of secondary data from peer-reviewed literature, thesis reports from academia, government and national statistical reports, as well as limited primary data based on key informant interviews from major stakeholders to identify ongoing monitoring efforts, regulatory and policy needs, and political engagement. Through the country-specific SANA process, critical gaps in research, policy frameworks, and implementation were identified spanning OSH, air pollution, and climate change across the region (Berhane, Kumie, Afullo, et al., 2016; Kumie et al., 2016; Mitike et al., 2016; Simane et al., 2016; Tefera et al., 2020). The SANA process informed the development of the initial paired research and training aims of the Eastern Africa Hub. Specifically, the SANA conclusions supported an initial focus centered on air pollution in the region, while also identifying limited research opportunities around climate change induced heat stress on occupational health.

3. Eastern Africa GEOHealth Hub Activities

The Eastern Africa Hub addresses the urgent need for more capacity and primary research to strengthen the evidence-based in support of (a) air pollution policy in low-income countries, (b) impacts of occupational exposures, and (c) health effects of climate change. The Hub's initial goal, as identified through the SANA process, is to advance public health in the region by providing the evidence required to support

Table 1
Core SANA Study Results

	Air pollution	Occupational health	Climate change
Ethiopia	• Inadequate research on air pollution levels and associated health impacts • Need to establish indoor and outdoor air quality monitoring systems	• Limited OSH research • Predominant OSH issues included accidents/injuries • Lack of systematic hazard surveillance • Existing regulatory documents did not address emerging industries such as construction industry and floriculture	• Climate changed recognized as a critical national concern • Lack of sufficient capacity and collaboration among organizations on the planning and execution of climate change and health activities • Lack of policies and programs
Kenya	• Inadequate research on air pollution levels and associated health impacts • Need to establish air quality monitoring systems	• Lack of systematic OHS monitoring system • Need for systematic OHS monitoring system • Need for specific OSH policies was greatest for the agricultural and informal sectors	• Limited climate change and health-related research and data available • Lack of policies and programs that target climate change and health • Need research and empirical data in an easily retrievable information system
Rwanda	• No data on air pollution levels and associated health impacts • Lack of infrastructure and capacity for air quality monitoring • Growing number of motor vehicles becoming a significant contributor to air pollution • Need for capacity building to conduct exposure assessment research • Need to establish air quality monitoring systems and to prioritize traffic-related air quality monitoring and policy development	• Substantial governmental efforts in promoting OSH through laws, regulations, and policies • OSH challenges remain due lack of capacity, implementation, and enforcement • Need for further capacity building and improved monitoring and information management	• Some climate change research and data available; irregularities in climate patterns including rainfall variability found • Policy and institutional responses, particularly to support small farmers adapt to climate change • Lack of coordination in policy implementation across governmental agencies • Need for a harmonized institutional framework for coordination and delivery of services related to the environment
Uganda	• Limited research on air pollution levels and associated health impacts • Lack of capacity among universities to conduct research • Lack of air pollution policies and guidelines including vehicle and factories emissions which are increasing in number • Low awareness around the health effects of air pollution • Need to establish air quality monitoring systems	• Governmental efforts in promoting OSH through laws, regulations, and policies • OSH challenges remain due lack of capacity, implementation, and enforcement • Need for further capacity building among stakeholders around existing policies	• Climate changed recognized as a national concern • Documented impacts of climate change include extreme weather events, reduced agricultural productivity, and shifts in disease • Lack of policy, legislation, and guidelines for mainstreaming climate change into development programs • Need for capacity building and comprehensive research and policy development

the development of policies and investments aimed at reducing ambient air pollution, particularly cleaner transport, throughout the Eastern African region. The Hub headquarters are housed at AAU in Ethiopia and now at Columbia University in the United States, for the research (U01) and training (U2R) components, respectively. The Hub's research and training achievements, described below, have included data collection, capacity building, infrastructure strengthening, policy-relevant research, stakeholder and community engagement, and continued assessment of research gaps.

3.1. Policy-Relevant Research

The Hub's air pollution research program is organized under four interrelated aims and has included various studies to date (Figure 1). An additional exploratory research study focused on occupational health threats from heat stress among floriculture workers has also been carried out. Country teams adapted common study protocols and instruments for the local context. Countries implemented research projects using a tiered approach allowing for lessons learned to be shared across countries (Table 2). To date, Hub investigators have published a handful of peer-reviewed research papers on the problem (Berhane, Kumie, Afullo, et al., 2016; Berhane, Kumie, & Samet, 2016; Woodward & Samet, 2018), air pollution levels and composition (Tefera et al., 2020), and health effects of air pollution (Chen &

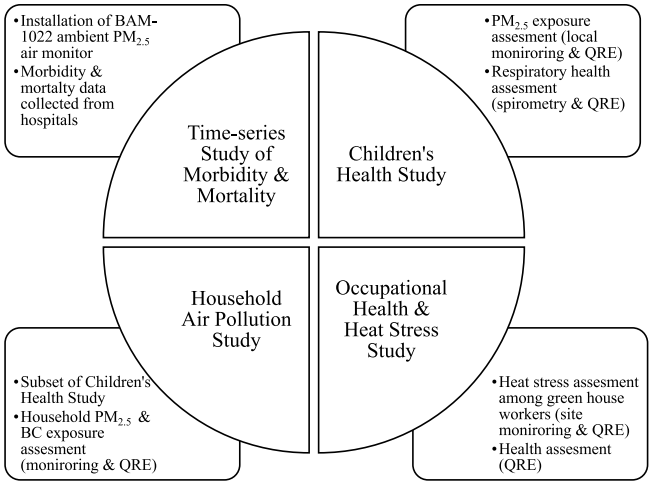

Figure 1. HUB Program of Research: The HUB's research program has focused on four core studies that have involved a range of data collection methods.

Samet, 2017; Joubert et al., 2019; Samet, 2018; Samet et al., 2018; Tefera et al., 2016; Toe et al., 2021), with a number of additional publications forthcoming.

3.1.1. Aim 1.1: Ambient Exposure Assessment

A continuous central site monitoring for $PM_{2.5}$ was established first using a Met One Instruments, Inc. (USA) Beta Attenuation Monitor (BAM-1022) in each capital city; in Addis Ababa (Ethiopia) since 2016, in Kampala (Uganda) since 2017, and finally in Nairobi (Kenya) and Kigali (Rwanda) since Spring 2019. Daily $PM_{2.5}$ levels are measured following a standard protocol across all four countries to enable the comparison of levels across the region. To our knowledge, continuous monitoring for $PM_{2.5}$ had not been in place in these cities except at the US Embassies in Addis Ababa and Kampala.

A second exposure study involved school-based monitoring for $PM_{2.5}$ using Met One Instruments, Inc. E-Samplers. The study was initially carried out in 2016–2017 in 10 schools located in each of the 10 subcities of Addis Ababa. At each school, continuous $PM_{2.5}$ data were collected for up to 10 months. This school monitoring program was coordinated with a school-based respiratory health study (described below), and the respective national air quality and meteorological management agencies were engaged. The same protocol was conducted in Kampala (Uganda) in 2017–2018 and in Nairobi (Kenya) in 2019–2020.

3.1.2. Aim 1.2: Household Exposure Assessment

A third air monitoring study carried out by the Hub was real-time personal $PM_{2.5}$ exposure and location monitoring, initially conducted in a panel of 300 households (in two waves of 150 households each) in Addis Ababa using UPAS and PATS + monitoring devices. These data were generated to develop microenvironmental models to estimate personal exposure to $PM_{2.5}$ outdoors, indoors at home, school, and work for the larger health studies where personal monitoring is not feasible. Once again, based on insight gained

Table 2
Tiered Timeline of Key Research Activities in Each Partner Country

	2016	2017	2018	2019	2020
Central site ambient air pollution monitoring	Ethiopia AAU	Ethiopia AAU			
		Uganda MU			
				Kenya UoN	
				Rwanda UR	
Mortality & morbidity ascertainment	Ethiopia AAU	Ethiopia AAU			
		Uganda MU			
				Kenya UoN	
				Rwanda UR	
Children's Health Study	Ethiopia AAU	Ethiopia AAU			
			Uganda MU		
				Kenya UoN	
Household Air Pollution Study			Ethiopia AAU		
				Uganda MU	Uganda MU
Occupational Health & Heat Stress Study			Ethiopia AAU		
			app		Uganda MU

Note. The shading was to emphasize the staggered start of each study by country.

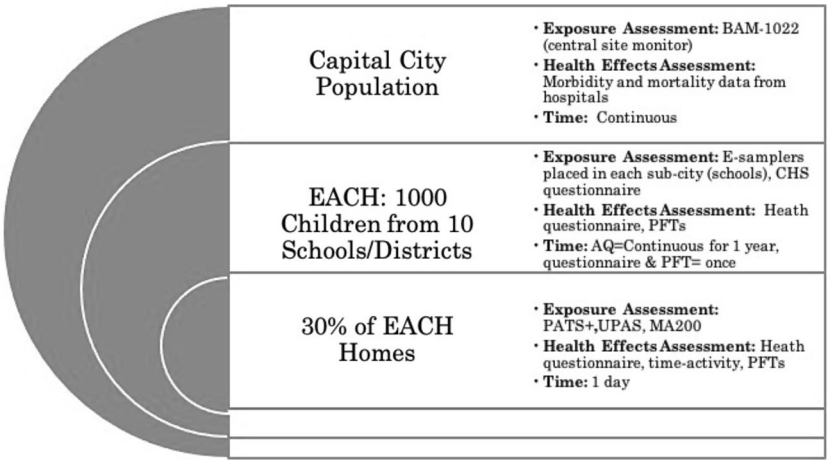

Figure 2. Components of the East African Children's Health Study (EACH): The EACH study involved multileveled data collection, including cities, schools, and homes.

from study implementation in Ethiopia, Uganda, and Kenya were scheduled to subsequently carry out similar studies.

3.1.3. Aim 2: Multicity Time-Series Study of Acute Effects of $PM_{2.5}$ on Morbidity and Mortality

The Hub's second aim focuses on linking the exposure data (from Aim 1 above) on $PM_{2.5}$ to the burden of disease in the region. To do this, the Hub took advantage of the recent establishment of health management information systems (HMIS) in each of the four capital cities, to establish a multicity daily time-series study of morbidity and mortality linked to $PM_{2.5}$ exposure. In each of the capital cities, Hub researchers established partnerships with local hospitals to create databases of daily morbidity and mortality data and extract information on sex, age, residence, cause of admission, diagnosis of the diseases after admission, and cause of death. The mortality/morbidity data from this study are being linked with the daily levels of $PM_{2.5}$ to examine the short-term (acute) effects of $PM_{2.5}$ exposure on daily mortality and morbidity (with focus on overall nonaccidental causes, respiratory causes, and cardiovascular causes).

3.1.4. Aim 3. Eastern African Children's Health (EACH) Study

This study is loosely based on the Southern California Children's Health Study (CHS), one of the largest and most detailed studies of the long-term effects of air pollution on the respiratory health of children (Navidi et al., 1994; Peters, Avol, Gauderman, et al., 1999; Peters, Avol, Navidi, et al., 1999). The goals of the EACH study are (a) to determine the effects of ambient and biomass-derived $PM_{2.5}$ exposure on attained levels of lung function in children, and respiratory symptom morbidity; (b) to determine the dose-response relationships with ambient pollution; and (c) to determine personal exposure to $PM_{2.5}$ via spatio-temporal modeling techniques whenever it is possible to assess and estimate personal $PM_{2.5}$ exposure using microenvironmental models (Figure 2). School-based data collection has been carried out in three of the four partner countries involving ~110 students (9–10 years old) from one selected school in each of 10 distinct subcities from the capital cities in Ethiopia, Kampala, and Kenya. The schools were selected to represent contrasting levels of indoor and outdoor $PM_{2.5}$, including (a) high indoor (biomass fuels) and high outdoor $PM_{2.5}$ (traditional and/or rural housing districts), (b) low indoor $PM_{2.5}$ (clean fuels) but with high and low outdoor $PM_{2.5}$ (urban areas), and (c) low outdoor $PM_{2.5}$ but high indoor $PM_{2.5}$ (outskirts of urbanized areas). The locations are selected to have similar climate, elevation, and social characteristics in each country. Ambient $PM_{2.5}$ exposure is measured at each school for a 10–12 month period as described above, lung function performance of participants is measured using computerized spirometry, and prevalence of respiratory symptoms over one calendar year is collected via questionnaire.

3.1.5. Exploratory/Pilot Study on Occupational Health and Heat Stress

In 2018, a pilot study was conducted in Ethiopia to assess the potential occupational health impacts of climate change among those working in the floriculture industry. Floriculture is a fast-growing and largely unregulated industry in East Africa. Kenya and Ethiopia are the two largest exporters of fresh flowers on the continent, generating over $1 billion in 2019 and employing hundreds of thousands of individuals, primarily impoverished women, across the two countries (Bhalla & Wuilbercq, 2010). Using a cross-sectional study design with stratified sampling, occupational heat stress was assessed in six greenhouses across three regions of the country with varying agro-ecologies. Heat exposure was measured using Wet Bulb Globe Temperature (WBGT) instruments during two seasons (warm and cool) and worker perceptions and possible health impacts of heat exposure were collected via interview-administered questionnaires. A similar study is currently underway in Kampala, Uganda.

3.2. Training and Capacity Building

The Hub developed and implemented a progressive and tiered training program designed to support both the foundational and operational concepts of this work with the goals of (a) supporting researchers to develop teams to carry out the research agenda of the Eastern Africa Hub; (b) to facilitate the translation of the research findings into impactful actions by key stakeholders; and, (c) strengthen in-country capacity and create a center for excellence regionally for future environmental and occupational health research. The training activities utilized three main approaches: In-country training workshops, distance education, and the Hub Scholars training program. Training activities supported the development of a common protocol and standard operating procedures for each of the studies described above grounded in rigorous scientific methodology and best practices.

3.2.1. In-country Training Workshops

Fifteen in-country training workshops and site visits lasting up to 2 weeks were conducted during the initial 5-year project period. Each workshop was designed with specific learning objectives covering focus areas, including air pollution and exposure assessment, respiratory and physiological health assessments, questionnaire development and administration, data management and analysis, and publication development. Workshops focused on both technical and infrastructural capacity building activities, such as training on the foundations of air pollution and exposure assessment coupled with the installation of air monitors within each capital city and training the data teams in each country to carry out the advanced modeling needed for analysis of exposure and outcome data. Workshops occurred in the implementing country to maximize the number of field staff who could attend trainings. Workshops would often include trainees from each Hub country to foster cross-country partnership and collaboration. In addition, this allowed for a "train-the-trainer" approach to be utilized with researchers from a country who had already implemented supporting the training efforts of the next country and sharing their expertize.

3.2.2. Distance Education

Virtual training modules on air pollution, respiratory health, and exposure assessment were developed by Hub experts to build a strong conceptual foundation for all members of the Hub. The Hub has also utilized online platforms to support training and capacity building. In April 2017, the Eastern Africa Hub Training and Study Implementation Portal was launched to help better disseminate training resources and study materials developed as part of the Hub. The portal contains training videos and presentations developed by Hub experts to provide essential background information to country teams in the areas of air pollution, exposure assessment, spirometry, and time-series studies. Reference materials for additional explanation are provided for each subject area, as well. The most up-to-date study materials, including standard operating procedures (SOPs), questionnaires and operations manuals for each study arm, can also be found on the portal. The portal is currently only available to Hub partners. Virtual training workshops have been adopted in the wake of the COVID-19 pandemic. In recent months, virtual workshops have been conducted to support paper writing, policy translation, and development of strategic dissemination plans.

3.2.3. Hub Scholars Training Program

Eight scholars, two from each partner country, participated in a 2–3 week immersive training and mentorship program at US-based Hub universities. In 2016, the first cohort included the principal investigators from each country. They underwent intensive training at USC ensuring their core competency in the methods underlying the core research projects and in project management. A second cohort of emerging investigators was subsequently recruited in 2018. Once again, these trainees participated in multiple training events and spent 2 weeks studying in the United States in 2019, the first week at USC and the second at the institution of their dedicated Hub mentor. The training curricula and activities were tailored for the needs of trainees and included principles of air pollution and exposure assessment, respiratory and physiological health assessments, questionnaire design, general research methods, and ethical considerations. Each Hub Scholar was paired with a primary mentor (and also secondary mentors in the second cohort of junior researchers) for an active year-long follow-up.

3.3. Community Engagement and Policy Translation

A key element of the initial SANA process was identifying the broad range of stakeholders at the local, national, and regional levels that needed to be integrated into the Hub's activities. Early on in the Hub's development, these stakeholders were invited to planning meetings and training workshops to ensure that they were aware of the Hub's aims and activities. For example, in Ethiopia, the Federal Ministry of Health, Federal Ministry of Environment and Forestry—formerly the Ethiopian Environmental Protection Authority, Federal Ministry of Labor and Social Affairs, National Meteorological Services Agency, and non-governmental environmental agencies such as PAN-Ethiopia have all engaged in HUB activities. In Uganda, core stakeholders have included the Ministry of Gender Labor and Social Development, the Ministry of Health, and the Ministry of Water and Environment, the National Environment Management Authority and the Climate Change Unit; the Uganda National Association of Community and Occupational Health; and the Makerere University Institute of Environment and Natural Resources and Makerere University School of Public Health. International team members also make courtesy visits to such stakeholders when they are in-country.

The Hub's training curriculum has also stressed community engagement, data dissemination, and policy translation. Specific training workshops have focused on stakeholder mapping and outreach and data dissemination strategies, as well as development of fact sheets, policy briefs, and white papers to share with policymakers and other key partners. Unfortunately, the project's planned dissemination workshops in 2020 were postponed because of the COVID-19 pandemic, although we are currently in the process of rescheduling both in-person and online webinars in May and June 2021 to share our research findings with diverse local, national, and regional stakeholders. The Hub's website (www.geohealth-hub.org) provides a repository of all the Hub's outreach materials and resources, including country-specific landing pages.

4. Achievements and Lessons Learned

During its planning and first research phase, the Eastern African Hub has fulfilled most of its stated aims, including establishing an additional air monitoring site in each of the capital cities, carrying out research on the acute and long-term impacts of air pollution exposure on adults and youth in the region, training a cohort of emerging air pollution researchers, and engaging key stakeholders in each county in air pollutions discussions. A number of lessons have been learned while carrying out these activities. These lessons relate to the effectiveness of the Hub model: the need for effective communication and coordination, navigating complex governmental and academic bureaucracies, and managing logistical and administrative complexities, while maintaining flexibility and managing unforeseen crises.

4.1. Achievements

As mentioned, the Hub has already successfully accomplished a number of research and training objectives. The Hub has generated novel data on exposures through a new air quality monitoring network, carried our multi-country research on children in a coordinated and uniform fashion, enabled the acquisition

of mortality/morbidity data from hospitals in the absence of electronic records, and carried out limited research related to climate and health. Moreover, Hub trainees have become recognized experts in the field both nationally and internationally. They have presented their research at numerous conferences and Hub network meetings, and notably the country Principal Investigator from Uganda was invited to speak at the landmark First WHO Global Conference on Air Pollution and Health in 2018. In addition, Principal Investigators have taken on their own mentorship roles leading in-country teams and serving as PhD advisors for related work within their universities. The Hub has also been successful in maintaining strong communication and engagement among the project partners and individual researchers, having established a strong team capable of responding to future challenges and opportunities in the field.

4.2. Lessons Learned

4.2.1. Effectiveness of the Tiered Approach

The tiered approach to training and research implementation has proven to be effective both in terms of capacity building as well as cost. This structure maximized learning across countries and allowed for building on the successes of implementers and avoiding experienced challenges from country to country. Utilizing the "train-the-trainer" method helped further solidify training efforts as well as foster cross-country partnership within the Hub. The tiered approach was also cost-effective in that it allowed for an ambitious program of research to be undertaken across four countries through the shared use of costly equipment by moving it from partner to partner.

4.2.2. Continuous Communication and Teambuilding

Through constant interaction, team members have been able to learn from, and build on, each other's experiences and a cohesive team approach has been built. The Hub's success at teambuilding and mentorship illustrates the importance of ongoing communication amongst all team members, even during slower project periods. This has been accomplished through weekly calls (Skype/Zoom) between the country PIs and core staff in addition to multiple in-person events each year, which have ensured ongoing communication and teambuilding. Weekly calls, for example, are well attended and have served to ensure that all partners are aware of the steps being taken to achieve the project goals in all countries. The calls involve quick country updates and, when relevant, are used to share exciting new research results, or address more difficult challenges faced by one or more project partners. During the COVID lockdown, weekly calls were pivoted from research updates into virtual training workshops focused on broader skills such as research dissemination and paper writing. In 2016–2017, Hub Principal Investigator (Berhane) spent 10 months in Ethiopia as a Fulbright Scholar. This allowed for an extended engagement with the team in Ethiopia during the crucial implementation period and also facilitated his ability to travel to other countries in the regions (e.g., Kenya) to solidify the Hub partnerships. The core lesson is that sustained and in-person communication and engagement were critical to building trust between the Hub partners and maintaining project momentum.

4.2.3. Logistical and Administrative Complexities

The logistical and administrative complexities of a tiered multicountry research study using shared research equipment cannot be overstated. Though overall the approach was effective, a number of challenges, many not anticipated, were encountered in regard to purchasing through cumbersome processes, shipping shared equipment between countries, releasing materials from customs, and getting funds released and transferred between universities and across countries in a timely manner. The Hub has also confronted significant international currency fluctuations that affected program budgets. From these challenges, the Hub learned that well-trained staff who can effectively navigate relevant bureaucracies must be in place and time for such activities must be built into project timelines.

4.2.4. Local Availability of Commodities

Hub activities called for research-grade equipment such as spirometers, air pollution monitors, and corresponding consumables that were not available locally within each country. The lack of a market for such goods further exacerbated the aforementioned logistical and administrative challenges resulting in often lengthy and complicated international procurement procedures with US-based manufacturers. Similar logistical challenges were associated with coordinating maintenance, troubleshooting, or repairs of

equipment as well. This lack of availability and resulting unfamiliarity with such items contributed to a weak onsite capacity to address mechanical issues with the monitors, including periodic cleaning and repairs, occasionally resulted in unreliable data and further project delays. Consequently, the Hub learned that budgeting time and human resources for such processes is integral for successful execution.

4.2.5. Adaptability

In order for training support to remain relevant and effective, there is a constant need to continually re-evaluate needs and tailor training activities. It was critical to adapt to realities on the ground while also maintaining stringent research protocols for aims to be met. For example, issues around interruptions in electricity became an issue for air monitors, so protocols and procedures for preventing and dealing with outages based on best practices such as establishing thresholds for acceptable data loss needed to be incorporated. For the E-Samplers, stable electrical power could not be established at the schools from existing electrical services and solar power was implemented. In addition, formal monitoring and evaluation efforts helped reveal training gaps and improve methods to maximize impact. Finally, natural emergencies and political instability periodically complicated the Hub's activities. The largest of these disruptions was the COVID-19 pandemic and subsequent lockdowns in all participating countries, while smaller health emergencies and political unrest resulted in periods with weak to no communication with the project sites and additional delays in data collection. These delays in getting projects up and running resulted in stretched-out data collection timelines and slower production of project-related publications than initially predicted. These experiences provided clear lessons on the need to remain flexible and taught the Hub team to assume unanticipated challenges will complicate international research project implementation.

4.2.6. Sustainability

A number of the lessons learned above speak to the overall sustainability of the Eastern Africa HUB. The establishment of such strong, collaborative teams within and between countries, as well as the enhanced research capacity among the HUB's members, has allowed the HUB partners to leverage the project to expand and build on the initial grant. For example, in Uganda, the HUB team has been able to secure additional governmental and university-level grants to study household air pollution in Kampala and the effects of urban air pollution on maternal and child health outcomes. Still, challenges such as equipment malfunctions have revealed the limits of how long infrastructure can last without ongoing large-scale investment. HUB members are actively seeking domestic and international sources of support and are currently in the process of preparing a renewal application for the renewal of the Hub from NIH to further solidify the Hub's activities and partnerships.

5. Conclusion

Environmental and occupational health challenges remain significant throughout Eastern Africa. However, over the past seven years, the Eastern African Hub has established a foundation on which it is building a credible research enterprise to inform policy development. The Hub has made significant progress in the development and refinement of research protocols, standard operating procedures, and training curricula for indoor exposure assessment, respiratory health research, and study data management. A number of other air pollution and climate initiatives have been initiated since the Hub was first established, including additional monitoring sites in the capital cities. This increased interest in addressing environmental health challenges and research capacity is a positive development as the Hub, as well as other initiatives, will require continued engagement and ongoing investment to sustain the training and data collection required to address the persistent air pollution challenges in the region. Armed with past successes and the lessons learned, the Hub is now well positioned to respond to this donor interest and build upon its research track record and enhance its dissemination activities to play a greater role in advancing clean air policies and programs at the national level in each of its target countries and can serve as a model for other large cooperative research initiatives.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

There is no original data cited in this paper requiring storage in a FAIR Data Repository, however, data collected through the Situational Analysis and Needs Assessment (SANA) was previously presented in Berhane, Kumie, Afullo, et al. (2016) and available on the Eastern African GEO Health (2020) website (https://geohealth-hub.org/planning-grant/reports/).

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