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the interacademy partnership

Save the Children

Climate and Health: Science-based policy solutions

A collection of case studies

CLIMATE AND HEALTH:
SCIENCE-BASED POLICY SOLUTIONS

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Contents

Foreword

Since its foundation in 1993, and especially since 2016 when three academy networks were merged into the single InterAcademy Partnership, IAP has developed a track record of providing credible, independent science-based recommendations to policymakers.

From 2015, with the launch of a project on 'Food and Nutrition Security and Agriculture' (FNSA), we have followed a methodology that includes regional reports on the topic under consideration each prepared by one of the four IAP Regional Networks (AASSA for Asia and Oceania, EASAC for Europe, IANAS for the Americas, and NASAC for Africa). Key findings from the four regional reports are then collated into a global synthesis.

This same methodology was used for IAP's second major regional-to-global project, this time on 'Climate Change and Health' (CCH), which ran from 2019 to 2022, when the global synthesis[1] was launched. Just as the FNSA project gained traction in international policy discussions – IAP and its Regional Networks were asked to contribute to the UN Secretary General's 2021 Food Systems Summit – so the IAP CCH project has helped raise awareness of the health co-benefits of tackling climate change. Indeed, the co-chair of the project (with Volker ter Meulen, former IAP co-president, Germany) Sir Andrew Haines (London School of Hygiene & Tropical Medicine and co-Director of the World Health Organisation (WHO) Collaborating

1 https://www.interacademies.org/publication/health-climate-emergency-global-perspective

Centre on Climate Change Health and Sustainable Development), has claimed that, at the start of the project governments were not aware of the strong interlinkages between climate change and health. For the first time, at the 28th Conference of the Parties (COP28) of the UN Framework Convention on Climate Change that took place in Dubai in November and December 2023, there was a dedicated 'Health Day' that focused on this nexus. This new awareness can be partly attributed to the success of the IAP project, which had been presented at COP26 and COP27.

Other organisations, too, have been urging action on this nexus – among them Save the Children (SC), which also in 2022 developed its organization-wide 'Climate and Health Strategy: Accelerating action on climate with health benefits'[2], which takes a multisectoral, systems-based approach to address climate, health and equity together. SC envisions a future where all children learn, survive, and are protected and can grow up to reach their full potential. To achieve this vision, SC is tackling the mutually reinforcing issues of climate change, health and inequity by taking actions to: (1) improve understanding of the multi-sectoral impacts of, and interconnections between, human activities, climate change and health; (2) foster community action to test, evaluate and scale up interventions with climate, health and equity benefits; and (3) support systematic and meaningful inclusion of children, adolescents, women and other disadvantaged groups in climate action for health.

It made sense, therefore, for Save the Children and IAP – two global organisations with the capacity to work regionally and nationally – to work together to build on these beginnings and develop a product that, we believe, will be useful in persuading policymakers that multi-sectoral, systems-based studies can provide solid evidence to directly inform their decision-making.

This is what we have attempted to do in this project. We received more than 80 proposals to our call for examples of case studies of approaches to problem-solving and policies, used to address the interlinked challenges of climate and health. Thanks to our expert review panel, these were whittled down to the 14 case studies that are presented in this book. The authors of the case studies attended a workshop in Trieste, Italy, in September 2023, where they shared their experiences with one another and a sub-set of our expert panel. Since then, each case study has been edited into

2 https://resourcecentre.savethechildren.net/document/save-the-childrens-climate-and-health-strategy-accelerating-action-on-climate-with-health-benefits-executive-summary/

a non-technical version, making it accessible to a wider audience, and published in this volume. The book will be distributed free of charge and also made available online[3]. By providing such a collection of case studies, it is hoped that countries, whether low-, middle- or high-income, will be able to identify appropriate examples of the multisectoral, systems-based approach to study design, partnering and implementation, and adapt them to their own particular national challenges.

As a global society, we need to act as quickly as possible to adapt to and mitigate climate change. These studies show that appropriate action can be taken and that, by taking a holistic view of the issue, health benefits can be attained (or at least negative impacts on health can be avoided) through actions to address climate change. We sincerely hope that they can be used as positive examples for others to follow, replicate, amplify and scale up.

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3 https://www.interacademies.org/publication/climate-change-adaptation-health-book-case-studies

Acknowledgements

The present publication has its roots in a 3-year IAP project on 'Climate Change and Health' that was completed in 2022.[1] As a follow-up, IAP has partnered with Save the Children to select and present the case studies collated here, with the aim of providing them as real-world examples of co-designed, systems-based, interdisciplinary approaches that can be used to support policy development at the nexus of climate change and health.

We hope, therefore, that this book will be useful for those considering developing such studies and implementing such policies.

We would like to extend our gratitude to the many individuals and organizations that have contributed to the planning and execution of the process that has resulted in the publication of this volume.

First and foremost, our thanks go to Save the Children, who funded the project, and especially to Montira Pongsiri, Senior Advisor, Climate Change and Health, who has worked closely with IAP staff in its implementation.

The project has been led by the IAP Coordinator in Trieste, Italy, Peter McGrath, supported by the other members of the IAP Secretariat in Trieste, Sabina Caris, Lucia Fanicchi (Administrative assistants) and Sofia Nitti (Communications assistant). Together they have managed to keep the project on track despite the complications caused by its global reach.

1 https://www.interacademies.org/project/climate-change-and-health

Following an open call, IAP received almost 80 case study proposals. To help review and select these proposals, our sincere thanks are due to the members of a specially convened international expert committee: Deoraj Caussy, Integrated Epidemiology Solutions, Mauritius; George Christophides, Imperial College, London, UK, and Adjunct Professor, the Cyprus Institute, Cyprus; Anthony Clayton, Professor of Caribbean Sustainable Development, University of the West Indies, Jamaica; Meghnath Dhimal, Chief, Research Section at Nepal Health Research Council, Government of Nepal; Robert Hughes, Field Research Director, London School of Hygiene and Tropical Medicine, UK; Shabhana Khan, Director, Indian Research Academy, New Delhi, India; Philip Landrigan, Director, Global Public Health Program and Global Observatory on Planetary Health, Boston, USA; working also with Robin Fears (IAP consultant, UK) and Montira Pongsiri.

The work of this expert committee helped us hone in on fifteen case studies – the principle authors of which were invited to present their work at a workshop held in Trieste on 5-7 September 2023. As well as receiving valuable feedback from their peers, the comments and advice from four of the expert committee members present (D. Caussy, G. Christophides, S. Khan and R. Fears) helped the researchers improve their case studies.

Of course, this volume would not have seen the light of day without the contributions of the authors of the 14 case studies. We thank them first of all for recognizing that IAP can help them in presenting their work to an important target audience – policy makers. Also for preparing their written case studies, attending the workshop in Trieste (some remotely, due to visa or other issues), and of course working with our editor to finalise the texts and images that you find in this book. It goes without saying that this volume would be nothing without their contributions – and we hope that they will continue to work with us as we present the book and its contents on suitable occasions in the coming months and years.

As mentioned, the 14 case studies presented in this volume were initially prepared by the researchers involved and, once again, we extend our thanks to them. Mez Packer, a freelance editor based in the UK, working closely with Peter McGrath, then adapted the texts to the format presented in this book, which were again reviewed by members of our expert committee. Giulia Gennari (UNESCO-TWAS) and Rafael Jimenez Aybar (GLOBE Legislators) also helped with peer reviewing some of the final versions of the case studies that appear in this volume.

We hope that, through this process, the scientific content of these (peer reviewed) case studies is now more accessible to a wider, non-technical audience, including policy makers.

The talent and commitment of each member of this diverse group helped to move the project forward efficiently and effectively. We express our thanks to them all.

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Introduction

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Summary

Climate change is a global health crisis and has disproportionate effects on vulnerable groups. Building on their previous expertise, in 2023, the InterAcademy Partnership (IAP) and Save the Children initiated a project to identify and disseminate case studies of health adaptation solutions in response to the diverse climate change pathways of risk from around the world. The selected case studies employed systems-based approaches, used transdisciplinary research, and involved the producers and users of knowledge working together with a focus on underserved, marginalised populations.

Outputs from this project help to:

- Clarify complex interactions between human-driven environmental change and human health, whether by direct pathways (e.g. heat) or indirect, via ecosystems (e.g. food), or socio-economic systems (e.g. livelihoods).
- Highlight and assess climate-health policy priorities across multiple sectors, e.g. urban planning, transport and agriculture, in addition to the health sector itself.
- Advise on how research findings can be used by policy makers and other end-users, by building capabilities and trust at science-policy interfaces, while emphasising throughout the necessary focus on vulnerable, underserved groups.
- Derive generalisable lessons for health adaptation good practice to indicate how to measure impact, avoid maladaptation, understand limits to adaptation and underpin health system resilience.
- Evaluate issues for transferability and scale-up of adaptation solutions, together with enablers of and barriers to action and longer-term capacity building.
- Clarify the intersection between climate change and other health crises, e.g. the COVID-19 pandemic and other infectious diseases, and the implications for global health strategic priorities, e.g. universal health coverage.
- Show how systems-based thinking provides the conceptual framework and tools for integrating policy actions between sectors and between the various levels of governance, local, national, regional and global.

Climate change threatens health

The pace and extent of environmental changes caused by climate change threaten to reverse the gains in global health made over recent decades (Whitmee *et al.*, 2015). Human activities, principally the emissions of greenhouse gases (GHGs) have unequivocally caused global warming (IPCC, 2023). Climate change is thus a global health crisis as well as an environmental and financial crisis. Among the world's environmental challenges, climate change is deemed the greatest threat (WHO, 2023).

Climate is one of the principal Earth system boundaries (see Rockstrom *et al.* 2023 for a recent update on safe and just Earth system boundaries) and climate change has the potential to increasingly disrupt health and wellbeing because, in addition to direct adverse effects on health, it affects the provision of food, safe water and clean air. Human and ecosystem vulnerability are interdependent (IPCC, 2023).

Therefore, countries' climate change adaptation and mitigation planning must not ignore health. Doing so could result in trade-offs and unintended consequences which could ultimately undermine well-intentioned efforts to improve health. In other words, actions to address climate change are opportunities to reduce and prevent risks to health (WHO, 2020). Addressing climate change and health together is appealing because of the potential win-win opportunities: achieving multiple benefits to human health and the climate (Frumkin and Haines, 2019).

Activities within and outside the health sector (e.g. industry, energy production, transport, agriculture) contribute to climate change and, at the same time, affect health. The relationship between climate change and health can be non-linear and involve time delays and feedback interactions among many factors (Whitmee *et al.*, 2015). This complexity can lead to health outcomes which are difficult to predict, including disproportionate adverse effects on children and other vulnerable groups. As a result, a multi-sectoral, systems-based[1], approach is needed to address climate, health and equity together.

The nature, distribution and timescale of the health impacts associated with climate risks differ between countries and within their populations, influenced by geography and socio-economic status, and are rooted in social inequalities. There are also commonalities in the deteriorating health outcomes that warrant shared approaches encompassing both climate mitigation and adaptation solutions. The largest adverse health impacts of climate hazards are felt in low- and middle-income countries (LMICs) and in economically and socially marginalised residents elsewhere, e.g. in urban areas (IPCC, 2023). To build resilience at many levels – individual, household, community and systems – health actions taken to identify and

1 A systems-based approach with cross-sector integration encompasses the complex interactions between natural and social systems and the integration of research outputs from across many disciplines throughout the processes for developing and implementing policy (IAP, 2022).

quantify solutions must concentrate on the most vulnerable groups. Actions must also address the current gaps in mobilizing scientific research findings to directly inform policy actions.

Pathways of risk and vulnerable groups

Health risk is a function of hazard, exposure and vulnerability. There are multiple pathways of direct and indirect risk and multiple physical and mental health consequences, as presented in Figure 1.

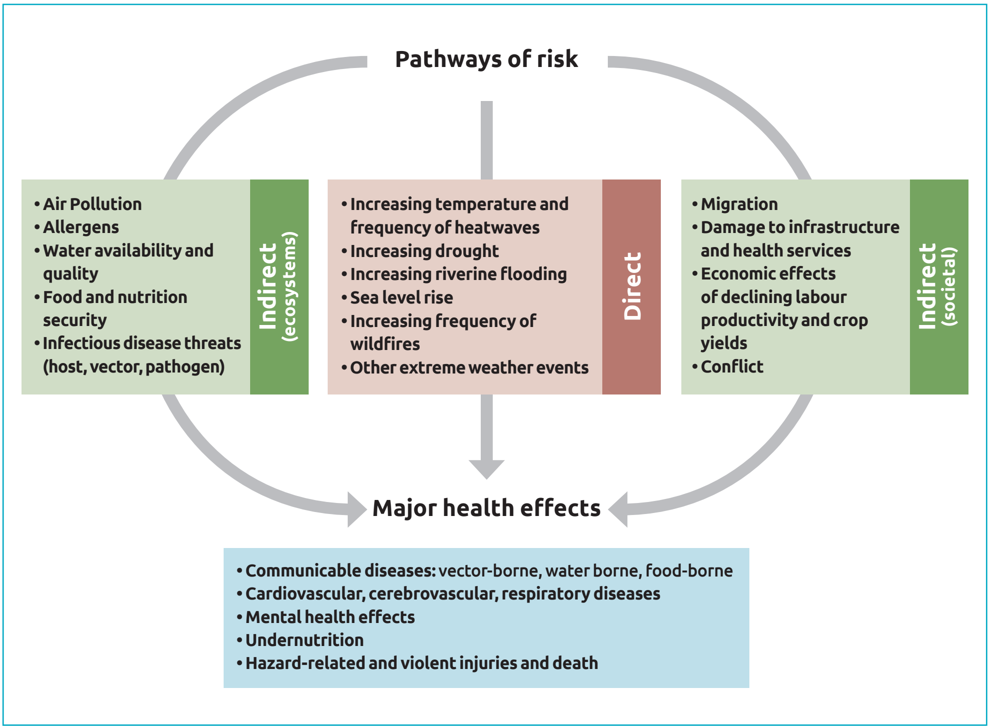

Figure 1: Multiple pathways of risk and health effects. Source: IAP (2022).

While there is still much to be done to quantify climate-sensitive health risks and their compound effects, there are major global initiatives underway generating an accumulating body of evidence on health effects (e.g. IPCC, 2023; Romanello *et al.* 2023), their interactions and attribution to climate change. Despite the accumulating evidence, it is still surprising to see how little has been done in the international political arena to combat the health threats posed by climate change (Mogwitz *et al.* 2022). There is still a significant gap between the recognition of the impacts of climate change on health and the actions taken to address it. Access to climate finance for health is a major barrier for building the evidence base and implementing action (Ebi *et al.*, 2019).

Previous work by IAP, using a regional-to-global model, incorporated evidence and perspectives from Africa, Asia, the Americas and Europe (IAP, 2022; Fears *et al.* 2023). The IAP work has helped to characterise how climate change is bringing serious threats to human health worldwide with the LMICs most vulnerable, and children and the elderly amongst the hardest hit and least protected within populations. There is also accumulating research literature on mental and physical health in children and the disproportionate burdens suffered by them[2]. However, there is much less research on interventions to protect children, and the climate crisis should be regarded as a child rights crisis (Save the Children, 2021). Indeed, the UN Committee on the Rights of the Child recently (UN OHCHR, 2023) called on states to take action to focus on climate change.

Innovative knowledge generation and utilisation

IAP (2022) has highlighted how rapid and decisive action could greatly reduce the risks to health in marginalised groups and populations more generally, and that many solutions are within reach using present knowledge. Both mitigation and adaptation approaches are needed, and multiple solutions must be better integrated across sectors, but action requires political will and sustained investment. The scientific community has important roles to play first in bringing existing knowledge that is relevant and actionable to the attention of end-users, and secondly in generating new transdisciplinary knowledge for feasible, equitable solutions. The widening social and health inequalities resulting from climate change could be reduced or prevented if the drivers and consequences of global environmental change were better understood and if this understanding was reflected in policy and planning.

2 For example, Clemens *et al.* 2020, Arpin *et al.* 2021, Hellden *et al.* 2021, Sahani *et al.* 2022, Bansal *et al.* 2023) and on neonatal health (e.g. in Africa, Nakstad *et al.* 2022) and maternal and foetal physiology (Bonell *et al.* 2022).

Mobilisation of both existing and new research outputs can be enabled by:

- Adopting a Planetary Health framework to encompass the health of human populations and the state of natural systems on which human health depends (Whitmee et al. 2015; Pongsiri *et al.* 2017);
- Executing systems-based research, integrated across sectors, to help clarify complex, dynamic interactions, some of which may contribute to unintended consequences, to guide towards improved health outcomes; and
- Co-producing solutions with end-users, for better understanding of context-appropriate actions, including their consequences and trade-offs for transformative change.

IAP-Save the Children case study project: focusing on adaptation

To build policy maker awareness of systems-based studies and policies, in 2023, IAP with support from Save the Children, opened a call seeking examples of health adaptation case studies of approaches to problem-solving which have been used to tackle the integrated challenges of climate and health.

Adaptation is defined by the Intergovernmental Panel on Climate Change (IPCC) as the process of adjustment in natural or human systems to actual and potential climate-led impacts, which moderates harm or exploits beneficial opportunities. Most observed adaptation responses are fragmented, incremental, sector-specific and unequally distributed across regions. Despite some progress, adaptation gaps across sectors and regions will continue to grow under current levels of implementation with the largest adaptation gaps among lower income groups (IPCC, 2023). Adaptation is not a substitute for mitigation. Rather mitigation increases the scope for adaptation (IAP, 2022). Climate change adaptation needs, as well as capacity to adapt, are unequally distributed around the world and this heterogeneity in societies' adaptive capacity is often overlooked (Andrijevic *et al.* 2023).

In this new IAP work supported by Save the Children, priority was given to:

- Food systems and agriculture;
- Energy, including production, distribution, access and efficiency;
- Urbanization, including urban planning; and
- Health systems strengthening;

particularly when focusing on underserved groups such as women and children and where a policy problem was addressed from the outset.

IAP invited case study proposals to:

- Describe the climate-health relationship of interest and the policy objective to inform solutions for sustainable development and public health;
- Specify the geographical location/spatial scale and population at risk;
- Help clarify the probable causal pathway by which climate variability affected health risk;
- Employ specific indicators to measure outputs, accounting for and, if possible, avoiding unintended consequences;
- Consider opportunities for the replicability of impacts, upscaling and generalisation to other contexts; exploring enabling factors and obstacles for policy application more widely;
- Take account of disproportionate impacts of climate change on vulnerable and underserved communities and embed study outputs into longer-term capacity building;
- Ensure robust study design (whether qualitative or quantitative), including multidisciplinary teams, systems-based approaches, recognition of uncertainties in databases, and engagement with end-users in production and application of findings;
- Address multisectoral impacts of climate change, potential policy synergies across sectors, and trade-offs among the array of effects of choices made.

The case studies submitted to IAP were peer-reviewed by a geographically balanced group of international experts and the successful proposers invited to a workshop hosted by IAP in Trieste, Italy, in September 2023, together with a sub-set of the peer-reviewers. Following the workshop, revised full-length case studies were edited for consistency of length and format and are now presented in this volume.

Emerging messages from the individual case studies presented in Trieste were assessed collectively to try to answer three general questions:

- What are the issues to consider when designing effective climate-health adaptation studies?
- What is the role of case studies as a basis for developing specific recommendations for adaptation policy and practice? and
- How can systems-based adaptation approaches help to build action at science-policy interfaces?

This collective assessment was used to prepare a Science Policy Brief, which was launched at COP28 (Dubai, 2 December 2023) (IAP, 2023). The individual case studies now published in this volume will, it is hoped, serve as a continuing resource to stimulate further discussion and guide policy action. A commentary on the project is also published in *The Lancet Planetary Health.*

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Bangladesh

Community engagement to reduce dengue transmission in Dhaka

Case study prepared by:

Uzzal Kumar Roy, Atikur Rahman and Nur-A-Safrina Rahman

Focus

The dengue virus is spread by aedes mosquitoes and is the most rapidly spreading vector-transmitted disease in the world (Brauer *et al.*, 2016). In the last 50 years, the global incidence of dengue has increased by a factor of 30. An estimated 390 million cases are now diagnosed annually in more than 130 countries, affecting more than two billion people in the tropics and subtropics (World Health Organization (WHO), 2000).

In Bangladesh, dengue cases have risen from 10,148 with 26 deaths in 2018, to almost 70,000 cases with more than 300 deaths in 2023 (Haider *et al.*, 2021). Also, the pre-monsoon aedes survey showed the density of mosquitoes and the number of potential dengue hotspots in 2023, were at the highest levels for five years.

Favourable climate conditions in the country have led to an unusual shift in the transmission of dengue and other vector-borne diseases, even outside traditional seasons. But a number of other factors have contributed to this rise, including building and lifestyle changes, inadequate water management, poor water storage and rainwater pooling in outdoor containers (Kesetyaningsih *et al.*, 2018).

The impact on health is severe. Dengue virus infections may be asymptomatic, but they can also cause dengue fever, dengue haemorrhagic fever and dengue shock syndrome – all of which include high fevers and bleeding that can cause severe dehydration and organ failure. There is no treatment or widely available vaccine for dengue, and so it is critical that efforts are made to reduce the disease's prevalence by eliminating vector habitats and promoting interventions that can protect the public. But this is only possible with community cooperation.

Dhaka, the largest and most populous city in Bangladesh with a population of almost 16 million, has the greatest number of dengue cases and is the geographical focus of this case study. The study's objectives are to:

1. Assess the community's awareness of dengue using a knowledge, attitude and practice (KAP) survey, and evaluate the efficacy of community-based teaching programmes in selected areas of Dhaka South City Corporation (DSCC);
2. Motivate policy makers to scale up successful interventions (gleaned from the evaluation) in urban areas.

Methods

The study investigated the knowledge, attitudes and practices (KAP) of 384 adult study participants around dengue. All the participants were permanent residents in a selected zone in DSCC.

Participants were selected using convenience sampling (i.e. people who were available to the researchers). These participants were then interviewed face-to-face using a semi-structured questionnaire, comprising five sections which were designed to assess:

1. Respondents' demographic data;
2. Their knowledge about dengue and how it is transmitted (categorized as poor, average, good or excellent);
3. Their attitudes towards practices that mitigate the spread of the disease (categorized as positive, neutral or negative);
4. Practices that respondents themselves had used or were using to mitigate against dengue (categorized as good, fair or poor);
5. Sources of information they used or had used to learn about the disease and its prevention.

After the questionnaire, participants received a structured teaching programme (about 40 minutes in length). The programme included information (pamphlets and flyers) on disease awareness and prevention, and face-to-face counselling in which participants were offered more personalized strategies to help them prevent dengue. Participants were then asked to share this information with their family and friends.

One month after the initial assessment, participants' households were revisited and the same questionnaire was used to assess changes in KAP. Progress was also measured through direct observation on dengue preventive practices (e.g. proper use of mosquito nets and elimination of stagnant water sources). The purpose of maintaining the timeframe between the pre- and post-tests was to ensure that participants had retained the information from the structured teaching programme.

Statistical Package for the Social Sciences (SPSS) data analysis software was then used to perform a series of analyses on the pre- and post-test data to ascertain a significant increase or decrease in participants' knowledge, attitudes and practices before and after the teaching programme. Spearman rank correlation coefficients (t-tests) were also calculated to observe whether there were statistically significant differences in pre- and post-test results.

Results

The 384 participants had a mean age of 39 years and were grouped into five age groups: 18–29, 30–39, 40–49, 50–59 and over 60 (Figure 1a).

The majority of the participants had completed secondary education 39.4% (Figure 1b) and 13.2% had experienced dengue fever in the past (Figure 1c).

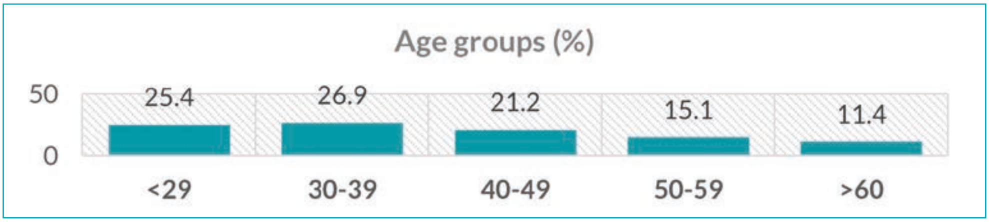


Figure 1a: Age distribution of the respondents where the mean age of respondents was 39 years

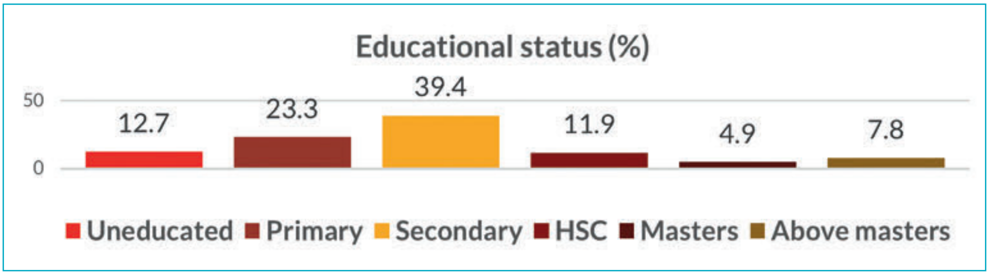
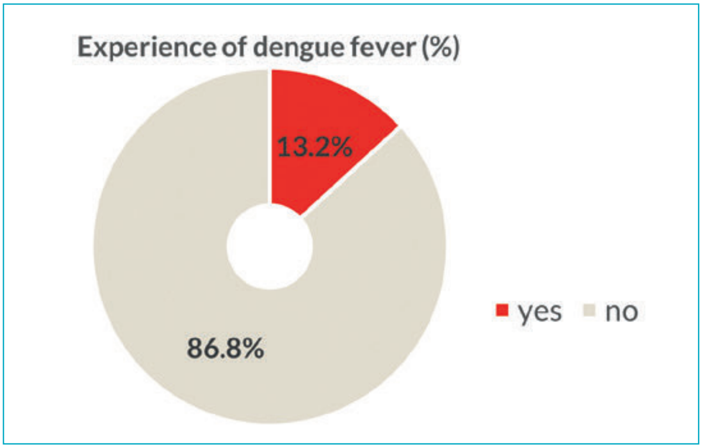


Figure 1b: Distribution of the respondents by educational status

Figure 1c: Distribution of the respondents by history of dengue fever



Following the structured teaching programme, mean knowledge scores increased, with large percentage gains in good and excellent knowledge and significant decreases in poor and average knowledge about dengue (Table 1).

Level of knowledge	Pre-test	Post-test	% Change
Poor knowledge (1-3 scores)	12.5%	0.5%	-12
Average knowledge (3-5 scores)	69.7%	3.1%	-66.6
Good knowledge (6-8 scores)	17.8%	46.9%	+29.1
Excellent knowledge (9-11 scores)	0%	49.5%	+49.5

Table 1: Comparison of knowledge level between pre-test and post-test

After the second KAP, 63.8% of the participants were found to have positive attitudes about dengue prevention – an increase of 17.3% from the pre-test (Table 2).

Level of attitude	Pre-test	Post-test	% Change
Positive (32–40 scores)	46.5%	63.8%	+17.3
Neutral (24–31 scores)	29.7%	24.1%	-5.6
Negative (8–23 scores)	23.8%	12.1%	-11.7

Table 2: Distribution of attitude levels toward dengue prevention

Pre-test results showed that a majority of respondents (34.8%) already engaged in good preventative behaviours, but this proportion increased to almost 60% after the teaching programme and counselling was administered (Table 3).

Level of practice	Pre-test	Post-test	% Change
Good (9–12 scores)	34.8%	59.9%	+25.1
Fair (6–8 scores)	39.4%	25.1%	-14.3
Poor (0–5 scores)	25.8%	15.0%	-10.8

Table 3: Distribution of practice level in dengue prevention

Television was the most common way people learned about dengue. This was followed by information provided by city corporation employees and newspapers (Figure 4).

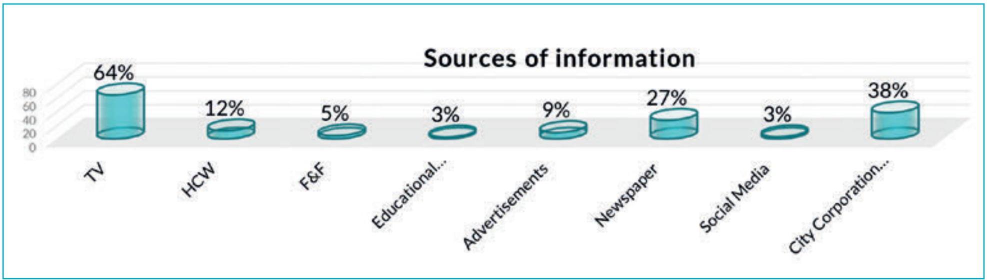


Figure 4: Sources of information on dengue

Independent t-test results (the SPSS data analysis, mentioned above) for KAP mean scores before and after the teaching programme indicated a statistically significant (greater than 0.05) increase in both knowledge and practice about dengue and how to prevent it (Table 4).

Criteria	Pre-test Mean±SD	Post-test Mean±SD	Probability (p) value
Knowledge	4.51±1.33	8.42±1.56	0.023*
Attitude	41.2±1.7	44.1±3.2	0.439
Practice	7.1±0.55	9.3±0.93	0.039*

Table 4: Independent t-test results for KAP mean scores before and after the teaching programme indicated a statistically significant probability (*p below 0.05) of an increase in both knowledge and practice (SD = standard deviation)

Results also showed that increased levels of knowledge were linked with higher levels of education, and that those with dengue experience were more likely to follow good practices. The link between knowledge and attitude was moderately positive, while weaker links were found between knowledge and practice and attitude and practice.

Overall, positive changes in the level of dengue prevention practice were found during the observation period. Comparing data from before and after the study, results showed that the incidence of dengue in the area significantly declined from the previous year - from 791 to 102 cases.

Lessons learned

The study revealed a number of key lessons:

1. With relevant guidance, people can improve their dengue knowledge, their attitudes about the illness and their preventative behaviours.
2. Disseminating correct information and education about the disease, changes people's perceptions and makes them better able to protect themselves and their families from potential health risks.
3. The media (television, radio, newspapers and social media) can play an important role in raising awareness and disseminating information about dengue symptoms, its mode of transmission and the preventative measures people can take. Additionally, the media may be utilized to communicate updates on outbreaks, educational programmes and other efforts to curb the spread of the disease.
4. With ongoing education, people's positive attitudes to dengue prevention continue to grow.
5. A person's level of education influences their understanding and perspective on health. It is crucial, therefore, to take educational background into account when planning future awareness campaigns (i.e. ensure awareness information is appropriate for its audience).
6. Knowledge, attitude and practices were all shown to have a positive correlation. This supports the idea that knowledge and attitude about a specific health issue, like dengue, are important factors in how people act and what they do to prevent and control diseases.

The importance of the discovery that knowledge of dengue affects attitude and behaviour in dengue control cannot be underestimated. When people have access to up-to-date and thorough information on a subject such as dengue, they are better able to generate favourable and well-informed opinions and take precautions against infection.

Overall, the interventions used in the study were cost-effective and scalable and therefore appropriate for other parts of Bangladesh and other developing countries in collaboration with urban public health authorities.

Limitations of the study

1. Participants were chosen based on their availability and accessibility to the study team, rather than being randomly selected from a larger population. As a result, there was no hypothesis or assumption that the post-intervention survey would reveal any changes.
2. Selection bias and social desirability bias are possible biases in case studies. Additionally, a direct causal link between the observed outcomes and the impact of the study itself could not be statistically identified due to limitations in the study design.

Conclusion

In conclusion, dengue awareness is essential for reducing the incidence of the disease and positively impacting health outcomes. This can be achieved by investing in education and awareness programmes and utilizing mass media to reach large numbers of people with dengue related information.

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Bangladesh

Aquifer storage and recovery technology for irrigation water supply

Case study prepared by:
Sara Nowreen

Focus

Bangladesh is one of the most vulnerable countries to climate change and the people living in its coastal regions face unique challenges. Once-abundant fresh groundwater has become more scarce and increasingly saline due to encroaching saltwater from the Bay of Bengal, rendering it undrinkable and unsuitable for agriculture.

Population growth, irrigation demand and rainfall variability (exacerbated by climate change), have put further stresses on groundwater. Warmer temperatures due to climate change, for example, increase the need for irrigation due to increased evapotranspiration (Döll, 2002), and in turn, more irrigation leads to more groundwater pumping.

Aquifer Storage and Recovery (ASR)

To address these issues, Bangladesh has adopted the Aquifer Storage and Recovery (ASR) technique, which involves storing fresh monsoon water underground and retrieving it during the dry season. Aquifers are expected to exhibit a significantly slower response to climate change fluctuations than surface water (Santosh and Raneesh, 2012) and thus provide enhanced water security.

More than 100 small-scale community-run ASR systems have previously been implemented in coastal areas for drinking water security purposes (Naus *et al.*, 2021). However, only a few systems have been implemented for agricultural water supply. Agriculture in coastal Bangladesh, however, faces major challenges including the issue of salinity, which restricts farmers to one or two rain-fed crop harvests per year (Rolf *et al.*, 2019).

Project overview

In 2019, to ensure dry season irrigation, farmers in Dacope of Khulna, Bangladesh, installed an ASR system with the help of a local, non-governmental organization (NGO). The system (Figure 1) consists of a three-metre-deep infiltration chamber and a 50-metre-deep borehole with a ten centimetre diameter. The chamber is filled with filtration materials which are arranged to promote safe, groundwater recharge (replenishment) of impure floodwater. During the dry season, this type of managed aquifer recharge (MAR) system can irrigate an area of approximately four hectares.

The aim of the technology was to reduce the salinity of groundwater and enhance agricultural productivity at the study site. Several studies have been conducted to

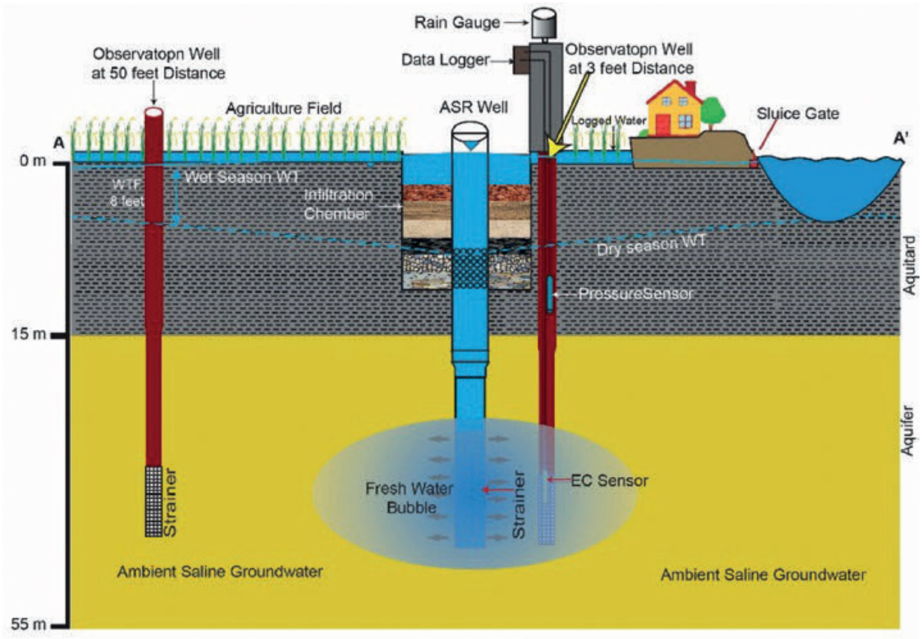


Figure 1: Diagram of an Aquifer Storage and Recovery (ASR) system (WT = water table)

assess the feasibility and health risks of ASR systems with regards potable water, but fewer studies have been conducted on the performance, health risks and feasibility of ASR in agriculture.

This case study aims to determine the efficacy of the ASR system in the agriculture sector and assess the potential health hazards of aquifer contamination.

Team

The collaborative team included researchers and partners from the Bangladesh University of Engineering and Technology; the Bangladesh Agricultural Development Corporation; and the Krishi Gobeshona Foundation, Bangladesh.

Method

The study used socio-technical methods in its investigation. The social component consisted of four focus-group discussions to generate resource maps and crop calendars, and compare changes in crop patterns and intensity over the ASR implementation period. The technological component involved real-time in-situ observations as follows:

1. Pressure sensor to measure groundwater level;
2. Rain gauge (tipping bucket) to record rainfall;
3. Electric conductivity (EC) to measure salinity;
4. Temperature sensors to measure temperature.

Automated logging devices were installed at an observation well, one metre from the ASR. Additionally, EC was manually measured in logged surface water, neighbouring canal water and at an additional 50-metre-deep observation well situated 15 metres from the ASR well. Readings were taken every 15 days using an EC meter.

Water samples were collected from both the ASR and the observation wells, as well as logged surface water and canal water, during four specific seasons: pre-monsoon, monsoon, post-monsoon and dry periods. The purpose of this collection was to monitor the contamination levels of coliform (faecal matter), as well as other water quality parameters including alkalinity, water hardness, iron, manganese, Total Dissolved Solid (TDS) and turbidity (the level of particles present in the water, such as sediment or organic by-products).

Chemical tests were performed as follows:

1. Alkalinity and hardness were tested using the titrimetric method (to assess concentration);
2. Coliform was assessed using the Membrane Filtered Method (a separation technique that utilizes a semi-permeable membrane to halt solids and dissolved components);
3. A turbidity meter was employed to analyse TDS;
4. Iron and manganese elements were analysed using the Atomic Absorption Spectroscopic method, which detects elements in liquid samples through electromagnetic radiation analysis (i.e. identifying elements by the way they absorb wavelengths).

Google Earth Engine was used to collect cloud-free satellite images prior and subsequent to ASR installation. The images were then compared to assess changes in land use and land cover (LULC) over the study period. The analysis was conducted during the dry season (January to April) when farmers typically use ASR water.

This study classified LULC using spectral bands (different ranges of wavelengths of light captured by satellite sensors) and estimated the extent of farmland in the study area using the Random Forest (RF) algorithm – a computational method in which land cover is constructed from existing data via machine learning. The team chose RF since it classifies remote sensing data more accurately than other methods (Belgiu and Drăguţ, 2016).

Results and products

Land use and land cover

Prior to the introduction of ASR (2018), farmers cultivated vegetables and watermelons in the dry season, or kept their land uncultivated. By 2022, after ASR implementation, the northern, western and eastern areas of the study area had undergone a transition from fallow to agricultural use, specifically rice cultivation (Figure 2a).

Figure 2b illustrates the increase in the agricultural area over the designated timeframe. Farmers who received the ASR system and employed it as an alternative irrigation water source, encountered notable benefits. The production of Boro rice, for example, increased from three to almost five tons per hectare.

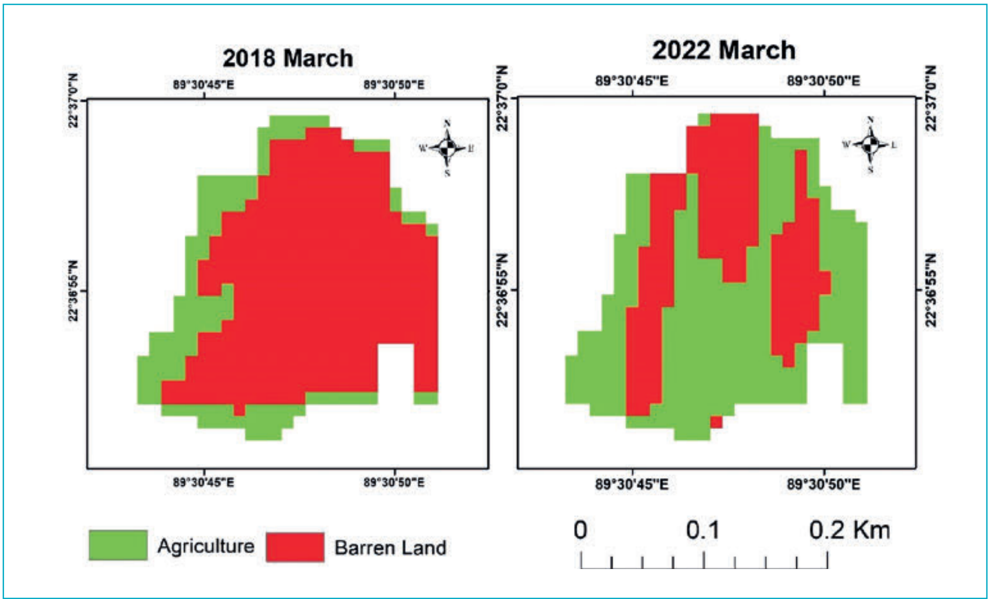
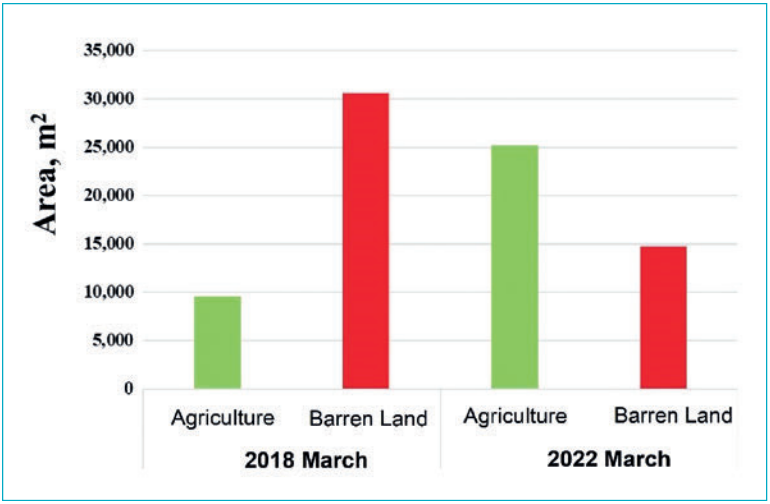


Figure 2: (a) Land use change before and after ASR implementation

Figure 2b: Increase in agricultural area after ASR implementation between 2018 and 2022



Water levels

Groundwater levels showed a direct correlation with rainfall events (Figure 3), with rapid increases in levels from pre-monsoon to early monsoon (May to July). However, after July, when the aquifer had reached saturation, there was only a minimal rise in the groundwater level despite heavy monsoon rainfall.

From July to November, the groundwater level continued to rise, if slowly, through to October despite the absence of significant rainfall. Tropical cyclone *Sitrang*, caused notable rainfall at the end of October (Figure 3a), recording 209 millimetres of rain in 24-hours and a subsequent rise in the groundwater level of 0.3 metres, which gradually returned to its initial position after five days.

The presence of a 'mound formation' inside the water table of the ASR system, in comparison to the surrounding ambient observation wells, suggested the occurrence of surface/rainwater percolation (movement through the soil) and subsequent recharge of groundwater.

In brief, the data suggests that ASR in coastal regions of Bangladesh can serve as an effective means of recharging groundwater, although its impact diminishes significantly when the aquifer becomes saturated during monsoon.

Salinity

There were similar fluctuations in the EC (salinity) data. When the land was waterlogged, for example, conductivity in the ASR dropped from 6,300 microsiemens per

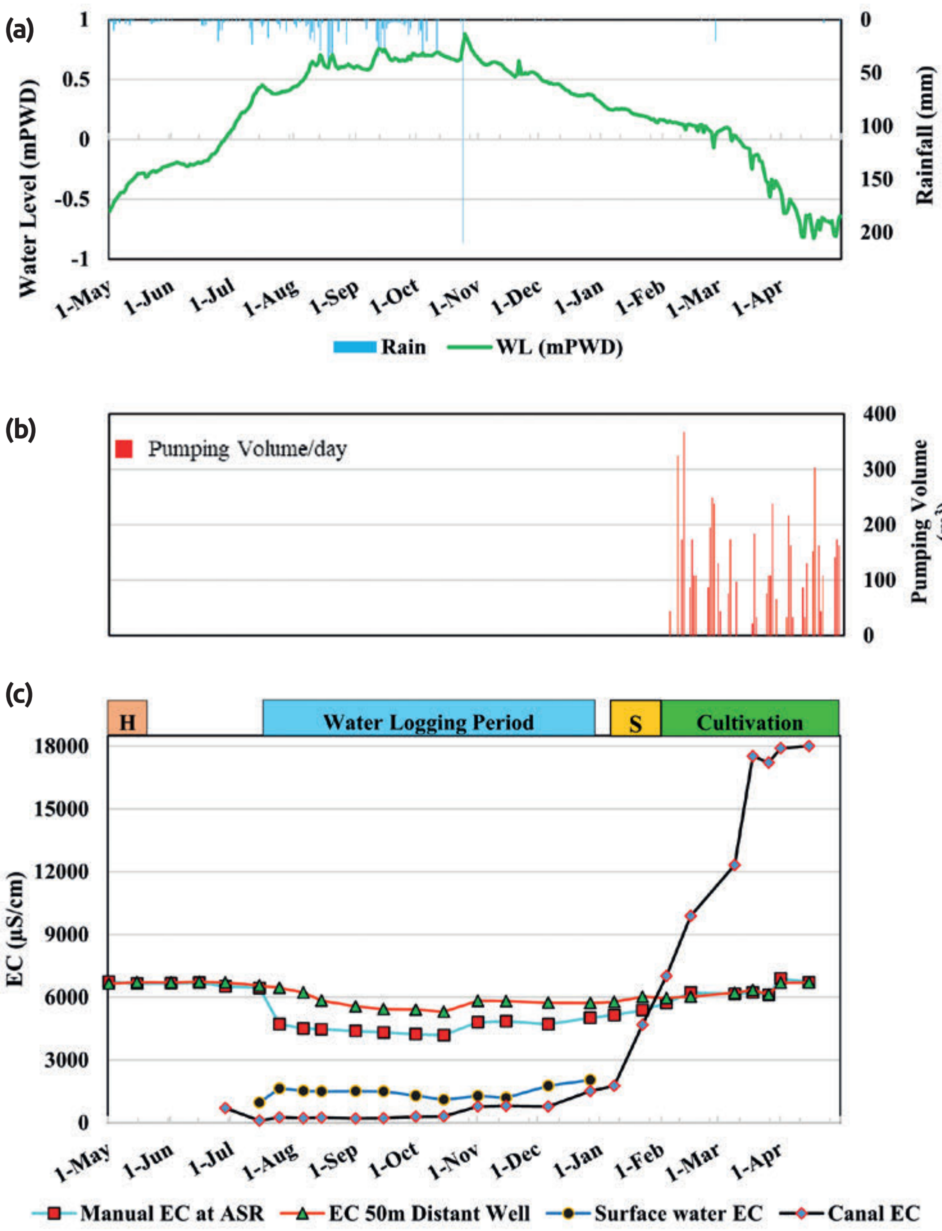


Figure 3: (a) Water level change in response to rainfall, (b) abstraction volume (cubic metres per day) from ASR well, (c) EC change in different sources of water at the ASR site

centimetre to between 4,100 and 4,850 microsiemens per centimetre (Figure 3c) indicating lower salinity. After waterlogging receded, the EC in the ASR exhibited a small increase in comparison to the neighbouring observation well. But after 367 cubic metres of irrigation water were pumped in February (Figure 3b), the EC went back to its original measurement (the same as the EC of ambient groundwater). This implied that freshwater recharge via ASR had limited impact on reducing salinity.

Water quality

Bangladesh standard limits (BSL) were used as the standard metric in all the following results (visualized in Figure 4). However, there is no BSL for alkalinity.

Alkalinity: the ASR system exhibited higher alkalinity in comparison to the logged surface water and canal water. This suggests ASR water underwent more rock-water interactions than the other water sources.

Water hardness: logged surface water with low hardness (below BSL), exhibited high hardness when percolated. This is similar to neighbouring observation wells and indicates good mixing with the aquifer.

Coliforms: total coliforms (including bacteria) were detected throughout the year in various water samples. In the ASR well, their absence was only observed after clogging clearance had been performed. Faecal coliforms were consistently present in canal water and logged surface water. This suggests that a successfully functioning ASR filtration chamber can effectively eliminate coliforms from surface water sources.

Manganese: manganese was frequently observed at elevated levels (above BSL) with the greatest concentrations occurring in September for groundwater and logged surface water, and in February for canal water.

Iron: elevated iron levels (above BSL) were found throughout all instances, with the exclusion of two (November and July).

Total dissolved solids (TDS): TDS in groundwater consistently exceeded the BSL whereas levels in logged surface water remained within limits. Canal water exhibited the largest peaks, exceeding 15,000 parts per million.

Turbitidy: All the water samples, including the ASR well, showed increased levels of turbidity (sediment or organic by-products).

In brief, the coexistence of higher concentrations of iron, TDS and turbidity, collectively, signifies the likelihood of well clogging within the ASR system.

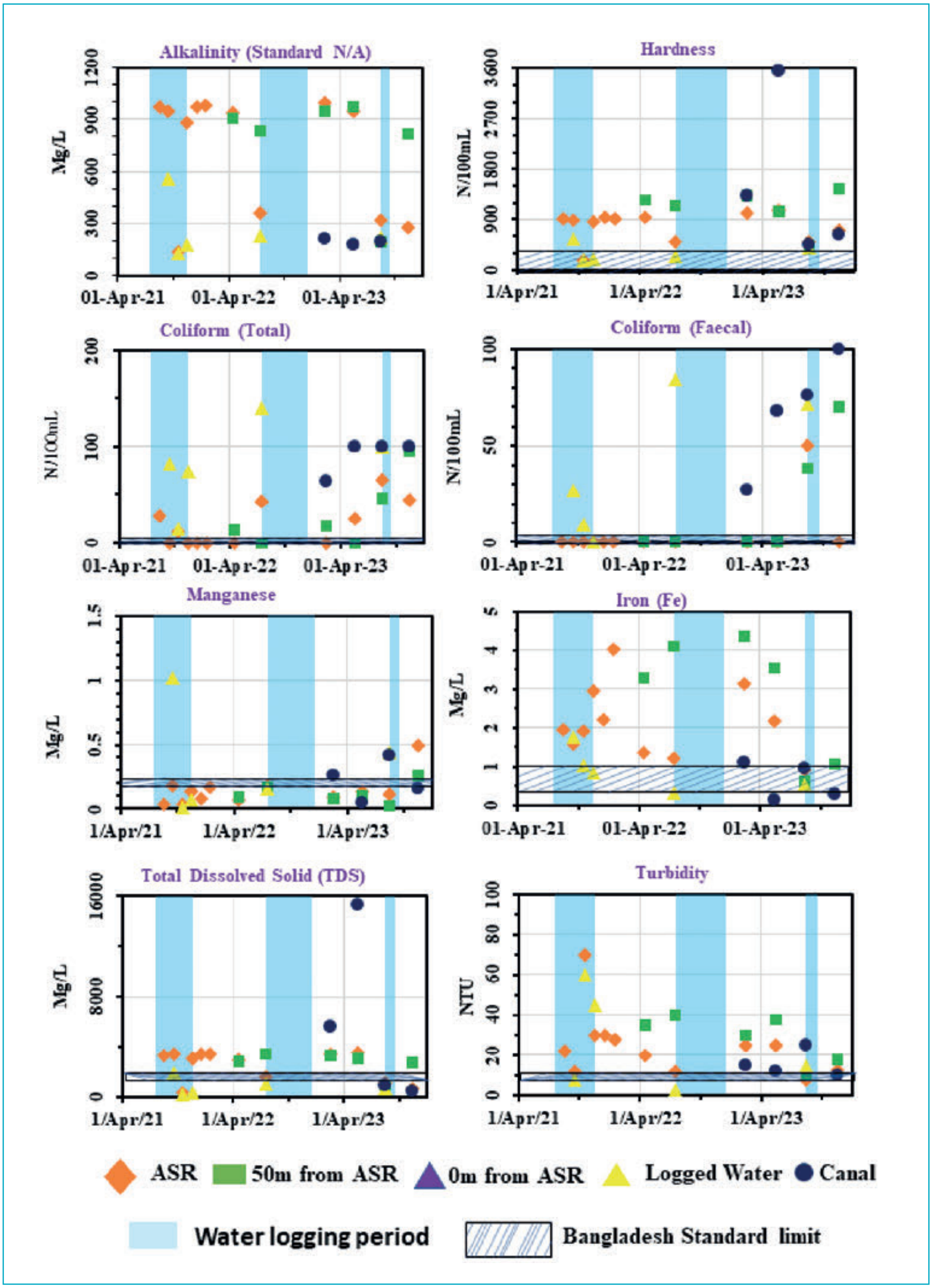


Figure 4: Different water quality parameters at ASR-Agri-MAR study site

End-users

This research is intended for policy makers such as the Ministry of Water Resources (MoWR) and the Bangladesh Ministry of Agriculture (MoA). Also, government entities such as the Water Resources Planning Organization (WARPO) and the Bangladesh Agricultural Development Corporation (BADC). As a collaborative partner, the BADC will disseminate research findings to relevant institutions.

At a local level, the NGO and the farmer who implemented the ASR system, serve as principal stakeholders and recipients of the study's outputs. Many more farmers have expressed an interest in ASR and more NGOs are keen to sponsor ASR services to farmers in exchange for a fee.

Lessons learned

1. ASR has the potential to reduce local saline levels against the backdrop of climate change stress. Early rainfall events and monsoon water have been found to have a beneficial effect on the groundwater recovery of ASR systems, as well as reducing local saline levels. ASR helped increase the production of dry rice and benefited farmers by enhancing cropping intensity and agricultural land use within the ASR catchment area.
2. Small-scale, single ASR chambers (1.2 x 1.2 x 3 cubic metres) have the capacity to deliver 367 cubic metres of mix-water before reaching equilibrium with ambient saline groundwater. Therefore, it is not feasible for a single ASR system to meet the irrigation needs of water-intensive Boro rice over the dry season. However, ASR can be used effectively for growing various non-rice crops such as vegetables and watermelon.
3. ASR systems successfully prevent the transfer of faecal coliform pollution into the aquifer. Water quality overall is acceptable but turbidity, iron, and TDS are beyond permissible limits and suggest ASR systems might face ongoing clogging issues. Frequent clogging removal is crucial.
4. ASR systems appear to be inadequate for meeting sustainable, all-year-round demand for freshwater irrigation in coastal regions. The feasibility of extending a single filtering chamber and/or using multiple ASR chambers needs to be evaluated, paying particular attention to economic viability.
5. While ASR is a promising strategy for tackling saline water challenges, other approaches could be incorporated. For instance, substituting rice with higher-value

crops such as watermelon. ASR technology could also be used in conjunction with other water filtration devices such as Pond Sand Filters (PSF).

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Benin

Lessons from the formulation of a National Adaptation Plan

Case study prepared by:

Hashim Hounkpatin

Focus

Benin is in the top quartile of countries most vulnerable to climate change. It has a high risk of flooding (river and urban), water scarcity, extreme heat and wildfire. It has a medium risk of coastal flooding, and some risk of landslides, tsunamis and earthquakes. These geographical hazards are compounded by weak coping mechanisms.

Over the past decades, the country has experienced several extreme climatic events resulting in significant loss of life and impacts on livelihoods and the economy. An historic flood in 2010, for example, covered two-thirds of the territory resulting in major disruption that affected almost a million people. It was the country's worst flooding event in half a century. But in 2019, Benin experienced yet another devastating flood, with damage estimated at USD 85 million. The impacts of climate change, therefore, are already being felt in Benin, and the projected consequences (Figure 1) give cause for concern (Osse *et al*., 2019).

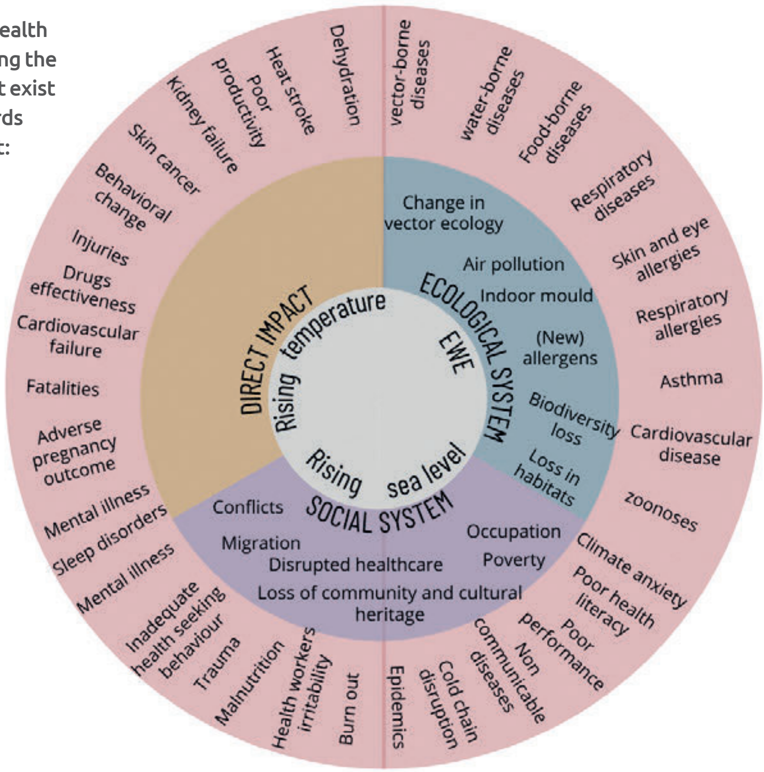

Figure 1: The climate health impact wheel illustrating the complex pathways that exist between climate hazards and health risks (Credit: Hashim Hounkpatin)

In May 2022, after ten years of negotiations, Benin released its National Adaptation Plan (NAP) to coordinate responses to climate change risks. Eight sectors were prioritized for adaptation: agriculture, freshwater resources, energy, infrastructures and urban design, tourism, forestry, coastlines and health. The health component of the NAP aimed to protect the population in general, and the most vulnerable people in particular, from climate change threats.

Policy content structure followed the continuum of hazards -> health risks -> adaptation measures -> implementation plans. The direct and indirect climate hazards that were investigated are summarized in Table 1.

	Type	Climate hazards
Direct	Extreme weather events	Heatwaves, heavy precipitation and flooding, windstorms
	Slower phenomenon	Temperature rise, drought, changes in season and precipitation patterns, and sea level rise
Indirect	Through socio-ecological pathways	Forced migration, food security and safety, economic activities perturbation, natural resources degradation, and coastal erosion

Table 1: Climate hazards included in Benin NAP, 2022

After listing potential hazards, the NAP prioritized three hazards in relation to health risks: heatwaves, flooding and drought. The actual health risks arising from these hazards were then identified. These were mainly physical health risks and were included alongside disruption in health service delivery (Table 2). It's worth noting that mental and social dimensions of health and wellbeing were neglected in the NAP.

	Physical	Mental	Social
Heatwaves	Food alteration and intoxication, heat stress, acute respiratory infection, cardiovascular diseases	-	-
Flooding and drought	Vector-borne diseases (malaria in rainy seasons and meningitis in dry seasons), malnutrition and food-borne diseases, water-borne diseases	-	-

Table 2: Prioritized climate hazards and the associated health risks

The relationship between climate hazards and health risks often involves complex pathways (Figure 1), but in the NAP policy document the pathways are presented as linear. In the past, this over-simplification has indicated policies and adaptation measures that might not address health risks in a systemic way. However, a more systematic approach has been observed with the NAP policy process. Table 3 shows the measures covered in the NAP for the health risks mentioned in Table 2.

Adaptation categories	Measures in the Benin NAP
Policy and planning	Policy, legislative development, climate change mainstreaming in existing and ongoing policies and budgets at all levels
Financing and implementation	Improvement of financing mechanisms and partnerships
Information and capacity building	Early warning systems, monitoring, surveillance, research, capacity building
Citizens' and migrants' resilience	Local adaptation practices reinforcement, social protection, cultural heritage protection, awareness-raising campaigns
Disaster management	Resilient infrastructures

Table 3: Adaptation measures in the Benin NAP, 2022

The overall policy vision in the NAP states that: "*by 2030 the country is climate resilient with sufficient adaptive capacity and appropriate mechanisms to anticipate and respond to climate risks, with low-carbon growth, and its institutions, organizations, businesses, and citizens adopt climate-sensitive practices, attitudes, and behaviours.*"

Team

The German Ministry of Environment mandated its international co-operation agency to support Benin. The agency provided financial assistance and commissioned Ceped (a multi-disciplinary development organization) and Climate Analytics (a global climate science and policy institute) for technical assistance. Green Climate Fund (GCF) and the United Nations Development Programme (UNDP) provided additional funding. Other actors (e.g. civil society organisations) participated in workshops.

Methods

The goal of the assessment was to analyse the actors involved in the Benin NAP as well as its context, content and process. The NAP itself was used as the main information source. Reports and institutional websites served as additional complementary data sources. The research team used the Walt and Gilson health policy triangle framework (a widely used health policy analysis tool) as it allows policy investigation through the interplay of four dimensions:

1. The context in which policy was developed;
2. The process that led to policy formulation;
3. The actors involved;
4. Policy content.

This case study will mainly focus on the content of the policy.

Results

This case study, undertaken immediately after NAP policy formulation, is intended to be an entry point for further actions to support the country's implementation process. It yielded several results that deserve attention.

1. The vulnerability and adaptation assessment study (V&A) which informed the Benin NAP was inadequate when one applies the World Health Organization's (WHO) quality criteria. WHO recommends a system adaptation whereby countries are ambitious in the coverage of hazards and plan for medium to long-term actions that build on vulnerability and adaptation assessment. This allows synergy within health systems and across sectors and appreciation of potential collateral effects (WHO, 2021). Further, WHO emphasises the critical role of information about specific vulnerable groups for targeted interventions and equity.

The V&A study in Benin, however, focused on one health risk (malaria) and targeted one health district over a short (six-month) timespan (Osse *et al.*, 2019). This may have been due to limited time and financial resources, but such a narrow focus begs questions regarding the validity of the V&A in guiding the NAP. Broader health risks are covered in the NAP, but comprehensive V&A is critical for ensuring policy is evidence-based.

2. There has been limited involvement on the subregional level (i.e. West Africa), which threatens cross-national cooperation. While limited involvement on the subnational level could challenge policy adoption and implementation.

3. Global governance bodies have a dominant role in adaptation policy making. Organisations such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) shape policies and actions and hold asymmetric powers over many sub-Saharan African countries, like Benin. In addition, their financial, technical and ideational position informs their approaches – which are not universal and cannot capture every (sub)national reality.
4. Similar to most European countries, the Benin NAP focused on three hazards. But relevant hazards were missing. Ultraviolet (UV) radiation and wildfire were not cited (although the latter was mentioned in the country V&A). Also, the intermediate consequences of included hazards were not covered, for example indoor mould, and increased indoor and outdoor air pollutant concentration.
5. The NAP covered mostly physical health risks. However, its failure to be comprehensive resulted in incidences of cardiovascular, respiratory and neurological impacts from poor air quality, zoonoses, reactions to existing or new allergenic species, and new infectious and vector-borne diseases (ECHO, 2022). Oversights included some risks related to identified climate hazards, such as injuries from extreme weather events, skin cancers due to ultraviolet radiation or diseases from bacteria and algae in bathing water. Such omissions imply that no specific adaptation measure will target these risks.

End-users

The Beninese population, broadly, is the main target, especially those who are most vulnerable.

Lessons learned

Strong political will and commitment were in evidence throughout the process. This enabled institutional arrangements and legislative development that supported policy development. Nevertheless, the challenges are numerous.

Financing

Money is the main barrier to climate action, and resource-constrained countries, like Benin, rely on international funding. To sustain their actions, Benin is advocating for:

1. More funding;
2. Cancellation of historical debt;
3. Reform in international trade.

The other challenge facing Benin is the choice between development imperatives to meet basic human needs and adherence to the expected global fossil fuel phaseout.

Cross-sectorality

There was a clear intent for a single policy document binding the eight prioritised adaptation sectors. However, each sector was able to extract its own, standalone adaptation plan. Also, the NAP fell short at integrating subnational and subregional actors. Neighbouring countries have similar challenges and could leverage economy of scale and learn from each other.

Vulnerability

Each vulnerability factor was approached as if it was unique, per vulnerable individual. But the same people often face multiple vulnerabilities, a phenomenon which must be better considered in policy making and planning.

Learning opportunities, both positive and less positive, are ubiquitous throughout the Benin case study. The planned update of the NAP every five years is an opportunity to integrate lessons learned to enhance its robustness.

Transformative approach to adaptation

"We cannot solve our problems with the same thinking we used when we created them"– Albert Einstein

Climate change is a manifest threat to public health, but it is only one of the current converging crises. Adaptation measures require whole system thinking to address underlying mental models that guide action. Figure 2 shows an iceberg with four layers. The tip represents perceived crises (e.g. climate change, Covid-19, political instability). The next layer represents patterns and trends that might explain the crises (e.g. ecocide, extractivism, hegemony). Next, are the systemic structures that generate these trends (e.g. anthropocentrism, power imbalance, globalisation). Finally, at the bottom, are the mental models – the true root causes of the perceived crises and where the actual crisis resides.

Focusing solely on the tip of the iceberg implies that perceived crises will reappear in different forms and maintain a vicious cycle. We cannot sustainably approach crises without acknowledging the underlying worldview(s) that lead to them in the first place. There is a need to adapt, but also a need to transform.

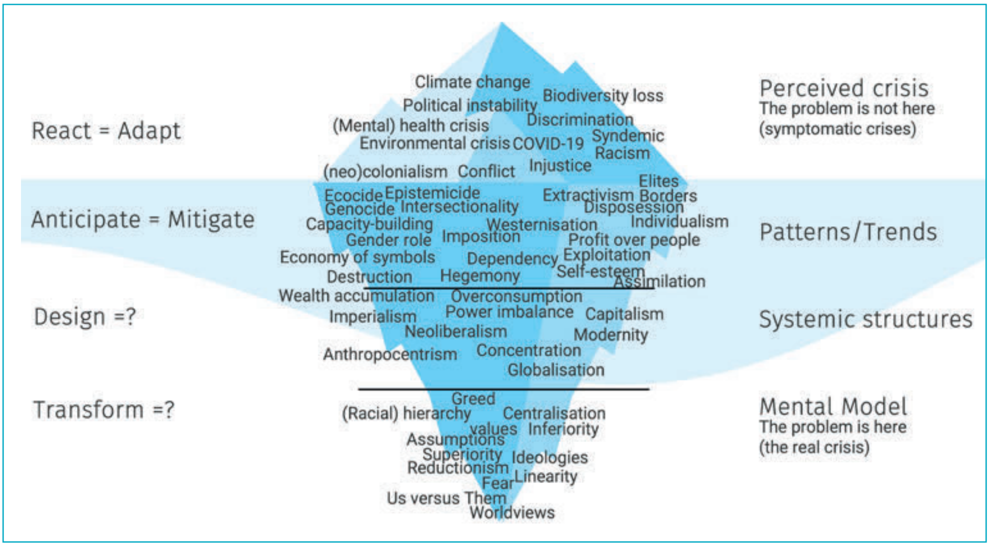

Figure 2: Perception of crisis and crisis of perception, iceberg adapted from Slidesgo and Freepik (Credit: Hashim Hounkpatin)

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Brazil

Climate, air pollution and socioeconomic vulnerability: a research platform to implement policies to improve environmental health

Case study prepared by:

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Focus

Humans have adapted to a wide range of environmental conditions. We live in habitats with temperatures ranging from minus 68 degrees Celsius, in the Arctic region, to 45 degrees Celsius in desert environments. This capacity to adapt has marked our success as a species. However, this is now being challenged by rapid changes in the global climate.

Different countries have varying levels of vulnerability to climate change-induced risks. Socioeconomic contrasts, migration and demographic changes are occurring in populations all over the world. But there are also marked disparities in human vulnerability to climate alterations within countries. It is unclear whether this unevenness is due to temperature alone, or a combination of other factors such as air pollution, socioeconomics and the presence and increase of clinical conditions that increase people's vulnerability.

This study aims to uncover these disparities and measure differences in vulnerability in different populations. The research focuses on Brazil, which has a number of characteristics that favour large-scale studies into climate-induced health risks, as follows:

1. A large population;
2. Significant climate variability due to the size of the territory;
3. The availability of daily health data, including morbidity and mortality;
4. Extreme social and economic contrasts.

This case study explores the effects of climate abnormalities and the impact these have on population health in 1,800 Brazilian cities. The cities represent a wide range of geographic and climatic areas – from tropical rainforest to semi-arid zones in the northeastern states.

Method

Researchers analysed national data sets, spanning 15 years of certified daily hospital admissions (including mortality) for more than 1,800 Brazilian cities. The relationship between climate and health was then quantified using the health data and meteorological conditions for each city.

Statistical data analysis software (Quasi-Poisson regression) was applied to the data to examine city-specific estimates of climate impacts on health. This data was then aggregated at the regional and national levels using random-effect meta-analyses (which assumed that underlying effects followed a normal distribution). Stratified analyses (organising data into groups) were then performed by sex, age and cause (health factor/mortality). Meta-regression (to combine and contrast multiple subsets of the study) was then used to examine temporal changes in each region and the effects these changes had on human health. These approaches were demonstrated to be robust and reproducible, and more details can be obtained in the papers referenced in the full version of this manuscript.

Results

Temperature variability, socioeconomics and health

Results indicated that the adverse health effects of temperature and temperature variability were significantly influenced by socioeconomic indicators (e.g. literacy rates,

	Number of cities	Number of cases	Increased hospitalisation risk, % (95% CI)	p values for difference*
Literacy rate quartiles				
Q1 (lowest)	454	15344354	0·80 (0·70–0·89)	Ref
Q2	453	23313694	0·61 (0·55–0·67)	0·0018
Q3	453	29918657	0·57 (0·53–0·62)	<0·0001
Q4 (highest)	454	79382538	0·43 (0·40–0·46)	<0·0001
Urbanisation rate quartiles				
Q1 (lowest)	454	14195131	0·63 (0·55–0·71)	Ref
Q2	453	16761150	0·56 (0·50–0·63)	0·21
Q3	453	24471426	0·53 (0·48–0·58)	0·030
Q4 (highest)	454	92531536	0·49 (0·45–0·52)	0·0010
Average household income quartiles				
Q1 (lowest)	458	15021111	0·77 (0·67–0·86)	Ref
Q2	449	25296158	0·59 (0·53–0·65)	0·0019
Q3	456	30011571	0·52 (0·48–0·57)	<0·0001
Q4 (highest)	451	77630403	0·46 (0·43–0·49)	<0·0001
GDP per-capita quartiles				
Q1 (lowest)	454	15983538	0·69 (0·60–0·79)	Ref
Q2	453	27860410	0·59 (0·54–0·64)	0·060
Q3	453	37544498	0·53 (0·49–0·58)	0·0026
Q4 (highest)	454	66570797	0·45 (0·42–0·48)	<0·0001
GDP per-capita classifications				
Lower-middle income	832	38223147	0·63 (0·58–0·69)	Ref
Upper-middle income	892	89366536	0·50 (0·47–0·53)	<0·0001
High income	90	20369560	0·39 (0·33–0·46)	<0·0001
Overall	**1814**	**147959243**	**0·52 (0·50–0·55)**	

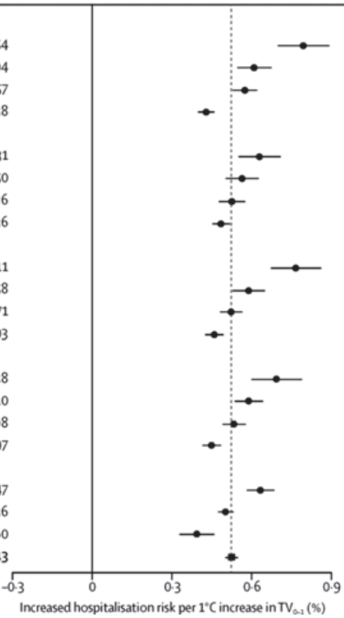

Table 1: Risk of hospital admissions associated with each one-degree Celsius (°C) increase in daily temperature variability (TV). The table shows Brazilian cities, disaggregated by several indicators of socioeconomic level, where the confidence interval (CI) is 95% and the P-value (probability) is 0.05 (5%). As a general rule, the magnitude of risk increases with socioeconomic vulnerability

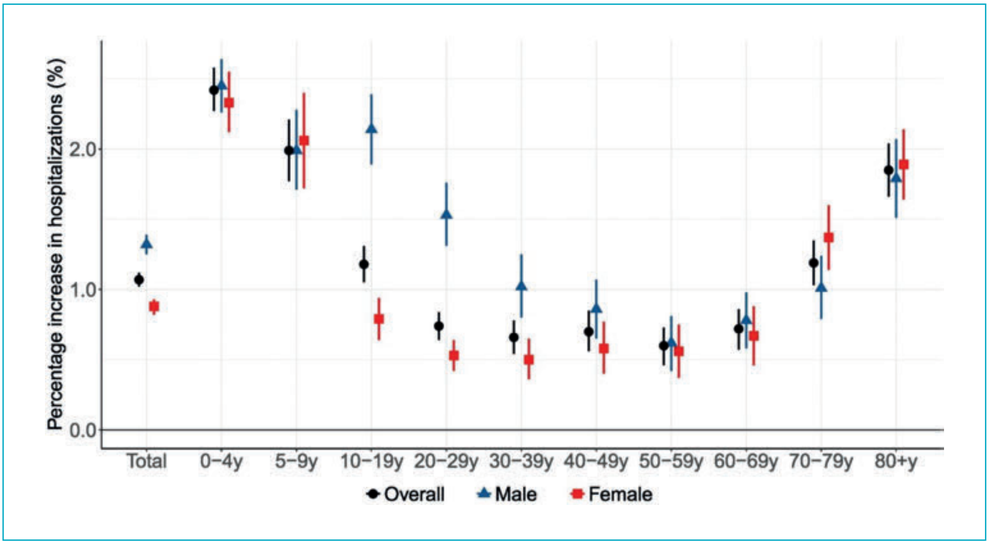

Figure 1: Percentage increase of hospital admissions associated with an inter-quartile change of temperature variability, expressed along different age groups and gender (Zhao, et al., 2018)

urban environment and average household income). In each case, the lowest quartile (Q) of the population experienced the highest increased risk of hospitalization with each one-degree Celsius increase in temperature, as demonstrated in Table 1.

Analysis also illustrated how different age groups exhibited different levels of susceptibility to temperature variability. Children and elderly people, for example, were more likely to be affected by climate-induced health risks (Figure 1).

Age-related vulnerability is probably due to natural processes (i.e. the functions of maturation and senescence). Thermoregulation (the biological mechanism responsible for maintaining a steady internal body temperature) is also markedly affected by age, with early infancy, early childhood and old age all representing periods of thermoregulatory inefficiency.

Finally, there is also evidence of an interaction between short-term heat exposure (heatwaves) and risk of hospitalization due to malnutrition (Xu, *et al.*, 2019).

Temperature comfort zones and mortality

The health comfort zone – defined here as the range of temperature variation without significant adverse health effects – varies within Brazilian cities. In Figure 2, the central dashed line indicates the observed optimal temperature, i.e. the temperature with the lowest risk of mortality. The two lateral dashed lines represent the bottom and top of the temperature range that still does not have a significant impact on health.

The blue and red lines indicate temperatures under or above the optimal temperature. Bars depict the frequency distribution of daily temperature for each city. Cold spells and heatwaves increase mortality risk, but with different intensities and at different temperatures. For example, São Paulo (in the southwest) and Teresina (in the northeast) have distinct thermal comfort zones. In Teresina, the minimum risk

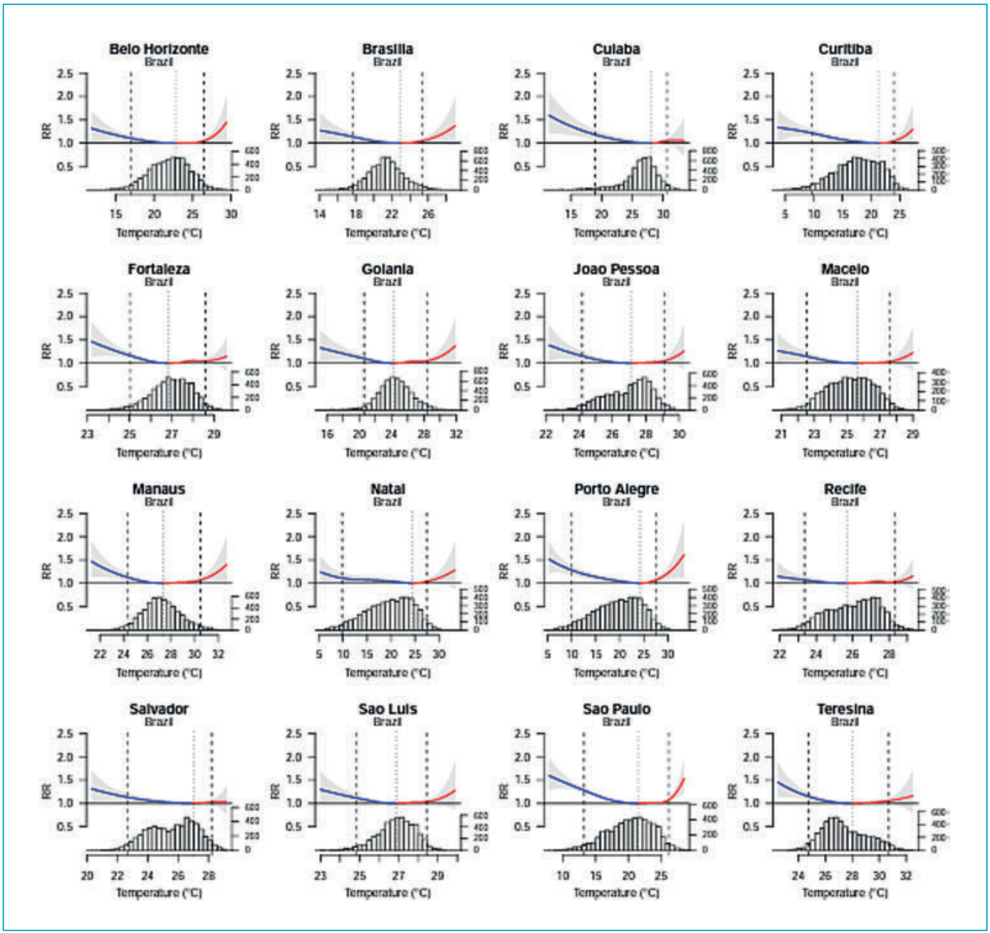

Figure 2: Relative risk (RR) of dying due to ambient temperature in 16 Brazilian cities

temperature is 28 degrees Celsius. In São Paulo, however, 28 degrees Celsius is in the thermal stress zone (Gasparrini, *et al.*, 2015).

Air pollution

Temperature and ambient air pollution interact significantly in promoting adverse health effects (Pinheiro, *et al.*, 2014). Results from this study indicated that children and people experiencing socioeconomic disadvantage, experience increased vulnerability to climate-induced health risks.

Autopsy analysis also demonstrated that levels of inhaled air pollutants are significantly higher in urban dwellers living in underprivileged areas (Figure 3). This is due to exposure to traffic and the modes of transport people use, and is exacerbated, in some cases, by wildfires. There is strong evidence that children and foetuses are particularly vulnerable to ambient levels of air pollution, with adverse consequences that include foetal outcomes such as low birth weight and premature birth (Jacobson, *et al.*, 2014; Saldiva, *et al.*, 2018).

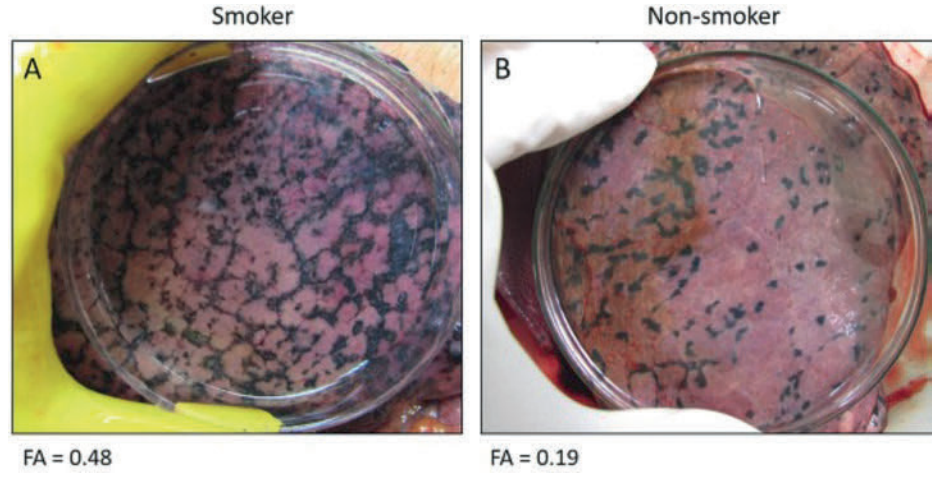

Figure 3: Autopsy images showing the pleural surface of two age-matched dwellers of São Paulo. Fraction area (FA) indicates the amount of pleural surface impregnated by black carbon based on a value of one – i.e. the smoker has 0.48 (48%) black carbon impregnation, while non-smoker has 0.19 (19%). For non-smokers, the study found that the amount of black carbon exhibited had a significant association with socioeconomic deprivation and daily commuting time (i.e. exposure to air pollution from traffic) (da Motta Singer et al., 2023)

The black spots in the pleural surface images (Figure 3) are foci of focal fibrosis with an accumulation of black carbon. The fraction area (FA) occupied by the black spots (0.48 and 0.19) represents a proxy indicator of lifetime exposure to urban particulates, evidenced by their visible component (i.e. black carbon). Non-smokers also exhibit spots of fibrosis with black carbon content. After adjusting for several co-variates (age, intensity of smoking, local traffic, occupation and length of time residing in São Paulo) the study found that the amount of black carbon exhibited had a significant association with socioeconomic deprivation and daily commuting time. As a general conclusion, people experiencing economic deprivation are more exposed to the risk of air pollutant-induced health risks.

Overall, results from this case study showed that extremes of ambient temperature and temperature variability are associated with higher risk of hospital admissions and mortality, notably due to chronic diseases such as stroke, myocardial infarction, congestive heart failure, peripheral arteriopathy, diabetes, kidney insufficiency, asthma and chronic obstructive pulmonary disorder (COPD). Specifically, the study found the following:

1. Temperature-associated health effects were more intense in children and elderly people, as well as amongst those living in areas with social and economic deprivation;
2. Children exhibited a five-fold greater risk of having a hospital admission promoted by temperature variability in comparison with adults;
3. Malnutrition and socioeconomic deprivation significantly aggravated the adverse effects of extreme temperatures;
4. The optimal temperature range varied across the Brazilian territory, probably due to human physiological adaptation as well as urban adaptation;
5. In large metropolitan areas, there were marked territorial differences in optimal temperatures, which were dependent on urban morphology (types of land cover), characteristics of soil occupation, density of green coverage and socioeconomic factors.

Lessons learned

1. Climate abnormalities and ambient levels of air pollution affect children's health.
2. Climate and pollution both interact to create adverse health effects.
3. The level of air pollution creates health effects of different magnitudes depending

on a complex set of factors such as urban islands, poverty (e.g. inadequate housing and sanitation), demography (age, sex and pre-existing health issues) and access to health services.

Finally, public policies that use scientific/quantitative information are necessary, but quantitative analysis alone is not sufficient to address the complex intersections between climate and health. Knowledge produced by researchers in the humanities is also crucial for designing policies and appropriate interventions that consider the values and culture of the people affected. This represents an enormous challenge and implies a close partnership with local communities in policy design and implementation.

One thing is clear; time is of the essence and rapid action is needed to build resilience and protect populations from climate-induced risks to health.

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Further information on this research is available at:

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Ethiopia

Mapping the urban overheating hazard and its driving factors in Addis Ababa

Case study prepared by:

Seyoum Melese Eshetie

Focus

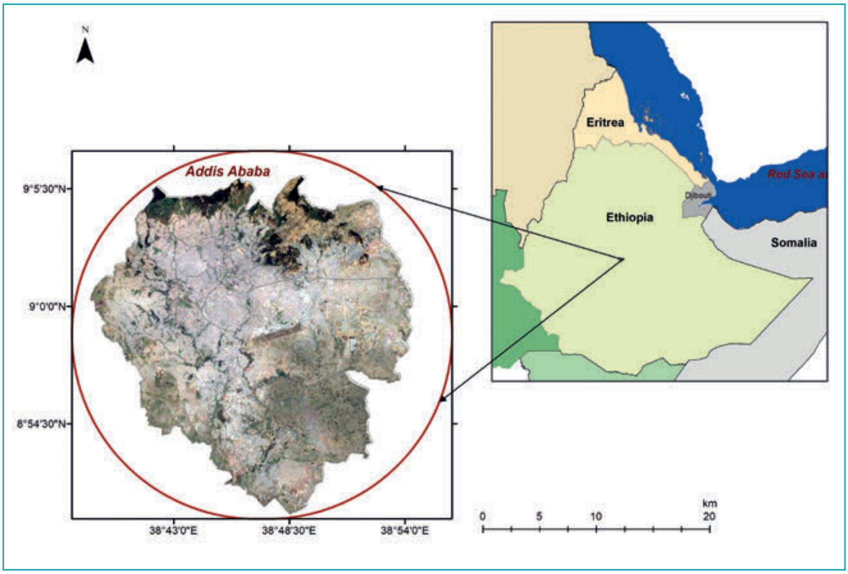
Global warming and the growth of cities are causing dramatic rises in surface temperatures in urban landscapes. The consequence is urban overheating, a global phenomenon in which urban areas exhibit significantly higher temperatures than surrounding rural areas.

The primary health risks of urban overheating are heat stress, which in turn causes increased heart rate and blood pressure, as well as cardiovascular events such as heart attacks and strokes (Mittal and Gupta, 1986). Urban overheating also endangers mental well-being, causing anxiety and sleep disturbances. Vulnerable populations are particularly at risk, such as the elderly, those with pre-existing cardiovascular conditions and children (Diniz *et al.*, 2020). Outdoor workers and individuals with lower socioeconomic status often endure heightened exposure to urban overheating due to limited access to cooling infrastructure and green spaces. This unequal distribution exacerbates health risks and further widens health inequalities (Gouveia *et al.*, 2022).

Project overview

Located in the central Ethiopian highlands, Addis Ababa is the country's capital and largest city (Figure 1). It is divided into ten sub-cities, each with its own administration (Table 1).

Figure 1:
Map of Addis Ababa city



It has a subtropical highland climate with two main rainy seasons: from June to September and February to April. Rainfall during the rainy season is generally moderate with occasional downpours, while the rest of the year there is little to no rainfall. However, like many cities in the developing world, Addis Ababa faces numerous challenges related to urbanization, including the urban heat island effect (Degefu *et al.*, 2021).

The city's population has grown significantly since 1950, with a current growth rate of around 4.4%. Table 1 shows each sub-city's population growth between 2007 and 2022. Most areas of the city are vulnerable to overheating and the increasing impacts of heat exposure on the population include the spread of vector-borne diseases, respiratory illnesses and heat-related ailments.

Sub-cities of Addis Ababa	2007 population	2022 population
Addis Ketema	255,372	359,735
Akaki Kaliti	181,270	255,348
Arada	211,501	298,044
Bole	308,995	435,421
Gulele	267,624	377,032
Kirkos	221,234	311,765
Kolfe Keraniyo	428,895	604,226
Lideta	201,713	284,208
Nefas Silk	316,283	445,683
Yeka	346,664	488,537
Total Population	2,739,551	3,859,999

Table 1: Addis Ababa city population by sub-city, 2007 and 2022 (Source: https://www.citypopulation.de/en/ethiopia/admin)

Mapping the urban overheating hazard and understanding its driving factors are essential to protecting and improving human health. By leveraging advanced mapping techniques and analysing the spatial distribution of land surface temperature, policy makers and urban planners can identify the worst-affected areas and implement targeted strategies to mitigate risks (Wyrwa and Chen, 2017).

The research objectives in this study, therefore, are to:

1. Map the spatial distribution of urban overheating in Addis Ababa;
2. Identify and analyse the driving factors contributing to urban overheating;
3. Develop recommendations for urban planning and public health interventions to mitigate the urban overheating hazard.

Team

The research project was initiated and designed by Seyoum Melese Eshetie of the Space Science and Geospatial Institute of Ethiopia. The Land Development Bureau and Addis Ababa City Health provided heat hazard data and information.

Method

Urban overheating hazard maps are powerful tools for identifying areas at higher risk of heat-related health impacts. By integrating geographical information systems (GIS) and remote sensing technologies, these maps provide detailed spatial data on the distribution of heat within urban areas. This information is crucial for identifying vulnerable populations and implementing targeted interventions to protect public health during heatwaves.

Satellite-derived urban overheating data can also be used in combination with other environmental and socioeconomic data to develop heat vulnerability maps. These maps identify areas and populations most at risk from heat hazards based on factors such as land cover, population density and socioeconomic indicators.

Understanding the driving factors behind urban overheating is equally crucial, and analysing these factors can identify areas at risk and enable targeted interventions that reduce urban overheating effects (Huang *et al.*, 2019).

Data sources

Landsat data from the NASA Earth Data portal (https://lpdaac.usgs.gov) were used to derive urban overheating, normalized difference vegetation index (NDVI), normalized difference built-up index (NDBI), normalized difference water index (NDWI) and elevation. Additionally, climate data (air temperature and rainfall) were obtained from WorldClim (https://www.worldclim.org) while population density data has been acquired from WorldPop (https://www.worldpop.org).

Workflow

1. Landsat imagery of the study area was calibrated to correct for atmospheric effects and distortions. These correction procedures were implemented to ensure consistency and accuracy in the calculations and to extract relevant information such as land cover classification and vegetation indices.
2. Using established algorithms, thermal band data and spatial analysis techniques were used to identify areas at risk of urban overheating and generate thematic maps to visualize the spatial distribution of the phenomenon and its drivers.
3. Regression analysis (Koenker Statistic and Geographically Weighted Regression (GWR)) was then applied to model the relationship between urban overheating and the identified drivers (taking spatial and temporal variations into account).
4. Findings from the analysis were interpreted to understand the drivers of land surface temperature and their implications for urban overheating.
5. Finally, the findings from the study were communicated to public health officials, policy makers and urban planners to inform decision making processes and develop effective mitigation strategies.

Results

Hotspot identification

The urban overheating pattern and spatial distribution information extracted from the NASA Landsat data is shown in Figure 2. The analysis reveals hotspot zones in many parts of the city. The sub-cities of Addis Kalema, Arada and Lideta exhibit the highest vulnerability to urban overheating, with significant populations at risk. Gulelie, Nifas Silk and Akaki Kality follow closely as the next most vulnerable areas. Bole and Yeka are identified as the sub-cities with the third most vulnerable populations.

Driving factors

Examination of relationships between urban overheating and explanatory variables reveal significant relationships with regards to air temperature, rainfall, built-up areas (NDBI), elevation, vegetation (NDVI) and population density. The NDWI (water) coefficient has a negative value of -1.51, indicating that areas with higher water content tend to have lower land surface temperatures. This finding aligns with previous research that has highlighted the cooling effect of water on land surface

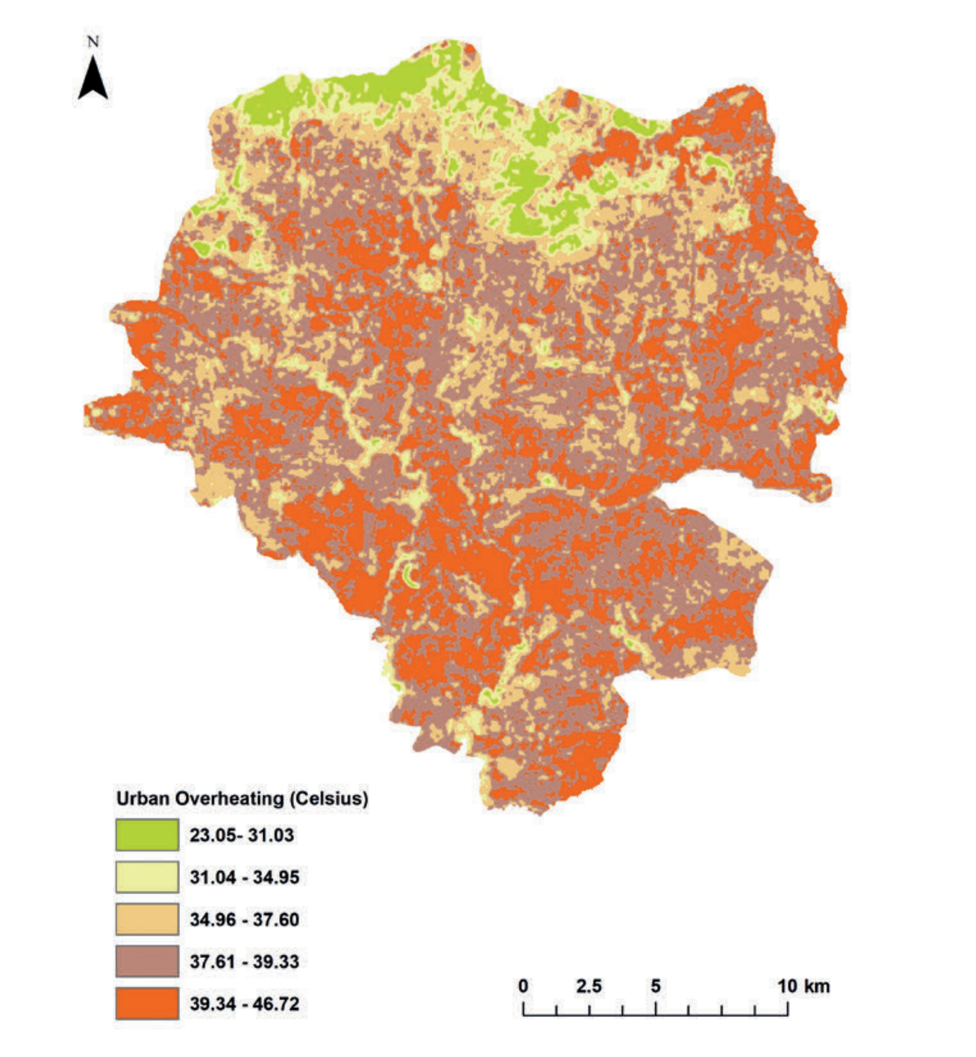


Figure 2: Map of the urban overheating pattern across Addis Ababa

temperature. Results are visually depicted in Figures 3a-c, which show that whereas there is a positive correlation between urban overheating and air temperature, urban overheating generally declines as either NDVI (vegetation cover) or elevation increase. The findings have important implications for land and urban planning and can inform efforts to mitigate the impact of urbanization and climate change on land surface temperature using adaptations such as tree planting.

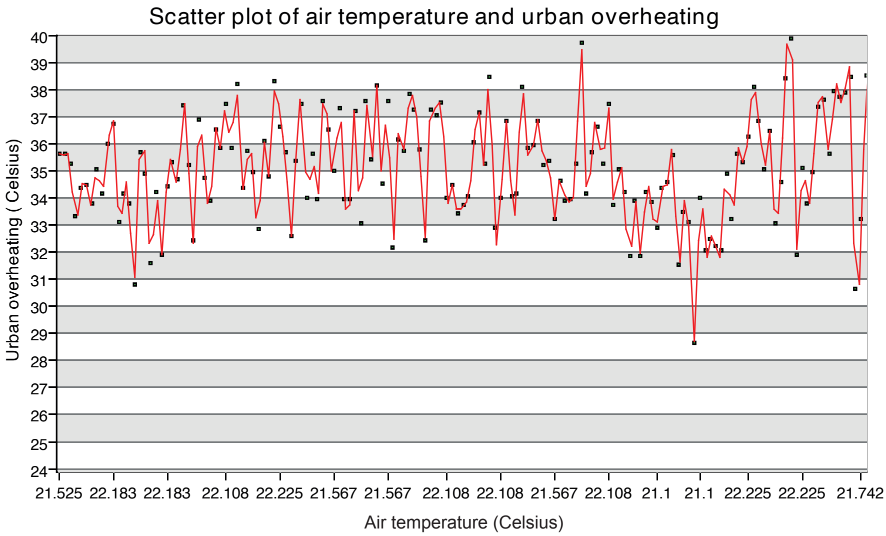


Figure 3a: Scatter plot graph showing positive correlation between air temperature and urban overheating

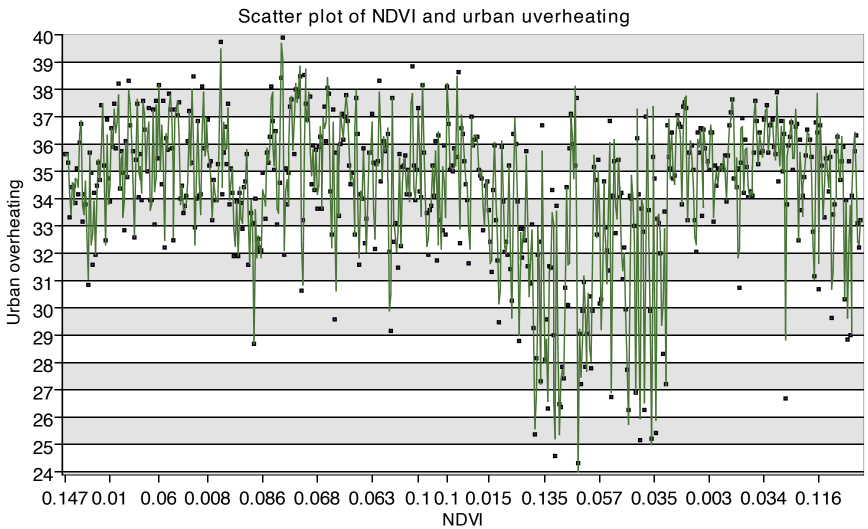


Figure 3b: Scatter plot graph showing that urban overheating declines as NDVI increases

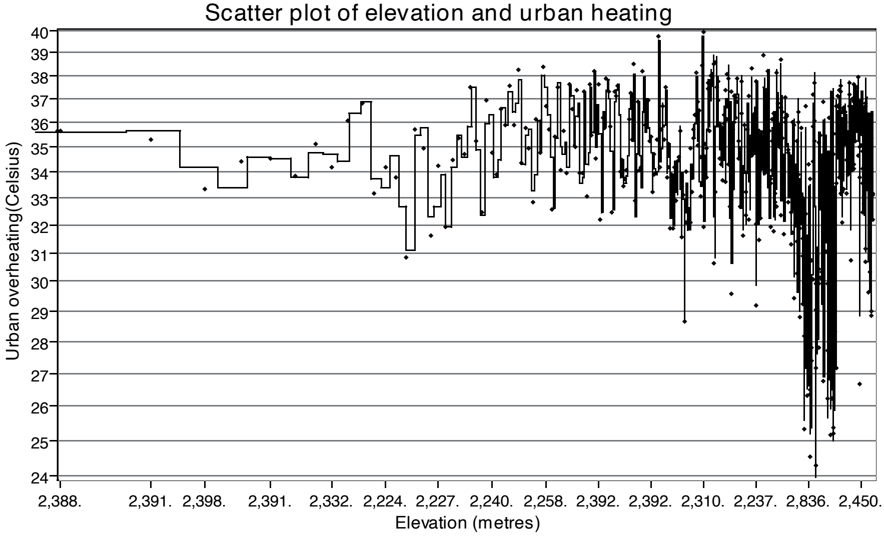


Figure 3c: Scatter plot graph showing that urban overheating declines as elevation increases

Regression models

The Koenker Statistic was employed in regression models to check the strength and reliability of the relationship variables in the study. In this case, non-stationarity was detected. Non-stationarity occurs when statistical properties of a process change over time. To account for this, an alternative model was required, and Geographically Weighted Regression (GWR) was used to rationalize local variations in the data.

GWR is a powerful analysis technique used to model spatially varying relationships between dependent variables and multiple explanatory variables. In this case, the dependent variable is urban overheating, and the multiple explanatory variables are air temperature, rainfall, built-up areas (NDBI), elevation, vegetation cover (NDVI), water (NDWI) and population density. The GWR values in this study indicate a significant spatial variability of relationships (Figure 4), meaning that each of these variables has an impact on urban overheating.

End-users

Health officials, policy makers and urban planners are the primary end-users of this study. Ongoing engagement with end-users provides them with opportunities to

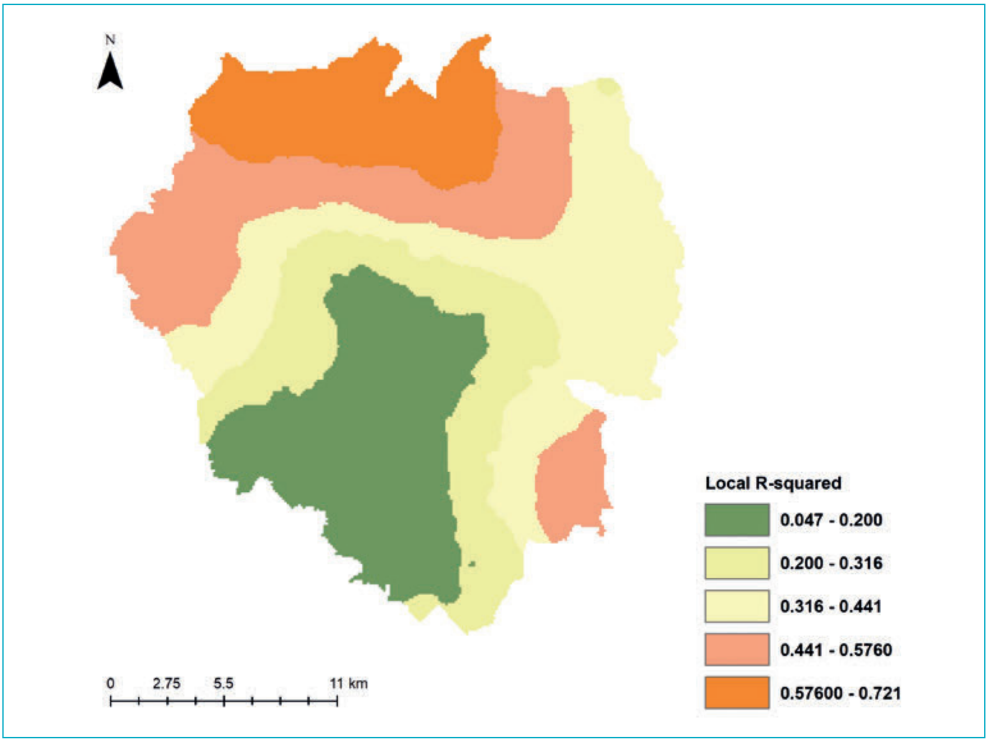


Figure 4: Geographically weighted regression (GWR) result indicated a significant spatial variability of relationships between urban overheating and its driving factors

suggest additional study questions and empowers them to make informed decisions and take appropriate actions based on the study's findings and the following recommendations:

1. *Urban greening initiatives (Addis Kalema, Arada and Lideta)*
   Increase green spaces such as parks, gardens and tree-lined streets. Green areas act as natural coolants, reducing the urban heat island effect and providing shade and cooling.
2. *Cool roof programmes (Addis Kalema, Arada and Lideta)*
   Implement cool roof programmes that promote the use of reflective and heat-reflecting materials for buildings. This will help reduce the amount of heat absorbed by rooftops and subsequently lower indoor temperatures. Additionally, incentivize the use of cool roof technologies through tax breaks or subsidies for building owners.

3. *Heat-resilient infrastructure*
   Incorporate heat-resilient design strategies into infrastructure planning and development. This includes using heat-reflecting materials for roads and pavements, designing buildings with effective ventilation systems and integrating green infrastructure, such as green roofs and vertical gardens, to provide natural cooling.
4. *Urban heat island monitoring and mitigation*
   Establish a comprehensive urban overheating monitoring system to identify hotspots and areas with increased vulnerability to extreme heat. Use the results of this research to prioritize interventions and allocate resources effectively. Implement heat mitigation strategies, such as cool pavements and urban shading structures, in identified high-risk areas.
5. *Public awareness and education*
   Launch public awareness campaigns to educate residents about the health risks associated with urban overheating and the importance of adopting heat mitigation measures. Collaborate with local community organizations and schools to promote sustainable practices, such as water conservation and tree planting.
6. *Collaboration and partnerships*
   Foster collaboration between public health agencies, urban planners, environmental organizations and community stakeholders to develop a holistic and bidirectional approach to address urban overheating. Create interdisciplinary task forces to ensure coordination and synergy between various sectors.

By implementing these recommendations, policy makers can work towards creating a cooler and healthier urban environment in Addis Ababa.

Lessons learned

While the study provided valuable insights into the health impacts of climate change and urban overheating, it is important to acknowledge its limitations. One notable limitation is that there may be other factors in addition to the explanatory variables that contribute to urban heat patterns. For instance, the study primarily examined the vulnerability of sub-cities based on population density and urban characteristics. Additional variables such as socioeconomic factors, infrastructure quality, or access to healthcare may also be relevant. By including them, future studies might provide a more nuanced analysis, allowing for a better assessment of the impacts and potential mitigation strategies.

Furthermore, the study focused on a specific geographical area, and the findings may not be directly applicable to other regions with different climate conditions or urban settings. It would be beneficial for future research to explore the generalizability of the findings across different contexts to ensure a more comprehensive understanding of the health impacts of climate change. Finally, additional analysis using spatial regression models or kernel density estimation, could also be used to uncover the causal factors behind land surface temperature hotspots.

Overall, however, this localized analysis highlights the need for targeted interventions and policies to mitigate the negative effects of urban overheating on human health and promote the development of sustainable and resilient urban environments.

Acknowledgements

Maps and graphs were created by the author except where another source is indicated

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Ghana

Co-production methodologies to deliver city-level flood resilience and reduce health inequalities in sub-Saharan Africa

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Researchers:

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Focus

The risk of flooding is increasing due to climate change, urbanization and population growth. More than 1.8 billion people globally are at risk. Of these, 44% live in sub-Saharan Africa.

Climate change is increasing the frequency and intensity of rainfall events and making them harder to predict. Urbanization can result in the confinement of waterways and a reduction in soil permeability (e.g. by paving). Combined with population growth, this increases the number of people inhabiting high risk areas such as floodplains, riverbanks and wetlands.

Flooding impacts almost every person, activity and industry, and can cause environmental degradation and biodiversity loss. These impacts can be classified into three categories:

1. Primary - as a direct result of contact with the flood (e.g. drowning);
2. Secondary - via intermediate mechanisms (e.g. water-borne disease);
3. Tertiary - longer-term and manifest months or years after (e.g. famine).

People subject to the same flood hazard will experience different risks based on their vulnerability. Vulnerability is determined by exposure (i.e. likelihood of being in the way) and susceptibility (i.e. potential to be negatively impacted) and is controlled primarily by socioeconomic factors. Effective flood risk strategies require an understanding of these components of risk. They involve managing the hazard (through actions that reduce the magnitude of the flood) and reducing vulnerability by targeting exposure (moving people away from high-risk areas) or susceptibility (e.g. by improving housing quality) (Moulds *et al.*, 2021).

Top-down measures have typically failed to achieve equitable outcomes (Moulds *et al.*, 2021; Reckien *et al.*, 2023). Similarly, adaptation strategies that are designed only to limit economic damage without considering impacts on population health, almost always represent maladaptation. The co-production of research with societal partners, represents an opportunity to deliver equitable outcomes and directly inform decision making (Audia *et al.*, 2021).

This case study presents an illustrative example of the application of co-production methodologies to deliver city-level flood resilience in sub-Saharan Africa with a focus on reducing health inequalities. Tamale is the third largest city in Ghana. It has a population of around 300,000 which is expanding by 3.6% per year (Tamale Metropolitan Assembly, 2021). The city has emerged as an economic centre in West Africa due to its strategic position, but it is also subject to challenges including high rates of poverty and increasing exposure to climate extremes – such as flooding.

Team

Pathways to Equitable Healthy Cities is a global partnership between universities which seeks to explore the links between environmental change and human health through the lens of equity. The team included researchers at the University of Ghana, Imperial College London and King's College London, complemented by researchers with technical or local knowledge. Local researchers from Tamale were pivotal in establishing the contextual landscape and in scoping and engaging societal partners.

Methods

The project followed the 'loops and building blocks' framework for co-production. This approach aims to structure inclusive engagement and governance, and ensure equitable contribution (Audia *et al.*, 2021). An important first step was to meet with traditional authorities, explain the research motivations and secure permission to work in Tamale. A two-day workshop including 50 participants served to identify challenges and opportunities relating to climate change and health.

Day one of the workshop included short presentations to introduce concepts of co-production and climate change. Open discussion sessions gave every participant the opportunity to speak. On day two, participants self-organized into breakout groups around key themes from day one (flooding, food, heat, and water, sanitation and hygiene) before reconvening to share insights and conclusions. Researchers collated a report which was shared with participants, with the opportunity to provide feedback. The report is available here: https://equitablehealthycities.org/focus-cities/tamale/.

Participants selected flooding as a priority challenge. Subsequently, researchers conducted semi-structured interviews with expert stakeholders which guided participants to discuss key themes such as climate change, equity, and barriers to adaptation, but also allowed them to discuss other themes that they identified as important.

Expert stakeholders identified six areas of high flood risk. Focus groups of between five and 20 participants (predominantly, male chiefs and elders) were selected by

Figure 1: Images representing some of the stages of the co-production methodology. Top left shows the installation of the ultrasound sensor over a storm drain. Bottom left shows some of the participants of the initial workshops. Right shows interviews, breakout groups and focus groups.
(Credit: Ben Howard and Cynthia Awuni)

community leaders and facilitated by local researchers, who relied on extensive note taking to capture data. A thematic analysis of this data was subsequently conducted.

At each stage, participants were asked to recommend further stakeholders. This served to validate the initial participant scoping exercises, whilst also ensuring that important partners were not unintentionally excluded. In future, household surveys would allow more citizens to engage with the process to capture a wider range of views.

Sensors were installed in the selected communities to provide hydrological data, used to characterize flooding. Sensors to measure inundation (i.e. flooded or not) were installed in communities and embedded in participatory monitoring networks. An ultrasonic water level sensor was installed in one of the Tamale's major storm drains, to use as a pilot to test the acceptability of this technology in future research.

Results

Actors

Flood management in Tamale involves a complex system of stakeholders. Institutional actors are organized around a centralized local government involving several departments. Precise responsibilities are not always clearly defined, leading to blind spots and limiting accountability. Direct interaction with communities is mostly facilitated by disaster response teams in response to a natural hazard.

Non-institutional actors also play a vital role. Traditional authorities – chiefs of the Dagomba people who represent 80% of Tamale's population – are primary stakeholders in local governance (Tamale Metropolitan Assembly, 2021). They can influence people's behaviour and they also manage land ownership and allocation. Communication between institutional and traditional systems is mostly facilitated by elected assembly representatives. The interaction of these systems creates a complex hybrid governance format, presenting both challenges and opportunities.

Drivers

Common themes emerged regarding the causes of flooding in Tamale. Reported drivers can be classified into three groups:

1. *Drainage networks*
   Storm drains are often built reactively following severe floods or to protect areas of high economic value. This piecemeal approach results in poor design and construction. Some drains, for example, stop in the middle of communities (Figure 2a). In some cases, participants reported problems with flooding only since the drains were constructed.
2. *Behaviour*
   Poor waste management practices have resulted in blocked drains (Figure 2c), which generate localized flooding. Furthermore, existing 'communal labour' to clean drains has diminished due to non-governmental organization (NGO) activities that have monetized community cleaning.
3. *Urban planning and enforcement*
   Paving and construction in urban areas has resulted in larger surface water volumes that overwhelm drain infrastructure. Despite planning rules that demarcate buffer and drainage zones, construction continues in high-risk areas due to (i) poor enforcement and (ii) land allocation by traditional leaders.

Few of the focus group participants highlighted climate change or changing rainfall patterns as a driver. When prompted, however, most reported that rainfall had become less predictable with higher intensity events. A lack of nuance in regional and city-level precipitation data means that signals of climate change are overlooked. For

Figure 2: a) A city-level storm drain that stops abruptly in a poor community. b) Piers of concrete blocks added to a mud house to increase its resilience to flooding. c) A roadside storm drain blocked with solid waste rendering it ineffective. (Credit: Ben Howard and Cynthia Awuni)

example, average daily precipitation is not able to capture rainfall intensity, which is the most important parameter for the flash floods in Tamale.

Impacts

In the focus groups, impacts were categorized as primary, secondary and tertiary. These have been simplified in Table 1.

Adaptation

Most participants were not familiar with the term 'adaptation', suggesting a lack of previous consultation. However, every participant had considered ways in which they, and the city, could adapt (Figure 3).

Inequitable access to adaptations is evident in Tamale, as in other cities in sub-Saharan Africa. City-level storm drains, for example, reduce exposure for some,

Primary	Secondary	Tertiary
Drowning	Disruption to services	Loss of business
Damage to housing	Damage to sanitation systems	Long term health effects
Damage to roads and bridges	Increases in disease	Repeated disruption of agriculture (food insecurity, shortages, and famine)
Damage of property	Limited access to economic and educational opportunities	Trapped in poverty by a cycle of shock-recovery
	Homelessness	Homes are abandoned
	Mental health challenges	

Table 1: Reported impacts of flooding classified into primary, secondary and tertiary effects

primarily in high-income areas, but increase exposure and exacerbate flood risk for others, primarily in low-income areas. However, most participants prioritized improving storm drain infrastructure, even those who are currently impacted by poor storm drain design.

Access to community and household adaptation was similarly determined by socioeconomic status. Poorer people had limited access to adaptation measures, at most using sandbags to build small embankments or adding piers to mud houses (Figure 2b). Many adaptation activities do take place in Tamale, but how they interact to determine individual risk remains unclear.

End-users

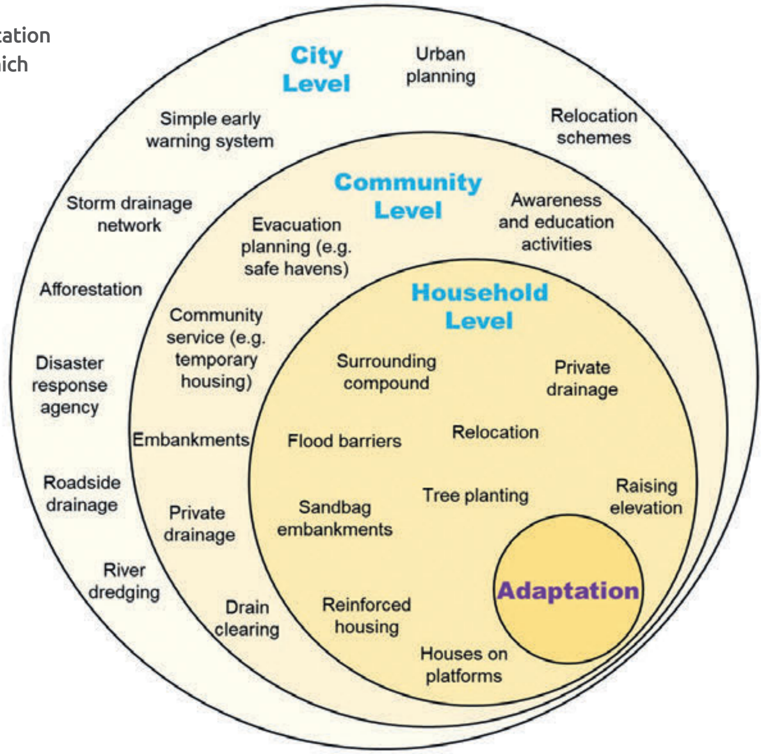
End-users were central to the research process and included traditional authorities (male chiefs and elders) and expert stakeholders. The outcomes of this research can be used by funders and investors (private, government and NGOs) to justify financing interventions in Tamale, as well as to inform how investment is allocated. Similarly, governments can use this evidence to lobby for investment.

Lessons learned

Inclusivity

Co-production is a collaborative approach that brings together typically isolated societal actors. It allows stakeholders to understand each other's challenges and

Figure 3: Levels of adaptation to flooding in Tamale which interact to influence an individual level of risk



generate shared goals. Methodologies, however, must allow inclusive participation without demoralising and disengaging community interviewees. The semi-structured style used in this study proved essential. It allowed flexible questioning on the same themes (i.e. pitched at the level of the participant) prompting deeper discussions between interviewees and subject experts.

Dissemination

Research insights must be disseminated in multiple formats suitable for a range of stakeholders and be made accessible to stakeholder communities. City-level flooding strategies cannot be successful without cross-sector awareness and buy-in. In this study, for example, most participants did not know about, or have access to, critical information such as flood management plans and policies, weather forecasts or resources about climate change. These plans do exist online (e.g. Tamale Metropolitan Assembly, 2021), but barriers to access, such as limited internet connection, remain. Information, therefore, must be delivered in inclusive and salient formats. A simple solution would be to distribute research outputs in both print and digital formats.

Trust-building

Traditional leaders provided detailed insights into flooding in their communities. However, engaging traditional authorities involves building trust over time, particularly where communities have been subject to extractive research practices in the past. Leveraging positive personal histories can accelerate trust building, for example, if local researchers have existing relationships with community leaders, or can be introduced by those who do. Thereafter, researchers must demonstrate a commitment to the co-production process and more generally to the well-being of participants. Further, local training on the maintenance of sensors and the use of hydrological data increases community awareness of flooding and empowers individuals and communities to take action themselves.

Impact inequality

This research revealed cross-cutting effects of flooding for society, including significant inequities in impacts and severe consequences for health and sustainable development. Flooding adaptations are evident on several levels but are typically implemented in a piecemeal approach. This has resulted in instances of maladaptation, whereby those with the highest risk end up with the least benefits. In some cases, this has even exacerbated the flood risk. Overall, this reduces city-level flood resilience. Financing adaptation efforts without resolving the failures in existing mechanisms is likely to accelerate maladaptation, risking the livelihoods and well-being of the most vulnerable people. Instead, investment should aim to generate a reliable and accurate evidence base, develop city-level strategic plans and fund local capacity building.

Conclusion

The outcomes of this research can be used by funders and investors to justify financing interventions, and by expert stakeholders who can make evidence-based decisions with a new emphasis on equity and justice. Community involvement is key. It empowers communities to transition from passive recipients of interventions to proactive agents of change. Ultimately, this encourages communities to take ownership of their resilience efforts to become influential contributors to high-level dialogues and international discussions.

Acknowledgements

This work is supported by the Pathways to Equitable Healthy Cities grant from the Wellcome Trust [209376/Z/17/Z]. For the purpose of Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

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India

The health benefits of response actions to air pollution and extreme heat in Ahmedabad

Case study prepared by:

Vijay S. Limaye

FOCUS

Overview

Climate change, extreme heat and air pollution are inter-connected public health threats. Extreme heat in India is already associated with significant, excess, all-cause mortality (Azhar *et al.*, 2010), while air pollution contributed to an estimated 980,000 deaths in 2019 (Pandey *et al.*, 2020). In the same year, only 6% of Indian households were estimated to have access to air conditioning (A/C) (Romanello *et al.*, 2022), and the demand for associated cooling energy is predicted to grow eight-fold by the 2030s. If India powers this demand by burning fossil fuels it may trigger higher emissions and worsen the crisis.

India's National Clean Air Programme (NCAP) provides a roadmap for reducing air pollution and includes controlling emissions from aging coal-fired power plants, which increased by 50% between 2007 and 2016. However, despite robust estimates of the health harms of air pollution in India, there is limited evidence quantifying these dangers at a local level.

Figure 1: The Torrent coal-fired power plant contributes to air pollution in Ahmedabad (Credit: Natural Resources Defense Council (NRDC))

Ahmedabad

Ahmedabad, in the western state of Gujarat, is one of 132 Indian cities that exceed current health-based air quality limits (Central Pollution Control Board, 2021). It is also one of India's megacities with a population above ten million and where premature mortality from air pollution has increased significantly between 2005 and 2018 (Vohra, *et al.*, 2022).

There are several reasons why the city is an ideal setting to investigate air quality and the health benefits of climate change response actions. First, one of India's oldest coal-fired power plants is located in central Ahmedabad (Figure 1). Second, the city experiences extreme air quality problems, and third, there is a civic appetite to improve public health. The city's pioneering Heat Action Plan, for example, includes adaptation measures such as a cool roofs initiative (Figure 2), which involves painting existing roofs with solar reflective paint to reduce indoor heat (Knowlton *et al.*, 2014).

Thus, the research aims to:

1. Describe the health toll of air pollution in the city;
2. Identify health-related co-benefits of climate solutions that reduce fossil fuel use;
3. Provide a rationale for stronger mitigation and adaptation policies.

Figure 2: A woman in Ahmedabad painting her home roof with solar reflective paint (Credit: Mahila Housing Trust)

Team

The collaborating team included researchers from the Indian Institute of Tropical Meteorology (IITM), the Gujarat Energy Research and Management Institute (GERMI), the Public Health Foundation of India/Indian Institute of Public Health-Gandhinagar (IIPH-G), and the Natural Resources Defense Council (NRDC), based in the United States (US).

Methods

Energy policy experts at GERMI estimated Ahmedabad's electricity demand in 2018 and 2030, and considered how demand for air conditioning is expected to rise due to climate warming, population growth and economic expansion. The team also considered the growth of renewable energy capacity and opportunities to substitute fossil fuel-generated electricity with renewable sources.

Climate and air quality scientists at IITM collected monitoring data for 2018 and modelled air quality for two different scenarios in 2030:

1. Business-as-usual (BAU), in which Ahmedabad continues to rely heavily on its coal-fired power plant and takes no further action to expand cool roofs beyond the existing 5% coverage;
2. Combined mitigation and adaptation (M&A), in which the city takes strong climate actions to completely substitute fossil fuel power with renewable energy and expand its cool roofs programme to cover 20% of available roof area (Vellingiri *et al.*, 2020).

Public health scientists at NRDC and IIPH-G collected baseline mortality data, developed population estimates for 2018 and 2030 and analysed the different air quality projections to estimate city-wide health effects in 2030 under the BAU and M&A scenarios.

Researchers then estimated the air quality and health co-benefits of potential climate change mitigation and adaptation actions in Ahmedabad by 2030, and explored two main actions that could be implemented at city level:

1. Mitigation of climate pollution through control of emissions from the Torrent Power Plant;
2. Adaptation to extreme heat via expansion of cool roofs across the city (Figure 2), which lowers indoor temperatures and reduces citywide demand for energy to power A/C.

The team linked models (Figure 3) to explore the air quality-related health effects of these responses, with a particular focus on fine particulate matter ($PM_{2.5}$), the most dangerous air pollutant regulated under India's National Ambient Air Quality Standards (NAAQS).

Population and demographic data for modelling

BenMAP-CE (Benefits Mapping and Analysis Program-Community Edition) is an open-source software application used widely in health impacts research. The team

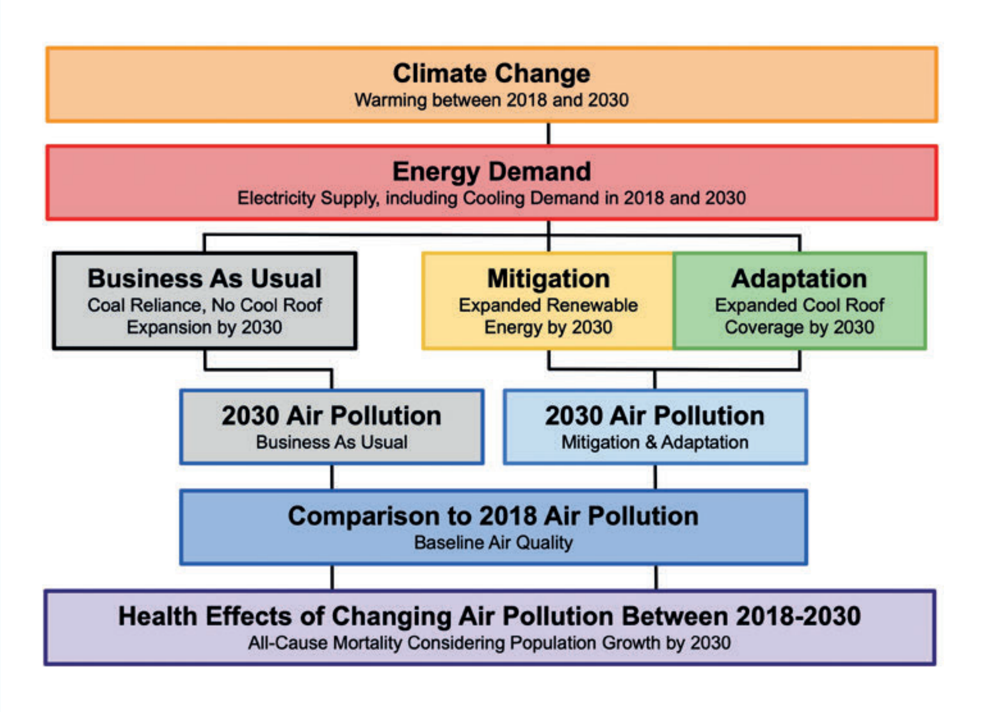

Figure 3: Flowchart depicting project model integrating projections of climate warming in Ahmedabad (orange box), energy supply and cooling demand (red box), and two 2030 comparison scenarios that shape air quality modelling (BAU, grey box and a combined M&A scenario, yellow and green box). Air quality modelling and monitoring data (boxes with blue outlines) were analysed using a health impact assessment approach (purple box) to arrive at air quality effects on all-cause mortality in the city in 2030, relative to a 2018 baseline (Credit: Limaye et al., 2023)

used this model to estimate exposure to air pollution by applying population-based weighting to air pollution output. The resultant dataset incorporated spatial, population growth and age structure profiles from several data sources.

Health metrics and baseline health estimates

Due to the lack of cause-specific mortality and morbidity data for Ahmedabad, researchers utilized all-cause mortality as the health metric. Researchers then compared $PM_{2.5}$ air pollution conditions for baseline 2018 versus those under the two future scenarios for 2030 (BAU and M&A) and quantified the health co-benefits from avoided mortality using BenMAP-CE.

$PM_{2.5}$ exposure-response

The team calibrated BenMAP-CE with the Ahmedabad population estimate for 2030. The Global Exposure Mortality Model (GEMM) (a widely used risk estimator for health impact assessment of air pollution) was then used to integrate air quality and health data from 16 countries with high annual $PM_{2.5}$ exposure levels (up to 84 micrograms per cubic metre (µg/m3)) (Yin *et al.*, 2018).

As shown in Figure 3, the baseline for analysis in the 2018 model included the demand for cooling energy and sources of energy (coal-fired power plants or renewables) to meet current electricity needs. Researchers then estimated demand in 2030, considering changes driven by population growth, economic development and climate warming. Energy modelling then informed the level of air pollution generated from thermal coal plant electric power, in 2018 and in 2030 BAU and M&A scenarios.

Results

Climate change and energy demand

Analysis shows that due to increases in both population and temperature, demand for energy to provide cooling in Ahmedabad could nearly triple by 2030. Encouragingly, renewable energy capacity in Gujarat is expected to expand by a factor of five over the same period as a result of India's national commitment to provide half the country's energy from renewable, non-fossil fuel sources by 2030 (Joshi *et al.*, 2022). Further, expansion of cool roofs from 5% to 20% of the total residential area would reduce cooling energy demand by 0.21 terawatt-hours (TWh) by 2030, and the energy savings would more than offset the city's climate change-driven increase in electricity demand.

Air quality

$PM_{2.5}$ air pollution levels averaged 71.04 µg/m3 in 2018 and modelling suggests air quality will further deteriorate if the city takes a BAU approach. In contrast, if Ahmedabad executes a robust M&A approach, annual $PM_{2.5}$ air pollution would slightly decrease to 70.94 µg/m3. This is still well above the national annual limit (NAAQS) of 40 µg/m3, but a significant outcome considering anticipated growth in both population and energy demand over the same period (Central Pollution Control Board, 2020).

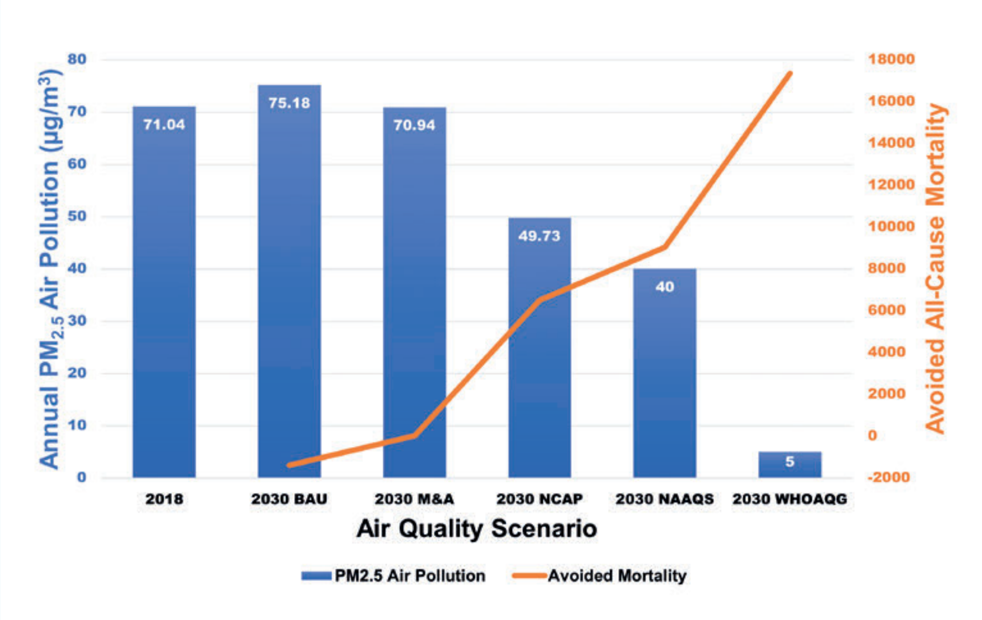

Figure 4: Key air pollution and health results: BenMAP-CE input air pollution values (blue bars) and health effect estimates (orange line) under 2018 baseline, 2030 business-as-usual (BAU), 2030 mitigation and adaptation (M&A), 2030 NCAP (National Clean Air Programme) attainment, 2030 NAAQS (National Ambient Air Quality Standards) attainment, and 2030 WHOAQG (World Health Organization Air Quality Guideline) attainment. Health effects are for each scenario compared to baseline air quality for 2018. For avoided all-cause mortality, negative values indicate excess deaths in 2030 relative to 2018, positive values indicate avoided deaths in 2030 relative to 2018 (Credit: Limaye et al., 2022)

Health

The study combined city population projections for 2030, baseline health data, and air pollution epidemiology evidence with air quality modelling results using BenMAP-CE (Figure 4) to estimate the health effects of $PM_{2.5}$ air pollution in 2030 under the BAU versus M&A scenarios. Results show that the air quality benefits of M&A actions result in up to 1,414 fewer annual all-cause premature deaths, compared to the BAU scenario.

Modelling also demonstrates that greater ambition to improve air quality will result in more significant health benefits. By 2030, Ahmedabad could avoid between 6,000 and more than 17,000 annual premature deaths if NCAP targets, NAAQS limits, or World Health Organization $PM_{2.5}$ air quality guidelines (WHOAQG) are achieved (Figure 4).

Limitations

Computational constraints meant researchers did not undertake a year-round, meteorology-constant simulation, nor run a modelling method across a range of future years. As a result, the portion of air pollution change between 2018 and 2030 due to changing meteorology alone could not be determined.

Additionally, the team did not have access to cause- or age-specific daily mortality data for Ahmedabad. Therefore, researchers were unable to estimate potential health co-benefits for residents under 25 years old. Since children are especially vulnerable to air pollution health harms, the avoided mortality co-benefits will therefore be underestimated.

End-users

Municipal, state and central government pollution control managers have been briefed on the results of this study and on ways that health considerations can be better integrated into planning efforts, including for implementation of the National Clean Air Programme in Ahmedabad.

Lessons learned

1. Results demonstrate that local actions that respond to climate change through M&A policies can achieve substantial air quality and health co-benefits at the local level.
2. Shifting India even further and faster away from fossil fuels and towards clean energy and stronger heat adaptation through cool roofs, can help reduce deadly air pollution, keep people cooler and healthier, and reduce carbon dioxide pollution.
3. Modelling provides a blueprint for future studies to estimate local air quality and health co-benefits of climate change responses. Such research can help the public understand how climate action can deliver cleaner air. It can also strengthen the understanding and implications of policies that affect energy use and air quality, such as the India Cooling Action Plan, India's climate change goals under the United Nations Framework Convention on Climate Change, and further implementation of the NCAP.

Policy recommendations

1. Move India's energy systems away from fossil fuels (coal, oil and gas) and towards renewable sources;

2. Implement low-cost adaptations to mitigate for extreme heat such as cool roofs that keep houses cool. These adaptations help deliver savings and reduce demand for energy;
3. Use well-established models that estimate the health impacts of air pollution, to strengthen support of health-protective policies;
4. Adopt interdisciplinary practices to enable comprehensive learning opportunities for team members, local policy makers and wider communities.

Acknowledgements

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Further information on this research is available at:

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Malaysia

A technology-based approach to predicting fire risk in tropical peatland and developing a transboundary haze alert system

Case study prepared by:
Aduwati Sali

Focus

Transboundary haze is a form of air pollution that affects tropical, ASEAN countries (Association of Southeast Asian Nations), particularly Indonesia, Malaysia, Singapore and Thailand. These countries are located in a region that has large areas of peatland, an important ecosystem and home to millions of people, plants and animals. However, in hot, dry weather the peatland combusts easily and the smoke and dust particles from fires can drift across country boundaries and cause transboundary haze.

Regional air quality in Southeast Asia is seasonally affected by the phenomenon, which is often the result of forest fires from traditional 'slash-and-burn' agricultural methods. In 2015, the fire and haze situation in Malaysia cost twice as much as the reconstruction after the 2014 tsunami (USD 16 billion). Transboundary haze does not only affect the economy; it has also led to health risks from exposure to air pollution such as respiratory and cardiovascular diseases (Yeo, *et al.*, 2014; Tan, *et al.*, 2000).

An integrated, technology-based approach to peatland forest management would allow for more accurate fire risk prediction and thus ameliorate the impact of transboundary haze. However, there are several challenges in ASEAN:

1. A of lack robust air quality monitoring infrastructure to enable reliable data collection at a regional level;
2. The locations of health events are often geographically distant from the nearest air pollution monitoring sites;
3. Some government agencies are reluctant to release air pollution data.

The Canadian Fire Weather Index (FWI) is one source of data used in fire prediction. It is the basis for the Fire Danger Rating System (FDRS), used to predict fires across Southeast Asia. However, the FDRS does not incorporate soil observation parameters such as groundwater level, which is particularly significant in tropical areas with a higher likelihood of rainy days. This limitation highlights the need for a model that integrates groundwater level and other soil parameters into the existing FWI.

Internet of Things (IoT) system

One approach is to monitor the moisture content of the peatland using an IoT system. This system incorporates sensors which can measure soil moisture (among other things) and then model the evaporation rate from the soil using various factors such as temperature, rainfall and humidity. Historical data from the sensors can be used to train the model to predict the evaporation rate in real time and provide early warning of potential fire risks.

Multi-layer neural network

Using data from the IoT system and existing indices (FDRS and FWI), researchers used a multi-layer neural network (a type of machine learning process) to predict localized fire risk with increased precision. To compare levels of accuracy, researchers used two neural networks: one that used four input factors utilized by the current FWI (temperature, humidity, wind speed and rainfall data); and another that used five further input factors, incorporating soil temperature and moisture content, solar radiation, groundwater level and air pressure.

This case study, therefore, focuses on a new approach for calculating moisture levels in tropical peatland. It deploys an IoT system at Raja Musa Forest Reserve (RMFR) as a proof-of-concept for technology-based peatland management and uses a supervised multi-layer neural network to predict the Fire Weather Index (FWI) of the peatland forests.

Method

IoT system for peatland forest management

Raja Musa Forest Reserve (RMFR) in Selangor, Malaysia, presented an ideal location for the study with its vast distribution of peatland, shown in dark brown (Figure 1).

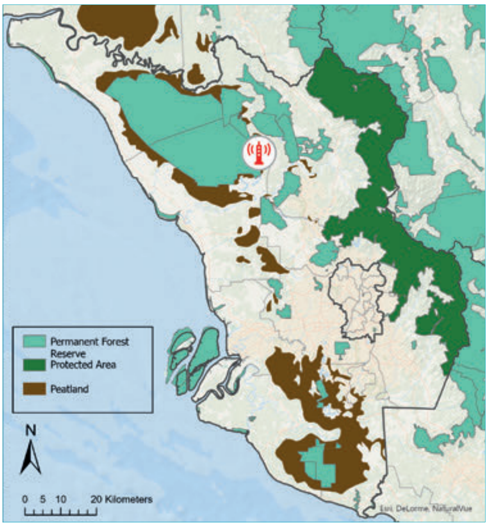

Figure 1: Peatland distribution in Raja Musa Forest Reserve (RMFR) and the location of the IoT system (3°27′58″ N, 101°26′31″ E)

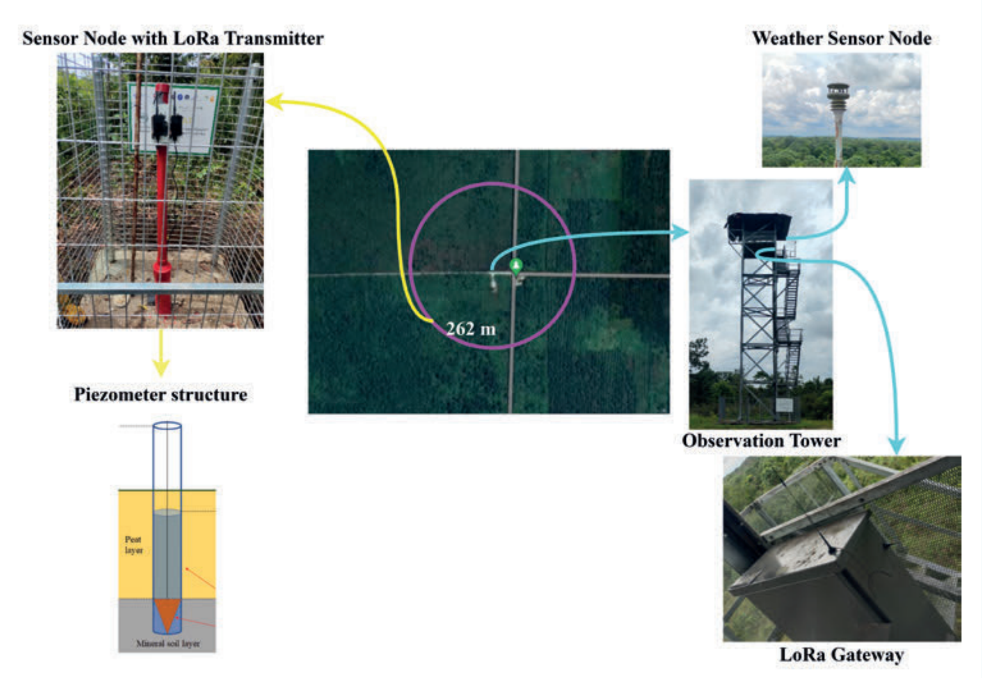

Figure 2: Deployment structure of the IoT system. Piezometer measures groundwater level. LoRa gateway allows data to be sent wirelessly to researchers

An IoT system was deployed to facilitate data monitoring and collection (Figure 2). The system's layout and structure were designed to enable efficient and comprehensive monitoring of relevant parameters and thus provide real-time data. Temperature, humidity and rainfall data, provided by the Malaysian Meteorological Department (METMalaysia), were obtained from a weather station situated approximately eight kilometres from the IoT system. The same parameters were also measured by sensors at the IoT site. A LoRa (long-range) transmitter allowed data to be sent wirelessly to researchers.

Results

Figure 3 shows the data from the nine parameters monitored by the IoT system in RMFR. The meteorological parameters were atmospheric temperature, atmospheric humidity, wind speed, rainfall, air pressure and solar radiation. The peatland parameters were groundwater level, soil temperature and soil humidity. Each subgraph's abscissa (horizontal axis) represents the parameter's value, while the ordinate (vertical axis) represents the number of times that value was measured. The number of samples for all nine meteorological and peatland (ground) parameters was the same (i.e. 47,306 samples).

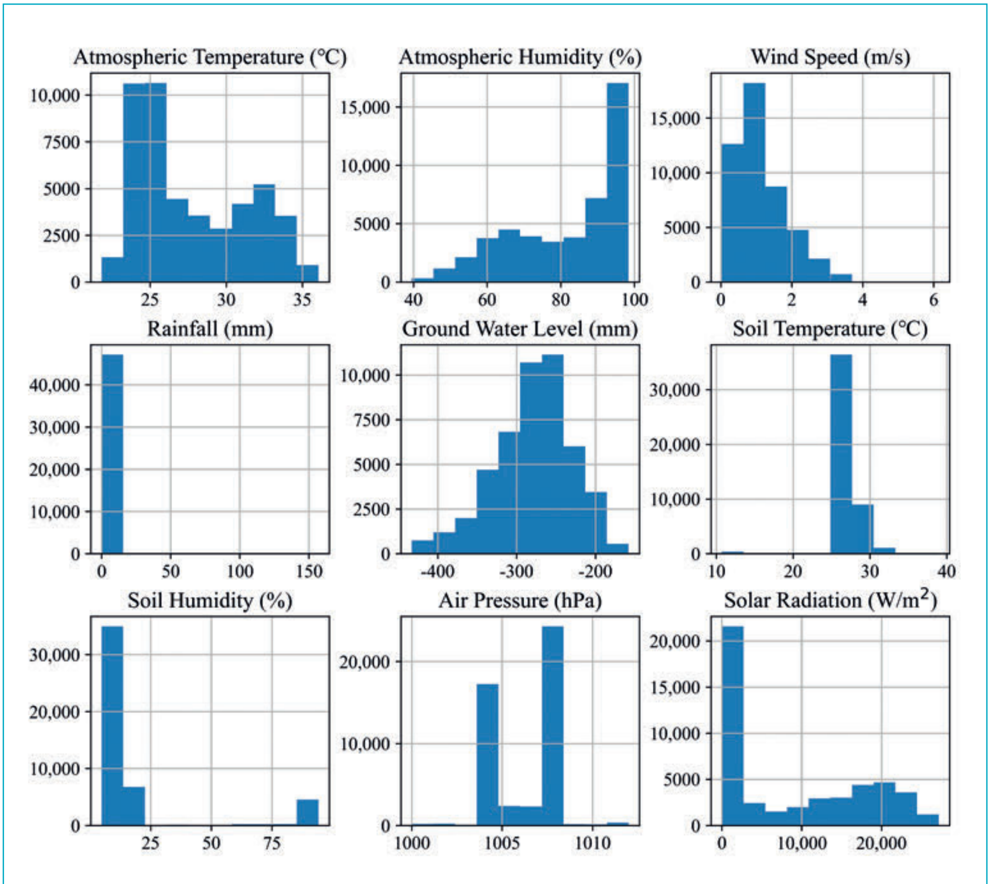

Figure 3: Peatland data measured by IoT system from ground and weather sensors

Neural network for predicting FWI

Neural networks have strong self-learning, self-organizing and adaptive capabilities (Chen, *et al.*, 2021). This has advantages in processing random or unclear information (Ahmadi, *et al.*, 2022). First proposed by Van Wagner (1987), the Canadian Fire Weather Index (FWI) uses four parameters to predict fires (temperature, humidity, wind speed and rainfall). In this study the same parameters were used to generate a four-input neural network (Figure 4).

Multi-layer neural networks calculate outputs by weighting inputs from the input layer (calculating the connections between temperature, humidity, wind speed and rainfall) and applying a series of activation functions to calculate output. Activation

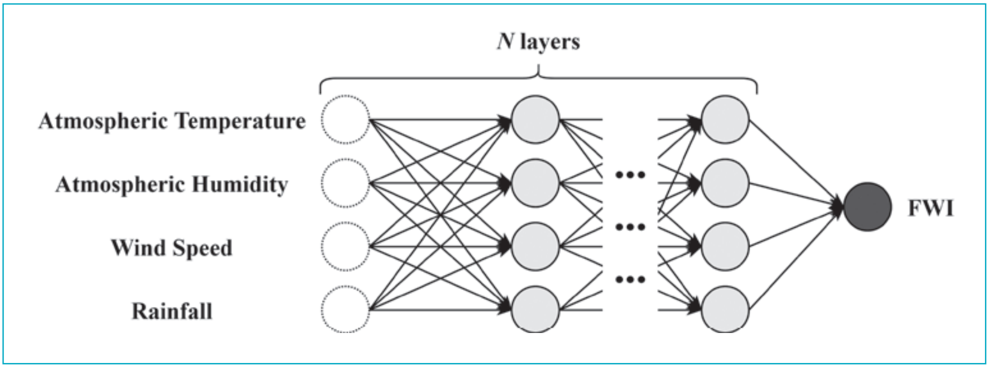

Figure 4: Four-input, (N-layer) neural network for predicting the Fire Weather Index (FWI) (where N is a neuron or node)

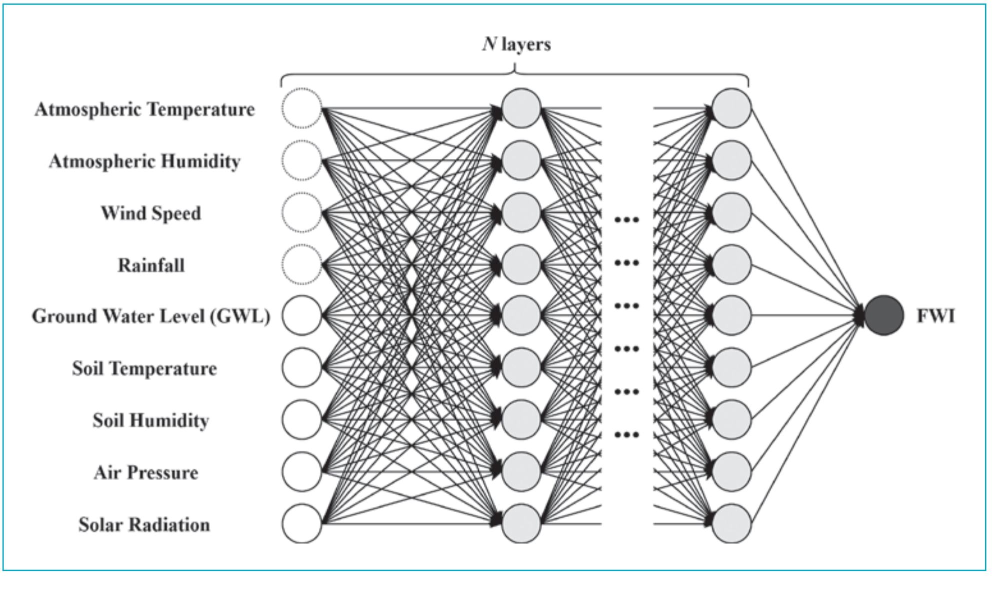

Figure 5: A multi-layer neural network structure with nine-input parameters

functions help the neural network to use important information while suppressing irrelevant data points. This process (input–>activation–>output) is repeated multiple times to minimize error and eventually produce a single output value – in this case, the FWI (Fire Weather Index).

However, atmospheric pressure, solar radiation and most importantly, soil parameters (groundwater level, soil temperature and soil humidity) need to be considered to accurately predict peatland fires in tropical areas. Therefore, this study employed a second multi-layer neural network that considered five further potential factors (nine in total) to predict the occurrence of peatland fires in Malaysia (Figure 5).

Results

The study found that while the existing Fire Weather Index (FWI) model calculated fire risk based on meteorological parameters such as temperature, humidity, rainfall and wind speed, it was indeed beneficial to consider additional parameters for a more comprehensive assessment of fire risk in peatlands.

1. The additional factors (solar radiation, soil temperature, soil humidity, pressure and groundwater level) can provide valuable insights into fire risk assessments in peatlands, as follows:
2. Solar radiation represents the amount of energy received from the sun and influences the drying potential of vegetation and fuel (vegetation available to a fire) moisture content. Higher solar radiation levels contribute to increased evaporation rates and can accelerate the drying of peatland vegetation.
3. Soil temperature plays a crucial role in determining fuel moisture content and the ignition potential of peatlands. Elevated soil temperatures can lead to drier conditions and more favourable conditions for ignition and fire spread.
4. Soil humidity, specifically moisture content in the upper layers of the soil, is a critical parameter for assessing fire risk. Dry soil conditions contribute to reduced moisture availability for vegetation, increasing the potential for fire ignition and spread.
5. Atmospheric pressure affects weather patterns and airflow, which can impact fire behaviour and fire spread. Changes in atmospheric pressure can influence wind patterns, the availability of oxygen for combustion and the overall stability of the atmosphere.

6. Groundwater level is a critical parameter for understanding the moisture conditions in peatlands. High groundwater levels indicate a higher availability of water for fire suppression and can serve as a natural firebreak. Monitoring groundwater levels helps identify areas with a lower fire risk due to the presence of sufficient moisture. Additionally, changes in groundwater level can affect peatland hydrology and contribute to variations in fire behaviour.

Lessons learned

1. The proposed method for predicting peatland forest fires in Malaysia demonstrates distinct advantages compared to the existing approaches (Hayasaka, *et al.*, 2022; Fitriany, *et al.*, 2021). It exhibits real-time capability and automation, setting it apart from traditional methods (Fernandes, 2019; Varela, *et al.*, 2019) that are reliant on manual data collection and analysis.
2. The utilization of machine learning algorithms (multi-layer neural networks) meant the data collected could be automatically processed and analysed in real time. This enabled the efficient and timely prediction of the Fire Weather Index (FWI).
3. The accuracy and reliability of the predictions were validated by comparing them with the actual values published by METMalaysia during the corresponding period.
4. The traditional 'slash-and-burn' land clearance method practiced by smallholder farmers, comes from the misconception that the burning process increases soil fertility. However, research shows that burning causes the greatest nutrient loss of any forest disturbance. Thus, community- and technology-based human activity monitoring can be included in the proposed IoT system. For example, high-resolution vision machines can be installed to monitor activities in peatland forests. This can be used in conjunction with social interventions, such as encouraging local involvement in fire prevention and control, to enhance communal responsibility.
5. The ASEAN Peatland Management Strategy (APMS) has reported that the high level of organic carbon in peatlands makes them significant carbon stores. Peatlands of the region are thought to store up to 5% of all carbon stored on the world's land surface. The clearance, drainage and burning of peatland is now leading to significant carbon emissions which are considered to have global significance. Hence, there is a need to study peatland soil degradation and its relationship to CO_2 emissions. Gas sensors can be installed in the IoT system and greenhouse gas emissions, such as carbon monoxide and methane, can be monitored more regularly.

Conclusion

Forest fires and transboundary haze have a devastating impact on local communities and people across the region. This case study presents a promising approach to predicting and preventing peatland forest fires using IoT technology and machine learning (Hayasaka, *et al.*, 2020), offering real-time capability and automation. It highlights the importance of considering a wide range of parameters, including soil conditions, in fire risk assessment. Given the transboundary nature of the issue, the research findings are particularly valuable for forest management and fire prevention authorities in the ASEAN region. In fact, since the start of this project, IoT systems have been replicated in peatland forests in Badas, Brunei and Jambi, Indonesia.

Therefore, this case study contains important guidance, significant for the future of fire prevention, and which contributes to the growing body of knowledge on leveraging technology to address environmental challenges.

Further information on this research is available at:

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Malaysia

The Urban Heat Island phenomenon and its impacts on vulnerable groups

Case study prepared by:
Mohd Norzikri Kamaruddin

Focus

The relationship between climate change and public health has become an increasingly important focus of global attention – particularly in cities where the majority of the world's population resides. Elevated temperatures in urban areas have been linked to a variety of heat-related health conditions ranging from mild symptoms such as heat cramps and heat exhaustion, to life-threatening conditions such as heat stroke. A pivotal issue in this nexus is the rise of urban heat islands (UHI) which have been shown to exacerbate heat-related illnesses. UHI occur in cities when natural land cover (trees and vegetation) is replaced with pavements and buildings, and other surfaces that absorb and retain heat.

With its tropical climate and high temperatures, Malaysia presents a compelling case study for heat-related illness. Also, the additional heat load that has occurred through rapid urbanization has made UHI an urgent public health issue in the country.

Project

The research focuses on a number of cities and towns across Malaysia which have differences in population density, built environment and green cover. This spatial diversity allows for a comprehensive understanding of the UHI phenomenon and its health impacts across various urban scales.

Further, the study aims to identify the most vulnerable groups in these areas. Preliminary findings suggest that children, the elderly and women – especially those in low-income households – are disproportionately affected by heat-related illnesses. By isolating other factors such as air pollution, physical activity and underlying health conditions, this investigation aims to quantify the extent to which UHI contributes to heat-related illnesses and provide a focused view of how urban planning can alleviate these health risks and allow for targeted intervention strategies that consider the specific needs of vulnerable groups.

Finally, the study aims to assess strategies that have been employed to mitigate the UHI effect in the past (e.g. green roofing, urban forests and reflective building materials). Previous approaches have often been fragmented or have not 'holistically' addressed the range of health risks presented by UHI. Some even had unintended adverse effects, such as increasing water consumption or displacing low-income communities. Understanding these shortcomings is crucial for developing more effective and sustainable solutions to combat the adverse health consequences of UHI.

The ultimate aim is to inform and influence urban planning policies that both mitigate UHI effects and safeguard public health.

Team

The project's multi-disciplinary team was at the heart of the systems-based approach which encompassed a diverse range of sectors and roles as follows:

1. **Academia**: Researchers from environmental science, urban planning and public health disciplines collaborated to develop the study's methodology and carry out the research. Their work served as the scientific backbone of the project, synthesizing existing data and conducting new empirical studies (collecting data) to explore the links between urban heat islands and public health in Malaysia (Jessani *et al.*, 2020).
2. **Public sector**: Local and national government agencies provided essential regulatory insights and access to publicly held data. They also played a critical role in ensuring the study's findings would be actionable from a policy standpoint (Khan *et al.*, 2023).
3. **Non-governmental organizations (NGO)**: NGOs in both the public health and environmental sustainability realms offered on-the-ground perspectives that helped shape the study and questionnaires. Their community networks were invaluable for participant recruitment and data gathering (Anbazhagan and Surekha, 2020).
4. **Private sector**: Companies in urban development and healthcare provided funding and technical expertise.

Methods and tools

The study employed a multi-faceted 'systems-based' approach. It looked at the structures and functions of health and climate systems, as well as how these systems operated and interacted with each other, to assess the impact of UHI on public health in Malaysian cities. A blend of qualitative and quantitative tools was used to derive comprehensive insights, as follows:

1. Environmental and health assessments were conducted that drew upon participatory mapping data, geospatial analysis and field surveys. These assessments were valuable in identifying 'hot spots' where urban heat and public health concerns overlapped.

2. Mathematical models were used to simulate the impact of temperature rise on specific health outcomes. The models were calibrated using both historical and current climatic and health data to ensure a precise understanding of the climate-health relationship in general, and a robust understanding of the health risks associated with UHI in particular.
3. Multi-criteria decision analyses were performed to evaluate various policy options. These statistical analyses consider multiple objectives such as public health improvement, cost-effectiveness and public acceptance. Interventions are rated to help guide policy makers when prioritizing strategies.

The study also included a thorough cost analysis that compared the multi-faceted, systems-based approach (used in the study) against existing business-as-usual strategies.

End-user engagement

Several strategies were employed throughout the research process to ensure the effective engagement of targeted end-users (policy makers, urban planne[a]rs and health agencies):

1. Initial consultations to ascertain each group's priorities and limitations;
2. Dissemination of preliminary findings to refine the study as it moved forward;
3. Targeted briefings at the end of the study to disseminate key findings and proposed action steps.

Results and products

The study found that initial setup costs for a systems-based approach were higher than business-as-usual approaches. However, the long-term benefits – in terms of improved public health outcomes, resource allocation and policy coordination – far outweighed the costs. For example, the systems-based approach helped identify highly effective, low-cost interventions such as green urban planning, which would not only mitigate heat but also promote public health (Sachs *et al.*, 2019). In contrast, business-as-usual strategies (e.g. the use of air conditioning) contributed to higher electricity consumption and increased greenhouse gas emissions, leading to greater long-term health risks and costs. Therefore, by adopting a comprehensive systems-based approach, the project achieved better health outcomes and policy synergies at a relatively marginal additional cost than business-as-usual.

The systems-based approach also proved to be instrumental in understanding the complex interplay between climate and health, giving it a clear edge over traditional methods that typically tackle these issues in isolation. By employing a multi-disciplinary team and integrating a range of methodologies and tools, the study could offer a more nuanced understanding of the problem. This resulted in more effective, holistic solutions and confirmed the findings of similar public health research that advocates for integrated systems-based approaches (Lacetera, 2019).

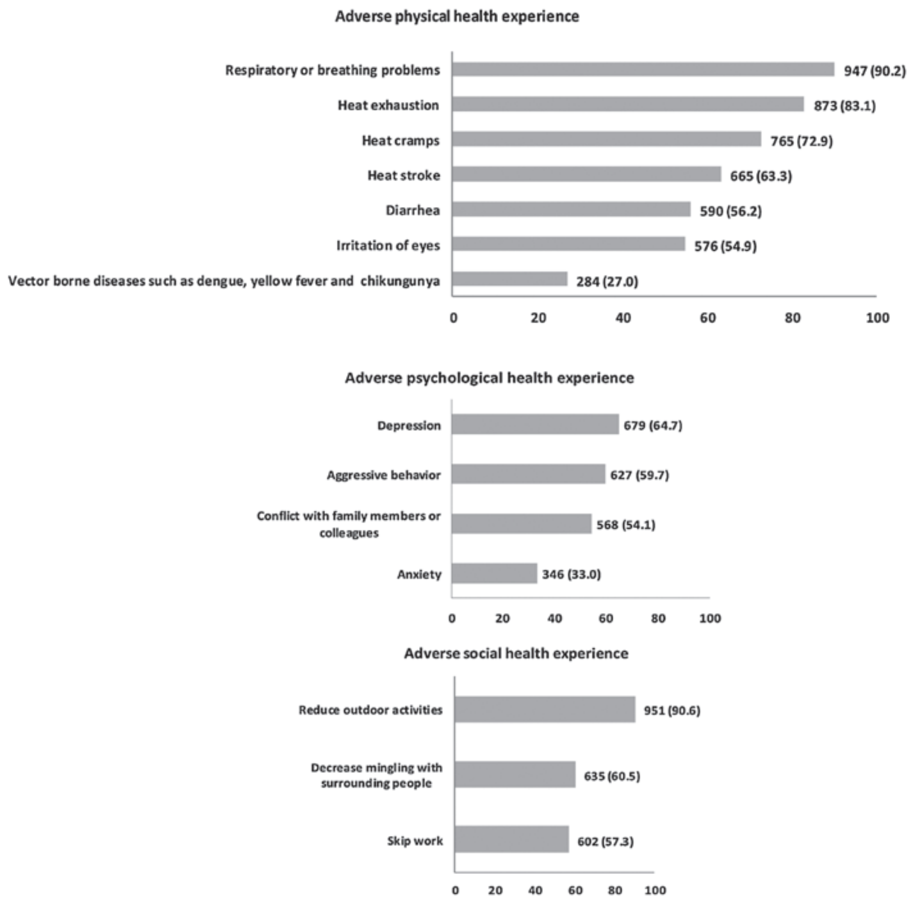

Figure 1: Physical, psychological and social health impacts associated to UHI effects (Wong et al., 2017). Figures refer to numbers of survey respondents (equivalent percentage)

Results show the physical, psychological and social health impacts associated with UHI (Figure 1), as follows:

1. Physical health: respiratory problems were experienced by more than 90% of respondents while heat stroke was reported by more than 63% of respondents. These results underscore the significant strain UHI places on physical health and emphasizes the need for improved urban planning to mitigate heat effects.
2. Psychological health: the prevalence of depression (almost 65%) and anxiety (33%) among respondents reflects the stress and discomfort caused by continuous exposure to elevated temperatures.
3. Social health: heat caused 90.5% of respondents to reduce their outdoor activities. Also, more than 57% of people had occasionally skipped work due to heat. These are clear indications of how UHI can impact social interactions and physical health and affect economic productivity.

Each of these variables not only indicates the direct effects of UHI but also outlines broader socioeconomic challenges. These results emphasize the need for integrated approaches to urban planning that consider the complex interplay between climate and health. This data strongly supports the necessity for multi-disciplinary strategies to effectively address and mitigate UHI impacts.

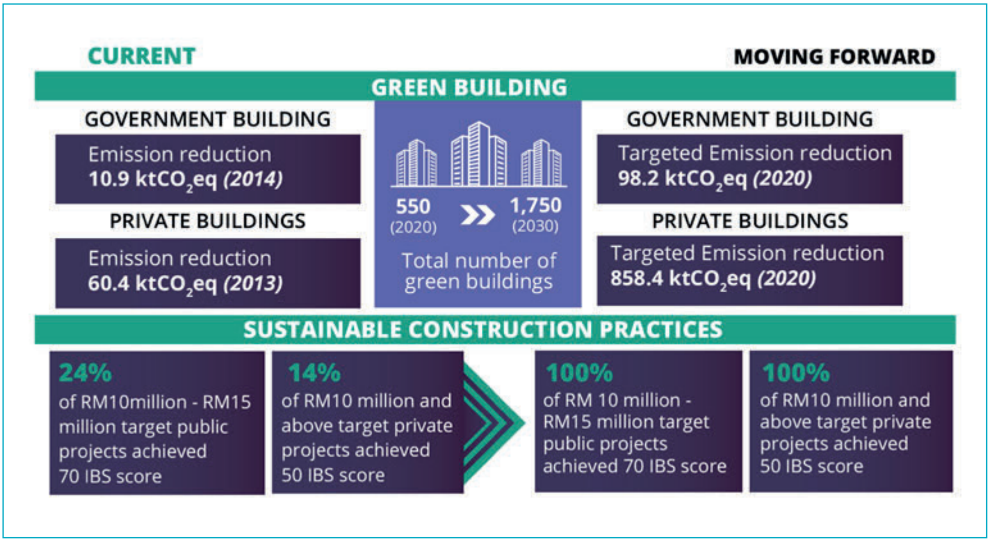

Figure 2: Malaysia Green Building Master Plan from: **https://www.pmo.gov.my/wp-content/uploads/2019/07/Green-Technology-Master-Plan-Malaysia-2017-2030.pdf**

Impact of the research on policy

A significant outcome of this research was the formulation of the new Malaysia Green Building Master Plan (Figure 2) which outlines the country's strategy for promoting sustainable development in the building sector from 2017 to 2030. The plan includes guidelines and targets for reducing energy consumption, increasing the use of renewable energy and implementing green building practices. It emphasizes the importance of creating environmentally friendly and energy-efficient buildings to mitigate the effects of climate change and improve public health.

End-users

The primary end-users of this study are policy makers, urban planners and health agencies. Based on the study's findings, it is these groups that have the authority (and potential) to effect significant change as follows:

1. Policy makers can use the evidence-based recommendations to draft or modify existing policies aimed at reducing heat-related health issues;
2. Urban planners can incorporate these guidelines into their designs for more climate-resilient cities;
3. Health agencies can formulate and execute public health interventions based on identified geographic and demographic risks (Ramirez-Rubio *et al.*, 2019).

The results of this study are already being disseminated via a multi-sectoral approach involving government departments, academic institutions and civil society organizations. Health agencies, which were particularly involved in interpreting the data around vulnerable populations, are currently working on creating targeted health interventions for vulnerable groups. Urban planners and policy makers are also involved in pilot programmes designed to implement some of the study's recommendations in selected urban areas.

Lessons learned

Unintended consequences and trade-offs

The transition to green building materials might initially be more expensive and potentially lead to increased housing costs. Additionally, analyses revealed that while green spaces could mitigate heat, they may also attract vectors for infectious diseases if they were not well-maintained (Patz and Frumkin, 2016).

Systems-based improvement

By considering UHI from a systems-based perspective, the project was more effective in identifying high-impact, low-cost solutions. It was also better suited to identifying and avoiding pitfalls related to unintended consequences or trade-offs.

Enabling factors

Existing laws around environmental conservation and public health meant the study's recommendations could be integrated more easily into urban planning policies. Politically, the timing of the study aligned with policy cycles and governmental interest in public health and environmental conservation.

Challenges and solutions

Bureaucratic inertia often slowed down the pace of policy adoption. Financial limitations were another significant barrier, since the study recommended infrastructural changes that required substantial investment.

Understanding these lessons is essential for scaling the impact of this study and others like it in the future. Recognizing these enablers and obstacles in the science-policy interface allows future research to be designed in a way that is inherently more impactful and relevant.

Conclusion

This study illuminated the significant impact of urbanization on heat-related illnesses in Malaysia, particularly through the mechanism of the Urban Heat Island effect. A multi-disciplinary team including stakeholders from academia, the public sector, NGOs and the private sector, collaboratively worked on this research to ensure a holistic approach. A systems-based methodology not only quantified the specific climate-health relationship but also provided a cost-effective solution compared to business-as-usual approaches.

By actively engaging critical end-users, the study ensured that its results are not just theoretically robust but practically useful, thereby increasing its potential for real-world impact and policy change. The next steps involve refining policy recommendations and executing a pilot program to validate the study's findings. By directly informing urban planning policies, heat-related health risks can be substantially mitigated, paving the way to more sustainable and healthier urban environments.

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South Africa

Using machine learning to map bioclimatic zones and crop yields in water-scarce conditions

Case study prepared by:

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Focus

Sub-Saharan Africa has severe dry spells associated with the annual Southern Oscillation, including the El Niño-Southern Oscillation (ENSO), causing worldwide precipitation and temperature anomalies. Since 1900, 80% of severe droughts in the region have been connected to El Niño episodes and a record-breaking ENSO-induced drought in 2015/2016 affected agricultural, water, food and nutrition security (Yan *et al.*, 2023)we investigated their interactive effects on tropical net ecosystem productivity (NEP.

South Africa is characterized by a mild, temperate climate, where only a small proportion of land (10.3%) is considered arable land, for agriculture. It is a water-scarce country with 61% of landmass receiving less than the minimum rainfall to support successful, rainfed farming. Evidence shows climate change has increased drought frequency and severity in the country. Drought, therefore, is a significant threat to crop production, water resources and, more importantly, food and nutrition security.

Mapping drought zones

Droughts can be meteorological, agricultural, hydrological or socioeconomic. Agricultural drought includes complicated soil water stress, vegetation growth and precipitation loss. Mapping drought-prone zones and predicting drought severity are crucial to reducing the impacts of shocks related to water scarcity. But given there are four types of drought, and given there are 150 available drought indices tracking multiple variables, it has proved difficult to map drought risk zones accurately and effectively. Standard indices can be used, but they require additional observations to compute weights, and although data mining strategies solve some limitations, these also have constraints.

Machine learning models can mitigate for these issues and be used to develop accurate drought data. Therefore, this study integrates existing indices, machine learning and data mining strategies in its model generation.

Matching under-utilized crop species

Sustainable farming practices can alleviate some of the impacts of drought. These practices include utilizing crops that successfully balance yield with environmental concerns, human health and general well-being. Recent research has focused on planting neglected and under-utilized crop species (NUS). These are typically wild and/or cultivated species that were once favoured, but have since been overlooked (Bvenura and Afolayan, 2015; Chivenge *et al.*, 2015)

NUS have lower yields, but they are nutritious, inexpensive and readily accessible. Most importantly, they are resistant to a variety of stresses (e.g. heat, salinity, drought), and thrive with minimal attention and fewer pesticides or fertilizers than commercial crops (Akinola *et al.*, 2020; Mabhaudhi *et al.*, 2019; Mohd Nizar *et al.*, 2021).

It is important to grow these species without affecting existing major crops, which are typically grown in arable and productive lands. Identifying drought-prone areas is also important since NUS can thrive in marginal lands – as compared to maize and wheat which require larger areas and more intensive farming.

This case study, therefore, uses an integrated 'hybrid' model that draws on existing indices and employs machine learning to identify bioclimatic zones with high rainfall variability in water-scarce conditions (drought risk zones). The resultant data is then used to match NUS with the selected, appropriate zones.

Team

The team included researchers at the University of KwaZulu-Natal, Pietermaritzburg, South Africa; the International Maize and Wheat Improvement Centre, Harare, Zimbabwe; the University of the Western Cape, Bellville, South Africa; the Water Research Commission of South Africa; the Council for Scientific and Industrial Research, Pretoria, South Africa; and the International Water Management Institute, Accra, Ghana.

Methods and models

The study used the Vegetation Drought Response Index (VegDRI); a 'hybrid' index that gleans data from existing climate tracking indices with regards rainfall (the Standardized Precipitation Index (SPI)), temperature (the Temperature Condition Index (TCI)), and vegetation (the Vegetation Condition Index (VCI)), to show the bioclimatic zones in South Africa that have both high rainfall variability and little water.

Rigorous machine learning techniques were used in the development of VegDRI. First, historical satellite climate data (1981–2019) was integrated with land use and cover maps of South Africa to generate five scales of drought, ranging from 'very severe' to 'no drought'. After that, a machine learning algorithm, the Classification and Regression Tree (CART) (Breiman, 2001) was used to produce a new dataset and

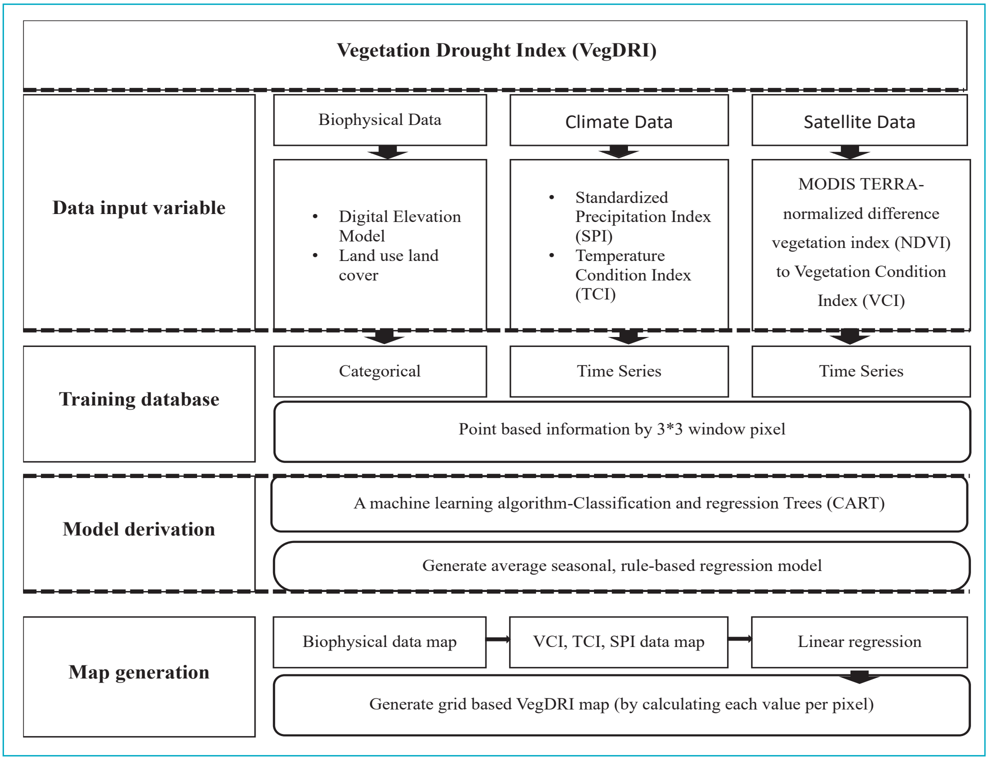

Figure 1: Flow chart of machine learning steps involved in generating the Vegetation Drought Response Index (VegDRI)

create map graphics. 80% of that resultant dataset was used for training and 20% for validation of the training model (a typical split to ensure accuracy in machine learning models). The dataset was then randomly sampled and split into calibration and validation datasets. This procedure was implemented 100 times to evaluate the stability of the model. The methodology is visually represented in Figure 1.

Drought index evaluation

Average sorghum yields obtained at the district level from official sources, were used to validate the results obtained from the mapping exercise. Farming households in the district were randomly selected as project focus areas. VegDRI, VCI, TCI, and SPI were then correlated against drought-tolerant crop yield data. The predictive accuracy of the drought risk maps was then computed from a pixel-by-pixel comparison using weighted Kappa statistics. The Kappa statistic is used to test how far the data collected in a given study represents the variables measured (Heikkinen *et al.*, 2006) In this case it was used to measure agreements between dry zones and sorghum-growing areas.

Results

Precipitation evaluation

Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) precipitation data was highly correlated with observed, in-situ weather data across all weather stations used in South Africa. Based on these results, CHIRPS datasets can be used confidently for agricultural drought analysis.

VegDRI

The VegDRI map (Figure 2) shows the locations and variations of drought intensity in South Africa. The five scales of intensity were classified as very severe drought (16%), severe drought (34%), moderate drought (38%), slight drought (11%) and no

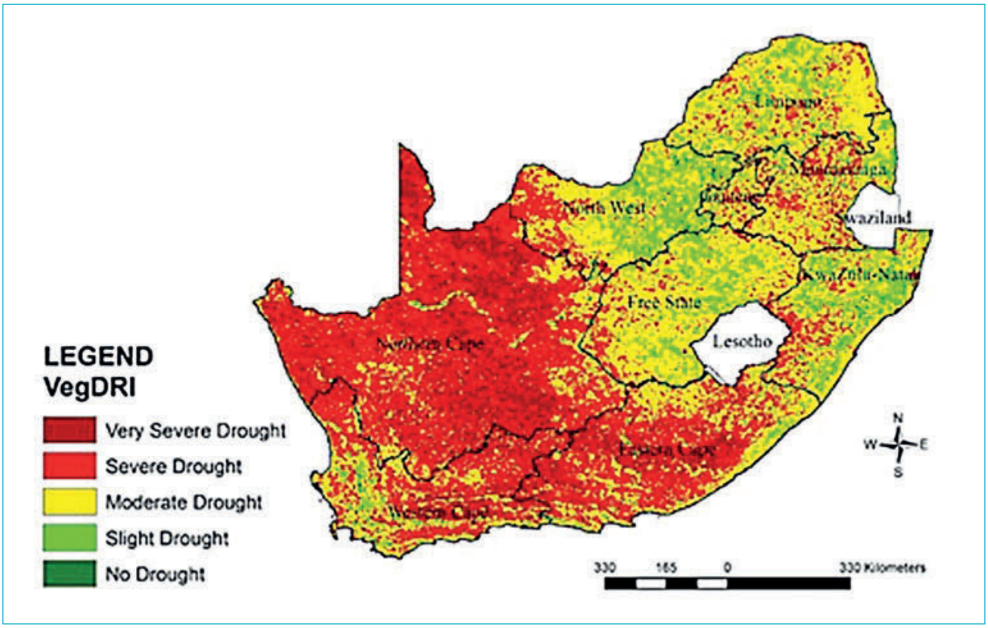

Figure 2: Average seasonal vegetation drought response index

drought (1% of South African agricultural land). Drought was very severe over the Northern Cape and Eastern Cape provinces, indicating acute water scarcity in the region. Moderate to no drought conditions were reported from the central province to the eastern provinces.

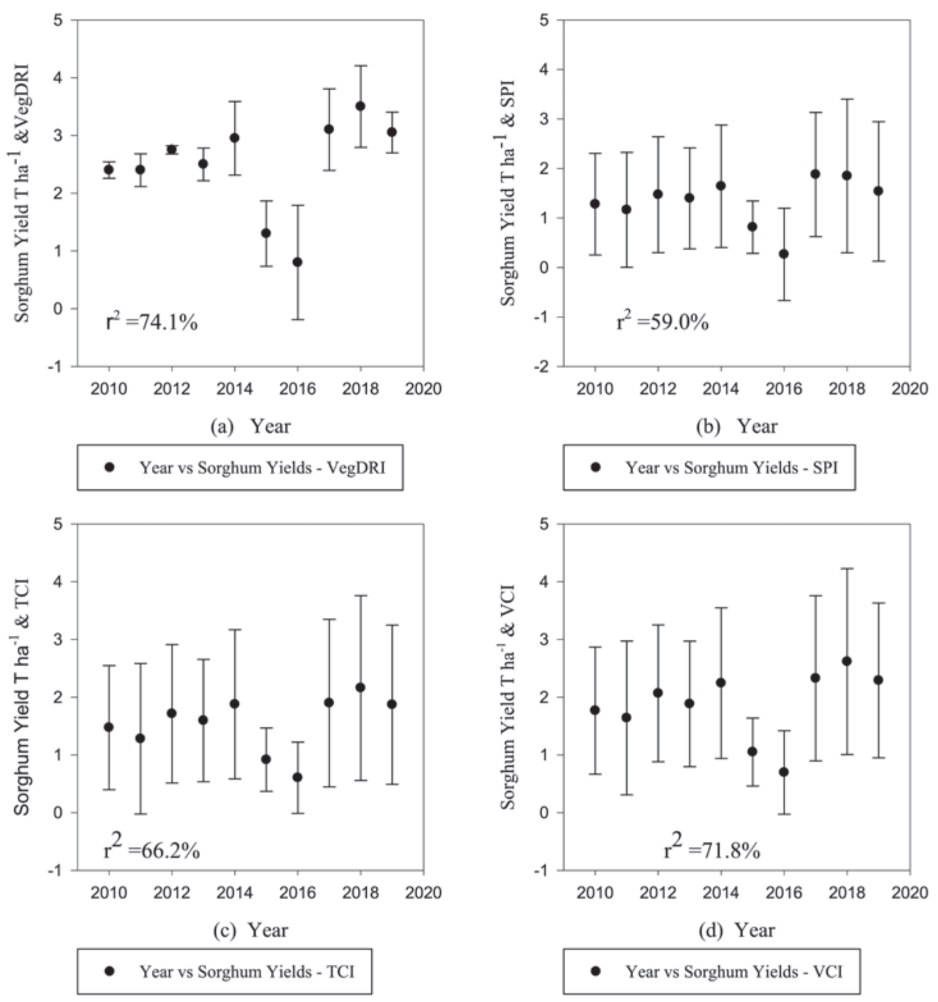

Figure 3: Showing the correlation between district sorghum yields and the drought indices used in the study for the period 2010 to 2019: (a) Vegetation Drought Response Index (VegDRI), (b) Standardized precipitation Index (SPI), (c) Temperature Condition Index (TCI), and (d) Vegetation Condition Index (VCI)

Drought index evaluation

Figure 3 illustrates the performance of the four indices (VegDRI, SPI, VCI, and TCI) when predicting sorghum yields using data from 2010 to 2019. VegDRI proved most successful at predicting yields (74.1% accuracy). All the indices, however, responded accurately to low rainfall in the 2015/16 agricultural season, which recorded the lowest sorghum yield in the research dataset. Overall, the three indices VegDRI, VCI, and TCI, performed systematically better than the precipitation-based SPI.

Figure 4 shows the accuracy of VegDRI to identify sorghum yields compared to VCI, TCI, and SPI using the Kappa statistic. Confidence intervals (±) indicate uncertainty in reported measurements, and in this case, confidence is 95%. The highest Kappa coefficients were observed between VegDRI and VCI, followed by TCI, meaning these indices were better at identifying yields than SPI, which had the lowest agreement. Again, the highest Kappa coefficients were observed in the 2015 agricultural season, which had the lowest rainfall, and which recorded the lowest sorghum yield.

The results suggest that VegDRI could map bioclimatic zones that are under stress and areas of high rainfall variability in South Africa. By integrating traditional drought

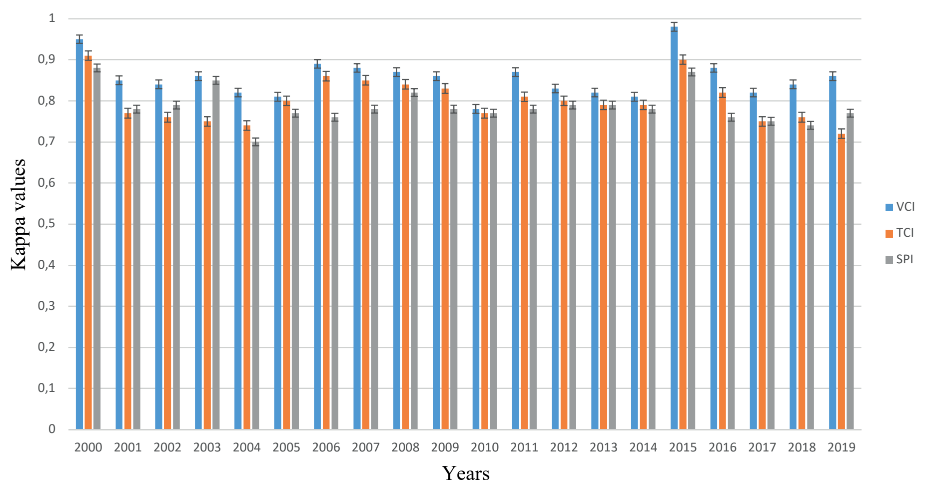

Figure 4: Kappa statistic compares the accuracy with which VegDRI can predict sorghum yields (2000 to 2019) versus the accuracy of VCI, TCI and SPI. Error bars (±) indicate 95% confidence intervals, meaning the results have 95% certainty of accuracy

indicators (VCI, TCI and SPI), the South Africa VegDRI map can select crops within bioclimatic zones, justify disaster management actions, identify livestock production risk zones and assess fire risk zones.

End-users

The intended end-users of this study are farmers, extension agronomists, researchers, non-governmental organizations (NGOs) and private sector companies, such as insurance companies and banks, who all need to understand and develop drought resilience strategies. Similarly, local and national decisionmakers, who need to improve drought response and mitigation.

Lessons learned

1. Water-stressed bioclimatic (drought risk) zones must be identified to inform crop management strategies and thus improve food security in South Africa's marginal lands;
2. The most effective index for identifying agricultural drought risk zones is VegDRI, although a combination of the VCI, TCI and SPI indices can detect drought risk, effectively;
3. Of the four indices analysed, three of them predicted sorghum yields with varying levels of accuracy: VegDRI (74%), VCI (72%), TCI (66%). SPI was the least successful at yield prediction at 59% accuracy (Figure 4);
4. Overall, VegDRI-based agricultural drought assessment is better at capturing water-stress, drought risk and yields.

Current maps can help with the planning and management of sustainable strategies in water-stressed and high rainfall areas. But drought impacts vary as much as their causes, and so validating and operationalising bioclimatic zone maps is crucial. Therefore, this study shows that the VegDRI hybrid index could be used to enhance agricultural support systems such as drought risk maps for early warning systems, crop yield forecasting models and water resource management tools.

Limitations

The study used biophysical factors to assess water-stressed bioclimatic zones that have high rainfall variability. These physical factors are inter-connected with the socioeconomic context of drought (i.e. those affected and their specific vulnerabilities).

In future, innovative methods are needed to integrate and model these socioeconomic factors.

Implications of the drought risk maps for crop production

Drought zone mapping is essential to drought management and integrated climate risk management. It helps policy makers and agriculturists plan and recommend sustainable agriculture production by identifying drought-prone areas. This aligns with the R4 Rural Resilience Initiative framework (2011), which helps vulnerable farmers adapt to climate risks by adopting sustainable intensification and climate-smart strategies.

Conclusion

The hybrid drought index, VegDRI, was developed using machine learning to characterize bioclimatic zones in South Africa with high rainfall variability and water scarcity. The resulting VegDRI outperformed other drought indices in identifying water-stressed zones and was verified using normalized sorghum crop yield data. A correlation test with the normalized sorghum crop yield data proved the index's applicability. VegDRI can be extended to more sub-Saharan African regions using climate, satellite and biophysical data. Future research could include hydrological, soil water, evapotranspiration and socioeconomic factors to improve drought management activities. This research suggests using VegDRI in agricultural decision support systems for crop yield forecasting, drought risk mapping and water resource management.

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South Africa

Addressing heat-health threats among women, infants and children in primary healthcare settings

Case study prepared by:
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Focus

Extreme heat and heatwaves are having physiological and psychological impacts on people's health in South Africa. Extreme heat affects productivity and is associated with morbidity and mortality, especially among vulnerable groups (Kapwata et al., 2022).

Until recently, South Africa has not had any heat-health guidelines. Neither has it had any education materials that healthcare professionals and practitioners can use to help raise awareness about the threats of heat to health and wellbeing. Filling these gaps is central to this research, which aims to protect communities and prevent adverse heat-health impacts in South Africa.

The focus of this case study is to find national and local solutions that can help strengthen health systems, especially in healthcare settings and other high-risk places where mothers and children may be exposed to high temperatures. A systemic, multi-pronged and multi-stakeholder approach was adopted by the local, provincial and national team (outlined below) to undertake research, co-create a risk tool and develop National Heat Health Action Guidelines.

Team

The team comprised Climate Change and Health Research Programme researchers at the South African Medical Research Council, the National Department of Health (NDoH): Environmental Health Directorate, the South African Weather Service and the National Department of Forestry, Fisheries and the Environment (DFFE). Non-governmental organizations (NGOs) were also involved including groundWork (a non-profit environmental justice organisation working primarily in South Africa), the Centre for Environmental Rights, the World Health Organization (WHO), the United Nations Environment Programme (UNEP) and the United Nations International Children's Emergency Fund (UNICEF). Other stakeholders (e.g. universities and local and provincial municipalities), collaborated throughout the project timeframe.

Initially, the team worked in an uncoordinated fashion but, in 2023, the National Climate Change and Health Steering Committee (NCCHSC) was inaugurated, thereby creating a formal body to implement and oversee the National Climate Change and Health Adaptation Plan, National Heat Health Action Guidelines and other climate change and health activities within the National Departments of Health and Environment. The NCCHSC, naturally, became the custodian of the work set out in this case study.

Methods

The methods adopted in the case study involved the following steps (expanded on, below):

1. Research to understand temperatures and heat-health risks in primary healthcare facilities in rural areas;
2. Co-creation of a heat-health risk vulnerability assessment tool (called HEAT) for small towns in South Africa (Wright et al., 2023);
3. Drafting and publishing the National Heat Health Action Guidelines (NDOH, 2022).

Temperature measurements in primary healthcare facilities

Temperature loggers, called iButtons, were installed in eight clinics in Giyani, Limpopo Province, to measure the indoor temperatures of waiting rooms in eight rural, primary healthcare facilities. Temperatures in each setting were measured 24-hours a day from December 2015 to May 2016. The data retrieved was analysed for trends to assess potential health risks to mothers and infants.

HEAT tool development

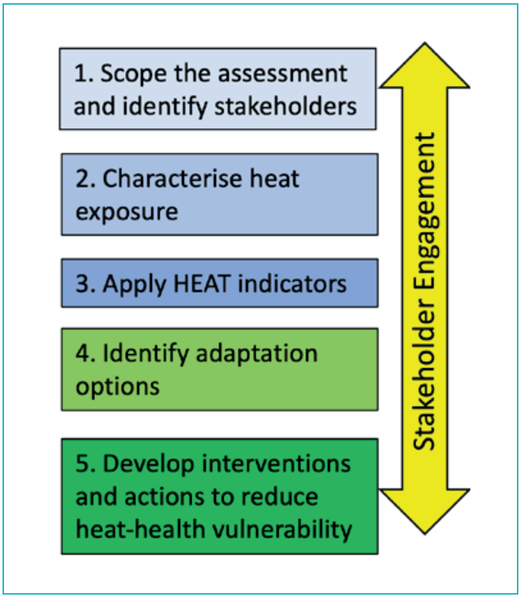
Results from temperature logging informed the development of a Healthy Environment Assessment Tool (HEAT) to assess heat-health risks in local communities. HEAT was co-developed with stakeholders, practitioners and professionals from the Rustenburg Local Municipality (RLM) – a setting in which heat had already been identified as a risk (Scovronick et al., 2018).

To ensure inclusive and robust stakeholder engagement, a five-step framework was applied to the HEAT tool development process (Figure 1). Feedback from this framework was used to:

1. Identify vulnerable groups and settings in the RLM;
2. Consider the opportunities and barriers for interventions;
3. Conceptualize a heat-health vulnerability assessment tool for a heat-resilient town.

Using the HEAT tool, areas were evaluated for their heat-resilience and vulnerability at the ward level (45 wards altogether). Indicators included population, poverty, education, access to medical facilities, sanitation, public transport, recreation and community centres and green spaces.

Figure 1: Five-step stakeholder engagement framework



Results

Clinic temperature and health risks for patients

Inside the clinics, mean monthly temperature measurements were warmer during summer months (December to February) and cooler during autumn months (March to May) (Wright et al., 2017). The highest mean outdoor temperature (approximately 32 degrees Celsius) was recorded in February 2016. In some clinics, however, maximum daily indoor temperatures exceeded 38 degrees Celsius. Overall results showed temperatures in clinic waiting rooms were higher than outdoor temperatures by an average of between two and four degrees Celsius.

When researchers incorporated the relative humidity readings made in the clinics, the results implied that 'real-feel' apparent temperatures were more than four degrees Celsius higher than actual measured indoor temperatures. This suggests people may have experienced a feeling of 'stuffiness' and discomfort in the waiting room areas.

Overall, during typical clinic operational hours, mean apparent temperatures reached levels associated with heat warning categories of 'caution' and 'extreme caution'. These two risk categories are associated with fatigue and heat stroke (caution) and heat cramps and heat exhaustion (extreme caution). It is likely that patients in these waiting rooms experienced these heat symptoms during the measurement campaign, but whether these conditions are a barrier to mothers and patients visiting the facilities, is unclear.

HEAT tool implementation and findings

Throughout the stakeholder engagement exercise, and with application of the five-step conceptual framework (described above), indicators for the HEAT tool were identified to assess heat and health vulnerability and resilience. Traffic-light colours were used to signify critical risk (red), medium-high risk (yellow) and low risk (green).

Out of 45 wards in the Bojanala District Municipality, three were identified as critical risk (red), 28 as medium-high risk (yellow) and six as low risk (green) in relation to heat-health vulnerability. Short-term solutions and actions to improve community heat-health resilience were proposed by participants. These included: increased shade at bus ranks, the installation of water fountains in parks and sports fields, heat protection uniforms for schoolchildren, and green building designs in all new buildings and dwellings (among many others).

Products

In addition to the HEAT tool, researchers produced the first National Heat Health Action Guidelines for South Africa. The aim of the guidelines is to assist local health providers to reduce the burden of disease from heat exposure. The HEAT tool itself, can be used in the short-term to help policy makers identify interventions to prevent adverse heat-health impacts, especially among vulnerable groups such as women, infants and children.

Additionally, the team co-developed posters and flyers (Figures 2a-b and 3) as well as a video for children (YouTube: https://youtu.be/FPj75DZKIRA), that described actions people could take to keep cool and reduce heat risk. These included drinking more water, staying in the shade, wearing a hat, using an umbrella and avoiding heavy physical exercise during the hottest times of the day.

In addition to the preparation and dissemination of these awareness materials, the study incorporated a visioning exercise (Figure 4) to promote physical changes to primary healthcare facilities that would reduce the impact of heat. Wide roof awnings, planting trees for shade, benches placed in the shade and access to clean drinking water were all proposed and illustrated in the exercise.

a)

b)

Figure 2 a-b: Two posters for primary school children designed to a) illustrate the best ways to protect yourself from extreme heat and b) have fun and play a game while learning about safe behaviours during hot weather

Figure 3: Flyer illustrating what to do to keep infants and children safe during periods of extreme heat

These products were co-developed with leading health and education stakeholders which led to their approval and uptake by a wide audience. For example, in February 2023, during a period of extreme heat, around 1,000 flyers and posters were dis-

Figure 4: Results of a visioning exercise to promote potential heat-health actions for primary healthcare facilities

tributed to municipalities across South Africa by the National Department of Health (NDoH).

End-users

At the heart of this research is the health of the South African people through an improved awareness of heat risks in local communities. The end-users for the research, therefore, are decision makers and professionals who can expand on, implement and deliver the products and tools that have arisen from this study. These are:

1. Researchers: Temperature measurements made in primary healthcare facilities helped inform researchers of the additional work required to identify vulnerable settings in relation to maternal and child health.
2. Policy makers: Temperature measurements also prompted policy writers to include a special section in the National Heat Health Action Guidelines on the specific interventions in antenatal and childbirth facilities in relation to heat exposure and extreme heat events. These measurements helped inform the interventions stated in the second National Climate Change and Health Adaptation Plan.
3. Officials, practitioners and professionals: The HEAT tool was co-created by its intended end-users in the Rustenburg Local Municipality and the Bojanala District Municipality. These stakeholders implemented the tool and found it easy to use and effective in identifying simple interventions to reduce heat-health risks. Since then, the National Department of Health has promoted the use of the HEAT tool in all 52 District Municipalities in South Africa.

Finally, the National Heat Health Action Guidelines were co-developed by members of the NCCHSC (described in the team section). Their intended audience is broad, but targets officials and practitioners in health and environmental health to prevent adverse heat-health impacts.

Limitations

A key challenge was the lack of funding for training sessions in different provinces. The proposed solution to reduce costs was to transport core team members to on-site venues and have presenters join and present their training slides online. However, this was not always possible due to power outages and technical issues, and so slides were shared via email (although this was less effective than face-to-face training).

Lessons learned

Collaboration and political will

Successful policy implementation around climate change and health (especially heat exposure) requires an effective approach, a positive attitude, strong commitment, tangible and visible political and administrative will, and high cooperative collaboration between all stakeholders and role players.

Training

Training sessions are essential to raise awareness and understanding of the National Heat Health Action Guidelines. Additional capacity for training will be required in the future.

For the next steps in this project, the research team recommends an assessment of the effectiveness and impact of both the National Heat Health Action Guidelines and the HEAT tool on healthcare facilities and vulnerable communities. Uptake can be evaluated using three measures:

1. Engagement with healthcare staff: healthcare professionals at all eight clinics were engaged with the research team, and heat-health risks and actions to mitigate them were discussed.
2. Distribution of newly made and revamped materials: more than 5,000 posters and flyers were distributed nationally in 2024.
3. Uptake of the guidelines and materials by the National Department of Health (NDoH): in the second part of 2023, over 2,500 posters and flyers were collected and circulated by the NDoH to all nine provinces in South Africa.

However, more work is required to identify in-depth metrics to evaluate the effectiveness of the guidelines and materials.

Conclusion

The research, tools and products developed in this study are applicable to low- and middle-income countries facing the challenges of extreme heat and health risks as a result of climate change. Effective implementation was also boosted by the political will shown by the establishment of the NCCHSC in 2023 that coordinated actions among different agencies. However, co-development with health and education stakeholders is key to their approval and uptake by a wide audience. Ultimately, it is hoped that these findings will help inform the development of locally appropriate tools and products to prevent heat-health impacts among vulnerable groups – especially women, infants and children.

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Thailand

The link between mental health and ecosystem health in Indigenous farming communities

Case study prepared by:

Victoria Pratt

Researchers:

Siwakorn Odochao, Samrawit Gougsa, Jennifer Katanyoutanant, Colin Luoma, Victoria Pratt and Romit Raj

Focus

Climate change is altering rainfall patterns in Thailand leading to reduced crop yields and affecting food security and nutrition for Indigenous farmers. Additionally, amidst the global climate crisis, the Thai government has implemented conservation policies that outlaw certain Indigenous agricultural practices, which has led to increased stress and mental health challenges for the communities affected.

The Pgak'yau are an Indigenous community in Thailand, many of whom have been displaced from their traditional lands and practices. Pgak'yau people live in small villages in Thailand's north-western highlands and are members of the Karen community who represent the country's largest minority (approximately one million people). For centuries, the Pgak'yau have used a shifting cultivation or rotational farming method which has now been targeted by Thai conservation policies. The method involves farming seven plots over seven years, leaving one plot fallow each year for the soil and the forest to regenerate (Figure 1). A controlled burn forms part of the soil preparation process, before the forest is left to regrow. There are widespread issues with large-scale agricultural burning in Thailand (air pollution, wildfire outbreaks), caused by monocropping and industrial scale processes with which the Pgak'yau's subsistence-based practice has been wrongly conflated. Consequently, the

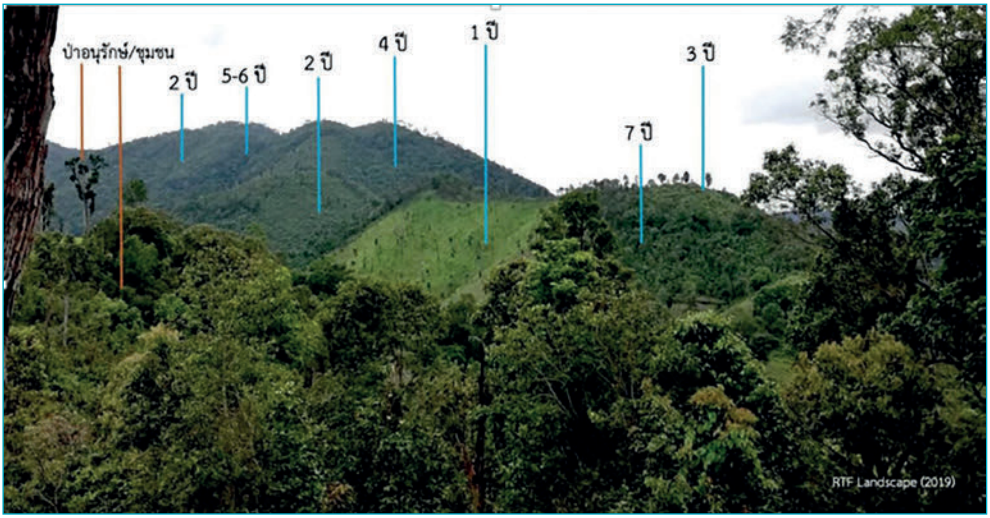

Figure 1: Rotational farming plots over seven years showing tree growth and regeneration of the forest (Credit: Thanagorn Atpradit of the Northern Development Foundation)

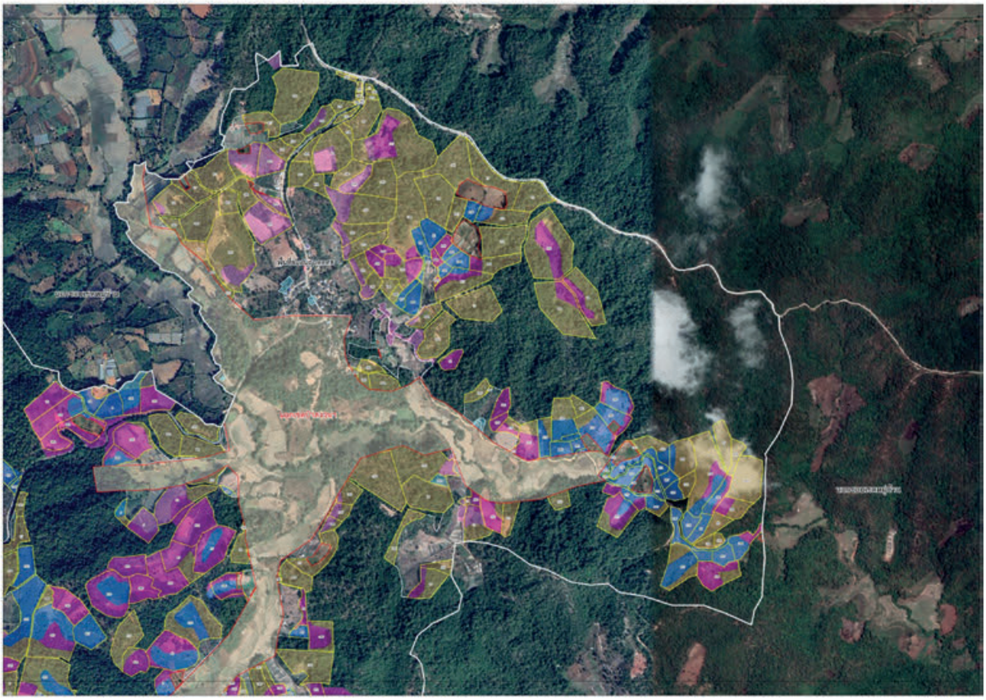

Figure 2: Community workshop, mapping activities to validate land claims

community has been portrayed negatively in the mainstream Thai media (Mostafanezhad and Evrard, 2020).

Rotational farming plots form an important cultural, spiritual and economic anchor for the community. The Pgak'yau have farmed this land for generations, but many do not hold official land titles and their plots are being reclassified through a rezoning process. In Lampang, for instance, Karen land is being reclassified to become part of the Tham Pha Thai National Park and Indigenous communities are growing increasingly concerned that further carbon-based conservation initiatives will serve as a pretext for additional rezoning of ancestral land.

In response, the community has mapped their rotational plots (Figures 2 and 3) in an attempt to validate ancestral land claims. However, despite Thailand adopting the United Nations Declaration on the Rights of Indigenous Peoples (2007), the government does not officially recognize the existence of Indigenous Peoples and, by extension, the Pgak'yau people's rights to their land.

Figure 3: Pgak'yau community map of plots, made to support claims to ancestral land

Project

The objective of this research is to explore the deep interconnections of mental health and ecosystem health in communities experiencing the impacts of climate change. The project site is Ban Nong Tao – a Pgak'yau community in Mae Wang District, near Chiang Mai in northern Thailand. The village is home to 120 families who practice rotational farming to sustainably grow and manage forest resources. Farming knowledge is transferred orally through music, stories and customs or through practice on the land.

The project is led by a team from Land Body Ecologies, a transdisciplinary network of researchers, artists and activists. The team uses qualitative methods such as context immersion (whereby researchers immerse themselves in the communities they study), and arts-based data collection techniques.

Team

Research and engagement in Thailand were led by Siwakorn Odochao, an Indigenous community leader, and Jennifer Katanyoutanat, a producer, artist and researcher working at the nexus of the environment and arts. Land Body Ecologies provided additional support for the duration of the project timeframe.

Methods

At the heart of the method was gathering data that focused on the Pgak'yau community's stories and cultural expressions. To achieve this, the team used a mixture of observation, interviews and ethnographic documentation of cultural practices and artefacts. Cultural probes (i.e. prompts and instructions) were also used to elicit artefacts such as stories and songs as well as people's thoughts and feelings. The team involved civil society actors in this process (artists and activists). This approach was designed to ensure Pgak'yau voices were accurately represented.

Data gathering activities included:

1. Gathering audio recordings, in collaboration with the community, that explored Pgak'yau philosophies and traditional stories about reciprocal relationships with the land;
2. Hosting a series of informal workshops with local youth that used traditional storytelling and illustration as starting points to gather songs, poems, community maps, documented walks and drawings;
3. Collecting drone footage of the local landscape.

A review of the data was then undertaken to discover the intersections and interconnections of mental health and ecosystem health in the lives of the Pgak'yau community.

Results

Loss of land is a cultural loss

The Forestry Department in Mae Wang maps forest versus agricultural land, including rotational farming plots (Maxwell *et al.*, 2020). This data is then used for reallocating land depending on whether it is being used for farming or whether it is classified as forestry. However, this method does not consider the fact that land can appear to be forested when in fact it is part of the rotational farming process. To avoid their land being wrongly classified, many farmers have resorted

Figure 4: Community illustration of a Pgak'yau traditional story

to over-farming their plots (using two- or three-year rotations instead of seven). Throughout the project, the community expressed a sense of suffering at the resultant soil degradation, which represents both a forced adaptation by the community and a form of cultural loss.

The following excerpts from transcribed recordings describe the impact of this loss:

"The government looks from the perspective of whoever rewards them ... Poor people don't give the government any benefits, so they don't have any rights to decide what a forest is."
– Community elder

"20% of people in Ban Nong Tao have land titles ... The forest officers decided themselves what is forest and what is community land and drew lines on the map from there."
– Community leader

Traditional knowledge is transferred through stories

Pgak'yau culture is passed on through stories, songs, poems and ceremonies which promote slowness, care and a reciprocal relationship with the land and other species. The struggle for land rights comes up time and again in these narratives. One, for example, involves the character of the Lazy Orphan (Figure 4), so-called by the king in the story. In reality, the Lazy Orphan moves respectfully through his environment, taking only what he needs and not exhausting the earth's resources.

These stories are part of Pgak'yau oral tradition and there have been many efforts to preserve them by transcribing and recording them. However, without land rights and to make ends meet, many Pgak'yau youth have been forced to leave their traditional villages to work low-wage jobs in the city. This means fewer people are retaining this important cultural knowledge. Elders mourn their inability to effectively transfer their culture to the younger generation, which to them is akin to 'losing nature' - the consequences of which, they believe, will be borne by the land through soil degradation and deforestation.

The language of health and nature are intertwined

Pgak'yau philosophies, ceremonies and farming methods are deeply interwoven in the community and expressed in the language of nature. The number seven, for example, has practical and spiritual meaning: rotational farming is a seven-year cycle which allows for regeneration; it takes seven days for seeds to sprout. The Pgak'yau even believe that human scars take seven days to heal.

Pgak'yau tradition includes ceremonies to bless rice planting and harvest. Families sing about the relationship between people and the spirits of the earth and ask for health, good food and a good life. In December, when the rice is threshed (Figure 5), communities perform '*got to git ko*' – a ceremony that celebrates the myth of the Tobeekah bird. The Pgak'yau send the bird back to the sky and keep seven seeds for

Figure 5: Annual rice threshing ceremony (Credit: Siwakorn Odocha)

future harvests. These ceremonies exemplify the deep connections in Pgak'yau tradition between land, spirituality and culture.

Losing nature is a physical and spiritual loss

'Losing nature' is an ongoing reality for the Pgak'yau community. When ancestral land is reclassified without consent or consultation, the community's practices, both cultural and spiritual, are entirely uprooted. This reclassification also devalues the traditional Pgak'yau knowledge and regenerative practices that have emerged from a deep understanding of their ecosystems.

Ownership represents a 'failure of humanity'

For the Pgak'yau, notions of land ownership are alien and have no place in their traditional philosophies. They believe that an inability to share land is a failure of humanity in general.

The following excerpt from transcribed recordings describes the Pgak'yau's relationship to the land and its ownership:

"Life and land are the same. We are the same as land. We come from land. We go back to land. We never needed special certificates or special rights to land. It's only ours for the year we use it. After we cultivate, drop seeds and harvest, we return everything. It only belongs to us when we're using it. The thing that changed is the idea of selling land."
– Pgak'yau elder

Lessons learned

The Kunming-Montreal Global Biodiversity Framework (Joly, 2022) calls for at least 30% of Earth's land and sea surface areas to be effectively conserved and managed. This has prompted some governments to prioritize nature conservation at the expense of Indigenous communities. While the framework recognizes Indigenous Peoples' rights, there are insufficient tools to monitor individual governments' actions. This presents a very real risk of land rights abuses for Indigenous Peoples, evident in the Thai government's continued reclassification of Pgak'yau lands as part of their push to meet biodiversity targets.

Pgak'yau communities, who have lived sustainably and responsibly alongside nature for millennia, are now under threat and their Indigenous land practices are at risk of disappearing. This has both physical and mental health impacts such as increased stressors of crop failure as well as severed connections to land-based cultural practices and beliefs.

There is a growing body of evidence that demonstrates the negative mental health and nutritional health impacts of forcibly removing Indigenous communities from their land in the name of conservation (Kokunda *et al.*, 2023; Barume, 2016). There is also growing evidence that land, culture and language are powerful tools for healing, and that control over land has a positive influence on Indigenous health (Vogel *et al.* 2022).

Recommendations

The case study aims to inform policy and provide solutions to help Indigenous communities maintain their traditional practices, preserve their culture, and ensure their health and well-being in the face of climate change. To this end, the research team offers the following recommendations:

1. Recognize Karen as Indigenous Peoples;
2. Recognize shifting cultivation as a system of wisdom agriculture based on the cultural heritage of the Karen Peoples;
3. Allow the teachings of Pgak'yau cultural land practices in the Thai national curriculum;
4. Recognize the role of Indigenous knowledge in conserving lands and biodiversity and Indigenous Peoples as effective, environmental stewards;
5. Accept community and local government-led mapping data as legal data;
6. Incorporate Indigenous knowledge and practices into climate change mitigation and adaptation efforts;
7. Change or dismantle the zoning system to align with the Pgak'yau way of life;
8. Evaluate and update policies every five years.

Acknowledgement

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Lao, Pakistan, Somalia, Sri Lanka

Systems thinking to estimate the health co-benefits of climate action

Case study prepared by:
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Focus

Sustainable development requires a systemic approach that will lead to effective policy making and investment options. This approach must allow researchers to understand social, economic and environmental drivers of change, identify entry points for intervention and identify and quantify systemic outcomes of action. This case study presents four different projects that employ the same underlying methodologies (systems thinking and system dynamics), supported by a multidisciplinary team.

Projects overview

The first project focuses on the health-food-climate nexus in Somalia. It involves the creation of a systemic, qualitative analysis using a participatory and multi-stakeholder approach to identify key drivers of change in the health-food-climate system. Specifically, it uses Causal Loop Diagrams (CLD) to visually represent these drivers and their causal pathways.

The second project, conducted for the World Health Organization (WHO), considers urban tree planting in Islamabad, Pakistan, and the health co-benefits of climate adaptation strategies in relation to extreme events (flooding or heatwaves).

The third focuses on national dynamics. Conducted in collaboration with Aroha (a non-profit organization that supports vulnerable people and regions) and the Government of Sri Lanka, it uses the Green Economy Model (GEM) to analyse the benefits of climate change mitigation and adaptation across a range of sectors and health outcomes.

The fourth project focuses on WASH (water, sanitation and hygiene), which promotes access to safe and reliable water supply and sanitation in Lao. The project uses an integrated cost benefit analysis (CBA) to capture the tangible and intangible benefits of action. It was implemented in collaboration with Save the Children and used in the preparation of a Green Climate Fund (GCF) funding proposal.

Team

The multi-disciplinary team comprises international and local members and covers both scientific knowledge and policy responsibilities. The team at KnowlEdge (an environmental consultancy specializing in customized methodologies) offered expertise in systems thinking and system dynamics as well as thematic knowledge on macroeconomics, urban development and spatial analysis. Project managers at Save the Children and Aroha provided knowledge of the climate and health nexus. Local partners also provided access to decision makers at the national level for the Sri Lanka case study and at the local and regional level for the Somalia case study.

Methods

Three main tools were used to understand the interrelations that exist between climate and human health. These tools were informed by, and customized based on, the use of a multi-stakeholder and co-creation process. The tools were Causal Loop Diagrams (CLD), quantitative simulation methods and models and integrated cost benefit analysis (CBA).

Causal Loop Diagram (CLD)

This is a visual tool, typically co-developed with stakeholders and experts, that represents the links that exist between key indicators within a given sector or system (Probst and Bassi, 2014). For example, a CLD might show the causal links between food prices, household income and food affordability. These links are illustrated using variables and arrows which also highlight the presence of circular relationships or feedback loops. There are two types of feedback loop: reinforcing and balancing. Reinforcing loops amplify change in the system – positive or negative – or arise when an intervention amplifies a desirable dynamic, thus reinforcing it (Forrester, 2002). Balancing loops represent counterbalancing forces that shift behaviour toward a goal or equilibrium (Forrester, 2002).

Quantitative simulation methods and models

System Dynamics (SD) models provide insights on the relative strength of various drivers of change (scenario analysis), and support policy makers to identify and prioritize policy interventions (policy analysis). Spatial models are a perfect complement to SD models, since they offer detail on location-specific impacts of action. This study used an open-source model, InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), that maps and 'values' ecosystems and resources. For example, InVEST was used to estimate the impact of land cover change (e.g. tree planting) on water retention (reducing flood risk) and temperature (reducing the impact of extreme heat).

Cost benefit analysis (CBA)

Integrated CBA allows the results from the biophysical models (SD and InVEST) to be integrated into a financial assessment (GCF, 2022; IFAD, 2015). CBA can determine the economic viability of specific climate interventions, both from the perspective of an investor (financial CBA) and from a societal perspective (economic CBA). In this case, the CBA allowed researchers to fully capture the health co-benefits of climate action.

These three methods, harmonized using a systemic approach, supported decision making for the climate and health nexus from conceptualization (using CLDs) to the assessment of intervention options (with the quantitative models), and ending with the creation of an investment and financing plan (using an integrated CBA).

Results

Project one: Exploring the health-food-climate nexus with Causal Loop Diagrams in Somalia

This project focused on food systems, specifically in relation to climate-related displacement, access to food and health services. The key goal was to create a shared understanding of the complexity underpinning the health-food-climate nexus in Somalia, and to stimulate coordinated action.

An integrated CLD depicting the relationships in this nexus was developed with Save the Children Somalia and local stakeholders. A simplified version of the diagram is presented in Figure 1. The core of the exercise was to identify links between climate impacts and health. For instance, flood damage leads to the closure of healthcare facilities, while damage to roads reduces access both to healthcare services and affected areas, which increases the prevalence of disease. These dynamics tend to grow stronger over time and are represented by two reinforcing feedback loops (R3 and R4 in Figure 1). Heatwaves reduce the availability and productivity of health workers and constrain access to healthcare, since the distance that can be travelled during high temperatures is limited. An additional pressure is caused by the displacement of people as a result of floods and droughts, which trigger migration to urban areas and may give rise to violent clan conflicts.

The full version of the Figure 1 diagram includes greater detail on food production and illustrates how cultural aspects, such as clan traditions and nomadic livestock herding, lead to adverse health outcomes that disproportionately affect women.

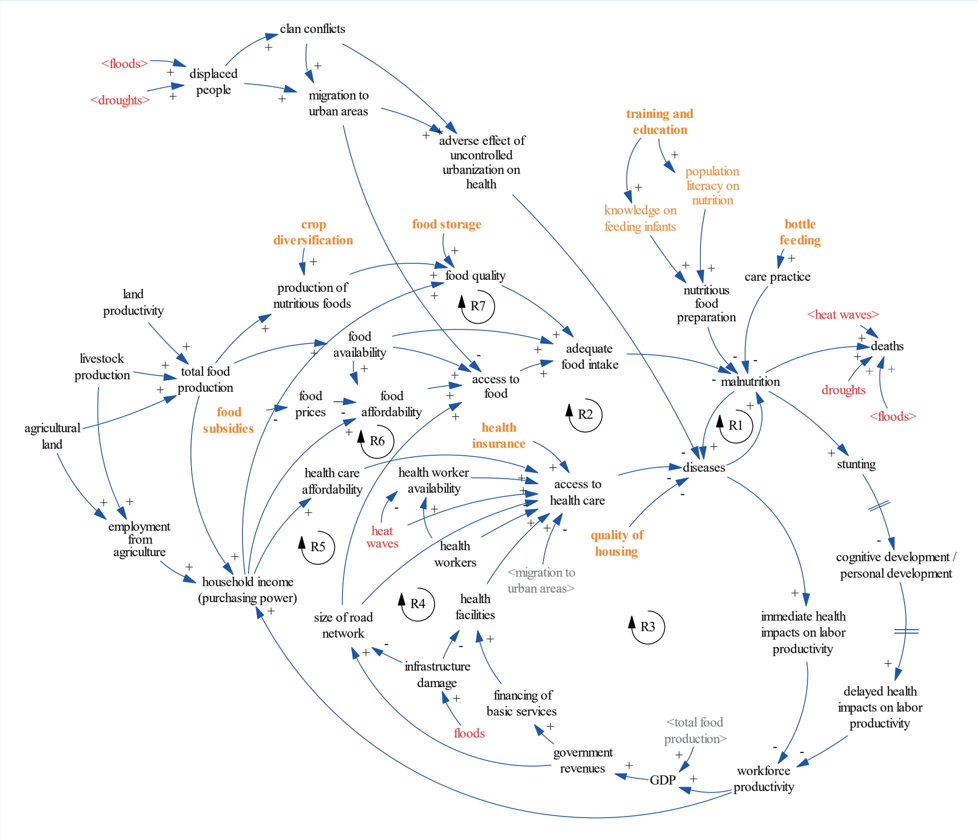

Figure 1: Causal Loop Diagram (CLD) depicting the relationships between health, food and climate in Somalia (simplified)

Project two: Assessing the impact of Nature Based Infrastructure (NBI) on flood risk and extreme heat in Islamabad, Pakistan

This project focused on urban issues, specifically flooding and extreme heat. The key goal was to highlight the importance of health co-benefits when analysing investments that primarily aim to reduce emissions (e.g. tree planting) as part of a climate mitigation strategy.

The InVEST model was used to estimate the extent to which tree planting could reduce heat via changes in land use, shade, evapotranspiration, albedo and proximity to cooling islands such as parks (WHO, 2023). Results showed that tree planting could result in a 0.7-degree Celsius reduction in temperature in Islamabad (Figure 2).

As well as reducing heat, another intangible benefit of urban tree planting is that it reduces cases of diarrhoea. In this analysis, the study projected a 3.22% reduction in cases in Islamabad as a result of tree planting, resulting in a 10% saving of the initial capital outlay. This is especially significant when considering the additional benefits of tree planting in densely populated areas such as air pollution reduction, water filtration and improvements in mental health and labour productivity. A similar analysis was carried out to estimate the impact of tree planting on water retention (and thus mitigate against damage through floods). Net savings in that analysis reached USD 51 million over 30 years.

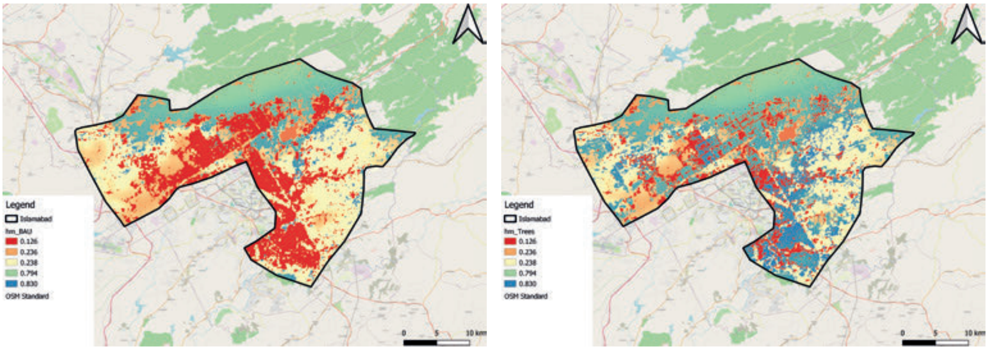

Figure 2: Heat mitigation index across Islamabad under two land use scenarios: the current situation (left) and with the addition of trees along major roads (right). Red zones indicate lower heat mitigation, while blue zones highlight the highest impact on heat mitigation (WHO, 2023)

Project three: Quantifying the health co-benefits of national climate adaptation strategies in Sri Lanka

This project focused on all food systems, urban issues and health system strengthening. The key goal was to estimate the many and varied outcomes of climate action.

KnowlEdge supported Aroha to create Climate Prosperity Plans (CPP) for countries most vulnerable to climate change, one of them being Sri Lanka. The Green Economy Model (GEM), an integrated systems model, was customized to include various health related indicators such as the impact of diets on non-communicable diseases, the impacts of heat on labour productivity, and the impacts of infectious disease on total factor productivity.

Results showed that investments in climate adaptation and mitigation would result in higher gross domestic product (GDP) and employment, improvements in labour productivity via better human health and savings in public finances via lower health and energy costs. The CPP for Sri Lanka was launched at COP27 (Climate Vulnerable Forum & V20, 2022).

Project four: Creating an integrated CBA for WASH investments in Lao

This project focused on health system strengthening. They key goal was the creation of an economic and financial analysis to support investment decisions in WASH for Lao. Save the Children and KnowlEdge partnered with Globalfields (a green finance consultancy) to develop a project that would improve health system climate resilience at a local level.

The proposal focused on 100 health facilities in 25 climate-vulnerable rural districts in Lao to address and manage dengue and diarrhoeal diseases. KnowlEdge assessed

ITEM	NPV	S-NPV	BCR	S-BCR	IRR	S-IRR	PP (years)	PP (years)
1: General health centre strengthening	USD 5,863	USD 104,032	1.07	2.20	12%	47%	8.00	3.00
2: Screened building to reduce vector-borne diseases	USD (1,279)	USD 3,875	0.07	3.83	-49%	98%	NEGATIVE	1.00
3: Climate proofing -passive and active design for building resilience	USD 12,982	USD 13,279	4.44	4.52	69%	71%	2.00	2.00
4: Climate proofing -undergrounding transmission lines	USD 5,463,972	USD 5,591,062	12.99	13.27	176%	180%	1.00	1.00
5: Photovoltaic system	USD 2,387	USD 66,383	1.11	3.99	13%	77%	8.00	2.00
6: Water wells	USD 3,013	USD 4,860	1.69	2.12	32%	44%	3.00	3.00
7: Water catchment	USD 4,018	USD 5,071	5.48	6.66	134%	165%	1.00	1.00
8: Latrines	USD (444)	USD 1,170	0.00	3.64	NEGATIVE	85%	NEGATIVE	2.00
9: Rainwater harvesting	USD 5,330	USD 6,126	1.60	1.69	26%	28%	4.00	4.00

Table 1: Cost Benefit Analysis (CBA) of nine investments in Lao. NPV (net present value), BCR (benefit cost ratio), IRR (internal rate of return) and PP (payback period) reflect a financial analysis; S-NPV, S-IRR, S-BCR and S-Payback Period (where S = social) reflect an economic analysis that considers the economic valuation of social and environmental impacts.

the health co-benefits of a proposed investment and summarized the analysis in an integrated CBA.

Outcomes indicated that an investment of USD 10.3 million would generate USD 47.2 million in tangible revenues. Furthermore, the results highlighted the beneficial nature of investments in the health sector with significant benefit to cost ratios (BCR). Specifically, the study considered investments in the adoption of interventions/products for one health facility, with a fixed lifetime of the investment (e.g. 20 years). The avoided costs of mortality included associated health care costs, avoided lost productivity costs and income from a healthy working person. These avoided costs represented what might be called societal benefits, among the multiple benefits that the project could generate.

Finally, nine investments were analysed for their likely impacts. In green are the investments found to be especially viable (Table1).

For several investments, including latrines, general health system strengthening and photovoltaic installation, the value of the societal benefits was significantly greater than the original investment or revenues created by them. These analyses reflect the importance of considering the societal impacts of investments in addition to the direct economic benefits they generate.

Lessons learned

This case study highlights the clear yet multi-faceted link between climate and health. It also shows that a multi-stakeholder approach is needed to make this link explicit and meaningfully aid developmental goals.

CLDs illustrate how reinforcing loops are strengthened over time, and how they may trigger vicious cycles when action is not taken. They also illustrate the many co-benefits of action and show, with coordinated resolve, that vicious cycles can be turned into virtuous cycles.

Integrated CBAs reflect the importance of considering the societal impacts of investments in addition to the direct economic benefits they generate.

A systemic co-creation and ownership approach encourages more active involvement from local actors.

Positive outcomes have already come out of this research:

- The Somalia, CLD is being used by Save the Children to coordinate action with local stakeholders and generate funding opportunities for future projects;

- The assessment carried out with Aroha has informed national policy on climate adaptation in Sri Lanka;
- The CBA for Lao has informed the preparation of a project proposal submitted to the Green Climate Fund, the world's largest fund mandated to support developing countries realize climate-resilient ambitions, resulting in an investment decision for projects that create societal benefits.

In summary, systemic assessments in the health-climate realm generate useful information for a range of audiences. It is important to include a variety of experts in the process, which puts them in contact with decision makers and gives them access to relevant policy domains. Additionally, decision makers – including government officials, private sector stakeholders and representatives of civil society – can learn about the impact of their actions on the performance system. This supports the co-creation of strategies and policies and underpins mutual development and synergy.

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Sub-Saharan Africa

Food security and resilience using a small-scale funding model

Case study prepared by:
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Focus

Climate change has slowed global progress towards food security. Agriculture is highly vulnerable to climatic changes, and an increasing number of people can no longer afford a healthy diet. In Africa, where the climate has historically displayed a high level of variability, there is a broad consensus that droughts will become both more frequent and more severe (Akinsanola *et al.*, 2020).

Current food systems contribute to food insecurity. Chemically intensive, monoculture-based patterns of food production account for close to one third of anthropogenic greenhouse gas emissions and contribute to both pollution and biodiversity loss (Crippa *et al.*, 2020). Improving nutrition, increasing the affordability of food supplies and increasing sustainability have become key global and national policy priorities (Jamul *et al.*, 2020; Wang *et al.*, 2019). However, attainment of these goals and reshaping current patterns of food production demands a systemic approach. This approach requires significant resources and expertise and is thus generally not feasible for small-scale interventions.

Kirkhouse Trust is a registered charity with a mandate to support projects that address food and nutrition security in India and sub-Saharan Africa (Holzeis *et al.*, 2024). Its model focuses on providing long-term hands-on support, building in-country scientific capacity and providing research infrastructure. Kirkhouse Trust targets agricultural production in countries where farming remains the backbone of the economy and makes a major contribution to employment. In the projects presented in this case study, Kirkhouse Trust has selected legumes as the target crop for support. The projects use a small-scale funding model to address multiple aspects related to climate change and health, as follows:

1. Increase availability of nutrient-rich crops;
2. Reduce reliance on chemical inputs (such as fertilisers and pesticides);
3. Improve resilience of production systems to climate shocks;
4. Reduce reliance on burning biomass for cooking (a source of dangerous indoor pollution and a driver of deforestation).

Legume improvement programmes

Legumes (Figure 1) belong to a diverse group of plants; the third largest land plant family in terms of number of species. Often referred to as the “meat of the poor”, legumes are typically grown by women and contribute directly to household food

Figure 1: Seed of the Stress Tolerant Orphan Legume (STOL) crops project, which assesses potential climate resilience of minor legumes (Credit: Felicien Zida)

security and nutrition. The grains are a source of dietary protein, fibre and essential micronutrients, and the leaves and immature pods of some species are appreciated as fresh vegetables. Pulse grains are traded in local markets, and there is a growing international export market linked to the rising demand for high protein plant-derived foods. The biomass left over at the end of the cropping season provides a source of high-quality feed which is used to tide livestock over the dry season. Since legume species establish a symbiotic relationship with nitrogen-fixing soil bacteria (which also act to mobilise phosphorus in the soil), their cultivation improves soil quality while simultaneously reducing dependency on fossil-fuel derived inorganic fertilisers.

Despite their many positive features, investment in legume productivity has been historically dwarfed by the support directed at the improvement of cereal crops. A further problem is that the average yield for legumes in sub-Saharan Africa is typically low due to their susceptibility to common pests and diseases and their inability to cope with erratic and extreme weather events.

The development of improved varieties of legumes with higher levels of resistance is a rational strategy to increase productivity. It represents the most appropriate solution for smallholder farmers who often cannot afford pesticides and/or fertilisers. In addition, the deployment of legume varieties that mature faster and can be harvested sooner, is seen as a means of mitigating against terminal drought (i.e. inadequate soil moisture at the end of the growing season). Breeding varieties that feature a pronounced tolerance of high air temperature and drought would substantially increase the resilience of production systems.

Team

Kirkhouse Trust currently funds crop improvement projects in eleven countries and has previously supported projects in another five countries. Teams are made up of legume breeders based in African and Indian public sector agricultural research institutions and universities. Breeders interact with farming cooperatives, and also with agricultural extension agents, relevant ministries, local governments and seed systems stakeholders. Researchers include MSc and PhD students, supported by an international group of scientific advisors who provide regular mentoring, project feedback and training visits. Administrative support is provided by a small team based at the trust's offices in the United Kingdom (UK).

Methods

Marker assisted selection

Kirkhouse Trust's long-term objectives are the development of improved crop varieties and the strengthening of in-country scientific capacity. Target crop species are selected based on their importance to smallholder farmers, household food security and income generation. The choice of recipient varieties (those put forward for improvement) is guided by farmers (Figure 2), who are the main intended beneficiaries. Farmers advise breeders which characteristics of the recipient varieties should be retained, such as seed coat colour, short cooking time and taste.

In each case, the aim is to exploit natural genetic variants from donor varieties that are likely to benefit productivity (e.g. resistance to a specific pest or disease).

Figure 2: Farmers select improved common bean varieties, Mozambique Institute of Agricultural Research, August 2013 (Credit: Celestina Jochua)

Researchers then make crosses between donor varieties and locally favoured, but unimproved, recipients.

The key accelerative technology is marker assisted selection (MAS). MAS is a plant breeding strategy in which a trait of interest such as productivity, disease resistance, or heat tolerance, is selected based on its genetic linkage to an easily detectable marker – either a visible marker such flower colour, plant height or seed colour, or a DNA marker. The aim is to breed a version of the legume that combines the characteristics favoured by local farmers with the traits of interest identified in the donor. Deployment of MAS has been proven highly efficient and cost-effective.

Stress Tolerant Orphan Legume (STOL) consortium

This is an ongoing project which aims to assess the potential climate resilience of a group of minor legumes reputed to be more heat and/or drought tolerant than widely grown species. The project allows for sharing germplasm (seeds) between India and eight African countries (Burkina Faso, Ghana, Mali, Namibia, Niger, Nigeria, Senegal and Tanzania). STOL focusses on eleven legume species: moth bean (*Vigna aconitifolia*), mung bean (*V. radiata*), horsegram (*Macrotyloma uniflorum*), dolichos (*Lablab*

Figure 3: A consignment of lab supplies arrives at the Savanna Agricultural Research Institute, Ghana (Credit: Frederik Awusu)

purpureus), Bambara groundnut (*Vigna subterranean*), marama bean (*Tylosema esculentum*), tepary bean (*Phaseolus acutifolius*), rice bean (*Vigna umbellata*), pigeonpea (*Cajanus cajan*), lima bean (*Phaseolus lunatus*) and adzuki bean (*V. angularis*). Multi-location trials (including in farmers' fields) aim to assess the potential of incorporating these species into local farming systems.

Further support includes the provision and maintenance of molecular biology laboratories and greenhouses to enable researchers to carry out molecular breeding programmes in their home institutions. Kirkhouse Trust ensures that these facilities remain operational by periodically sending consignments of research consumables and equipment (Figure 3).

Results

Improvement programmes in cowpea, common bean and Bambara groundnut as well as earlier phase support for the improvement of dolichos, both in India (Mahadevu and Gowda, 2005) and Kenya (Ngure *et al.*, 2021) have recorded positive outcomes, as follows:

Cowpea

Cowpea is a legume widely grown across West Africa. A key constraint to production is the parasitic weed *Striga gesneroides*. Infestation by this weed can be severe enough to destroy entire harvests. Kirkhouse Trust initiated appropriate MAS programmes, provided training, developed biological and genomic resources, and established molecular biology laboratories in Burkina Faso, Cameroon, Ghana, Mali and Nigeria. This approach allowed *Striga*-resistant varieties to be released after a few years in all participating countries. These varieties were further improved by incorporating resistances to various diseases and pests, and by introducing other beneficial characteristics such as early flowering and large seed size. More than 20 varieties of cowpea, combining several improved characteristics, have been released to date. Recently, Kirkhouse Trust also began funding cowpea breeding in Southern and Eastern Africa. The varieties and genomic resources developed in West Africa are now being tested by teams in Botswana, Malawi, Zambia and Zimbabwe.

Common bean

Kirkhouse Trust's common bean projects aimed to simultaneously introduce resistances to multiple diseases into farmer-preferred landraces (local varieties). The first improved varieties were released in Ethiopia in 2023 and in Uganda in 2024, with other releases imminent in Kenya and Zambia. Seed nutrition content (iron and zinc) has been added as an additional target characteristic, as has reduced cooking time. Many rural households rely on burning wood or charcoal as a source of energy for cooking, resulting in household air pollution (a major health hazard that affects mainly women and children) (Po *et al.*, 2011). Reliance on biomass as an energy source also exacerbates soil erosion and results in increased greenhouse gas emissions and deforestation. Thus, reducing cooking time has beneficial knock-on effects for both human and environmental health.

Not all projects have been successful. Reasons for failure include issues with the design of work plans, mismanagement of project activities and a lack of institutional support. However, a greater concern is that the improved varieties might not reach farmers. Seed systems in sub-Saharan Africa are not fully developed, and this is particularly true for self-pollinated crops (which include many legumes) that allow farmers to recycle seed. As a result, seed companies are less inclined to invest in legume species.

Kirkhouse Trust has previously financed seed dissemination activities. However, providing improved seed to millions of farmers proved beyond the charity's financial means. Nonetheless, the charity has been able to establish the impact of improved varieties, and record their increasing areas of production, via reports from other funding organizations.

End-users

Kirkhouse Trust's funded activities aim to deliver improved crop varieties that target constraints identified by farmers themselves. Thus, the primary intended beneficiaries are smallholder farmers. National legume breeders and research students represent the second and third target end-user groups as the trust strengthens its capacity to address in-country research priorities.

Lessons learned

A narrow intervention focus is essential for small-scale models to succeed. Additionally, the impact of interventions, and the increase on investment returns, is maximised through establishing communities and partnerships that jointly address problems and share knowledge and tools.

Crop improvement programmes require several years to reach fruition. Their success requires long-term, integrated support underpinned by national and regional enabling policies which allow not-for-profit and private sector actors to contribute to national development plans.

Enabling conditions include but are not limited to:

1. Funding and training to support effective agricultural extension systems;
2. Training health professionals;
3. Fair remuneration for smallholder farmers;
4. Developing and enacting regulations to control seed quality;
5. Creating incentives for the uptake of healthy foods.

It is important to stress that while climate change increasingly aggravates the problems faced by vulnerable populations, it is not the root cause of global food and nutrition insecurity, which is the result of poverty and economic inequality. The regions of the world that are already bearing the brunt of the impact of climate change have made a negligible contribution to the problem itself and have also, historically, experienced high levels of malnutrition and preventable morbidity. Nonetheless, it is not possible to address food and nutrition security and health without considering adequate climate change adaptation and mitigation measures.

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