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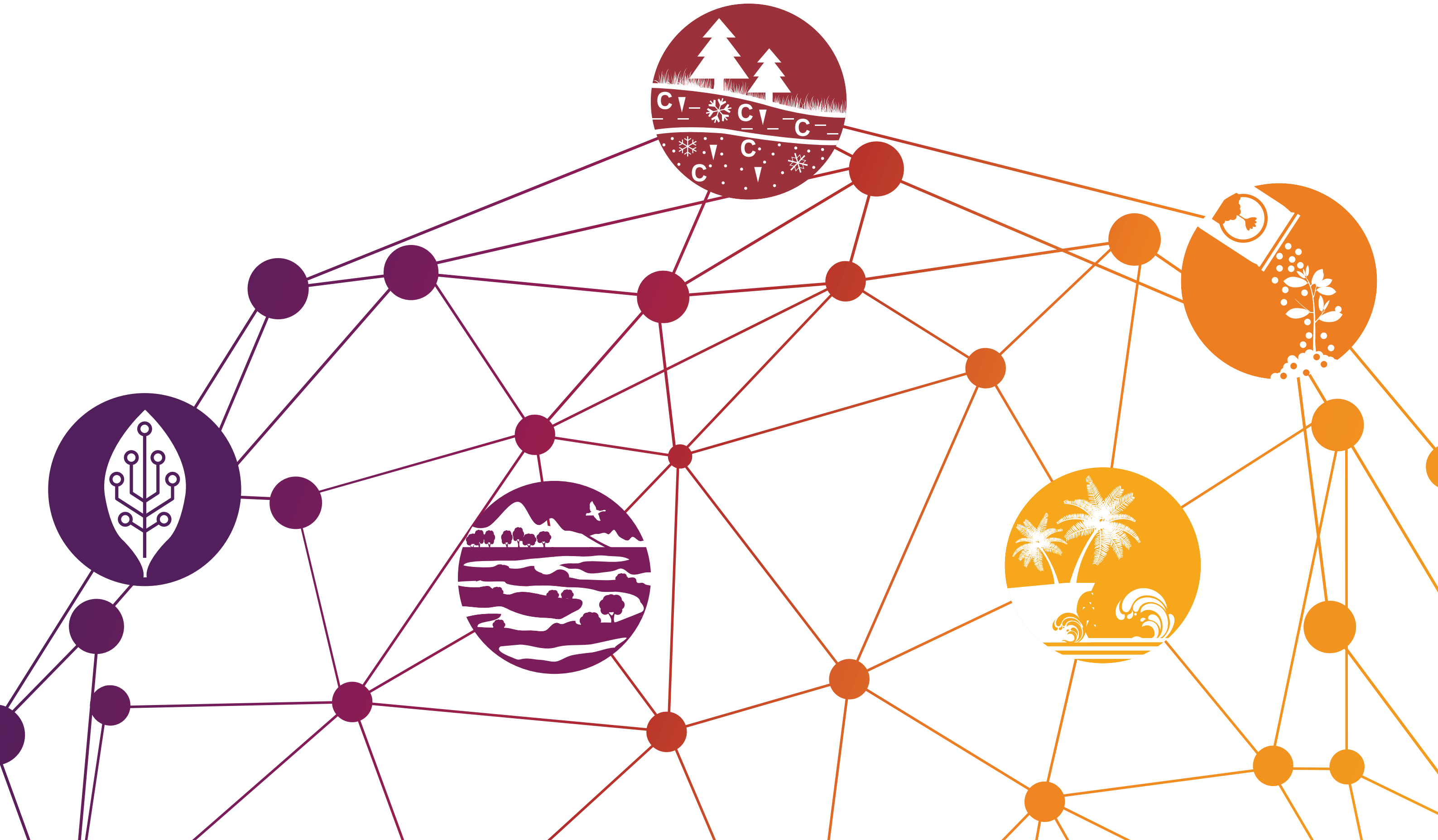
FRONTIERS 2018/19

Emerging Issues of Environmental Concern



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Science Division
UN Environment
P.O. Box 30552
Nairobi, 00100, Kenya
Tel: (+254) 20 7621234
E-mail: publications@unenvironment.org
Web: www.unenvironment.org

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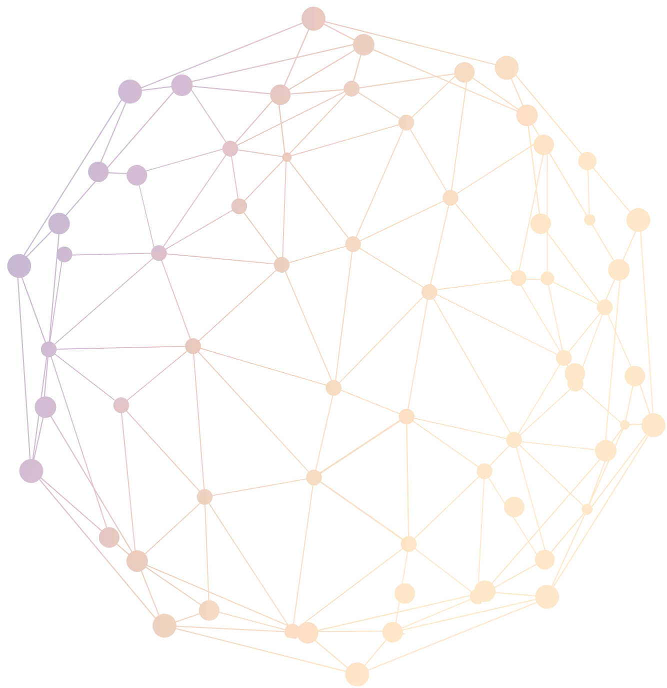

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Foreword

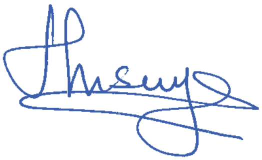
In the first decade of the 20th century, two German chemists – Fritz Haber and Carl Bosch – developed a way to produce synthetic nitrogen cheaply and on a large scale. Their invention spurred the mass production of nitrogen-based fertilizers, and thus transformed farming around the globe. It also marked the beginning of our long-term interference with the Earth's nitrogen balance. Every year, an estimated US$200 billion worth of reactive nitrogen is now lost into the environment, where it degrades our soils, pollutes our air and triggers the spread of "dead zones" and toxic algal blooms in our waterways.

It's no wonder that many scientists are arguing that "the Anthropocene" should become the official name of the current geological era. In just a few decades, humankind has caused global temperatures to rise 170 times faster than the natural rate. We have also deliberately modified more than 75 per cent of the planet's land surface, and permanently altered the flow of more than 93 per cent of the world's rivers. We are not only causing drastic changes to the biosphere, we are also now capable of rewriting – and even creating from scratch – the very building blocks of life.

Every year a network of scientists, experts and institutions across the world work with UN Environment to identify and analyze emerging issues that will have profound effects on our society, economy and environment. Some of these issues are linked to new technologies that have astonishing applications and uncertain risks, while others are perennial issues, such as the fragmentation of wild landscapes and the thawing of long-frozen soil. Another issue, nitrogen pollution, represents an unintended consequence of decades of human activity in the biosphere. While the final issue analyzed here, maladaptation to climate change, highlights our failure to adequately and appropriately adjust to the shifting world around us.

There is some good news to report. As you can read in the pages that follow, a holistic approach to the global challenge of nitrogen management is beginning to emerge. In China, India and the European Union, we are seeing promising new efforts to reduce losses and improve the efficiency of nitrogen fertilizers. Ultimately, the recovery and recycling of nitrogen, as well as other valuable nutrients and materials, can help us to farm cleanly and sustainably, a hallmark of a truly circular economy.

The issues examined in Frontiers should serve as a reminder that, whenever we interfere with nature – whether at the global scale or the molecular level – we risk creating long-lasting impacts on our planetary home. But by acting with foresight and by working together, we can stay ahead of these issues and craft solutions that will serve us all, for generations to come.



Joyce Msuya
Acting Executive Director
United Nations Environment Programme

Acknowledgements

Synthetic Biology: Re-engineering the environment

Lead Authors
Bartlomiej Kolodziejczyk, H2SG Energy Pte. Ltd., Singapore
Natalie Kofler, Yale Institute for Biospheric Studies, Yale University, Connecticut, United States

Contributors and Reviewers
Marianela Araya, Convention on Biological Diversity, Montreal, Canada
James Bull, College of Natural Sciences, University of Texas at Austin, Texas, United States
Jackson Champer, Department of Biological Statistics and Computational Biology, Cornell University, New York, United States
Chen Liu, Department of Biological Statistics and Computational Biology, Cornell University, New York, United States
Yongyuth Yuthavong, National Science and Technology Development Agency of Thailand, Pathumthani, Thailand

Ecological Connectivity: A bridge to preserving Biodiversity

Lead Author
Gary Tabor, Center for Large Landscape Conservation, Montana, United States

Contributors and Reviewers
Maya Bankova-Todorova, The Mohamed bin Zayed Species Conservation Fund, Abu Dhabi, United Arab Emirates
Camilo Andrés Correa Ayram, Alexander von Humboldt Biological Resources Research Institute, Bogotá, Colombia
Letícia Couto Garcia, Federal University of Mato Grosso do Sul, Campo Grande, Brazil
Valerie Kapos, UN Environment – World conservation Monitoring Centre, Cambridge, United Kingdom
Andrew Olds, School of Science and Engineering, University of the Sunshine Coast, Maroochydore, Australia
Ileana Stupariu, Faculty of Geography, University of Bucharest, Romania

Permafrost Peatlands: Losing ground in a warming world

Lead Author
Hans Joosten, Greifswald University/Greifswald Mire Centre, Greifswald, Germany

Contributors and Reviewers
Dianna Kopansky, UN Environment, Nairobi, Kenya
David Olefeldt, Faculty of Agricultural, Life and Environmental Sciences, University of Alberta, Edmonton, Canada
Dmitry Streletskiy, Department of Geography, The George Washington University, Washington DC, United States

The Nitrogen Fix: From nitrogen cycle pollution to nitrogen circular economy

Lead Authors
Mark Sutton, Centre for Ecology & Hydrology, Edinburgh, United Kingdom
Nandula Raghuram, Guru Gobind Singh Indraprastha University, New Delhi, India
Tapan Kumar Adhya, Kalinga Institute of Industrial Technology Bhubaneswar, Odisha, India

Contributors and Reviewers
Jill Baron, U.S. Geological Survey, Colorado, United States
Christopher Cox, UN Environment, Nairobi, Kenya
Wim de Vries, Wageningen University and Research, Wageningen, The Netherlands
Kevin Hicks, Stockholm Environment Institute, York, United Kingdom
Clare Howard, Centre for Ecology & Hydrology, Edinburgh, United Kingdom
Xiaotang Ju, College of Agricultural Resources and Environmental Science, China Agricultural University, Beijing, China
David Kanter, College of Arts and Science, New York University, New York, United States
Cargele Masso, International Institute of Tropical Agriculture, Ibadan, Nigeria

Jean Pierre Ometto, National Institute for Space Research, São José dos Campos, Brazil
Ramesh Ramachandran, National Centre for Sustainable Coastal Management, Ministry of Environment, Forest and Climate Change, Chennai, India
Hans Van Grinsven, PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands
Wilfried Winiwarter, International Institute of Applied Systems Analysis, Laxenburg, Austria

Maladaptation to Climate Change: Avoiding pitfalls on the evolvability pathway

Lead Author
Catherine McMullen, Stockholm Environment Institute, Bangkok, Thailand

Contributors and Reviewers
Thomas Downing, Global Climate Adaptation Partnership, Oxford, United Kingdom
Anthony Patt, Institute for Environmental Decisions, ETH Zürich, Zürich, Switzerland
Bernadette Resurrección, Stockholm Environment Institute, Bangkok, Thailand
Jessica Troni, UN Environment, Nairobi, Kenya

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Alexandra Barthelmes and Cosima Tegetmeyer, Greifswald Mire Centre, Germany; Marin Klinger, National Snow and Ice Data Center, Colorado, United States; Salome Chamanje, David Cole, Nicolien Delange, Angeline Djampou, Philip Drost, Virginia Gitari, Jian Liu, Ariana Magini, Nada Matta, Pauline Mugo, Susan Mutebi-Richards, Shari Nijman, Andreas Obrecht, Samuel Opiyo, Meses Osani, Roxanna Samii, Rajinder Sian, Nandita Surendran and Josephine Wambua, UN Environment

Production advisers
Maarten Kappelle and Edoardo Zandri, UN Environment

Production team
Editor-in-chief: Pinya Sarasas, UN Environment
Technical support: Allan Lelei, UN Environment
Copy editor: Alexandra Horton, United Kingdom

Graphics, design and layout
Graphic designer: Audrey Ringler, UN Environment
Cartographer: Jane Muriithi, UN Environment

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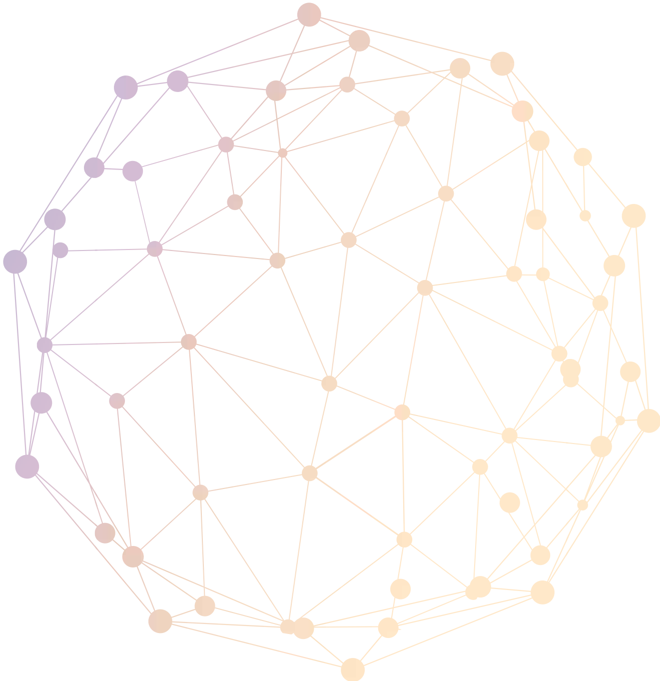


The 2011 flood in Bangkok, Thailand
Photo credit: Wutthichai / Shutterstock.com

Maladaptation to Climate Change:
Avoiding pitfalls on the evolvability pathway

Defining adaptation and maladaptation for the climate change context

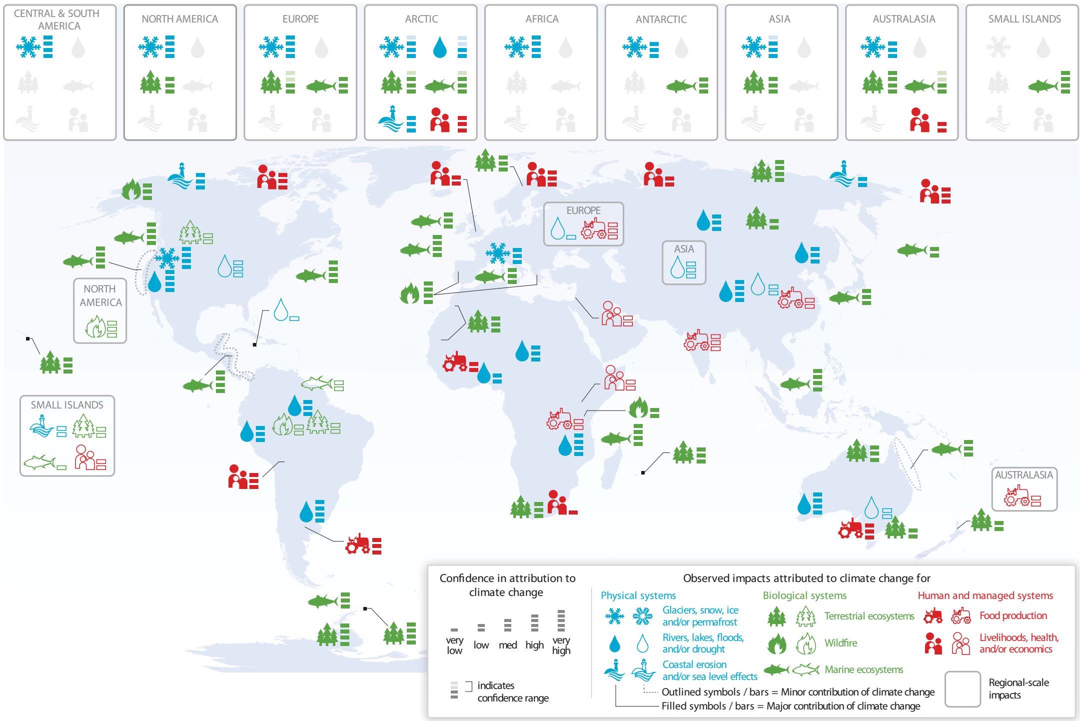
Metaphors are essential to logical thinking. As used for climate change research and policy, the terms adaptation and maladaptation originate from evolutionary biology.[1] Basically, genetic mutations spontaneously appear in every generation of a species and a natural selection process, imposed by the external environment, determines the success or failure both of those mutations and, as a consequence, of species. The idea can be applied to bacteria, to plants and animals, to ecosystems, and even to human behaviour. An important characteristic of successful adaptation is evolvability, the capacity to continue evolving through further adaptation as surrounding conditions continue to change.[2] In evolutionary biology, an identifying characteristic of a maladaptation is the absence of evolvability. It is a dead end.

While the origins of adaptation come from evolutionary biology, adoption of the term for successful human responses to environmental change started with disaster management. In that field, all human responses to a disaster are adaptations to the changed condition, including efforts to abate, or cut off, the source of the disaster.[3] The separation of what was called abatement from adaptation materialized in negotiations around the United Nations Framework Convention on Climate Change. One rationale for separating them was that negotiators would be distracted from agreement on pathways for abatement, or mitigation, if adaptation were available as an easier option.[4] Another explanation is that developed countries would only support efforts that had global outcomes, such as reduced carbon dioxide in the atmosphere, rather than locally focused adaptation objectives.[5]

As climate change negotiations progressed, researchers examined how and why some adaptation actions go awry, particularly those actions that waste substantial amounts of human, natural, or financial resources.[6] As these opinions developed, the United Nations Intergovernmental Panel on Climate Change (IPCC) realized the importance of precise, unambiguous terminology. In 2001, the panel suggested a nuanced definition of maladaptation, one that differs from its usage in biology or behavioural science, in the form of "… an adaptation that does not succeed in reducing vulnerability but increases it instead".[7] Discussions further focused on differences between a maladaptation and an unsuccessful adaptation. An unsuccessful adaptation may be neutral – it may simply mean an action did not work. But when an intended adaptation results in increased vulnerability for other groups and sectors, even in the future, that is a maladaptation.[8] At the same time, neither unsuccessful adaptation nor maladaptation should be confused with sham adaptation: wasteful projects presented as adaptation, such as expensive infrastructure serving only the interests of a small group, without actually improving resilience or reducing vulnerability to climate change.[9]

Maladaptation thinking continues to advance, and one influential study considered the problem according to the outcomes, identifying five categories of maladaptation when compared to alternative choices. According to this analysis, maladaptations are actions that increase greenhouse gas emissions, burden the most vulnerable disproportionately, incur high opportunity costs, reduce incentives to adapt, or set paths that limit the choices available to future generations.[8] These parameters were further articulated and broadened by the IPCC in their 2014 Fifth Assessment Report.[10] As the concept of adaptation versus maladaptation becomes clearer and we are better able to distinguish between them, managing the consequences of climate change should become less intimidating.

Global patterns of observed climate change impacts



Each filled symbol in the top panels indicates a class of systems for which climate change has played a major role in observed changes in at least one system within that class across the respective region, with the range of confidence in attribution for those region-wide impacts indicated by the bars. Regional-scale impacts where climate change has played a minor role are shown by outlined symbols in a box in the respective region. Sub-regional impacts are indicated with symbols on the map, placed in the approximate area of their occurrence. The impacted area can vary from specific locations to broad areas such as a major river basin. Impacts on physical (blue), biological (green), and human (red) systems are differentiated by colour. Absence of climate change impacts from this figure does not imply that such impacts have not occurred.

Graphic and caption source: The fifth assessment report of the Intergovernmental Panel on Climate Change[11]

Maladaptation at scale

In the face of climate change, the concept of maladaptation has developed from adaptation that does not work to adaptive actions that damage resources, narrow future options, worsen the problem for vulnerable populations, or pass on responsibility for solutions to future generations. If an adaptation action violates sustainable development, social equity and poverty eradication goals, particularly in the sense of disproportionately burdening the vulnerable, that action is maladaptive.[12] Efforts to avoid maladaptation at larger scales include research to identify major risks and responsible adaptation strategies throughout the infrastructure asset lifecycle that can inform the decisions, and the actions, of planners and regulators, designers, constructors, operators, investors and insurers.[13] Threats from maladaptation would likely escalate as the scale of the action increases. Recalling the characteristic of evolvability from biology could provide a preliminary screen for maladaptive actions, while prioritizing preservation of evolvability could forestall serious mistakes.

Limiting future options at the scale of installing a seawall along a domestic property may be considered a maladaptation as it will cause problems and limit options for neighbours, but such consequences are usually limited to the local vicinity. However, if a poorly considered action aggravates the original problems or limits future choices at a regional or global scale, then it becomes a much more dangerous maladaptation. At a larger scale, such maladaptations may not only constrain evolvability, but could also threaten the resilience of ecosystems, ways of life, and whole societies. This scale of maladaptive actions, especially those that increase greenhouse gas emissions or intensify ecosystem degradation, could contribute to the biogeophysical feedbacks to drive Earth system functions towards global tipping elements. Many of these tipping elements are irreversible – such as losses of permafrost, coral reefs or the Amazon rainforest – and that irreversibility could usher us over planetary thresholds.[14]

The IPCC's Global Warming of 1.5°C report of 2018 identifies multiple requirements for effective adaptation, demonstrating the importance of climate-smart planning and implementation during the transition to an acceptable

Abridgement of maladaptation in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change[10]

In the IPCC's 2014 Fifth Assessment Report, Working Group II on the Impacts, Vulnerability and Adaptation (WGII) defined maladaptation as "…actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future". It also offered a summary table of twelve broad categories for maladaptation.

Two of the WGII categories describe actions that deliberately ignore what is known: failure to anticipate expected climate change, and failure to take wider implications into account. Other categories concern trading off long–term vulnerability for short–terms benefits, including resource depletion that leads to later vulnerability; procrastination versus impetuous action; installation of infrastructure that cannot last; and engaging in moral hazard, where risk-taking is encouraged by various schemes offering payouts.

Further categories emphasize actions that promote one group, often an elite, over other groups, warning that perpetuating privilege may lead to conflict, as well as actions that ignore local knowledge, traditions and relationships. However, persisting with traditional but inappropriate responses is also considered maladaptation.

WGII also warns against actions that set path dependencies that cannot be easily corrected, and actions, especially engineering defences and solutions, that preclude alternative approaches, such as ecosystem-based adaptation. Finally, migration may be appropriate adaptation or maladaptation – or both – depending on the context and outcome.

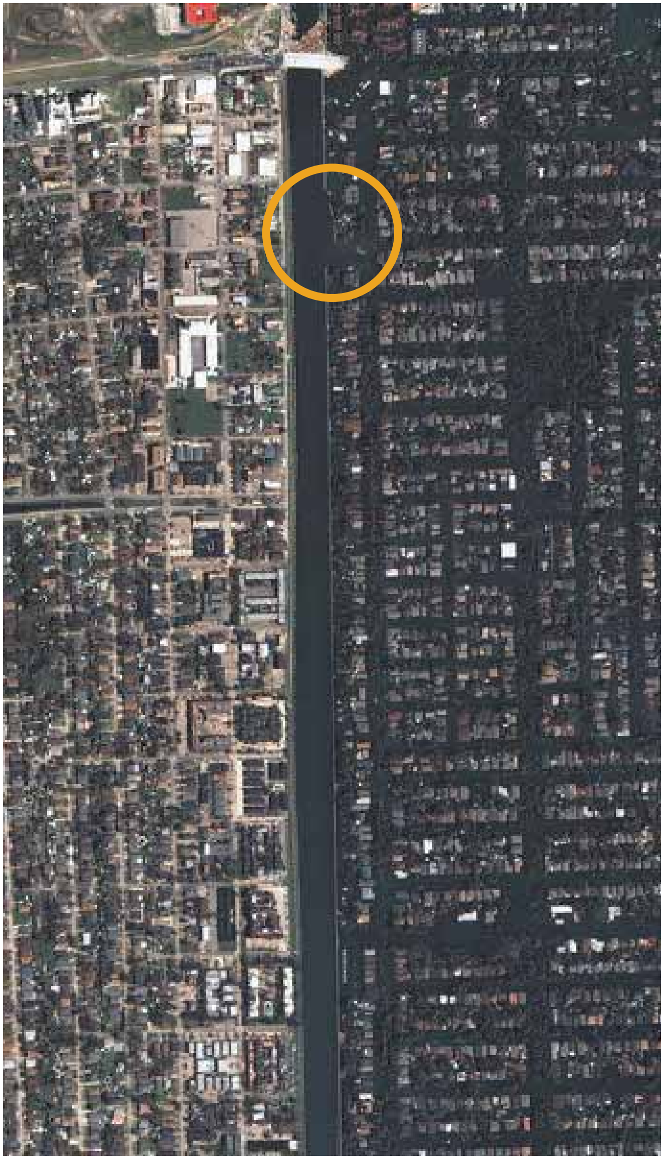
temperature increase.[15] Avoiding maladaptation is a crucial component of this transition. A number of regional-scale cases, self-identifying or not as climate change response, can serve as examples for useful inquiry as we face a future disrupted by climate change. These cases are quick samples of categories presented by the IPCC's Fifth Assessment Report and other distillations of current literature.

Balancing short–term demand against planning for long–term resilience

As an example of the balance between shorter- and longer-term benefits, the Coastal Climate-Resilient Infrastructure Project in southwest Bangladesh has already been presented as a case study of a possible maladaptation.[16] Conditions that frame the question are the adaptation benefits over the next two decades versus the longer-term maladaptive costs that will dominate by 2050 as rising sea level inundates the region.[16] Potential maladaptive outcomes include complex issues for migration, both out of and into the region. Investors expect that the new markets and better roads, bridges, drainage, and cyclone shelters will encourage the coastal populations to stay, when perhaps they should migrate inland. There is a significant likelihood that these facilities will lure newcomers, possibly including some of Dhaka's informal settlement population who have already been displaced by environmental disasters.[19]

Burdening the most vulnerable disproportionately

In some cases, attempts to adapt to changing conditions on multiple fronts can become maladaptations for particular population groups. After 2005's Hurricane Katrina devastated New Orleans and the surrounding region in the USA, initial plans for new green areas to build urban resilience against future floods appeared to concentrate acquisition in the low-lying land that traditionally belonged to poor African-Americans, rather than to other groups.[12,19] That particular urban-renewal proposal was not accepted. However, more than a decade later, studies show that many of the city's poorest and most marginalized people never regained what little they did possess, and a significant proportion of them had to migrate out of the region.[12,20]



Hurricane Katrina of August 2005 damaged many sections of the levee system designed to protect the low-lying city of New Orleans against floods and storm surges. The satellite image shows how a levee breach (yellow circle) allowed flood water from the 17th Street Canal to inundate neighborhoods on the east side of the canals, causing billions of dollars in property damage, while the west side remained dry.

Photo credit: Digital Globe (www.digitalglobe.com)

Maladaptation to Climate Change

The case studies presented in the infographic demonstrate a range of actions to adapt to changing climate at different scales. Some cases are maladaptive given the unintended consequences or will become maladaptations in the near future. Others are actions taken after consideration of many factors to avoid maladaptation.

Maladaptation, defined by the IPCC, is an intended adaptation that instead increases risk of climate-related damages, increases vulnerability to climate change, or diminishes welfare, now or in the future.

Maldaptations are poor choices among alternatives, choices that increase greenhouse gases, unfairly burden the most vulnerable, incur unjustifiable costs, reduce incentives to adapt, or limit choices available to future generations.

Decision-making that **ignores science**, wider implications, or likely consequences

Actions favouring one interest group over another, laying ground for **future conflict and damage**

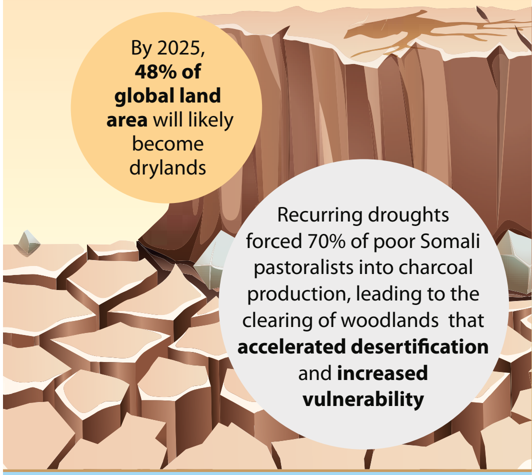
Unwise trade-offs: short vs long term benefits, risk vs reward (moral hazard), too short vs too long consideration period

Actions that determine **path dependency** and lock in or that eliminate choices of future generations

Relocation that puts populations in even **more threatening conditions**

Drought

Climate change disrupts the hydrological cycle. Drought will become more intense, frequent and persistent, threatening all human uses and ecological functioning. Extended drought conditions lead to groundwater overexploitation and aquifers are seldom recharged sufficiently once rains arrive.



By 2025, **48% of global land area** will likely become drylands

Recurring droughts forced 70% of poor Somali pastoralists into charcoal production, leading to the clearing of woodlands that **accelerated desertification** and **increased vulnerability**

Water scarcity

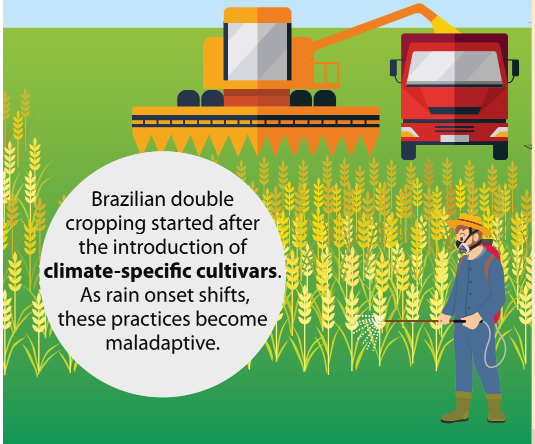
By 2050, 5.7 billion people could be living in water scarce areas. Regions are already adapting to water scarcity through groundwater exploitation, water rationing, or desalination. Such measures may be maladaptive in the long term.

Mexico City faces water scarcity. Exploiting distant groundwater sources is a short-term solution. Actual adaptation invests in longer-term solutions, such as rainwater harvesting and greywater treatment and reuse.

Agriculture

Persistent climate change extremes threaten agricultural production systems. Farmers pride themselves on their adaptive capacities, but these extremes arrive so frequently and persist so unpredictably that adaptation becomes a constant concern.

Some Zimbabwean farmers offset climate uncertainty by increasing pesticide use. Too often, beneficial insects are also eliminated, making conditions worse.



Brazilian double cropping started after the introduction of **climate-specific cultivars**. As rain onset shifts, these practices become maladaptive.

Health

Shifting climatic zones and increases in frequency and intensity of climate extremes produce health consequences. This variability causes crop losses and expanded ranges for disease vectors threatening critical plant and animal species, as well as human populations.

Antibiotics are overused and misused for both preventing and treating veterinary challenges. This maladaptation to **vector-borne diseases** exacerbates threats of antibiotic resistance.

A study showed that the dung from cattle treated with antibiotics **emitted more methane** than antibiotic-free dung. Antibiotic residues also altered dung beetles' gut microbes.

Sea level rise

Sea levels continue to rise globally, threatening infrastructure, groundwater resources, natural barrier islands and coastal communities. An existential threat to low-lying nations and small island states extends to a way of life for millions of people.

Florida canal water levels are used to recharge and maintain pressure against **saltwater intrusion** into groundwater. Raising canal water levels to counter the intrusion inadvertently increases flood threat.

State law guarantees coastal access to native Hawaiians for cultural purposes and subsistence fishing. Sea level rise curtails public access, disproportionately affecting the poor, while development for private profit persists.

Flood

Flooding is one of the most common climate change impacts experienced worldwide. Flood and water management systems suited to the past no longer suffice. As climate continues to change, adaptive management and wide-ranging stakeholder buy-in are required to avoid maladaptations.

Bangkok's metropolitan region is flood-prone due to the lack of planning and investment. Unplanned and uncoordinated **autonomous adaptation** leads to flooding downstream and weakens the entire public drainage system. In 2011, official responses to flood protected the wealthy and burdened vulnerable groups.

Wildfire

Globally, the length of the fire season increased by 19% from 1979 to 2013. Wildfires play important roles in ecosystems worldwide, but their destruction can ruin socioeconomic systems. In some regions, standard management strategies exacerbate conditions.

After decades of fire suppression and five years of climate–related drought, Californian forests are full of **wildfire fuel**. With transformation in mind, the State is initiating ***prescribed burning*** to manage that threat.

Cities

By 2050, 70% of the global population will live in cities. Around the world, cities already experience changing climate in the form of heatwaves, floods, and adaptation failure. Urban adaptations can be policies, infrastructure development, or technological fixes. Remedies seldom benefit all, and they can threaten some marginalized groups.

Warming temperatures and water shortages prompted Melbourne, Australia to increase air-conditioning and desalination. These are maladaptations: b-y increasing GHG emissions, they compound vulnerability in other systems, sectors and communities.

Societal vulnerability

Around the world, people have adapted to climate impacts in various ways: water supply rethinking, insurance schemes, livelihood strategy changes, voluntary or forced migration, and resettlement projects. When these well-intentioned methods are ill-suited to local conditions, or do not consider multiple facets of the issue, vulnerability may increase.

Some farmers seek protection from climatic extremes through **crop insurance** that can inhibit further adaptation strategies.

Insurance policies are maladaptive when they support risky behaviour, such as rebuilding in dangerous locations, or they promote replacement rather than redesign according to changing conditions. As climate threats intensify, insurance may provide a **false sense of security**.

China's climate adaptation resettlement projects offered financial incentives and improved living standards. They also produced **disproportionately heavier burdens** on those left behind, those already displaced, and the poor.

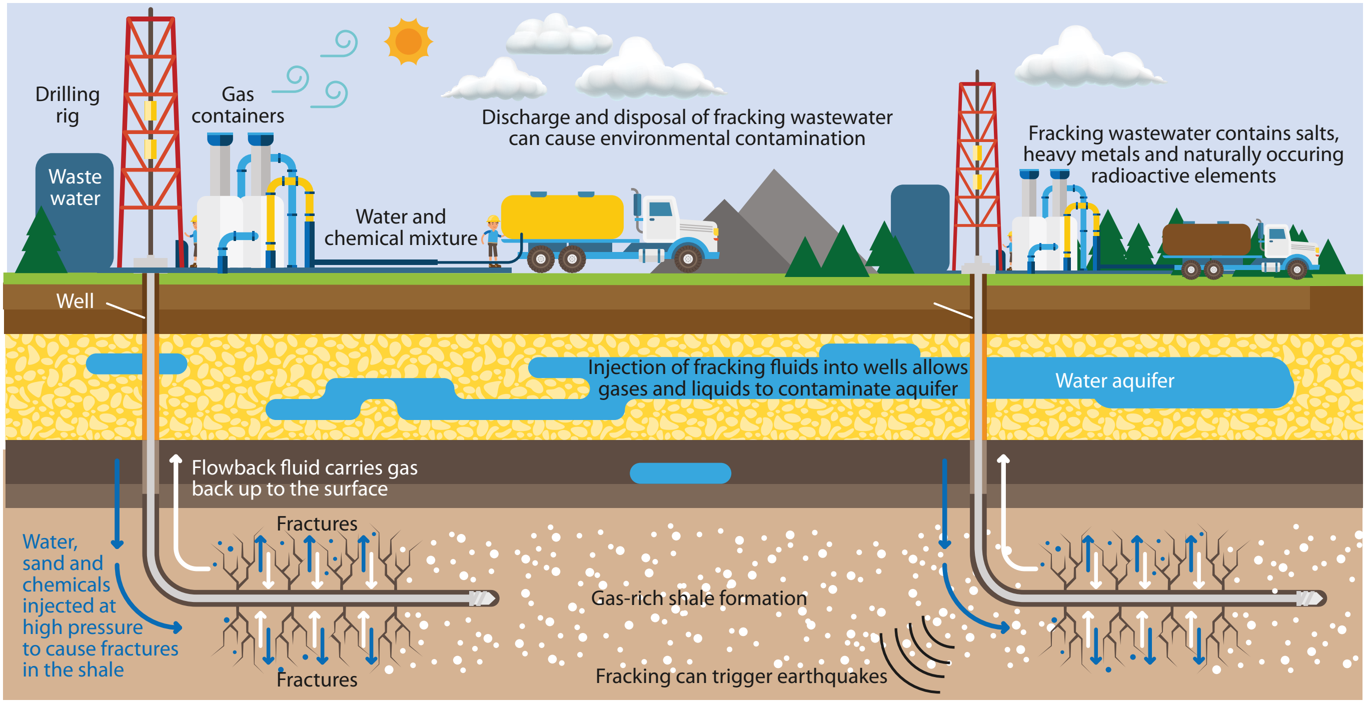
On small island states, increasingly rising tides wash over coastlines, ruining freshwater resources and crops. Researchers suggest **labour mobility** is the best long-term solution to avoid maladaptation associated with resettlement.

Limiting options for future action

Petroleum geologists and engineers developed the capacity to extract oil and gas from deep earth reservoirs sealed by the caprock formations.[21] Some of the depleted reservoirs are considered well suited to sequester carbon dioxide over centuries and longer.[22] Their suitability is due to our understanding of reservoir permeability and the quality of the caprock layer that seals the reservoir.[21,23] When natural gas was promoted as a mitigation strategy, that is, a bridging fuel from coal and oil to renewables, investment grew and the technology evolved.[24] However, there are more problems with that bridge than had originally been anticipated. Much of it was related to the evolution of an extraction technique called hydraulic fracturing, or fracking.[25,26] This technology injects a mix of water, sand and chemicals at high pressure to deliberately force fissures and cracks in the reservoir to release the natural gas. A number of environmental challenges arise from fracking, including aquifer depletion and contamination from chemicals used in drilling and injection, leakage of methane into the environment, and increased seismicity.[27-30] Further, some suggest that hydraulic fracturing may destroy the caprock seal that makes the depleted reservoirs valuable for carbon sequestration.[31,32]

The IPCC Global Warming of 1.5˚C report details two pathways of emission reduction and atmospheric greenhouse gas limitation that will achieve the goal of keeping the global average temperature increase above pre-industrial levels at 1.5˚C. Both pathways rely heavily on the promise of sequestering carbon in geological formations.[15] This hydraulic fracturing industrial policy demonstrates maladaptation on two fronts: the possibility of foregoing long–term benefits for short–term gains and locking into path dependency by damaging future resources. At the same time, fracking increases greenhouse gas emissions by leaking methane throughout its production cycle.[26,33-35]

Hydraulic fracturing or fracking



Jonah gas field, Wyoming, United States

Photo credit: EcoFlight

Avoiding maladaptation in a 1.5°C constrained future

The vision offered by the IPCC's Global Warming of 1.5°C report, and the wisdom of keeping temperature increase to that mark, suggests that climate change consequences need to be more widely considered in decisions made by public and private sector actors, as well as by civil society.[14] Rather than narrowing the concept of maladaptation to unfortunate and complicating outcomes of actions formally labelled as adaptation, policy advisers and decision makers at various levels and in a broad range of institutions could be widening their deliberation to avoid climate change maladaptations in their planning.

The 1.5°C report also emphasizes the United Nations Agenda 2030 and its sustainable development goals, particularly those concerning equality and equity.[14] This vision for meeting the climate challenges ahead focuses on a future that is worth living in, that is better than the one experienced by too many people today. Reducing the root causes of conflicts, wars, insecurities, poverty, and migrations is a vital component of this vision. The human species has always adjusted to changing conditions and we are by nature adaptable creatures. Learning by trial and error is a dependable methodology to guide our adaptations. But we are also a species that uses foresight and that plans ahead. We can design our future. Avoiding maladaptations means we learn not only from our own errors, but also from those experienced by individuals and communities around the world. Using foresight is not limited to each group's suspicions, presumptions, or even aspirations, but needs to be based on scientific evidence and realistic probabilities.

Evidence indicates that maladaptation can be avoided by evaluating all costs and benefits, including co-benefits, for all groups in society, and by being explicit about who the winners and losers will be, and how the burdens could be better shared. Entrenched habits of dismissing the interests of future generations are not appropriate along either of the IPCC 1.5°C pathways that will keep the global average temperatures within that manageable range. We are now living in the future that was overly discounted when the Framework Convention on Climate Change was agreed in 1992. Avoiding maladaptation means evading lock-ins and path dependence, and optimizing evolvability instead. Otherwise, in biological terms, we will find we are at a dead end.

References

1. Darwin, C.R. (1859). *On the origin of the species by means of natural selection*. London: John Murray.

2. Martínez-Padilla, J., Estrada, A., Early, R. and Garcia-Gonzalez, F. (2017). Evolvability meets biogeography: evolutionary potential decreases at high and low environmental favourability. *Proceedings of the Royal Society B,* 284(1856), 20170516. https://doi.org/10.1098/rspb.2017.0516

3. Burton, I., Kates, R.W. and White, G.F. (1993). *The environment as hazard.* New York: Guilford Press.

4. Greenhill, B., Dolšak, N. and Prakash, A. (2018). Exploring the adaptation-mitigation relationship: Does information on the costs of adapting to climate change influence support for mitigation? *Environmental Communication,* 12(7), 911-927. https://doi.org/10.1080/17524032.2018.1508046

5. Bodansky, D. (1993). The United Nations Framework Convention on Climate Change: A commentary. *Yale Journal of International Law*, 18, 451. https://digitalcommons.law.yale.edu/yjil/vol18/iss2/2

6. Burton, I. and van Aalst, M.K. (1999). Come hell or high water: integrating climate change vulnerability and adaptation into Bank work. Environment Department working paper No. 72, Climate change series. Washington DC: World Bank. http://documents.worldbank.org/curated/en/212171468756566936/pdf/multi-page.pdf

7. McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. and White, K.S. (eds.). (2001). Climate change 2001: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press

8. Barnett, J., and O'Neill, S. (2010). Maladaptation. *Global Environmental Change,* 2(20), 211-213. https://www.sciencedirect.com/journal/global-environmental-change/vol/20/issue/2

9. Dolšak, N. and Prakash, A. (2018). The politics of climate change adaptation. *Annual Review of Environment and Resources*, 43, 317-341. https://doi.org/10.1146/annurev-environ-102017-025739

10. Noble, I.R., Huq, S., Anokhin, Y.A., Carmin, J., Goudou, D., Lansigan, F.P. *et al.* (2014). Adaptation needs and options. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Field, C.B., Barros, V.R., Dokken, D.J. Mach, K.J., Mastrandrea, M.D., Bilir, T.E. *et al*. (eds.). Cambridge, UK: Cambridge University Press. 833-868. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap14_FINAL.pdf

11. Cramer, W., Yohe, G.W., Auffhammer, M., Huggel, C., Molau, U., da Silva Dias, M.A.F. *et al*. (2014) Detection and attribution of observed impacts. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E. *et al*. (eds.). Cambridge, UK: Cambridge University Press. 979-1037. https://www.ipcc.ch/report/ar5/wg2/

12. Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z. *et al*. (2016). Equity impacts of urban land use planning for climate adaptation: critical perspectives from the global north and south. *Journal of Planning Education and Research*, 36(3), 333-348. https://doi.org/10.1177%2F0739456X16645166

13. Hayes, S. (2019). Adapting infrastructure to climate change: who bears the risk and responsibility? In *Asset Intelligence through Integration and Interoperability and Contemporary Vibration Engineering Technologies*. Mathew, J., Lim, C.W., Ma, L., Sands, D., Cholette, M.E. and Borghesani, P. (eds.). Proceedings of the 12th World Congress on Engineering Asset Management and the 13th International Conference on Vibration Engineering and Technology of Machinery. Switzerland: Springer Nature. https://doi.org/10.1007/978-3-319-95711-1_24

14. Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D. *et al*. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, 115(33), 8252-8259. https://doi.org/10.1073/pnas.1810141115

15. Intergovernmental Panel on Climate Change (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R. *et al*. (eds.). Switzerland: IPCC. https://www.ipcc.ch/sr15/

16. Magnan, A.K., Schipper, E.L.F., Burkett, M., Bharwani, S., Burton, I., Eriksen, S. *et al*. (2016). Addressing the risk of maladaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, 7(5), 646-665. https://doi.org/10.1002/wcc.409

17. Asian Development Bank (2018). *Bangladesh: Coastal Climate-Resilient Infrastructure Project.* Sovereign (Public) Project 45084-002. https://www.adb.org/projects/45084-002/main

18. International Organization for Migration (2009). Climate Change and Displacement in Bangladesh - A Silent Crisis? https://www.iom.int/migrant-stories/climate-change-and-displacement-bangladesh-silent-crisis

19. Kates, R.W., Colten, C.E., Laska, S., and Leatherman, S.P. (2006). Reconstruction of New Orleans after Hurricane Katrina: a research perspective. *Proceedings of the National Academy of Science,* 103(40), 14653-14660. https://doi.org/10.1073/pnas.0605726103

20. Bleemer, Z. and van der Klaauw, W. (2017). Disaster (over-)insurance: the long-term financial and socioeconomic consequences of Hurricane Katrina. Staff Report, No. 807. New York, NY: Federal Reserve Bank of New York. https://www.newyorkfed.org/research/staff_reports/sr807

21. Orr Jr, F.M. (2003). Sequestration via injection of carbon dioxide into the deep earth. In *The Carbon Dioxide Dilemma: Promising Technologies and Policies.* National Academy of Engineering and National Research Council. Washington, DC: The National Academies Press. https://www.nap.edu/read/10798/chapter/3#17

22. Benson, S. M. and Orr, F. M. (2008). Carbon dioxide capture and storage. *MRS bulletin,* 33(4), 303-305. https://doi.org/10.1557/mrs2008.63

23. Huppert, H.E. and Neufeld, J.A. (2014). The fluid mechanics of carbon dioxide sequestration. *Annual Review of Fluid Mechanics,* 46, 255-272. https://doi.org/10.1146/annurev-fluid-011212-140627

24. Weissman, S. (2016). Natural Gas as a Bridge Fuel – Measuring the Bridge. Center for Sustainable Energy, San Diego. http://energycenter.org/sites/default/files/docs/nav/policy/research-and-reports/Natural_Gas_Bridge_Fuel.pdf

25. Howarth, R.W., Santoro, R., and Ingraffea, A. (2011). Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change,* 106(4), 679. https://doi.org/10.1007/s10584-011-0061-5

26. United Nations Conference on Trade and Development (2018). Commodities at a glance. *Special Issue on Shale Gas 9.* New York and Geneva: UNCTAD. https://unctad.org/en/PublicationsLibrary/suc2017d10_en.pdfS

27. Chen, H. and Carter, K.E. (2016). Water usage for natural gas production through hydraulic fracturing in the United States from 2008 to 2014. *Journal of Environmental Management,* 170, 152-159. https://doi.org/10.1016/j.jenvman.2016.01.023

28. U.S. EPA. (2016). Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States. United States Environmental Protection Agency/Office of Research and Development, Washington, DC. EPA/600/R-16/236Fa. https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=332990

29. Drollette, B.D., Hoelzer, K., Warner, N.R., Darrah, T.H., Karatum, O., O'Connor, M.P., Nelson, R.K. et al. (2015). Elevated levels of diesel range organic compounds in groundwater near Marcellus gas operations are derived from surface activities. *Proceedings of the National Academy of Sciences of USA,* 112(43), 13184-13189. https://doi.org/10.1073/pnas.1511474112

30. Skoumal, R.J., Brudzinski, M.R. and Currie, B.S. (2015). Earthquakes Induced by Hydraulic Fracturing in Poland Township, Ohio. *Bulletin of the Seismological Society of America,* 105(1), 189-197. https://doi.org/10.1785/0120140168

31. Elliot, T.R. and Celia, M.A. (2012). Potential restrictions for CO2 sequestration sites due to shale and tight gas production. *Environmental Science & Technology,* 46(7), 4223-4227. https://pubs.acs.org/doi/10.1021/es2040015.

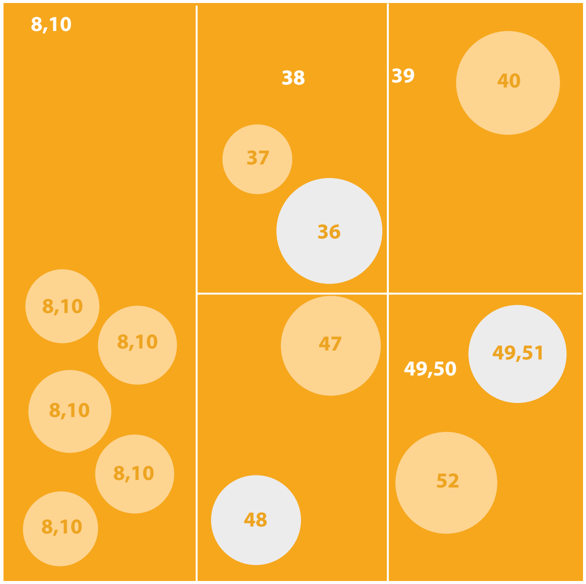
32. Moriarty, P. and Honnery, D. (2018). Energy policy and economics under climate change. *AIMS Energy,* 6(2): 272-290. https://doi.org/10.3934/energy.2018.2.272

33. Jackson, R.B., Vengosh, A., Darrah, T.H., Warner, N.R., Down, A., Poreda, R.J., Osborn, S.G., Zhao, K. and Karr, J.D. (2013). Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proceedings of the National Academy of Sciences,* 110(28), 11250–11255. https://doi.org/10.1073/pnas.1221635110

34. Omara, M., Sullivan, M.R., Li, X., Subramanian, R., Robinson, A.L. and Presto, A.A. (2016). Methane Emissions from Conventional and Unconventional Natural Gas Production Sites in the Marcellus Shale Basin. *Environmental Science & Technology,* 50, 2099–2107. https://doi.org/10.1021/acs.est.5b05503

35. Osborn, S.G., Vengosh, A., Warner, N.R. and Jackson, R.B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences,* 108(20), 8172–8176. https://doi.org/10.1073/pnas.1100682108

Graphic references



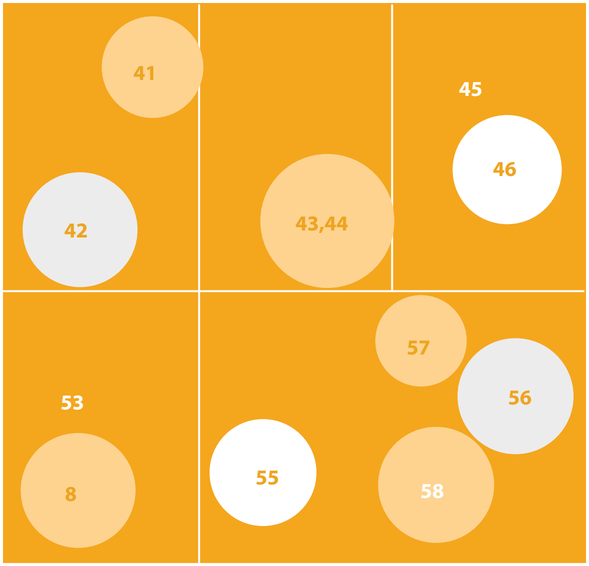
36. Hartmann, I., Sugulle, A.J. and Awale, A.I. (2010). The Impact of Climate Change on Pastoralism in Salahley and Bali-gubadle Districts, Somaliland. Heinrich Böll Stift ung, East and Horn of Africa, Nairobi. https://ke.boell.org/sites/default/files/the_impact_of_climate_change_on_pastoralism_in_salahley_and_bali-gubadle_districts_-_somaliland.pdf

37. Huang, J., Yu, H., Guan, X., Wang, G. and Guo, R. (2015). Accelerated dryland expansion under climate change. *Nature Climate Change*, 6, pages166–171. https://doi.org/10.1038/nclimate2837

38. IPCC (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

39. WWAP (2018). The United Nations world water development report 2018: nature-based solutions for water. United Nations Educational, Scientific and Cultural Organization, Paris. https://unesdoc.unesco.org/ark:/48223/pf0000261424

40. Tellman, B., Bausch, J.C. ,Eakin, H., Anderies, J.M., Mazari-Hiriart, M., Manuel-Navarrete, D. and Redman, C.L. (2018). Adaptive pathways and coupled infrastructure: seven centuries of adaptation to water risk and the production of vulnerability in Mexico City. *Ecology and Society,* 23(1):1. https://doi.org/10.5751/ES-09712-230101



41. Czajkowski, J., Engel, V., Martinez, C., Mirchi, A., Watkins, D., Hughes, J., Sukop, M. (2015). Economic impacts of urban flooding in south Florida: Potential consequences of managing groundwater to prevent salt water intrusion. Working paper no. 2015-10, Risk Management and Decision Processes Center, University of Pennsylvania. http://opim.wharton.upenn.edu/risk/library/WP201510_GWLevelsFloodClaims_Czajkowski-etal.pdf

42. Finkbeiner, E.M., Micheli, F., Bennett, N.J., Ayers, A.L., Le Cornu, E. and Doerr, A.N. (2017). Exploring trade-offs in climate change response in the context of Pacific Island fisheries. *Marine Policy,* 88, 359-364. http://dx.doi.org/10.1016/j.marpol.2017.09.032

43. Limthongsakul, S., Nitivattananon, V. and Arifwidodo, S.D. (2017). Localized flooding and autonomous adaptation in peri-urban Bangkok. *Environment and Urbanization,* 29(1), 51-68. https://doi.org/10.1177/0956247816683854

44. Marks, D. (2015). The Urban Political Ecology of the 2011 Floods in Bangkok: The Creation of Uneven Vulnerabilities. *Pacific Affairs*, 88(3), 623-651. http://dx.doi.org/10.5509/2015883623

45. Jolly, W.M., Cochrane, M.A., Freeborn, P.H., Holden, Z.A., Brown, T.J., Williamson, G.J. and Bowman, D.M. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, 6:7537. https://doi.org/10.1038/ncomms8537

46. Little, J. B. (2018) Fighting Fire with Fire: California Turns to Prescribed Burning. Yale Environment 360. Yale School of Forestry & Environmental Studies. https://e360.yale.edu/features/fighting-fire-with-fire-california-turns-to-prescribed-burning

47. Zinyemba, C., Archer, E. and Rother, H-A. (2018). Climate variability, perceptions and political ecology: Factors influencing changes in pesticide use over 30 years by Zimbabwean smallholder cotton producers. *PLoS ONE,* 13(5): e0196901. https://doi.org/10.1371/journal.pone.0196901

48. Pires, G.F., Abrahão, G.M., Brumatti, L.M., Oliveira, L.J.C., Costa, M.H., Liddicoat, S. and Ladle, R.J. (2016). Increased climate risk in Brazilian double cropping agriculture systems: Implications for land use in Northern Brazil. *Agricultural and Forest Meteorology,* 228: 286-298. http://dx.doi.org/10.1016/j.agrformet.2016.07.005

49. Bett, B., Kiunga, P., Gachohi, J., Sindato, C., Mbotha, D., Robinson, T., Lindahl, J. and Grace, D. (2017). Effects of climate change on the occurrence and distribution of livestock diseases. *Preventive Veterinary Medicine*, 137, Part B, 119-129. https://doi.org/10.1016/j.prevetmed.2016.11.019

50. UNEP (2016). UNEP Frontiers 2016 Report: Emerging Issues of Environmental Concern. United Nations Environment Programme, Nairobi. www.unenvironment.org/frontiers

51. UNEP (2017). Frontiers 2017: Emerging Issues of Environmental Concern. United Nations Environment Programme, Nairobi. http://www.unenvironment.org/frontiers

52. Hammer, T.J., Fierer, N., Hardwick, B., Simojoki, A., Slade, E., Taponen, J., Viljanen, H. and Roslin, T. (2016). Treating cattle with antibiotics affects greenhouse gas emissions, and microbiota in dung and dung beetles. *Proceedings of the Royal Society B: Biological Sciences,* 283:20160150. http://dx.doi.org/10.1098/rspb.2016.0150

53. UN (2014). World Urbanisation Prospects: the 2014 Revision, Highlights (ST/ESA/SER. A/352). Department of Economic and Social Affairs. Population Division, New York: United Nations.

54. Ford, J.D., Labbé, J., Flynn, M., Araos, M. and IHACC Research Team (2017). Readiness for climate change adaptation in the Arctic: a case study from Nunavut, Canada. *Climatic Change*, 145(1-2), 85-100. https://doi.org/10.1007/s10584-017-2071-4

55. Lei, Y., Finlayson, C.M., Thwaites, R., Shi, G. and Cui, L. (2017). Using Government Resettlement Projects as a Sustainable Adaptation Strategy for Climate Change. *Sustainability,* 9, 1373. https://doi.org/10.3390/su9081373

56. O'Hare, P., White, I. and Connelly, A. (2016). Insurance as maladaptation: Resilience and the 'business as usual' paradox. *Environment and Planning C: Government and Policy*, 34(6), 1175-1193. https://doi.org/10.1177/0263774X15602022

57. Bryant, C.R., Bousbaine, A.D., Akkari, C., Daouda, O., Delusca, K., Épule, T.E. and Drouin-Lavigne, C. (2016). The roles of governments and other actors in adaptation to climate change and variability: The examples of agriculture and coastal communities. *AIMS Environmental Science*, 3(3), 326-346. https://doi.org/10.3934/environsci.2016.3.326

58. ILO (2016). Labour Mobility and Regional Climate Adaptation. International Labour Organization Technical Note https://www.ilo.org/wcmsp5/groups/public/---ed_protect/---protrav/---migrant/documents/publication/wcms_534341.pdf

Sunset Crater Volcano National Monument near the Coconino National Forest
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