Resilient Landscapes and Livelihoods Through Better Conservation Planning

Proposal for Boise State Hazard and Climate Resilience Institute Research Grant

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2021-02-23

Executive Summary

From 2001–2019, the world lost 9.7% of total tree cover, largely due to deforestation. These losses directly reduce ecosystem and human resilience to climate change. Despite decades of effort into international and community-based conservation, preventing deforestation is still a critical problem. Conservation projects that work in one place are abandoned in others, or worse, have adverse impacts on local communities. Much of the literature around deforestation has focused either on the relevant ecological processes or social processes in isolation. This project will explicitly study the feedbacks between social and ecological processes in the context of conservation interventions. Thus, our project aims to understand how features of the natural system interact with features of the social system to create conservation outcomes.

Our research integrates both empirical data collection and theoretical land use simulations of our study system, Pemba Island, Tanzania. Because of the variation in natural features, as well as the fact that Pemba has been host to a variety of both international and community-based conservation interventions, the island serves as an ideal place to assess the factors driving conservation success. To ensure that our research produces findings that help local communities in Pemba combat deforestation, we are collaborating with Community Forests Pemba, a nonprofit organization focused on climate resilience through sustainable agroforestry.

Results of this project will significantly improve our ability to predict conservation outcomes for both the environment and communities. To communicate simulation outcomes, we will produce an interactive dashboard displaying alternative conservation scenarios. We will host a workshop with our community partner to demonstrate how project results can inform ongoing conservation efforts. This work advances the HCRI Natural Environment pillar by providing a roadmap for conservation planning on Pemba and in complex social-ecological landscapes broadly. This work also contributes to the Economy & Society pillar by explicitly demonstrating the local economic viability of intervention strategies.

Project Team

Project Narrative

Background and Rationale

Extreme climatic events such as the hurricane that devastated Puerto Rico in 2017, the deadly European heatwave in 2019, and the recent Texas snowpocalypse are becoming more common due to anthropogenic-caused climate change (1, 2). Intact natural areas buffer the effects of these extreme climatic events on both ecosystems and human communities (3, 4). Conserving a broad and diverse array of natural areas is unequivocally our best insurance policy against the worsening impacts of climate change (5–7).

Today, on average, we degenerate our natural areas at a rate 56% faster than they regenerate (8). In response, $24 billion is allocated to conserving natural areas annually (9, 10). Thirty six biodiversity hotspots have been identified globally as priority areas for these conservation dollars (11, 12). These biodiversity hotspots greatly overlap with the world's poorest communities (13). Because of this overlap and also due to the price and availability of land, many conservation areas are adjacent to, or even contain low income, often indigenous populations (14).

One area in particular, the Coastal Forests of Eastern Africa biodiversity hotspot (Figure 1), has seen considerable foregin and community-based investment in conservation (15). Despite these efforts, deforestation and biodiversity loss in the area continue to worsen (15, 16). Pemba Island, our study system for this project is one of two main islands in the Zanzibar archipelago, located in the Coastal Forests of Eastern Africa biodiversity hotspot.

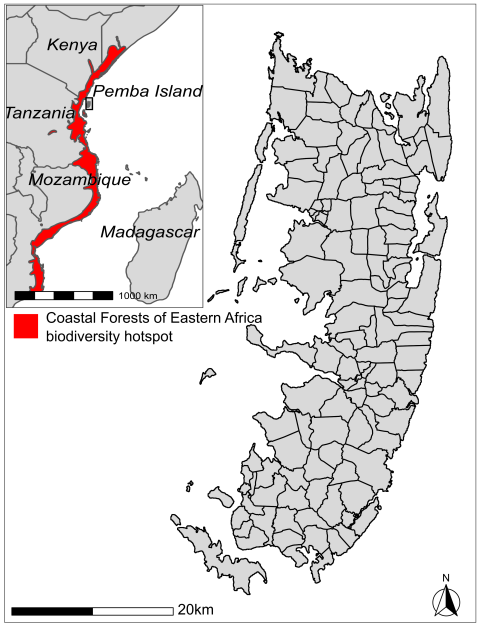

Figure 1: Pemba Island, Tanzania. Black lines show geographic boundaries for 121 distinct wards on the island. Subfigure shows East Africa with the Coastal Forests of Eastern Africa biodiversity hotspot highlighted in red.

Deforestation is a perennial issue on Pemba, as the yearly deforestation rate is nearly 2% and 90% of households rely exclusively on forest products (fuelwood and charcoal) to meet their daily cooking needs (17, 18). As such, Pemba has been subject to a stream of foregin conservation initiatives since the mid 20th century. Meanwhile, despite the initial enthusiasm for conservation, deforestation remains apace in Pemba. Unfortunately, anecdotal evidence suggests that resentment is mounting amongst residents towards the train of conservation projects that have failed to deliver any kind of sustained economic compensation or ecological benefits.

This phenomenon is not rare. Conservation projects, while well intentioned, often fail to meet both ecological and community development goals (19, 20). In areas like Pemba, where the environment and livelihoods are closely linked, economic and ecological processes may have complex interactions and feedbacks, which make conservation outcomes difficult to predict.

Community Forests Pemba, our local collaborator, is a Pemban nonprofit organization established in 2009 with a mission to conserve and restore Pembas forests while supporting livelihood development on the island. The organization specifically seeks to build a resilient Pemba, ecologically and economically, with respect to climate change. Community Forests Pemba also works in 35 vulnerable communities across the island to disseminate information on sustainable agroforestry and gender equity to remote households. Our collaborative effort, if funded by this proposal, will seek to build an integrated understanding of why conservation and development initiatives have continued to fall short on Pemba, and how we can do better in the future.

Aims and Objectives

Forest conservation is a complex mix of individual behaviors, informal group-level institutions, and formal programs or interventions. These social features exist on top of underlying variation in the natural environment. We will construct and parameterize an agent-based land use simulation to produce insights about how all of these moving parts interact and provide a roadmap for implementing successful conservation projects on-the-ground. Our model will generate predictions for ecological and economic viability of two common conservation interventions: protected areas and payments for ecosystem services Table 1.

We will produce two specific deliverables to immediately inform conservation efforts on-the-ground in Pemba.

1. We will create and host an interactive web tool to let individuals run our agent-based simulations to test alternative scenarios and better predict conservation outcomes. This web tool will accompany the scholarly publication of this work to better communicate findings to a broad audience.

2. In the winter following the work outlined here, we will hold a community information and training session with Community Forests Pemba to communicate the findings and implications of this project and to give a live demonstration of the web tool described above. This session will be designed to immediately inform ongoing conservation efforts.

Research Methods

Data Collection

Empirical data collected for this project will inform the decision rules built into our agent-based land use simulations. Our objective is to understand how individuals make decisions in response to varying ecological and economic conditions. To achieve this, our Community Forests Pemba will identify community members who have been subject to a variety of different conservation interventions and rely on each of the four forest types on the island: high tropical rainforest, mangroves, coral rag forest, and agroforestry scrub matrix. Only community members who actively rely on harvesting fuelwood for household needs will be interviewed. Respondents will be compensated for their time (see budget).

With the help of a local translator arranged by Community Forests Pemba, Matt Clark and Dr. Jeff Andrews will conduct structured interviews with each of these community members. Interviews will consist of a series of scenarios where the respondent is asked how they would modify their wood harvesting strategy based on the environmental and economic conditions of interest.

Modeling

Dr. Vicken Hillis and Dr. Monique Borgerhoff-Mulder will oversee the agent-based modeling portion of this project. All model coding will be done by Matt Clark. Our simulations will vary features of the natural environment including: dispersal distance, market substitutability, regrowth rate, and starting degradation. We will then impose three different conservation intervention scenarios and features within them, all listed in Table 1.

Within this backdrop, individuals make harvesting decisions about where (protected or not) and how much fuelwood to harvest. Decision-making and learning rules are motivated by insights from cultural evolutionary theory. In particular, we're interested in how intervention types affect individual's access to resources given their environment, how individuals respond to these changes, and how community response further impacts their environment.

Table 1: Three conservation intervention scenarios to be tested with the proposed agent-based model.

Intervention	**Scheme**	**Features**
No intervention	Individuals harvest renewable resources at a rate which matches their household need, regardless of the location on the landscape or harvest rate compared to resource regeneration rate.	N/A
Protected areas	Some portion of the landscape is designated for conservation and resources inside are socially unacceptable to harvest. Resource units produced inside conservation area may spillover to use area under sink/source dynamics. Some agents may defect and harvest from the conservation area.	Protected area size
Payments for Ecosystem Services	Agents are incentivised to forgo harvesting resources in return for economic payments. Payments may offset resource collection when agents previously sold harvested resources, but may fail to change incentive structures when agents directly depend on resources harvested.	Market value for harvested fuelwood, Payment amount

Key Implications

Intellectual Merit

Predicting if and how conservation actions will evolve has proven to be a major challenge for conservation scientists and practitioners (21). Conservation social science largely relies on case studies to draw correlations between social phenomena and conservation outcomes. Widely applicable theory around the long-term adoption of conservation norms is therefore sparse (22). Recently however, theories from cultural evolution, a field of anthropology, have been identified as a potentially useful tool to better understand the mechanisms which drive the evolution of conservation initiatives (23).

Cultural evolution offers theories on the mechanisms behind the evolution of cooperative behaviors such as adhering to community conservation. Existing cultural group selection theory however, is highly abstract, relying on simple, analytical models of nonspecific behaviors (24, 25). Current theory therefore does not offer predictions about the evolution of conservation norms specifically (26, 27). This is problematic as conservation behaviors have behavior-environment feedbacks which are fundamentally different from generic cooperative behaviors. They operate under the sink/source dynamics of renewable, mobile resources as well as variable resource regeneration rates. Specific resources may also be substitutable for other goods on the market or communities may rely on them directly. As such, cultural group selection theory must be extended to include these dynamics in order to be effectively applied to conservation.

Broader Impacts

The broader impacts of this research will advance the overall mission of HCRI to build resilient communities by providing methodology and tools to better plan conservation projects for nature and communities as an integrated system, both on Pemba and elsewhere. The project as described also closely aligns with both the Natural Environment and Economy & Society HRCI pillars in the following ways:

- *Natural Environment* - The work here will provide immediately actionable insights for conservation on Pemba Island and Zanzibar overall. Our community partner, among others, will be provided with the tools to make use of these insights as part of ongoing conservation and community development efforts. More generally, conservation is in need of unifying theory about which kinds of interventions succeed or fail as a result of underlying ecological and social conditions. This research will serve as a foundational building block for conservation science to consider complete social-ecological landscapes moving forward.

- *Economy & Society* - Fuelwood and charcoal are the primary source of energy to 40% of the world's rural poor, producing more renewable energy than solar, wind, and hydroelectric sources combined (28). Conservation may be the key to ensuring continued access to vital resources for communities in an uncertain climatic future, but it may also backfire and disenfranchise communities to much needed resources. Similar to the pillar above, the work described here will be immediately relevant to

better designing conservation projects in our study system, but the implications of the scholarly work are notably far-reaching. Our simulations will explicitly consider the access to resources of local communities both as an outcome and as a driver of conservation efficacy.

Dissemination Plan

Scholarly results from this project that advance conservation science broadly will be published in a peer-reviewed academic journal. Currently we are targeting *Environmental Modeling and Software*. All model code will be posted on a public GitHub repository and linked to the publication. Before publication we will contribute to open, reproducible science by making our pre-print manuscripts available online using the preprint science repository arXiv.org.

Pemba specific results and the web tool which will accompany this project will be presented at a workshop with Community Forests Pemba described earlier in this proposal. This workshop is currently planned as an online, remote workshop given budget restrictions and the covid-19 pandemic. If possible, we would like to host this workshop in-person if conditions change.

Timeline

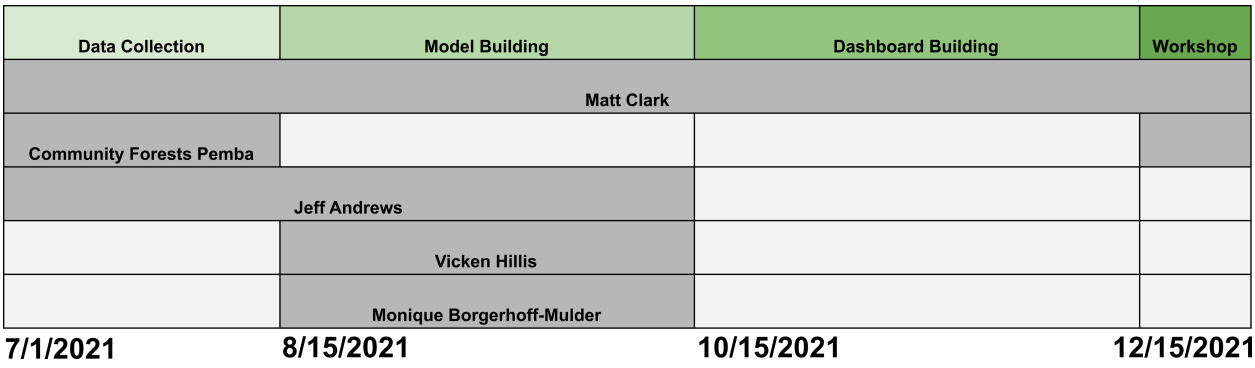

Figure 2: Timeline of proposed research activities and team members involved. Top (green) row shows activities, bottom five (grey) rows show which team members will be involved in each activity.

Future Directions

The Human-Environment Systems research center at Boise State has built a partnership with researchers at the Max Planck Institute for Evolutionary Anthropology already working on conservation research on Pemba Island, Tanzania. Although we consider our partnership to be strong, Boise State personnel have not yet visited the field site. If funded, this project will begin what we anticipate will be a long-lasting and fruitful research program. Thus, this proposal will not only fund necessary conservation research, but will also fund an international research partnership between both institutions.

Future research will seek to collect quantitative data in our system to validate the outcomes of our land use simulations. These data will include biodiversity and land cover data from Pemban forests, as well as community metrics on exposure to conservation interventions and willingness to participate in future interventions.

Matt Clark CV

CURRICULUM VITAE

Last updated February 2021

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EDUCATION

Boise State University, Boise, Idaho
Ph.D. in Ecology, Evolution, & Behavior: Human-Environment Systems
Expected graduation: May 2023
GPA 4.0

Boise State University, Boise, Idaho
M.Sc. in Biology: Human-Environment Systems, June 2019
Thesis: *Methodological Advances for Understanding Social Connectivity and Environmental Implications in Multi-Use Landscapes*
GPA 3.8

California State University Chico, Chico, California
B.S. in Ecological, Evolutionary, and Organismal Biology, December 2016
GPA 3.5

RESEARCH INTERESTS

- Protected areas management
- Human decision making
- Science communication
- Social-ecological systems

METHODS INTERESTS

- Hierarchical modeling
- Network analysis
- Mixed methods
- Agent-based modeling

PEER REVIEWED PUBLICATIONS

Clark, M., Wilkins, E. J., Dagan, D. T., Powell, R., Sharp, R. L., & Hillis, V. (2019). *Bringing forecasting into the future: Using Google to predict visitation in U.S. national parks*. Journal of Environmental Management, 243, 88–94. https://doi.org/10.1016/j.jenvman.2019.05.006

Clark, M., Hillis, V.. *Network Governance of Natural Resources: Making collaboration count*. (In prep. Manuscript available upon request)

OTHER PUBLICATIONS

Clark, M. (2019). *Methodological Advances for Understanding Social Connectivity and Environmental Implications in Multi-Use Landscapes.* Boise State University Theses and Dissertations. https://scholarworks.boisestate.edu/td/1586/

Skinner, A., **Clark, M**., Lobo, R., Mahajan, S., De Nardo, M. (2019). *Social Outcomes of the CARE-WWF Alliance in Mozambique: Research Findings from a Decade of Integrated Conservation and Development Programming.* Impact assessment for the CARE-WWF Alliance and the Alliance for Conservation Evidence. *Full report and impact brief available upon request.

Dagan, D., Wheeler, I., Beck, L, Benedetti, A., Blacketer, M., **Clark, M**., McHugh, K., Noss, C., Sizek, J., Wilkins, E., Powell, R., & Sharp, R. *2018 Park break report: Developing a visitation forecasting tool and management recommendations for the Mojave Desert Region NPS Units*. Research report to the National Park Service. *Full report available upon request.

OPEN-SOURCE WEB APPLICATIONS

Clark, M. (2018). National Park Service Visitation Forecast Explorer. http://hillislab.boisestate.edu/GoogleTrendsForecasting/

CONFERENCE PRESENTATIONS

Clark, M. Computation for Communities and Conservation. Boise State Three Minute Thesis Competition 2020. Boise State University. Boise, Idaho.

Clark, M., Hillis, V. Network Governance of Natural Resources: Making collaboration count. 2019. Annual meeting American Association of Geographers. Washington, D.C.

Clark, M., Wilkins, E., Dagan, D., Powell, R., Sharp, R., & Hillis, V.. "Bringing forecasting into the future: Using Google to predict visitation in U.S. National Parks. 2019. Research Computing Days, Boise State University. Boise, Idaho. *2nd place poster, student poster competition.

Clark, M., Hillis, V. Network Governance of Natural Resources: Making collaboration count. 2018. Annual meeting Ecological Society of America. New Orleans, Louisiana.

Clark, M., Hillis, V. Network Governance of Natural Resources: Making Collaboration Count. 2018. International Symposium on Society and Resource Management. Salt Lake City, Utah.

Dagan, D., **Clark, M**., Blacketer, M., Wilkins, E., Beck, L., Benedetti, A., McHugh, K., Noss, C., Sizek, J., Wheeler, I., Sharp, R., Powell, R. Using Google Trends to forecast visitation and proactively manage visitors at three NPS units: Park Break 2018 products. 2018. International Symposium on Society and Resource Management. Salt Lake City, Utah.

Clark, M., Hillis, V. Applying social-ecological networks to analyze collaborative management strategies in the high divide. 2017. Annual meeting National Science Foundation Idaho, Established Program for Stimulating Competitive Research (EPSCoR). Pocatello, Idaho.

TEACHING EXPERIENCE

Invited Talk **2020**
Research Directions in Conservation Sciences - Boise State Summer Research Community Ten Talks seminar

Laboratory Instructor **2019 - Present**
Introduction to the Diversity of Life. BIOL 192 - Two sections- Boise State University, ID

Data Carpentry Instructor & Workshop Leader **2019**
R for Social Scientists - Two day workshop - Midwest Big Data Hub, OH

Intermediate R Instructor & Workshop Leader **2019**
Intermediate Level R for Researchers - Half day workshop - Boise State University, ID

Software Carpentry Instructor & Workshop Leader **2019**
R for Reproducible Scientific Analysis - One day workshop - Boise State University, ID

Software Carpentry Instructor & Workshop Leader **2019**
R for Reproducible Scientific Analysis - Two day workshop - New York Academy of Sciences, NY

Software Carpentry Instructor & Workshop Leader **2018**
R for Reproducible Scientific Analysis - Two day workshop - University of Minneapolis, MN

Teaching assistant & Guest lecturer **2018**
Network Analysis - Boise State University, ID

Invited Talk **2018**
Applied Linear Modeling & Avenues in Science - Antioch High School Environmental Academy, CA

Discussion Leader **2017 - 2019**
Boise State R User's Group - Boise State University, ID

PROFESSIONAL EXPERIENCE

Boise State Research Computing **2019**
***Data Science for Non-Scientists* - Curriculum Developer**
Created a semester long curriculum for non-science graduate students to build computational capacity and learn to work with data. Responsible for all aspects of curriculum development and for leading a semester-long, weekly beta-testing workshop with 6 graduate students.

World Wildlife Fund **2019**
Quantitative Social Science Intern
Top candidate selected from a nationwide search (U.S.). Responsible for harmonizing and analyzing data from a ten year, flagship CARE-WWF Alliance project in Mozambique. Key research objectives are to explore the food security and wealth impacts of community-managed fisheries, forests and mangrove interventions, using time-series quantitative household surveys.

Lost Grove Brewery **2019**
Data Analyst
Completed an independant side project to assess the efficacy of social media advertising for a local business. Results allowed for managers to identify points of diminishing returns and optimize advertising expenditure across social media platforms.

Software & Data Carpentry **2018 - Present**
Certified Instructor
Certified instructor for software and data carpentry. Experience leading multi-day workshops on the principles of reproducible data science, data analysis, and data management and manipulation among other topics for graduate students and faculty.

Boise State R User's Group **2017 - Present**
Founder and Manager
I founded the Boise State R User's Group to bring together statistical computing expertise at Boise State and create a collaborative environment for undergraduates, graduate students, and faculty to further develop the necessary skills to succeed in the scientific arena. Brought in over $800 of outside funding. Created an online open-source repository for others to access R tutorials. Brought in outside speakers on a bi-weekly basis to provide tutorials on novel content

George Wright Society & National Park Service Park Break **2018**
Graduate Student Participant
One of 10 graduate students selected nationwide to travel to Joshua Tree National Park on behalf of the George Wright Society to help manage and forecast increased visitor use. Primary quantitative researcher on the team. Developed a Bayesian forecasting model to predict park visitation. Developed an interactive web application to assist park managers in park planning

Gallaway Enterprises **2017**
Wildlife Biologist & Environmental Consultant
Conducted pre-construction surveys and compliance monitoring on construction projects in Northern California. Regularly worked with contractors and the public to develop mitigation plans. Surveyed for a number of sensitive avian and plant species. Managed large project budgets and construction personnel.

Forest Restoration Research Unit, Chiang Mai University **2016**
Forest Restoration Intern
Worked with local Hmong villages to build community support for non-timber forest products and local reforestation projects. Developed educational workshops for up to 50 visiting students. Primary team statistician, analyzed and presented data using R software. Organized collaborative reforestation site maintenance with local peoples and university researchers.

MENTORSHIP EXPERIENCE

Graduate Student Mentor - Boise State Vertically Integrated Projects **2020**

Financial Impacts of Wildfire Smoke on the National Park Service

Graduate Student Mentor - Boise State Vertically Integrated Projects **2020**
Assessing Fuel Efficiency of Improved Cookstoves in Rural Tanzania

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AWARDS AND FELLOWSHIPS

2nd Place Best Student Poster, Boise State Research Computing Days **2019**
Graduate College Travel Award, Boise State University **2019**
Biology Dept Travel Award, Boise State University **2018**
Park Break Fellowship, George Wright Society **2018**
STEM Study Abroad Award, Chico State University **2016**

PROFESSIONAL SOCIETIES

Ecological Society of America
International Association for Society and Natural Resources
American Association for the Advancement of Science
American Association of Geographers

Community Partner Letter of Support

References

1. D. R. Easterling*et al.*, Climate extremes: Observations, modeling, and impacts. *science* **289**, 2068–2074 (2000).

2. M. Beniston, D. B. Stephenson, Extreme climatic events and their evolution under changing climatic conditions. *Global and planetary change* **44**, 1–9 (2004).

3. F. Lloret, A. Escudero, J. M. Iriondo, J. Martinez-Vilalta, F. Valladares, Extreme climatic events and vegetation: The role of stabilizing processes. *Global Change Biology* **18**, 797–805 (2012).

4. D. M. Alongi, Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science* **76**, 1–13 (2008).

5. F. Isbell*et al.*, Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* **526**, 574–577 (2015).

6. M. Loreau*et al.*, Biodiversity and ecosystem functioning: Current knowledge and future challenges. *science* **294**, 804–808 (2001).

7. T. H. Oliver*et al.*, Biodiversity and resilience of ecosystem functions. *Trends in ecology & evolution* **30**, 673–684 (2015).

8. D. Lin, L. Wambersie, M. Wackernagel, P. Hanscom, Calculating earth overshoot day 2020: Estimates point to august 22nd. *Global Footprint Network, Oakland* (2020).

9. A. Waldron*et al.*, Protecting 30% of the planet for nature: Costs, benefits and economic implications (2020).

10. A. Waldron*et al.*, Reductions in global biodiversity loss predicted from conservation spending. *Nature* **551**, 364–367 (2017).

11. R. A. Mittermeier, W. R. Turner, F. W. Larsen, T. M. Brooks, C. Gascon, "Global biodiversity conservation: The critical role of hotspots" in *Biodiversity Hotspots*, (Springer, 2011), pp. 3–22.

12. F. W. Larsen, W. R. Turner, T. M. Brooks, Conserving critical sites for biodiversity provides disproportionate benefits to people. *PloS one* **7**, e36971 (2012).

13. B. Fisher, T. Christopher, Poverty and biodiversity: Measuring the overlap of human poverty and the biodiversity hotspots. *Ecological economics* **62**, 93–101 (2007).

14. L. Naughton-Treves, M. B. Holland, K. Brandon, The role of protected areas in conserving biodiversity and sustaining local livelihoods. *Annu. Rev. Environ. Resour.* **30**, 219–252 (2005).

15. N. D. Burgess*et al.*, Two decades of change in state, pressure and conservation responses in the coastal forest biodiversity hotspot of tanzania. *Oryx* **51**, 77–86 (2017).

16. I. Cuadros-Casanova, C. Zamora, W. Ulrich, S. Seibold, J. C. Habel, Empty forests: Safeguarding a sinking flagship in a biodiversity hotspot. *Biodiversity and Conservation* **27**, 2495–2506 (2018).

17. Revolutionary Government of Zanzibar, Zanzibar's climate change strategy (2014).

18. A. V. Ely*et al.*, A participatory study of the wood harvesting industry of charawe and ukongoroni, united republic of tanzania. *A participatory study of the wood harvesting industry of Charawe and Ukongoroni, United Republic of Tanzania.* (2000).

19. P. Christie, Marine protected areas as biological successes and social failures in *In Southeast Asia. American Fisheries Society Symposium*, (2004), pp. 155–164.

20. J. E. M. Watson, N. Dudley, D. B. Segan, M. Hockings, The performance and potential of protected areas. *Nature* **515**, 67–73 (2014).

21. B. Child, G. Barnes, The conceptual evolution and practice of community-based natural resource management in southern africa: Past, present and future. *Environmental Conservation*, 283–295 (2010).

22. S. L. Mahajan*et al.*, A theory-based framework for understanding the establishment, persistence, and diffusion of community-based conservation. *Conservation Science and Practice*, e299 (2020).

23. J. S. Brooks, T. M. Waring, M. Borgerhoff Mulder, P. J. Richerson, Applying cultural evolution to sustainability challenges: An introduction to the special issue. *Sustain Sci* **13**, 1–8 (2018).

24. L. Lehmann, L. Keller, The evolution of cooperation and altruism – a general framework and a classification of models. *Journal of Evolutionary Biology* **19**, 1365–1376 (2006).

25. R. Boyd, P. J. Richerson, J. Henrich, Rapid cultural adaptation can facilitate the evolution of large-scale cooperation. *Behav Ecol Sociobiol* **65**, 431–444 (2011).

26. T. M. Waring*et al.*, A multilevel evolutionary framework for sustainability analysis. *Ecology and Society* **20** (2015).

27. T. M. Waring, S. H. Goff, P. E. Smaldino, The coevolution of economic institutions and sustainable consumption via cultural group selection. *Ecological Economics* **131**, 524–532 (2017).

28. E. Muller*et al.*, The state of the world's forests: Forest pathways to sustainable development (2018).