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RAPID: The impact of the 2022 tropical cyclone season on forest health, human development and disease transmission, SE Madagascar

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Overview. Following the fifth tropical depression to hit Madagascar this year- an inter-tropical convergence zone event (17 Jan 2022), Tropical Storm Ana (22 Jan), Tropical Storm Dumako (15 Feb), and Tropical Cyclone Batsirai (5 Feb)[1]- we propose undertaking a rapid satellite-based assessment of the impacts on forest and human communities from tropical cyclone Emnati, which made landfall on 22 February. We will use a combination of satellite data from before and after the cyclone season (synthetic aperture radar, LANDSAT and visible Planet data), drone surveys and visible groundtruthing to determine damage done to the forest in the Manombo Special Reserve and areas of standing water that provide breeding grounds for disease vectors (malaria, dengue) and affect the drinking water supply which can impact enteric infections including cholera and diarrheal diseases (Dunston et al., 2001). Coastal areas inundated by storm surge might also have some standing water shortly after an event, but the long-term damage to coastal agriculture flooded with saltwater could impact local food security. Furthermore, damage to the forest and surrounding human communities also impacts human-wildlife interactions, as animals such as lemurs will move away from areas of damaged forest where they would otherwise forage, and humans may need to make incursions into the less damaged forest to collect food and building material, increasing the probability of cross-species zoonotic disease transmission.

It is critical that Madagascar-based teams are able to get to the impacted areas **as soon as possible** to assess the degree of the damage to help groundtruth and calibrate the remotely sensed data using drones and other observational data uploaded via the cellular network. Standing water, defoliation of trees, and salt-damage to coastal vegetation are **ephemeral** and depending on the ensuing weather conditions, could be gone in days or weeks. Other places will sustain longer-term damage, therefore it is critical that we document and understand the initial conditions that affect the longer-term recovery of the forest.

Our overarching scientific **goals** for this project have broad societal impacts-

- **Develop a rapid, remote post-disaster assessment tool.** Even prior to the COVID-19 pandemic, it was both practically and ethically challenging to get to areas hit by

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[1] https://reliefweb.int/report/madagascar/southern-africa-cyclone-season-flash-update-no-8-22-february-2022

disaster, especially in developing nations where the risk is often highest. Using a suite of satellite data, this RAPID proposal will allow us to begin developing tools to do a quick, post-disaster assessment of damage done to ecosystems that have immediate impact on the response and recovery efforts, as well as guiding scientific teams to areas of specific interest.

- **Rapid-onset vs. slow-onset disasters.** This proposal is part of a larger effort that is tracking efforts in tropical forest conservation in the face of both climate and societal stressors. As this coupled human-environment system responds to long-term climate changes, an event like a tropical cyclone accelerates the degradation of stressed systems, and immediate documentation of the damages can help us better understand how these systems respond.
- **Disease outbreaks** are an unfortunate secondary-effect of many disasters. By determining and mapping areas of standing freshwater we can better understand the distribution of nurseries for disease vectors and how drinking water quality is impacted over large swaths of the impacted landscape. Furthermore, we aim to remotely map areas of saltwater inundation that can affect long-term food security. Finally, as we learn more about how forest communities respond to tropical cyclones, we can better predict how animal populations might come into contact, increasing the possibility of zoonotic disease exchange.

Background. Climate change and intense weather systems are impacting the economically marginalized communities in Madagascar that rely on natural forest ecosystems and local agricultural production, resulting in a devastating food crisis (Nematchoua et al., 2018). The country also receives on the order of 3-4 tropical cyclones a year which impact tens of thousands of people (*EM-DAT | The International Disasters Database*, n.d.)- heavy, climate-change amplified rains fall on the parched landscape causing soil erosion, flooding and pooling water which can provide nurseries for disease-carrying mosquitoes (Thompson et al., 2021). Adding to the changes in the system, the increasing frequency of category 5 cyclones (which were not present prior to 1994) further threatens developing nations like Madagascar (Fitchett, 2018).

Trees in the humid, tropical lowland forests surrounding the Manombo Special Reserve in SE Madagascar are still recovering from the damage caused by the 1997 cyclone Gretelle (Goodman et al., 2019). These disturbances, changes in climate, and varied soil types all drive high variation in the tree species composition here, such that extreme storms may have significant impacts on tree biodiversity and structure (Rakotonirina et al. 2007). Cyclones have impacted forest resiliency by reducing crown volume, tree stem density, and overall forest biomass, while increasing tree mortality and abundances of non-woody vegetation such as herbs and lianas, especially on forest margins (Lewis et al., 2012, Birkinshaw & Randrianjanahary, 2007). These disturbances to lemur food trees have led to adverse physical short-term consequences for lemur populations (Lewis & Axel 2019) and behavior changes including altered foraging sites (LaFleur & Gould, 2009).

Healthy tropical rainforests also provide critical ecosystem services to the people of SE Madagascar, including a foundation of biodiversity, buffering and provisioning services that reduce the risk of disaster triggered by tropical weather systems. While forests may provide buffers that reduce the magnitude of the hazards (flooding, erosion control, high winds, etc.), people from marginalized communities who are forced to make incursions into the undamaged forest to secure food and building supplies may increase forest degradation. Furthermore, these incursions could bring humans and/or their domesticated animals into contact with animals displaced from their native habitat by the storm, increasing the potential for disease exchange (Barrett et al., 2013). Understanding how the forest is responding to the changes in this strongly coupled human-environment system is a critical component of community resiliency, hence reducing the risk of climate-related disasters.

The 404 plant species at Manombo— 288 of which are endemic to Madagascar (Goodman et al., 2019)— provide critical food and habitat for lemurs, as well as resources for humans in nearby communities. Immediate and continued post-cyclone forest assessments will inform the extent of cyclone damage, as well as potential long-term effects of altered forest structure and composition for the human and non-human populations. NDVI (Normalized Difference Vegetation Index) remote sensing data show that cyclones in other regions caused decreased vegetation productivity (e.g. Charrua et al. 2021), and field-based demographic studies (e.g. Tanner et al. 2014) have highlighted the long-term consequences of storms on tree mortality. Pairing remote sensing data with a field-based tree analysis will enable us to understand the short-term and long-term consequences of cyclones on Manombo's forests.

While the landscape of Madagascar has been altered by humans for thousands of years, the present state and rate of deforestation has caused disproportionate losses of biodiversity (Allnutt et al., 2008), and the traditional slash-and-burn agriculture has left broad swaths of land without forest cover. As water filtration and evapotranspiration are critical regulating services provided by forests, areas without tree cover are more likely to flood and hold standing water after a storm. Prevalence of diarrheal diseases, leptospirosis, dengue, cholera, and acute respiratory infection (from pathogens such as viruses and bacteria), just to name a few, have risen as a consequence of cyclone activity (Zheng et al. 2017, Shultz et al. 2005, Mitchell et al. 2014). Disruptions in public health services and damage to water sources, human migration and shifts in population density, and ecosystem instabilities that impact host-pathogen interactions all contribute to infectious disease outbreaks post-cyclone (Ivers & Ryan, 2006).

Heavy rains from the cyclone may increase food availability for disease-carrying rodents and promote hatching of infected eggs and breeding of arthropod disease vectors (Chretien et al. 2015). Furthermore, as the human-wildlife interface is expanded by cyclone damage, disease transmission between humans and lemurs has the potential to be especially easy and deadly due to their phylogenetic relatedness as primates and lemurs' at-risk conservation status (Estrada et al. 2017). As human communities' infrastructure is damaged and they look to forest resources to rebuild, humans and their domestic animals may interact more frequently with lemurs leading to zoonotic pathogen transmission. It is therefore critical to understand where and why we have areas of standing water present for extended periods. In addition, as human communities' infrastructure is damaged and they look to forest resources to rebuild, humans and their domestic animals may interact more frequently with lemurs and other wildlife leading to high potential for zoonotic pathogen transmission from wildlife to humans or reverse zoonotic pathogen transmission from humans to wildlife.

Our Approach. We are proposing a year-long monitoring program to document and measure the environmental changes that followed the 2022 austral summer storm season as well as the restorative efforts of NGOs aimed at supporting socio-ecologically linked communities in rural SE Madagascar. We plan to measure the impacts on the forests at Manombo Special Reserve and ecosystem services they provide using a combination of space-based instruments (Landsat, MODIS, Sentinel, Planet etc.), targeted drone surveys and field observations to map areas damaged and destroyed trees (uprooted, sheared off mid-trunk and defoliated) as well as areas of freshwater flooding and saltwater inundation. We will analyze post-event satellite imagery and complete repeat drone surveys at intervals of 2 weeks, 1 month, 3 months, 6 months and one year, allowing us to detect ecosystem responses to impacts (either storms, drought or fire) and how the human, faunal, and tree communities are responding. This will be done in partnership with our NGO partner Health in Harmony who is working on forest conservation, livelihoods and healthcare programs in the region (Jones et al., 2020). By completing a similar monitoring program in the patch of forest just south of Manombo, we can document how similar socio-ecosystems respond without the NGO interventions.

Partnerships (satellite and ground truthing). Our strategy is to take a two-pronged approach to rapidly assessing damage remotely, groundtruthing the satellite interpretations using both drones and visual observations, and communicating results back to us as well as to in-country academic, non-governmental and relief organizations as the local partners see fit. Leveraging the existing relationship between MIT's Space Enabled group and BlueRaster (https://www.blueraster.com/), we propose to collect appropriate data to measure the damage to forest canopy and felled trees as well as structures and roads, areas of standing freshwater, and regions along the coast inundated with saltwater from the storm surge. These data should be collected as soon as possible after the clouds from the storm clear (save SAR which can sample the surface through clouds), then repeated at intervals of 2 weeks, one month, two months, six months and one year after the storm to determine short-term and long lasting changes to the landscape. BlueRaster will produce a low-overhead webpage that can be accessed by anyone with a viable internet connection where users can download raw data, processed geolocated raster images, and/or interpreted shapefiles that can be used for evidence-based post-disaster needs assessment and aid delivery for the most at-risk communities.

Results of the analysis will be used to-

- **Map flooded areas** and determine duration of standing water to prevent infectious disease outbreaks including malaria and enteric infections;
- Measure degree of **storm surge inundation**, and assess impacts on agricultural lands, forests and water supplies;
- Determine the **impacts of storms on the forests**;
- Help **assess forest resource use and conservation efforts**;
- Consider how changes in the forest might **impact lemur communities**;
- Predict areas of increased **animal-human interactions**.

To monitor forest response to cyclone damage on the ground and assess species-level variability in resiliency, working with our NGO partners, we will establish six 50m by 50m botanical plots throughout the field site. We will compare the structure, composition, and damage of three plots that sustained severe storm damage with three plots that sustained minimal cyclone damage (as identified in initial remote sensing analysis). In each plot, we will:

- Demarcate plot boundaries and organize them into 5m by 5m grid cells on an y-x coordinate plane;
- Survey every tree of a Diameter at Breast Height (DBH) ≥ 10 cm:
    - Identify to the species level, to be completed by the botanist (in the case that there is an unknown species, we will collect herbaria voucher specimen for future identification at the Missouri Botanical Garden in Antananarivo);
    - Measure DBH;
    - Measure height, using a measuring tape or hypsometer when possible and visual estimation when other methods are not feasible;
    - Map tree location within the plot using the coordinate system;
    - Tag all measured trees in plot;

    - Record any sign of damage (defoliation, broken trunk, fallen branches, fallen tree, human-cut tree);
- Establish three 5m x 5m subplots in which we will survey all plants DBH > 1cm, following the same methods outlined above;
- Observationally characterize anthropogenic disturbance, including signs of hunting, mining, logging, agriculture, etc.;
- Measure canopy cover using a densiometer;
- Estimate understory cover and dominant species composition;
- Measure soil moisture content using a digital soil moisture analyzer.

These forest plots will provide ground-truthing of the remote sensing data, enable comparison of forest structure and composition between resilient and vulnerable forests, and set the baseline for future long-term forest plot monitoring. Drone surveys will be undertaken at regular intervals (to be determined).

Using this storm season as a template, we hope to develop a protocol to rapidly determine the impacts of global change events using this combination of satellite data, drone observation and visual ground truthing that can be deployed anywhere around the world where we can partner with local organizations. As far as we are aware, this novel approach is evolving in a post-COVID world where international travel is both more difficult and less desirable. Furthermore, reliance upon our partners in the impacted countries builds local capacity, making the local scientific community itself more resilient.

- This supplementary document should describe how the proposal will conform to NSF policy on the dissemination and sharing of research results (see [Chapter XI.D.4](#)), and may include:
    1. the types of data, samples, physical collections, software, curriculum materials, and other materials to be produced in the course of the project;
    2. the standards to be used for data and metadata format and content (where existing standards are absent or deemed inadequate, this should be documented along with any proposed solutions or remedies);
    3. policies for access and sharing including provisions for appropriate protection of privacy, confidentiality, security, intellectual property, or other rights or requirements;
    4. policies and provisions for re-use, re-distribution, and the production of derivatives; and
    5. plans for archiving data, samples, and other research products, and for preservation of access to them.

Data management requirements and plans specific to the Directorate, Office, Division, Program, or other NSF unit, relevant to a proposal are available at: http://www.nsf.gov/bfa/dias/policy/dmp.jsp. If guidance specific to the program is not available, then the requirements established in this section apply. Simultaneously submitted collaborative proposals and proposals that include subawards are a single unified project and should include only one supplemental combined Data Management Plan, regardless of the

number of non-lead collaborative proposals or subawards included. In such collaborative proposals, the data management plan should discuss the relevant data issues in the context of the collaboration.
A valid Data Management Plan may include only the statement that no detailed plan is needed, as long as the statement is accompanied by a clear justification. Proposers who feel that the plan cannot fit within the limit of two pages may use part of the 15-page Project Description for additional data management information. Proposers are advised that the Data Management Plan must not be used to circumvent the 15-page Project Description limitation. The Data Management Plan will be reviewed as an integral part of the proposal, considered under Intellectual Merit or Broader Impacts or both, as appropriate for the scientific community of relevance.

Data Management Plan

It is critical that the data we collect is made accessible to aid organizations, government agencies and our fellow Malagasy and other international researchers as soon as possible. By partnering with BlueRaster, we will be able to make our interpretations available to the community in a variety of formats that will allow the data to be accessible to scientists and field technicians alike. The geospatial data will be provided in GeoTIFF files of the raster data (SAR, Planet, LANDSAT, etc.), and shapefiles will be created of the flooded areas, areas of damaged forest, sections of damaged road, and coastal zone saltwater inundation. We will also create maps with gridded coordinates that can be downloaded in PDF or JPG formats that can be viewed simply on any mobile device or printed on a color or black and white printer. This website created by BlueRaster will also serve as a long-lived archive for all data collected and analyzed.

Budget

RAPID: The 2022 Tropical Cyclone season's impact on forest health, human development and disease transmission, SE Madagascar					
(McAdoo or Yoder or Poulsen or Wood), Paietta, DeSisto					
Budget					
Item	**Provider**	**Cost**	**number**	**Total Cost**	**Justification**
Satellite Data Analysis	BlueRaster (https://www.blueraster.com/)	$15,000.00	1	$15,000.00	BlueRaster will provide analysis of the appropriate satellite data to map out forest damage, standing water and saltwater inundation at 1) ASAP after event, 2) 2 weeks post event, 3) 1 month post event, 4) 6 months post event and 5) one year out. They have access to multiple streams of data (e.g. Planet, Sentinel SAR, etc.) and will help co-develop the analysis methodology. Over time, the process will become more efficient and effective with learning.
Travel to Madagascar					

Airfare	Delta	$2,600.00	8	$20,800.00	Raleigh-Durham to Antananarivo for 4 people (Paietta, DeSisto, McAdoo, Poulsen), over two trips (2022 and 2023 for followup)
room, board, overland transport	Health in Harmony	$500.00	30	$15,000.00	$100 room and board per person (4 people) plus $100/day transport over a 30 day trip. This is an estimate and will also cover other miscellaneous on-the-ground expenses.
Field support	Health in Harmony/Centre Valbio staff	$300.00	2	$600.00	A technician is ~$200/ month plus added expenses for food/overnight compensation (~$3/day). https://www.stonybrook.edu/commcms/centre-valbio/documents/CVB%20Price%20List%202021.pdf .
Malagasy Graduate Students	TBD	$250.00	4	$1,000.00	As part of our capacity-building so that we can have someone trained to do ground truthing as the need arises.
Equipment					
Drone	DJI Mavic Pro 3	$2,199.00	1	$2,199.00	Drone can be used to map damaged forest at a higher resolution and provide ground truth to calibrate the satellite interpretations as well as high-res basemaps including canopy height from structure from motion. We can do return surveys annually to monitor post-disaster recovery and changes in carbon storage.
remote controller	DJI RC Pro	$1,199.00	1	$1,199.00	Needed for the drone survey mode.
Tablet PC	Samsung A7 Lite 8.7", protective case and powerbank	$163.93	10	$1,639.30	Used to collect field photos and document conservation efforts in the plots and transects the cloud-based data collection/storage (A7 is connectable via cellular networks and WiFi).
Salaries	McAdoo Summer Salary	$11,667.00	2	$23,334.00	This will allow me to dedicate time to field work (~1 month) and data analysis
Indirect Costs	Duke (61%)	$49,270.49	1	$49,270.49	
	MIT (55.1%)	$30,744.70	1	$30,744.70	
TOTAL				**$160,786.49**	

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CUT AND PASTE

Ecological Interactions. Climate change vulnerability assessments have identified almost all lemur species as highly vulnerable to climate change-induced extreme weather events. Cyclones impact lemur population size, reproduction, and body weight[7, 2,3, 15]. Further, lemurs may need to switch their diets to less-preferred food items post-cyclone, leading to changes in foraging and resource acquisition[16]. In Manombo, 1997 Cyclone Gretelle diminished over half of diurnal lemur populations and forced black-and-white ruffed lemurs to shift to fallback foods including fruits and leaves from invasive shrubs that grew rapidly in damaged areas on the margins of the forest where they are more likely to encounter human populations[16,17]. As lemurs shift their ranging patterns in search of food and shelter post-cyclone, lemur population density may increase in habitats with higher resiliency. These resilient habitats may include low-canopy forests with few emergent trees and, possibly, dense stands of invasive species close to forest edges. As Manombo consists of inland forest with high canopy trees and littoral forest with

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