**Detailed Counterpoints for “*Madagascar’s fire regimes are typical of the global tropics and highlight obstacles to fire risk management: A response to Joseph and Rakotoarivelo”***

*Phelps, L.N., Andela, N., Gravey, M., Davis, D.S., Kull, C.A., Douglass, K., Lehmann, C.E.R.  
Global Change Biology*(1) Joseph & Rakotoarivelo: *“Madagascar is burning: 95-99% of Malagasy Central Highland (MCH) fires are 16 human-lit, and forest-cover has declined by 50% since 1950 (Joseph et al., 2021; Kull, 2004; 17 Styger et al., 2007).”*Joseph & Rakotoarivelo’s opening statement is charged and misleading. Human-lit fires are a global norm, with high proportions on Madagascar unremarkable. Joseph & Rakotoarivelo imply that recent anthropogenic fire use across Madagascar’s Central Highland grassy biomes have driven forest decline – concentrated in Eastern forests – since 1950. Joseph & Rakotoarivelo’s assertions are based on problematic assumptions, which we examined in our analyses (Phelps et al.: <https://doi.org/10.1111/gcb.16206>). Contrary to Joseph & Rakotoarivelo’s claims, we showed that landscape-scale fires escaping from grassy biomes into forests did not explain high tree loss anomalies on Madagascar.

It is well documented that the general role of people in grassy ecosystems is to preempt the season of fire. Examples include Kruger National Park (South Africa: van Wilgen et al. 2004) and Arnhem Land (Australia: Evans & Russell-Smith 2019), where in untransformed grassy ecosystems, a similar area is burned regardless of whether there is active intervention by people lighting fires. Our findings show that burned area trends in Madagascar’s grassy biomes broadly reflect tropical patterns and trends, and have even declined at a relatively fast pace (Phelps et al. Figure 4b), likely as a product of increasing land transformation (Andela et al 2017).  
  
  
(2) Joseph & Rakotoarivelo: “*Globally, savanna presence, and fire frequency, are limited by increasing mean annual precipitation (MAP).* Once MAP exceeds 2000-2500 mm, likelihood of landscape-scale and small-scale fire, and of encountering fire adapted, C4-grass dominated savannas, becomes minimal (Lehmann et al., 2011). Instead, fire-sensitive, closed-canopy forests prevail (Joseph et al., 2022).”  
Lehmann et al. 2011 statistically examined environmental correlates of likelihood of savanna occurrence, and where these analyses were correlative rather than causal in line with the type and scale of analysis. Within that study, where effective rainfall (not mean annual rainfall) exceeds 2000mm, the probability of savanna occurence is generally less than 20% with variation among continents in the limits linked to mean annual rainfall. As Lehmann et al. 2011 describe, across the tropics some proportion of land is always “not savanna”, and the relationship between vegetation limits and climate is not a deterministic one. Hence, while the probability of savanna versus forest changes along continental rainfall gradients, assuming a set rainfall related transition between biomes is a misreading of Lehmann et al 2011. Lehmann et al. (2011) suggest dynamic relationships among environment, disturbance, and vegetation govern biome limits, emphasising that interacting elements of geology, geomorphology, soils, and rainfall seasonality combine to influence plant growth, plant life history strategies, and the rates of vegetation recovery to disturbance regimes.   
  
(3) Joseph & Rakotoarivelo: *“The dataset from Phelps et al. captures this nicely: in Amazon, Congo, Western Ghats, Sunda Shelf and New Guinea rainforests, landscape-scale fire regimes are largely absent (Figure 1). Sharing closed-canopy vegetation structure, MAP, and ecological patterns and processes, Malagasy eastern forests should also be spared landscape-scale fires.”*Our study empirically shows that fire, vegetation and climate characteristics were broadly shared between Madagascar and the rest of the tropics, including the blue and green fire regimes and the NLSF regime (“No landscape-scale fire regime”: landscapes without fires > 21ha: Fig. 4a, S2a-e, S3a-c). Our datasets show that the blue and green fire regimes and NLSF regime span two NDVI-based vegetation structures (Fig. S3-S4): closed, dense vegetation and open, variable vegetation. For Madagascar, we showed that these two NDVI structures correspond to closed forest and grassy biomes respectively (Moat & Smith 2007). We are not aware of any reliable vegetation atlas covering the tropics, and it is unclear how the authors came to this conclusion. However, our study demonstrated that NDVI structures were shared between similar (MESS >24) fire regimes on Madagascar and the rest of the tropics, for both blue and green regimes. We therefore do not see an empirical basis for the authors’ claim.  
  
(4) Joseph & Rakotoarivelo: “Y*et the dataset reflects an unreported, but ecologically extraordinary anomaly: Malagasy eastern forests burn with landscape-scale fire regimes typical of open-canopy, low-MAP, fire adapted mesic savannas [regimes 1&2; with highly variable burned area, fire size, and number, despite relatively low fire presence (Phelps et al.)]. This confirms that fire regimes in Malagasy eastern rainforest (where MAP can approach 3500 mm) are like those of South America’s Cerrado savanna (MAP 1600 mm), Africa’s Angola-Namibia mopane, and Kalahari Acacia-Baikiaea woodland savannas (MAP < 1000 mm), and Australia’s Kimberley, Victoria Plains, Carpentaria, Einasleigh, and Brigalow tropical savannas (MAP < 1200 mm). This incongruity corroborates widespread eastern lowland anthropogenic fire (Frappier-Brinton & Lehman, 2022).”*As above, our data on fire characteristics, climate and vegetation do not correspond to this interpretation of our results. While the authors are correct that blue and green fire regimes occur in environments with open-variable vegetation, our study demonstrates that blue and green fire regimes also occur in environments with closed-stable vegetation across the tropics. Our dataset shows that Madagascar’s eastern forests share climate and vegetation (dense-stable) characteristics with similar fire regimes elsewhere in the tropics. We suspect these statements are based on a misunderstanding of the ecology behind blue and green fire regimes, or misunderstanding of our methodology. These claims are not supported by our data (e.g. Fig. 1).   
  
(5) Joseph & Rakotoarivelo: *“The MCH, a treeless-grassland with < 2% woodland, also has fire regimes in common with systems that share neither precipitation nor vegetation.”*  
It is unclear which data the authors are using to support these statements, and how the authors define “grassland” and “woodland”. This characterisation does not correspond to our analysis of vegetation using the Moat & Smith vegetation atlas (2007: see Phelps et al. Table 2).  
  
(6) Joseph & Rakotoarivelo: *“Mostly characterised by high MAP (1200-2500 mm; levels that support fire-free forest in Africa), MCH regimes are like those of low-MAP, fire-driven Sahelian [MAP < 1000 mm], and miombo woodlands (with > 80% woodland cover and MAP 550-1200 mm), where fires range from medium presence 45 with moderately dense tree cover, to high presence (regimes 3-5; Phelps et al.).”*  
Our dataset does not reflect this characterisation of MAP in red, orange, and yellow fire regimes, which are focused in the Central Highlands. Our dataset shows that average MAP values in Madagascar’s red, orange and yellow fire regimes sit firmly within tropical averages (1212-1268mm), ranging from ~500-2500mm (Fig. 1). We did not find an empirical basis for Joseph & Rakotoarivelo’s claims that MAP ranges from ~1200-2500 in Central Highland fire regimes.

Madagascar’s red, orange and yellow regimes do indeed have less climatic similarity to the tropics than the blue and green regimes, and minimum MAP values are somewhat elevated. However, this corresponds to higher than average elevations on Madagascar, with fire regimes clustered by elevation and MAP. As discussed in our study, this points to geographic dispersal barriers (Goel et al. 2020) rather than globally anomalous human-fire-vegetation relationships. While it is possible that people play a role in this dynamic (e.g. by influencing *Lavaka* life cycles: Brosens et al. 2022), empirical analysis is needed to determine any such role at present.

The authors’ statements appear based on the assumption that MAP is the sole driver of vegetation distribution. However, research – including that cited by Joseph & Rakotoarivelo (Lehmann et al. 2011) – has repeatedly demonstrated that complex climate-disturbance-vegetation relationships determine the distribution of grassy biomes and fire, requiring consideration (Lehmann et al. 2011; Archibald 2016; Bradstock 2010).  
  
  
(7) Joseph & Rakotoarivelo: *Figure 1*  
As above, Joseph & Rakotoarivelo’s Fig. 1 appears based on the assumption that fire and grassy biome distribution are determined solely by MAP. We view this as fundamentally problematic and an oversimplification, as whole fields of research and process-based model development are devoted to predicting biome limits and fire dynamics. As discussed in our study, the distribution of NLSF regimes is determined by complex factors, which include but are not limited to precipitation (Phelps et al.: section 4.1). We did not find any empirical evidence to support the authors’ claims. Finally, Joseph & Rakotoarivelo’s figure draws a simplification of our results, with large areas labeled as NLSF or LSF, where we found a diversity of fire regimes. Figure 1 does not offer an empirical critique of our work, despite our publicly available code or dataset. In our view, simplified visual comparison of our maps does not challenge the validity of our empirical results (Monmonier 2018).  
  
(8) Joseph & Rakotoarivelo: *“In summary, globally-exceptional anthropogenic fires have decoupled Malagasy habitat from precipitation. Why was this unnoticed?”*   
We did not find any empirical evidence to support this claim and the authors did not offer an analysis of relevant drivers to support this causal claim.   
  
(9) Joseph & Rakotoarivelo: *“Use of tree-cover alone allows heavily-degraded, closed-canopy, eastern forests (where landscape-level fires are ecologically unanticipated) to group with open-canopy, fire-adapted savanna woodlands (as it discounts ecological processes).”*  
We do not understand how the authors have drawn this conclusion, but believe it may be based on a misunderstanding of our results, as described above. Our study included analysis of both NDVI and vegetation type (Moat & Smith 2007), and we empirically showed that vegetation characteristics were shared between landmasses. As above, we would like to point out that blue and green fire regimes and NLSF regimes are comprised of different vegetation structures (dense-stable and open-variable), both of which occur across the tropics. Indeed, our analysis of vegetation overlap showed that unique vegetation characteristics were highly similar between Madagascar and the rest of the tropics – most notably for blue and green fire regimes (Figure 4a). Please see our methodology to understand how we selectively compared mutually exclusive pixels between Madagascar and the rest of the tropics for robust comparison (i.e. with MESS >24: Fig. S6).

(10) Joseph & Rakotoarivelo: *“Geographic discrepancies likely compound matters; e.g. Phelps et al. report “global analogs” (of landscape-scale fires like those that burn in eastern lowlands) “include…the Namib”. Yet the Namib is a fire-free coastal strip west of systems that experience landscape-scale fires.”*   
Arid continental regions in Namibia and Australia experience boom and bust cycles of rainfall that govern patterns of fuel accumulation over decadal to multi-decadal cycles. Hence, some arid continental regions in these countries were also clustered into blue regimes where landscape scale fire is infrequent due to constraints on fuel accumulation and consequently fire spread.  
  
(11) Joseph & Rakotoarivelo: “*Furthermore, limiting fire-induced degradation to ‘tree-loss’ in MCH, a system where palaeoanthropogenic fire has already removed most trees (Joseph et al., 2022), discounts other fire-induced degradation [e.g.; spread of poorly-palatable fire-selected grasses / topsoil loss through erosion (Joseph & Seymour 2020; Joseph & Seymour 2021)].*”  
Degradation is complex and context-specific, with tree loss in forests widely considered as a facet of degradation. Our study examined patterns of fire related to vegetation, climate and human metrics, and we did not seek to discount any other elements of degradation. Rather we focused on what is achievable with MODIS remote sensing (landscape-scale). Future empirical studies focused on other facets of degradation (e.g. using functional traits or erosion) can provide added value. However, as widely recognised, the assertion that paleo-anthropogenic fire has already removed most Central Highland trees is deeply controversial. The necessary data coverage to draw such conclusions about past land cover change does not currently exist.  
  
(12) Joseph & Rakotoarivelo: “*Phelps et al. acknowledge that limiting fire-effects to landscape-scales discounts fire-impact…*”  
We did not acknowledge this statement, and view it as inappropriate twisting of our words. We stated: “Such small-scale fires associated with land clearance are often conflated with landscape-scale fire processes (e.g., pastoral burning) and interpreted without empirical understanding of fire regimes, leading to generalized blame of fire use by local communities… Appropriate fire interventions will therefore consider fire, land use, and land cover processes at multiple scales, and within a local socio-ecological context aimed at co-benefiting ecosystems and livelihoods (e.g., Martin et al., [2022](https://onlinelibrary.wiley.com/doi/10.1111/gcb.16206#gcb16206-bib-0081))...Because landscape-scale and small-scale fires may reflect important differences in land use and land cover processes (e.g., landscape burning versus small fires associated with landscape clearing), each requires explicit investigation. Our global analysis focuses on landscape-scale fire processes, with the analysis of small-scale fires beyond the scope of this study.”  
  
(13) Joseph & Rakotoarivelo: “*…and explicitly state small-scale fires are beyond the study’s scope.*”  
This statement is correct. Our study nonetheless provided a detailed discussion of small-scale fires and their importance, as well as a supplementary analysis of where small-scale fires are occurring (2016), to support future studies on small-scale fire in socio-ecological context (Fig. S1).  
  
(14) Joseph & Rakotoarivelo: *“This is problematic given Madagascar’s widespread small-scale fires (Kull, 2004), because remote fire-sensing using course pixel-size can underestimate burned area by 80% where small-scale fires are frequent (Roteta et al., 2019; Ramo et al. 2021). E.g., this landscape-scale approach leads to conclusions that tree-loss in eastern forests without landscape-scale fire is “unexpectedly” high, and that “the role of small-scale fires is unknown”.”*  
Our study focuses on landscape-scale fire (>21ha), and not small-scale fires (<21ha). This is explicit within our study. Our conclusions about landscape-scale fire fit within the scope of our study and how we defined it. We cited the work of Roteta et al. (2019) and Ramo et al. (2021) to discuss the importance of small-scale fires. We also provided supplementary analysis of small-scale fires using an associated dataset (Fig. S1: Roteta et al. 2019). Therefore, we do not see a utility for this critique. Tree loss in Madagascar’s NLSF forest regimes were unexpectedly high, and we make clear that this does not preclude small scale fires. Small scale fires need to be empirically investigated in socio-ecological context to understand their role in degradation areas of NLSF regimes. The authors have not presented evidence to the contrary.  
  
(15) Joseph & Rakotoarivelo: “Forty-five thousand annual fires (Frappier-Brinton & Lehman, 2022) burn 2000-7000 km2 of primary and secondary eastern forest per year (Kull, 2004).”   
Frappier-Brinton & Lehman (2022) use the term “fire” to refer to each detected 375m hotspot, however, they acknowledge that, “A single burning front can result in multiple fire hotspots…”. We therefore cannot agree with equating a single fire point as a single fire, and indeed this is not how NASA intended the use of these data. We acknowledge that VIIRS data provides useful information about small-scale fires, e.g. biomass burned, and hope future studies will build on the understanding of fire regimes using VIIRS data linked to MODIS and Sentinel data.   
  
In addition, we note that Kull (2004) was published 18 years ago, with fire trends on Madagascar changing substantially since.  
  
  
(16) Joseph & Rakotoarivelo: *“Far from being unexpected, it is widely recognised that following cutting, repeated small-scale fire-cycles drive degradation, entrenching high-level tree-loss (Frappier-Brinton & Lehman, 2022; Styger et al., 2007).”*  
We appreciate this point, but this was not the focus of our study. We discussed the role of small-scale fires in detail in our discussion section, and provided a supplementary analysis of Sentinel data, which better captures small fires. Further, we discuss tavy and charcoal production as likely drivers of degradation in NLSF regimes via small scale fire.

(17) Joseph & Rakotoarivelo: *“Initially fires enhance crop and rangeland production, but after 30 years, the final cycles (exacerbated by frequent ‘escape-fires’ degrading entire hillsides) leave eroded, nutrient-depleted landscapes of fire-adapted, poorly-palatable, treeless-grasslands with “minimal productive and ecological value” (Styger et al., 2007).”*   
Fire and environment vary across Madagascar with dynamic relationships to human land use. Styger et al. (2007) is based on one such region and time period – the “Vohidrazana/Beforona study area, located at the margins of the Ankeniheny-Zahamena rainforest corridor” (Styger et al. 2007). While we appreciate that there are a variety of regionally important processes relating to small-scale fire, it remains unclear what these points add to what is already discussed in our manuscript. Our study noted that small fires can escape, and we imagine that landscape-scale fires in forested blue regimes across the tropics are a result of anthropogenic degradation such as this. For this reason our study stated: “Where associated with forests, low-variable fire regimes [blue] likely include fires that follow recent clearing.” We also extensively discussed the importance of small-scale fires.  
  
(18) Joseph & Rakotoarivelo: *“Madagascar emerges as atypical, an ecological peculiarity, where excessive human-lit fires burn forest like savannas, and where large aspects of the Central Highlands endure the highest-level landscape-scale fire regimes, despite sharing precipitation with African rainforests.”*  
As discussed elsewhere, we do not find any empirical basis for these conclusions.   
  
(19) Joseph & Rakotoarivelo: *“Here, we caution that global-scale studies offer broad application, but their coarse-scale can lead to simplification or omission of finer-scale patterns that harbour important ecological processes. This in turn can distort conclusions and limit their applied value.”*   
MODIS data in all its dimensions is the foundation of remote observation of the Earth at global and regional scales, and these data have led to major progress in our understanding of the Earth System. While we are unsure how the authors define ‘coarse-scale’ and do not necessarily agree with their interpretation of MODIS data (500m) as ‘coarse-scale’, we agree that coarse-scale patterns often do not capture small-scale patterns. However, this does not make coarse-scale or landscape-scale patterns any less valuable. Issues do not arise from investigating patterns at different scales, but from poor interpretation of coarse-scale patterns and conflation between processes that occur at different scales and/or socio-ecological contexts. We presented our results at their appropriate scale and included discussion of their relationship to small-scale processes, which are important and require further investigation. Joseph & Rakotoarivelo’s critique fundamentally overlooks the contributions of our landscape-scale study, without providing added value.  
  
(20) Joseph & Rakotoarivelo: *“For Madagascar, underestimating and normalising anthropogenic fires, which remain the critical threat to biodiversity island-wide, imperils both hard-won anti-fire legislation and conservation efforts at a range of scales (Frappier-Brinton & Lehman, 2022).”*  
Fire has been a part of ecosystems for hundreds of millions of years, and today, anthropogenic fire is the primary source of ignitions across the tropics. As above, suggesting that anthropogenic fire on Madagascar is abnormally high is misleading without providing empirical evidence – particularly evidence that does not rely on equating fire points with individual fires. As discussed in our study, it is likely that degradation processes, linked to small-scale fires in fire-sensitive ecosystems such as forests (e.g. via tavy and charcoal production) are driving abnormally high degradation rates on Madagascar. However the primary drivers of degradation and the direct contributions of small-scale fire processes are still poorly understood.

Our study focuses on landscape-scale fire (>21ha). The authors have not provided evidence that we underestimate landscape-scale fires, and have not expanded our discussion or analysis of small-scale fire. Limited understanding of multidimensional fire processes threatens effective land management, rather than acknowledgement that humans ignite the majority of fires across the tropics. We agree that fire in fire-sensitive ecosystems is an important driver of tropical degradation and requires effective management – both within and outside of forests. Practical and effective management of fire regimes is fundamental to managing fire risk under rapidly changing global conditions (e.g. Cochrane & Bowman 2021).

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