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LETTER

Identifying climate-smart tropical Key Biodiversity Areas for protection in response to widespread temperature novelty

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Abstract

Key Biodiversity Areas (KBAs) are a cornerstone of 21st-century area-based conservation targets. In tropical KBAs, biodiversity is potentially at high risk from climate change, because most species reside within or beneath the canopy, where small increases in temperature can lead to novel climate regimes. We quantify novelty in temperature regimes by modeling hourly temperatures below the forest canopy across tropical KBAs between 1990 and 2019. We find that up to 66% of KBAs with tropical forests have recently transitioned to novel temperature regimes. Nevertheless, 34% of KBAs are providing refuge from novelty, 58% of which are not protected. By conducting the first pan-tropical analyses of changes in below-canopy temperature conditions in KBAs, we identify KBAs that are acting as climate refugia and should be considered for expansion of the conservation network in response to the post-2020 Global Biodiversity Framework target to conserve 30% of land area by 2030.

KEYWORDS

climate change, climate novelty, conservation prioritization, Key Biodiversity Areas, microclimate, tropical biodiversity

1 | INTRODUCTION

Key Biodiversity Areas (KBAs) are sites of global importance for biodiversity in the face of an ongoing sixth mass extinction (Cowie et al., 2022). They are identified following internationally recognized criteria that account for biodiversity metrics, such as the presence of globally threatened and/or range-restricted species (IUCN, 2016). KBAs foster species persistence (Butchart et al., 2015, 2012) and are a critical tool for an evidence-based approach to expand site-based global conservation efforts in line with international ambition (Plumptre et al, 2024). The Post-2020 Global Biodiversity Framework includes a draft target to ensure that at least 30% of land area globally is conserved by 2030 (CBD, 2020; Ward et al., 2020) and specifically identifies KBAs as a core priority for any expansion.

Tropical forests are global hotspots of terrestrial biodiversity (Barlow et al., 2018; Mittermeier et al., 2011), providing critical ecosystem services and sustaining the livelihoods of over a billion people worldwide (Fedele et al., 2021). Yet, as well as increasing pressures from deforestation, fragmentation, and degradation (Vancutsem et al., 2021), there is an escalating threat from anthropogenic climate change. The environment below the forest canopy is climatically very stable. Here, sunlight is reduced and evapotranspirative cooling is increased, dampening temperature fluctuations compared to open habitats and resulting in cooler below-canopy maximum temperatures, warmer minimum temperatures, and lower seasonal and interannual variability (Barry & Blanken, 2016; De Frenne et al., 2019). As such, species here are at particularly high risk from novel climate conditions—climates with no historic analogs (Dobrowski et al., 2021; Senior et al., 2019; Trew et al., 2024)—because they have evolved under a narrow range of thermal conditions and may only be able to tolerate a small margin of warming above their thermal optima (Jirinec et al., 2022; Tewksbury et al., 2008; Trew & Maclean, 2021). The ongoing transition of tropical forest environments to novel temperature regimes has the potential to undermine the effectiveness of tropical KBAs as a prioritization tool for conservation strategy (Araújo et al., 2011) by precipitating changes in niche availability (Zellweger et al., 2020) and triggering changes in community composition (Gilman et al., 2010; Lensing & Wise, 2006).

Assessing the threat of climate change to tropical forest KBAs is a crucial step in applying effective protection or conservation initiatives on a site-by-site basis (Brown et al., 2022). Temperature is an important constraint on species distributions and ecological function (Deutsch et al., 2008; Neate-Clegg et al., 2021). However, temperatures are typically recorded inside well-ventilated protective shields placed 2 m above the ground, in open habitats carefully selected to be unaffected by local microclimatic influence (Bramer et al., 2018; Maclean et al., 2021). We now have the ability to model microclimate conditions of the below-canopy tropical forest environment at high spatiotemporal resolutions, and so we know that temperature regimes below the forest canopy—those actually experienced by tropical forest organisms—are becoming increasingly novel (Trew et al., 2024). Accordingly, we can identify climate-smart KBAs that are, thus far, not experiencing novel temperature regimes—currently acting as climate refugia—whose addition to the global conservation network using protected areas (PAs) or other effective conservation area-based conservation methods (OECMs) would greatly improve the future resilience of tropical biodiversity.

Here, we conduct the first global analysis of changes in below-canopy temperature conditions in tropical KBAs. To accurately represent temperature conditions experienced by the majority of forest-dwelling organisms, we modeled below-canopy, near-ground, hourly temperatures across the world's tropical KBAs between 1990 and 2019. We integrate a recently developed mechanistic microclimate model (Maclean & Klinges, 2023) with empirical temperature measurements and satellite-derived land-cover data to derive an index of novelty for seven temperature variables widely shown to affect species distributions (Hijmans & Graham, 2006). Since tropical forests typically experience low temporal variability in temperature, incremental changes can push climate conditions beyond a species' normal thermal range. Consequently, we posit that evaluating temperature novelty is a more reliable measure of climate vulnerability than simply the magnitude of temperature changes (Foden et al., 2013). Ergo, the novelty index represents the fraction of years in the recent period in which temperature regimes lie outside their recent historical range and identifies (i) KBAs that are already highly threatened by shifting temperature regimes and (ii) unprotected or partially protected KBAs that already provided refuge from shifting temperature regimes and should be priority areas for expansion of the global conservation network.

2 | METHODS

Using a mechanistic microclimate model (Maclean & Klinges, 2023), we quantified hourly below-canopy climate conditions across the global tropics (−30 to 30°S; −109 to 180°E) between 1990 and 2019. The microclimate model was first run in daily time increments and then hourly temperatures—at 0.05 m above the ground—were derived using the model's interpolation methods, which infer hourly data from daily minima and maxima using the diurnal cycle in the ambient temperatures provided as inputs to the model. The *microclimf* model is open source and available as a documented R package on GitHub (Maclean & Klinges, 2023).

In summary, the following workflow is implemented. The model downscales hourly input climate-forcing data to the desired spatial resolution (in this case, 5 km gridded resolution) using spatial interpolation and the application of an elevation- and humidity-dependent lapse rate correction. Temperature and water vapor at the desired height are then modeled mechanistically using principles of energy conservation, that is, by assuming that components of the energy budget remain in balance and by solving the energy budget for foliage temperature using the Penman–Monteith equation (Maclean & Klinges, 2021). Radiative energy is assumed to be influenced by slope, aspect, and canopy cover. Radiative fluxes through the canopy are estimated using a two-stream approximation model (Sellers, 1985). Sensible and latent heat fluxes are assumed to depend on wind speed, which in turn is attenuated vertically by canopy foliage using the method described in Harman and Finnigen (2007) and terrain–shelter adjusted using the method described in Ryan (1977). Latent heat fluxes are assumed additionally to depend on the stomatal conductance of leaves, which is quantified from the availability of photosynthetically active radiation using the method described in Kelliher et al. (1995). Ground heat fluxes are quantified from soil properties and from diurnal and annual cycles in temperature, using the method described in de Vries and Van Wijk (1963) and also given in Campbell and Norman (2012). Air temperature is then derived from foliage temperatures using the localized near-field model described by Raupach (1994). Further details regarding the climate and environmental parameters, including canopy cover, driving the model are described in the Supporting Information. Validation of the modeled below-canopy temperatures across the global tropics was conducted and described in Trew et al. (2024).

The hourly modeled below-canopy climate conditions were used to calculate annual bioclimatic variables detailed in Fick and Hijmans (2017), namely, (1) mean annual temperature, (2) mean diurnal temperature range, (3) isothermality, (4) seasonality, (5) maximum temperature of the warmest month, (6) minimum temperature of the coldest month, and (7) annual temperature range. For each below-canopy temperature variable, we measured the fractional overlap between (1) annual values from the baseline historical time period (1990–2004) and (2) annual values from the most recent time period (2005–2019). This was done by computing the frequency distribution curves of the annual values across historical and recent time periods separately, and then novelty was derived as 1 minus the proportion of overlap in annual values between the two periods, calculated as

$$\begin{aligned}&\text{Novelty}\\&= 1 - (2 \times \text{IntersectionArea}/\text{TotalAreaofBothCurves}).\end{aligned}$$

This novelty index represents the fraction of years in the recent period (2005–2019) in which the climate lies outside the range of conditions that occurred in the baseline historical period (1990–2004). For example, if both mean annual temperatures and interannual variance in mean annual temperature were identical in both periods, the novelty index would be zero. If two thirds of the mean annual temperatures in the latter period lay outside the range of temperatures in the historic period, then the novelty index would be 0.6667. Thus, the locations with novelty indexes closer to 1 are those with no recent climate analog relative to the recent historical baseline (period 1). Here, we have presented results for mean annual temperature, which have been used to test critical thresholds for tropical forests (Doughty et al., 2023), with results for the six other temperature variables in the Supporting Information.

We define relatively novel temperature regimes as KBAs with >0.4 fractional mean novelty in the temperature variable when compared to the historic baseline and relatively stable temperature regimes as those with <0.4 fractional mean novelty in the temperature variable when compared to the historic baseline. There is very little temporal variability in below-canopy tropical temperatures, ergo 0.4 fractional novelty in temperature regimes was chosen here as a conservative, early-warning threshold for tropical KBAs where species will be highly sensitive to environmental change (Jirinec et al., 2022; Tewksbury et al., 2008). For the same reasons, we consider a fractional novelty of 0.8 or more as an almost entirely novel temperature regime.

Global KBA boundaries (BirdLife International, 2022) were filtered to include KBAs that held at least one 5-km gridded cell of tropical forest ($n = 2663$), including undisturbed and degraded tropical forest in 2019 as defined by Vancutsem et al. (2021), a detailed definition of which can be found in the Supporting Information. For each KBA and each temperature variable, we calculated the mean fractional novelty occurring recently (2005–2019), weighted by area, and the coefficient of variation of fractional novelty. Lastly, global PA boundaries were sourced from the World Database on Protected Areas (Protected Planet, 2021) and cleaned as per the standard protocol using the *wdpa* package (Hanson, 2022) in R (R Core Team, 2022). Tropical forest KBAs lacking formal protection were identified by intersecting KBA and PA boundaries to calculate the percentage coverage of formal protection.

3 | RESULTS

3.1 | Tropical KBAs are already highly threatened by shifting temperature regimes

Approximately 66% of KBAs holding tropical forests have recently transitioned to novel mean annual temperature regimes (>0.4 mean fractional novelty), with the remainder experiencing relatively stable temperature regimes over the last three decades. The proportion of KBAs in Africa and Latin America with relatively novel temperatures was particularly high (72% and 59%, respectively), while fewer KBAs across Asia and Oceania are shifting to relatively novel temperature regimes (49%).

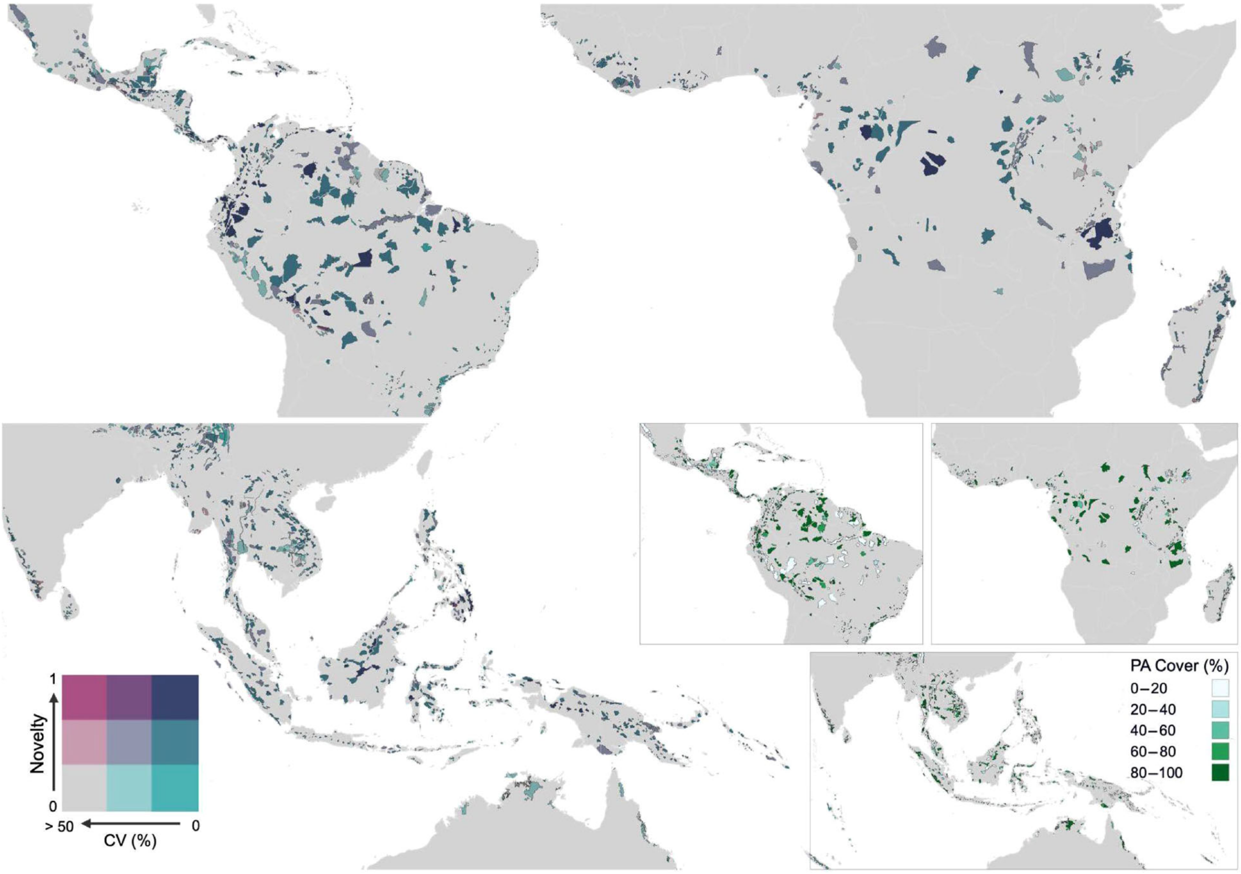

FIGURE 1 Mean fractional novelty (0–1) in recent mean annual temperatures (2005–2019) compared to the historic baseline (1990–2004) and the coefficient of variation (CV) in novelty values (%) across Key Biodiversity Areas (KBAs) containing tropical forests in Latin America ($n = 867$), Africa ($n = 395$), and across Asia and Oceania ($n = 1262$). A value of 1 for novelty indicates entirely novel mean annual temperature regimes in 2005–2019, while a CV close to 0% indicates minimal variability in novelty values across the KBA. KBAs with high mean novelty and low variation in novelty across geographical space are likely to be most at risk. Individual inset maps show protected area coverage (%) for each KBA.

There are KBAs across Latin America (2.9%) and a small number in Asia and Oceania (0.4%) that have recently transitioned to almost entirely novel temperature regimes (>0.8 mean fractional novelty). In Latin America, these KBAs were all located in Ecuador, Colombia, Venezuela, or Panama (Figure 1), with the Tropical Andes particularly affected by recent novel mean annual temperatures, including the Cayambe-Coca National Park (0.83) and Kutukú-Shaimi Protection Forest (0.84). Across Asia, KBAs experiencing strong shifts in mean annual temperatures were predominantly located across Indonesia and the Philippines (Figure 3), including the Mt. Agtuuganon and Mt. Pasian KBA (0.86) and the indigenous territory of Pangasananan (0.85). We found no KBAs in Africa experiencing almost entirely novel mean annual temperature regimes, although some KBAs experienced strong shifts in recent temperature regimes, including the Gueoule and Glo Mountain Forest Reserves and Mt. Nimba Strict Nature Reserve (0.76 and 0.74, respectively), both located across Côte d'Ivoire and Guinea (Table S1). KBAs in the Central Congo basin moist forests in the Democratic Republic of Congo have also transitioned to novel temperature regimes, including Africa's largest tropical rainforest reserve: Salonga National Park (0.70).

3.2 | Many tropical KBAs are acting as climate refugia but they lack protection

In Latin America, approximately 40% of KBAs experienced recent mean annual temperatures similar to the historic baseline, many of which were located in the Peruvian Yungas, Mexican Yucatan, and Guianan Shields. Latin America had the highest number of KBAs (0.06%) that experienced negligible novelty in mean annual temperature regimes, and these were predominantly located in the coastal Atlantic Forest of Brazil. However, only 16% of climatically stable KBAs benefit from PA coverage over at least half of their area and 6% do not benefit from any PA coverage (Figure 2). For example, the Sierra Madre

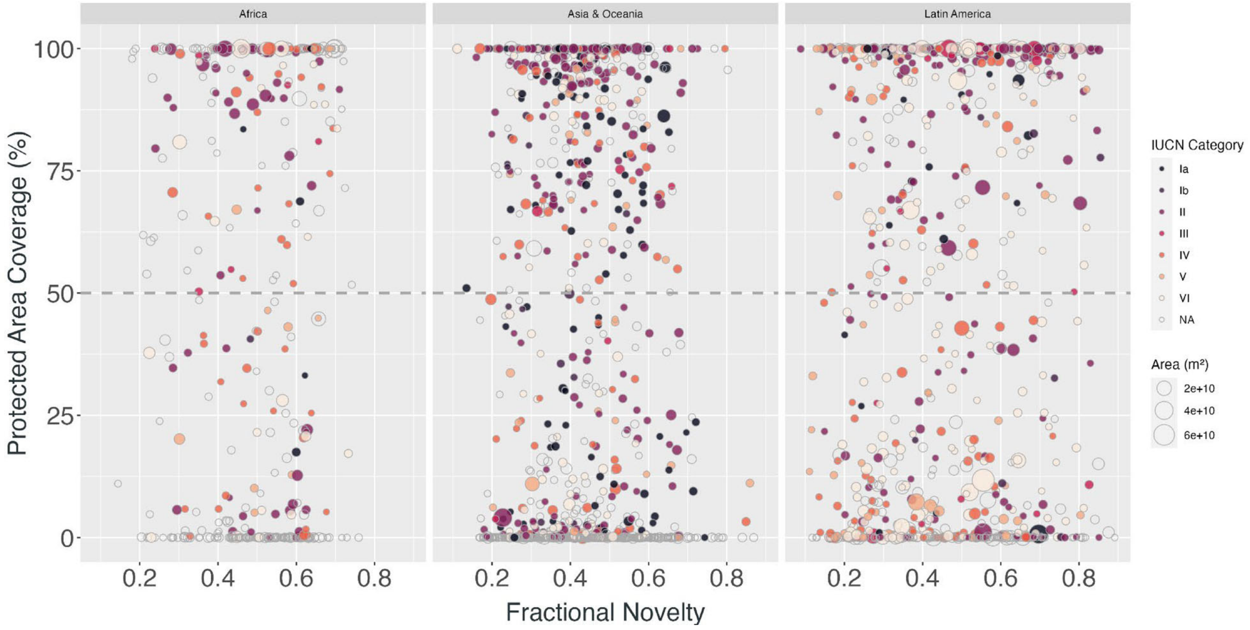

FIGURE 2 Each point represents a Key Biodiversity Area (KBA) containing tropical forest in Africa, Asia, Oceania, and Latin America. The points demonstrate the relationship of the mean novelty in recent mean annual temperatures experienced by each KBA and its formal protected area coverage (%). Point colors correspond to the IUCN category of the protected area, and the size of each point corresponds to the geographical size of the KBA (m^2). KBAs with low protected area coverage and low mean novelty in mean annual temperature should be prioritized for area-based conservation planning.

Occidental Canyon Corridor in Northern Mexico (0.36) has no PA coverage (Figure 3). Of those KBAs with at least 80% PA coverage, 37% did not experience significant shifts in mean annual temperature regimes, including the UNESCO designated Iguazú National Park spanning Brazil and Argentina (0.27), part of the Atlantic Forest biome, and La Tigra National Park in Honduras (0.31).

Across Africa, far fewer KBAs experienced recent mean annual temperatures similar to the historic baseline (24%); these were mainly located in the Western Congo Basin, the East African montane forests, and the highland forests across Equatorial Guinea and Cameroon. Only four KBAs experienced almost entirely stable mean annual temperature regimes, including the Rio Pongo and Iles Tristao KBAs and Ramsar sites in Guinea (both 0.18) and forest reserves in Uganda (Mount Kadam: 0.18) and Kenya (Kitale West: 0.14). Moreover, 13% of KBAs that have not shifted to novel mean annual temperature regimes were found to have PA coverage over at least half of their area and 4% do not benefit from any PA coverage. For example, the South Nguruman KBA (0.20), forming the western wall of the Rift Valley in Kenya, has no PA coverage (Figure 4). Of those KBAs with at least 80% PA coverage, 20% did not experience significant shifts in mean annual temperature regimes, including the Western Area Peninsula Forest National Park (0.24) in Sierra Leone, an important remnant of West African rainforest.

Of the KBAs in Asia and Oceania, 46% experienced recent mean annual temperatures similar to the historic baseline. These KBAs were predominantly located across Southern Papua New Guinea, Central mainland Malaysia, and North-East Borneo. Only 0.02% of KBAs across Asia and Oceania experienced almost entirely stable mean annual temperature regimes (<0.2 mean fractional novelty). For instance, KBAs in Northern Australia's tropical forests experienced some of the least novel temperature regimes globally, including Daintree Rainforest (0.11) and Wooroonooran National Park (0.17). However, a considerable number of KBAs experiencing low novelty in recent mean annual temperatures also lacked PA coverage (Figure 2). The Tiwi islands in North-West Australia experienced temperatures with relatively low novelty (0.19 fractional novelty) without benefiting from any formal PA coverage (Figure 5). Indeed, only 12% of KBAs that have not shifted to novel temperature regimes across Asia and Oceania have PA coverage over at least half of their extent, and 23% did not benefit from any PA coverage. Of those KBAs with at least 80% PA coverage, 48% did not experience significant shifts in mean annual temperature regimes, including the world's largest tiger reserve, the Hukaung Valley Wildlife Sanctuary KBA in the Northern Forest Complex of Myanmar (Figure 5).

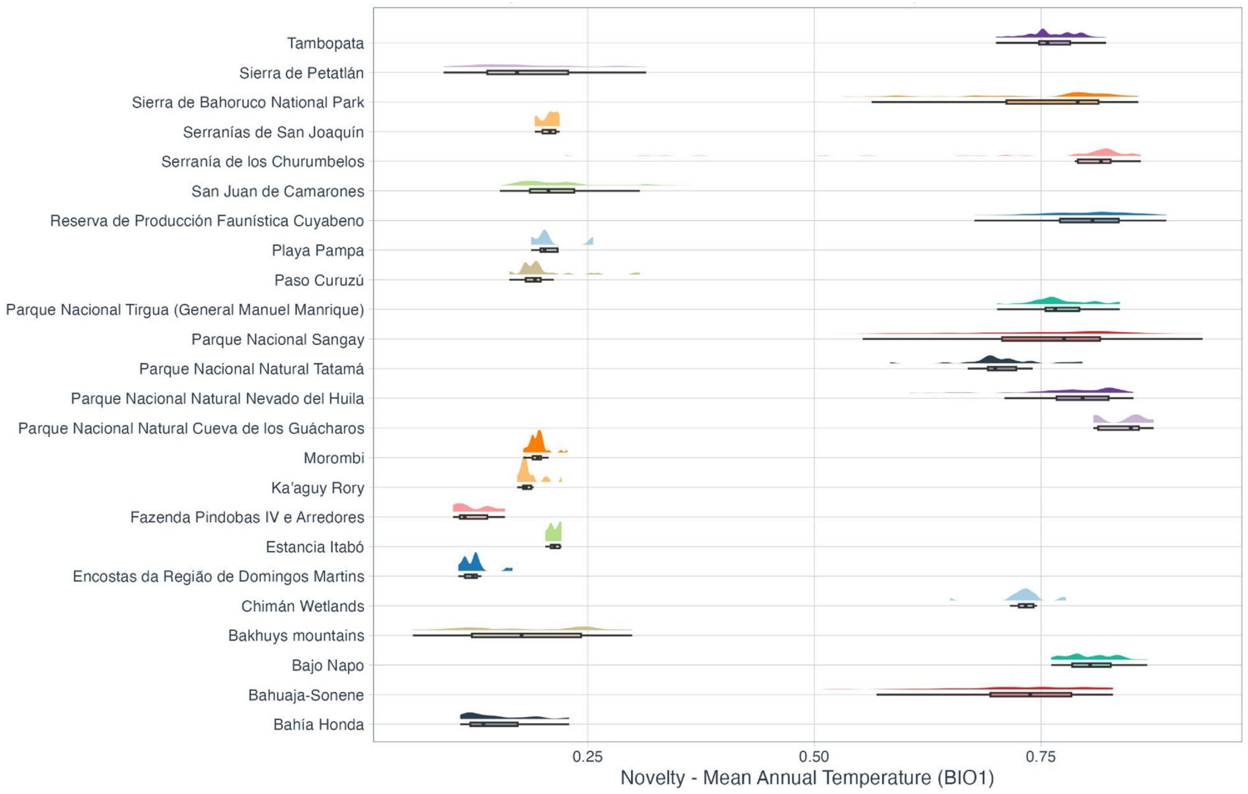

FIGURE 3 Fractional novelty in recent mean annual temperatures (2005–2019) compared to the historic baseline (1990–2004) for the 12 KBAs in Latin America containing tropical forest with at least 99% protected area coverage and the highest recent mean fractional novelty in mean annual temperature and the 12 KBAs in Latin America containing tropical forest with the lowest recent mean fractional novelty in mean annual temperature and no protected area coverage. Novelty is measured between 0 and 1, where 1 indicates entirely novel mean annual temperature regimes in 2005–2019. The vertical line within the boxplot displays the median of the data, the box limits refer to the interquartile range (IQR), and the whiskers extend to the minimum and maximum values. The data points falling outside the whiskers are outliers.

4 | DISCUSSION

Global conservation efforts would be increasingly effective if the potential impact of ongoing climate change was appropriately considered. Shifts from climate regime baselines are not uniform across the globe, and the impact of these shifts depends, in part, on the prehistoric variability of climate (Trew & Maclean, 2021), which varies geographically and vertically in space (De Frenne et al., 2021; Lembrechts et al., 2018). As a result of naturally lower climate variability below the forest canopy, tropical forests are now subject to increasing threats from novel climates (IPCC, 2021; Trew et al., 2024). This is particularly concerning as tropical forests host the majority of biodiversity worldwide (Pillay et al., 2022) and KBAs here hold particular conservation value, having been identified on the basis of the biodiversity they host as well as holding some of the largest areas of high-integrity forest (Crowe et al., 2023). Thus, it is crucial that KBAs that are so far providing refuge from shifting temperature regimes and those already at risk are identified for climate-smart decision-making. To achieve this, we quantified the recent novelty of below-canopy temperatures across KBAs with tropical forests between 2005 and 2019 relative to a historic baseline. As well as highlighting a large proportion of KBAs already impacted by novel temperature regimes, many of which are internationally important national parks and indigenous lands (Garnett et al., 2018), we have identified substantial numbers of KBAs that could benefit from expansion of the global conservation network using PAs, OECMs, or other approaches.

4.1 | Biodiversity is at high risk in KBAs experiencing climate novelty

Conservation schemes in regions affected by shifts to novel temperature regimes will need to explicitly consider climate-driven changes in biodiversity patterns (Dowbrowski et al., 2021). Exemplars of KBAs already experiencing novel temperature regimes are those within the Yasuní Biosphere Reserve—a designated Ecuadorian UNESCO World Heritage Site with some of the highest biodiversity per square meter globally (Bass et al., 2010)—which have

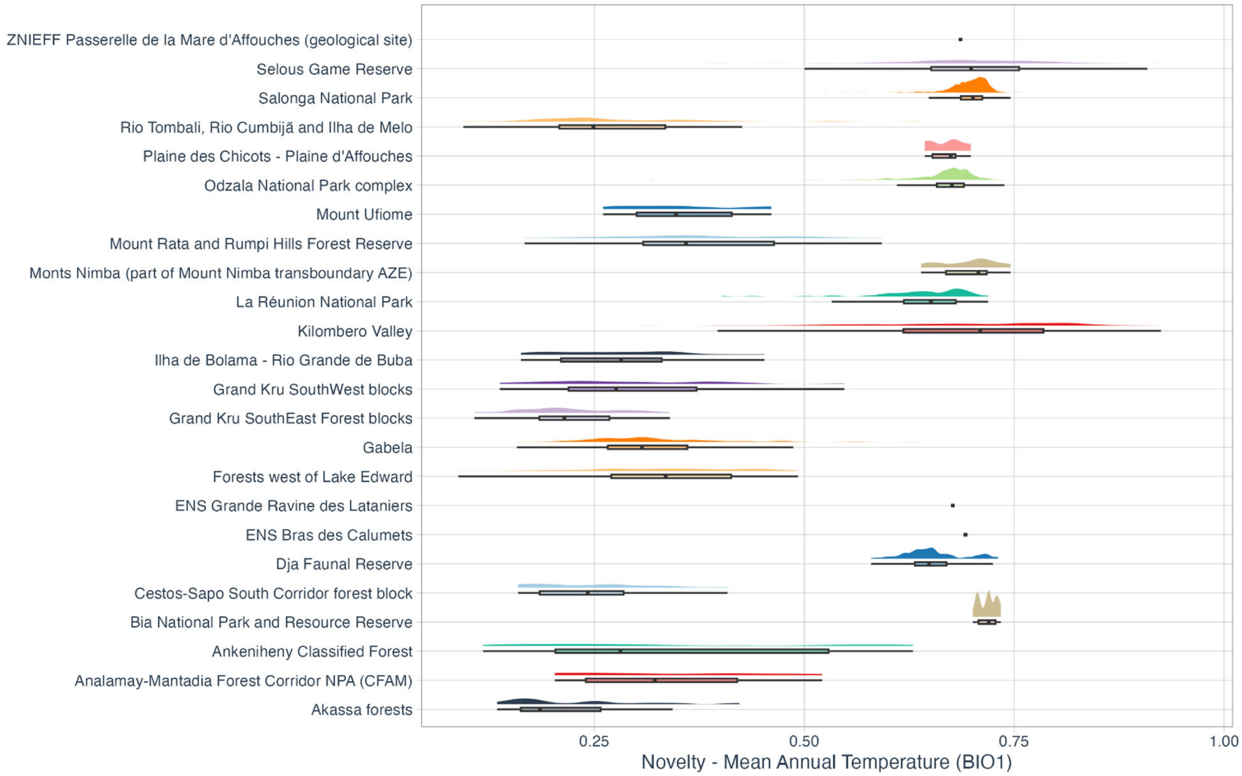

FIGURE 4 Fractional novelty in recent mean annual temperatures (2005–2019) compared to the historic baseline (1990–2004) for the 12 KBAs in Africa containing tropical forest with at least 99% protected area coverage and the highest recent mean fractional novelty in mean annual temperature and the 12 KBAs in Africa containing tropical forest with the lowest recent mean fractional novelty in mean annual temperature and no protected area coverage. Novelty is measured between 0 and 1, where 1 indicates entirely novel mean annual temperature regimes in 2005–2019. The vertical line within the boxplot displays the median of the data, the box limits refer to the interquartile range (IQR), and the whiskers extend to the minimum and maximum values. The data points falling outside the whiskers are outliers.

experienced some of the strongest shifts in recent temperature regimes pan-tropically. KBAs within both lowland PAs like Salonga National Park in the Democratic Republic of Congo and PAs covering mountainous forests such as the Mount Nimba Strict Nature Reserve have also recently experienced strong shifts to novel temperature regimes. Species inhabiting lowland areas will struggle to track their environmental niche due to an absence of elevational gradients (Trew & Maclean, 2021). Equally, many species inhabiting mountain regions such as Mount Nimba—a UNESCO World Heritage Site in West Africa that encompasses 1752 m in elevation—could be highly vulnerable to temperature changes. Species here are likely to have narrow ranges and limited dispersal ability. Consequently, novel temperature regimes may mean they lose access to their climate envelope and are outcompeted by downslope taxa (Enquist, 2002; Laurance et al., 2011).

To mitigate anticipated biodiversity loss within KBAs experiencing high rates of local climate change, it is paramount that distant wealth-related drivers of deforestation, degradation, and climate change are addressed (Carmenta et al., 2023). Locally, large-scale forest restoration programs are needed (Gillson et al., 2013) within and outside of KBAs to connect forest fragments and promote climate connectivity, as well as the overall size and interior (i.e., non-edge affected) of forest (Gonzalez del Pliego et al., 2016; Strassburg et al., 2020). Such restoration efforts and any expansion of a conservation network must be undertaken in a socially just manner, preferably with local organizations representing people living in and managing tropical forest landscapes (Fleischman et al., 2022).

4.2 | Prioritizing climate-smart KBAs for expansion of the global conservation network

There are considerable numbers of unprotected and partially protected KBAs, highlighted here, that provide refuge from novel temperature regimes and are prime candidates for expanding conservation programs. For example, the Central Suriname Nature Reserve—a UNESCO World Heritage Site—covers multiple KBAs and has a large elevational range (over 1200 m), safeguarding

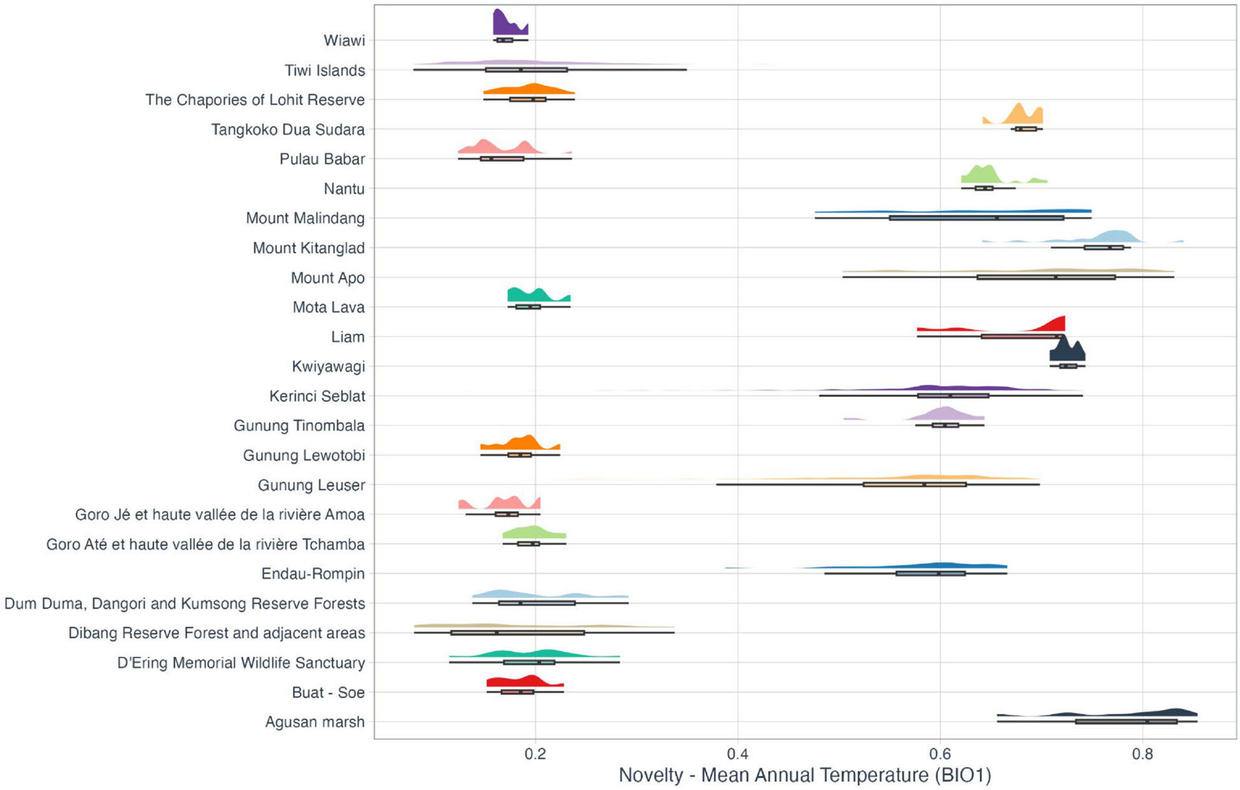

FIGURE 5 Fractional novelty in recent mean annual temperatures (2005–2019) compared to the historic baseline (1990–2004) for the 12 KBAs in Asia and Oceania containing tropical forest with at least 99% protected area coverage and the highest recent mean fractional novelty in mean annual temperature and the 12 KBAs in Asia and Oceania containing tropical forest with the lowest recent mean fractional novelty in mean annual temperature and no protected area coverage. Novelty is measured between 0 and 1, where 1 indicates entirely novel mean annual temperature regimes in 2005–2019. The vertical line within the boxplot displays the median of the data, the box limits refer to the interquartile range (IQR), and the whiskers extend to the minimum and maximum values. The data points falling outside the whiskers are outliers.

multiple habitats that support exceptional levels of biodiversity and act as a buffer against climate change impacts. However, as is the case for many tropical PAs (Leberger et al., 2020; Mascia & Pailler, 2011), there is very little on-the-ground management capacity to address intensifying threats from human activities such as nearby mining and logging (Osipova et al., 2020). Pressures on biodiversity can accumulate if protections for KBAs are inadequate or underresourced, as climate change can also interact with and act as a multiplier of anthropogenic threats like habitat fragmentation and degradation (Bowler et al., 2020).

For ambitious area-based conservation targets like the Post-2020 Global Biodiversity Framework's "30×30" to be effective, expansion of the global conservation network needs to urgently consider the spatiotemporal patterns of climate change and expand area-based methods of protection to those climate-smart KBAs that currently lack any formal protection. However, as demonstrated here, it is crucial that local conservation planning exercises use measures of climate change that reflect the microclimatic conditions under which species evolve and persist. In tropical forests, incremental changes in temperature regimes can translate to entirely new temperature conditions (Trew et al., 2024), to which many tropical forest species are not pre-adapted (Watson et al., 2019).

Pan-tropically, this means those KBAs that have experienced low novelty in recent temperature regimes are among the highest priorities for assessing required conservation actions to target drivers of forest loss and degradation, especially in locations where pressure is highest, via a combination of legal protection (Roberts et al., 2020), carbon payments (Crossman et al., 2011), empowering indigenous communities (Sze et al., 2022), or OECMs (Dudley et al., 2018). Moreover, to ensure an adequately representative sample of pantropical biodiversity is protected, conservation programs should consider how climate-smart KBAs can be prioritized across biogeographical realms. By considering ongoing climate change, global conservation efforts would be increasingly effective in maintaining the future resilience of tropical biodiversity.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Global hourly climate data are available from https://cds.climate.copernicus.eu/. Environmental parameters include (a) leaf area index and surface reflectance available from https://www.ncei.noaa.gov/data/avhrr-land-leaf-area-index-and-fapar/, (b) global habitat types available from https://www.esa-landcover-cci.org/, (c) vegetation height available from https://webmap.ornl.gov/ogc/, (d) soil types available from https://www.soilgrids.org, and (e) digital elevation model available from https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1. The microclimate model is freely available for download and adaptation via a GitHub repository: https://github.com/ilyamaclean/microclimf. The global tropical forest monitoring dataset is available from https://forobs.jrc.ec.europa.eu/TMF. Temperature records used for validation are available from the global SoilTemp dataset on request: https://www.soiltempproject.com/the-soiltemp-database/. Protected area shapefiles are freely available from the Protected Planet database: https://www.protectedplanet.net. Key Biodiversity Area shapefiles are available on request: www.keybiodiversityareas.org. The code used for the analysis is published online (available at https://doi.org/10.5281/zenodo.10997880) with examples of the open access datasets needed to reproduce the results shown here. The mechanistic microclimate model is freely available to use in the *microclimf* package (Maclean & Klinges, 2023) for R: https://github.com/ilyamaclean/microclimf.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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