

# Assessing climate change-driven wildfire risk to African rock art

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## Article

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# Abstract

Wildfires pose an increasing threat to cultural and natural heritage, including rock art sites in Africa, which are predominantly located within protected areas that experience frequent wildfires. Here, we conduct a continental-scale spatial assessment using the Intergovernmental Panel on Climate Change (IPCC) risk assessment framework to evaluate future wildfire risk to African rock art by integrating fire-weather hazard, fuelbed vulnerability to intense fires, exposure of documented rock art sites, and wildfire response capacity. Results show that days with extreme fire weather are projected to increase by 5–10 annually in the near future (2035–2064), with the spatial extent of these increases expanding by the far future (2071–2100), when some areas are projected to experience more than 10 additional days annually. The largest and most robust increases in extreme fire weather are concentrated in Southern Africa and parts of North Africa, where they coincide with fuelbeds exhibiting moderate to high vulnerability to intense wildfire. Combining fire-weather hazard and fuelbed vulnerability into wildfire-pressure classes, we find a spatial expansion of areas classified as experiencing high, very high and extreme pressure, particularly in regions containing high concentrations of recorded rock art sites. The highest wildfire-risk areas occur where increasing wildfire pressure overlaps with substantial rock-art exposure and limited wildfire response capacity, highlighting Southern and North Africa as key regions of emerging risk. Integrating wildfire risk into rock art management, improving site inventories and implementing proactive fire management and non-combustible visitor infrastructure will be critical to safeguarding Africa's irreplaceable rock art heritage under future climate conditions.

## 1. Introduction

More than half of the global annual burned area from wildfires occurs in Africa<sup>1</sup>, making it the continent with the highest amount of burned area. While fires may provide environmental services<sup>2</sup>, they can also spread rapidly, causing significant damage to natural landscapes and threatening biodiversity, human life and property. Anthropogenic climate change is already increasing the frequency of weather conditions that favour wildfires in parts of Africa<sup>3,4</sup>. Rising temperatures and altered precipitation patterns are increasing the number of weather-driven extreme fire events<sup>5</sup>. Growing evidence from attribution studies demonstrates that anthropogenic climate change has increased the likelihood and severity of extreme fire weather and wildfire events in many regions of the world<sup>6</sup>. In addition to climate, vegetation and land use changes are also influencing fire regimes across the continent<sup>7</sup>, making wildfire a complex and dynamic issue that may pose a threat to vulnerable aspects of both the natural and cultural environment.

Fire causes significant damage to both natural<sup>8</sup> and cultural heritage<sup>9</sup> sites. Africa has a rich collection of rock art sites, which are often located in national parks – among the most extensively burned areas in Africa<sup>10</sup>. Rock art across the continent takes the form of paintings, engravings and carvings on natural rock surfaces. There have been several incidents in the past two decades of fires at rock art sites. Tsodilo Hills, a World Heritage Site in Botswana hosting one of the highest concentrations of rock art in Africa, experiences frequent fires, with reportedly up to three major outbreaks per fire season<sup>11</sup>. Rock art

sites in South Africa similarly identify wildfire as a major threat, including the Maloti-Drakensberg and the Tandjesberg<sup>12,13</sup>. The Chongoni Rock-Art Area in Malawi likewise identifies wildfire as a recognised threat<sup>14</sup>. Sites such as the Matobo Hills in Zimbabwe have also reported fire and recurrent drought as significant threats to the cultural and natural values of the property<sup>15</sup>.

At rock art sites, fire can act by discolouring rock surfaces, damaging rock varnish, depositing ash and soot and causing microcracks and spalling (Fig. 1)<sup>16–20</sup>. Where high temperatures are reached, cracking and shattering of boulders have also been noted<sup>20,21</sup>. Importantly, the impact of wildfire on rocks is not always perceivable in the short term from macroscopic observation<sup>20</sup>. Over longer timescales, decay processes may take advantage of microcracks and weakened surfaces, accelerating future erosion<sup>21</sup>. Ash deposited on rock panels can also persist well beyond the initial exposure to fire when deposited within peels and cracks<sup>22</sup>. Considerable increases in pH levels of rock surfaces exposed to smoke have also been reported<sup>23</sup>, with implications for the chemical weathering behaviour of the rock. At the landscape scale, fire can have considerable impacts on the hydrology and geomorphology of landscapes, which can directly and indirectly affect rock weathering<sup>24</sup>.

Despite increasing fire weather, projected with high confidence to intensify across Southern and North Africa by mid-century under medium emissions scenarios (RCP4.5 and SSP3-4.5)<sup>7</sup>, and the numerous cultural heritage sites across the continent that are expected to be impacted, the broader literature on climate change and cultural heritage continues to exhibit a geographical bias toward Europe and North America<sup>25,26</sup>, with approximately 1% focusing on Africa<sup>27</sup>. This disparity limits the applicability of existing methods and risks overlooking the continent's heritage in global management strategies. Studies that do address climate change impacts on heritage in Africa have focused on sea level rise<sup>28</sup>, wood decay<sup>29</sup> and broad assessments of weathering and fire risk to rock art based on climate trends without explicitly tracing how projected climate change translates into deterioration<sup>30</sup>.

The limited understanding of the risk of wildfire to rock art under future climate change impedes the development of adaptation strategies. To address this gap, this study assesses how climate change affects the risk of wildfire-related damage to African rock art sites. The International Panel on Climate Change's (IPCC) risk assessment framework is adopted in this study because it provides a pathway for heritage to be integrated into future climate assessments, facilitates interdisciplinary collaboration<sup>31</sup> and enables a multi-determinant approach in which vulnerability, exposure, response capacity and fire hazard can be assessed together<sup>32,33</sup>. This continental-scale approach provides a broader perspective than site-specific risk assessments, which offer detailed understanding at individual sites but are challenging to upscale across large regions<sup>34,35</sup>. By identifying regional patterns and priority areas, the assessment can help prioritise sites for more detailed local investigations and support the targeting of conservation and management efforts.

## 2. Methods

To assess the risk of wildfire to African rock art, we applied the IPCC risk assessment framework using spatial datasets from multiple sources to represent the key components of risk: hazard, exposure, vulnerability, and response capacity. Historical burned-area data and projected changes in fire weather were used to characterize wildfire hazard, while the locations of documented rock art sites represented exposure. Vulnerability was assessed using fuelbed characteristics, and response capacity was estimated using proxies of fire management. These datasets were integrated through spatial overlay analyses to evaluate how the different components of risk combine to influence the overall wildfire risk to rock art sites.

## 2.1 IPCC AR6 multideterminant risk framework

With the aim of having a consensus and standardised definition of risk across its working groups, the IPCC has developed a risk framework that has evolved through its assessment cycles. The latest (Assessment Report 6) risk framework defines risk “as the potential for adverse consequences for human or ecological systems”<sup>36</sup>. Risk results from dynamic interactions between climate-related hazards with exposure and vulnerability, with response acting as a modulator of risk<sup>37</sup>. With the exception of response, the three other determinants are defined in the IPCC appendix as the following:

- Hazard: “the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.”<sup>38</sup> (p. 2911).
- Vulnerability: “the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.”<sup>38</sup> (p. 2927).
- Exposure: “the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.”<sup>38</sup> (p. 2908)

In this study, this framework is applied to assess the risk from wildfire to rock art in Africa. A key advantage of adopting the IPCC AR6 risk framework is that it is a widely recognised standard methodology for risk assessment. Its use enables direct comparison with other studies while ensuring consistency in terminology and methodology.

## 2.2 Burned area data

Burned area data were obtained from the MODIS MCD64A1 Version 6 Burned Area product, accessed via Google Earth Engine in January 2026, covering the period from 2015 to 2024. This dataset provides global monthly burned area estimates at a spatial resolution of 500 m × 500 m. The data are distributed in the MODIS sinusoidal tiling system, using a Cartesian coordinate framework, with a temporal resolution of one month<sup>39</sup>. The product is derived using a hybrid remote sensing approach that

combines spectral change detection and active fire information to identify burned areas, a methodology widely applied in global fire studies<sup>39,40</sup>.

The analysis was spatially constrained to the African continent, defined using a bounding box extending from  $-20^{\circ}$  to  $55^{\circ}$  longitude and  $-35^{\circ}$  to  $38^{\circ}$  latitude.

It is important to note that global burned area products at medium resolution, like the one used in this study, underestimate total burned area. This is because their spatial resolution is not capable of detecting small, burned patches, as indicated by several studies<sup>41–43</sup>.

## 2.3 Exposure of rock art sites

In research that assesses climate change risk to heritage, “the first element of exposure (location) determines the likelihood of the risk, while the second and third (density and significance) act to magnify the consequences of this risk”<sup>31</sup>. In this study location of rock art sites is used to determine the presence and distribution of rock art sites. Due to the poor knowledge of density and significance of rock art sites in Africa, it was not possible to integrate these elements into the study.

Location of rock art sites was comprehensively compiled from studies that covered continental distribution of sites such as Anderson et al.<sup>44</sup> and others that were limited to individual countries<sup>45–48</sup>. Additional sources consulted included the South African Heritage Resources Agency’s online database<sup>49</sup> and the Libyco-Berber Inscriptions Online Database<sup>50</sup>; however, locations from these fell within areas already covered by Anderson et al.<sup>44</sup>.

## 2.4 Fire hazard indicator

Fire weather indices quantify the meteorological conditions conducive to fire ignition and spread. The Canadian Forest Fire Weather Index (FWI) System<sup>51</sup> calculates fire danger through a structured sequence of codes and indices derived from four daily meteorological inputs: temperature, relative humidity, wind speed, and precipitation. The system first computes three fuel moisture codes – the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC) – which represent the dryness of forest floor fuels at progressively deeper layers. These are then combined into two behavioural indices: the Initial Spread Index (ISI), which integrates wind speed and surface fuel dryness to estimate potential fire spread rate, and the Buildup Index (BUI), which combines DMC and DC to represent the dryness of deeper fuel layers that can sustain burning. Finally, the FWI integrates the ISI and BUI into a single index representing the overall meteorological conditions conducive to wildfire ignition and spread, with higher values indicating conditions that are increasingly favourable for wildfire occurrence. It is worth noting that the FWI is entirely based on atmospheric variables and its purpose is to provide a sense of how likely or intense a fire would be in certain conditions<sup>52</sup>. Nonetheless, FWI and annual burned area have been found to be well correlated over broad regions globally<sup>53</sup>.

This study uses pre-calculated FWI outputs from Quilcaille et al.<sup>52</sup> to quantify the wildfire hazard component of the risk assessment. Data from 14 CMIP6 model simulations were used, selected on the basis that they contained both historical and SSP2-4.5 scenario runs with matched r1i1p1f1 ensemble members and had values for minimum relative humidity (Table 1). The SSP2-4.5 scenario was chosen as estimates of future emissions under current climate policy closely match this scenario<sup>54</sup>. The input values used by Quilcaille et al.<sup>52</sup> from CMIP6 models were minimum relative humidity (hursmin), maximum temperature (tasmax), wind speed (sfcWind) and precipitation (pr).

Quilcaille et al.<sup>52</sup> applied modifications to the FWI algorithm originally developed by Van Wagner<sup>51</sup> to improve its accuracy across different regions and climatic conditions. These modifications included adjusting the effective day length used in the DMC calculation to better represent conditions across all latitudes, adapting the drying factor by hemisphere to more accurately reflect regional drying patterns, and incorporating an overwintering adjustment to the DC to account for the carry-over effects of seasonal moisture conditions into spring.

The CMIP6 runs listed in Table 1 are those used by Quilcaille et al.<sup>52</sup> to generate FWI. They cover three 30-year periods: a historical period (1985–2014), a near-future period (2035–2064) and a far-future period (2071–2100).

Table 1  
List of selected model inputs used by Quilcaille et al. (2023) that were used in this study.

| Model         | Institution                                                             | Country                 | Ensemble Member | Scenario |
|---------------|-------------------------------------------------------------------------|-------------------------|-----------------|----------|
| ACCESS-CM2    | CSIRO and ARCCSS                                                        | Australia               | r1i1p1f1        | SSP2-4.5 |
| ACCESS-ESM1-5 | CSIRO                                                                   | Australia               | r1i1p1f1        | SSP2-4.5 |
| CanESM5       | Canadian Centre for Climate Modelling and Analysis (CCCma)              | Canada                  | r1i1p1f1        | SSP2-4.5 |
| CMCC-ESM2     | Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)               | Italy                   | r1i1p1f1        | SSP2-4.5 |
| EC-Earth3     | EC-Earth Consortium                                                     | Europe (multi-national) | r1i1p1f1        | SSP2-4.5 |
| FGOALS-g3     | Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP/CAS) | China                   | r1i1p1f1        | SSP2-4.5 |
| GFDL-CM4      | NOAA Geophysical Fluid Dynamics Laboratory (GFDL)                       | USA                     | r1i1p1f1        | SSP2-4.5 |
| INM-CM4-8     | Institute for Numerical Mathematics (INM)                               | Russia                  | r1i1p1f1        | SSP2-4.5 |
| INM-CM5-0     | Institute for Numerical Mathematics (INM)                               | Russia                  | r1i1p1f1        | SSP2-4.5 |
| IPSL-CM6A-LR  | Institut Pierre-Simon Laplace (IPSL)                                    | France                  | r1i1p1f1        | SSP2-4.5 |
| MIROC6        | MIROC Consortium (JAMSTEC, AORI, NIES, R-CCS)                           | Japan                   | r1i1p1f1        | SSP2-4.5 |
| MPI-ESM1-2-HR | Max Planck Institute for Meteorology (MPI-M)                            | Germany                 | r1i1p1f1        | SSP2-4.5 |
| MPI-ESM1-2-LR | Max Planck Institute for Meteorology (MPI-M)                            | Germany                 | r1i1p1f1        | SSP2-4.5 |
| MRI-ESM2-0    | Meteorological Research Institute (MRI)                                 | Japan                   | r1i1p1f1        | SSP2-4.5 |

One FWI-derived indicator was used to characterise the hazard: the local annual number of days on which the FWI exceeds the 95th percentile of values recorded during the preindustrial (1850–1900) reference period (FWIXD), capturing the frequency of days with extreme fire weather conditions. Local is defined as the 2.5 grid cell which is also the resolution of this data. The use of a locally defined percentile threshold is considered a relevant metric for analysing high fire hazard, as it accounts for location-specific baseline conditions<sup>55</sup>. This indicator captures the frequency of days that have extreme

fire weather conditions, or put in a different way, hazardous weather condition that make it more probable for fire ignition and spread.

Projected changes in FWIXD were assessed by comparing three 30-year climatological periods representing the near past (1985–2014), near future (2035–2064), and far future (2071–2100). While the 95th percentile threshold was defined using the pre-industrial baseline, changes in FWIXD were expressed relative to the near past period (1985–2014). Hazard is represented as the projected change in the annual number of days exceeding this threshold between the near past and future periods (see workflow in Fig. 2). For each grid cell and climate model, the temporal median annual number of FWIXD days was calculated separately for each period, and the change in hazard was quantified as the difference between the future and near past median values. The median was used in preference to the mean because the distribution of fire weather indices is typically skewed, with frequent low values and occasional extremes.

To determine whether projected changes between the near past and future periods were statistically significant, a two-sample Kolmogorov-Smirnov (KS) test was applied to each model's historical and future time series at each grid cell. The KS test was selected because it compares the full shape of two distributions, and makes no assumption about distributional normality, making it well-suited to the skewed character of fire weather data. With  $p < 0.05$ , the KS test indicates that the observed difference is unlikely to have arisen by chance and that, at a 95% confidence threshold, the difference between the distributions is significant.

Ensemble robustness was then evaluated following the approach proposed by Tebaldi et al.<sup>56</sup> and applied to African climate change assessments by Dosio et al.<sup>57</sup>. A projected change was considered robust where more than 50% of models showed a statistically significant change and more than 80% of models agreed on the direction of that change.

## 2.5 Vulnerability indicator

Vulnerability of rock art to wildfire is controlled by both the intrinsic properties of the rock and the characteristics of the fire. Petrophysical properties and mineralogical composition influence the susceptibility of rock surfaces to cracking, spalling, and mineral oxidation, while fire temperature and the duration of sustained heating determine the thermal response of the rock, with higher temperatures generally causing more extensive damage<sup>58</sup>. Incorporating site-specific rock properties into a continental-scale assessment is not feasible because these data are unavailable for most rock art sites and the thermal response of different rock types to wildfire remains poorly understood. At this scale, the capacity of vegetation to sustain intense fire is therefore the primary determinant of whether damaging thermal conditions are likely to occur. For example, in the hyper-arid Sahara, the near absence of vegetation severely limits wildfire occurrence regardless of rock type. Accordingly, this study uses the fire behaviour potential of the vegetation surrounding rock art as a proxy for the vulnerability of rock art to wildfire.

Fire behaviour potential was represented using the Fuel Characteristic Classification System (FCCS)<sup>59</sup> Flame Length Potential (FP). FP is a scaled index (0–9) of predicted flame length under fixed environmental conditions and is strongly correlated with fireline intensity—the rate of energy released as a fire spreads—which provides a measure of potential fire intensity<sup>60</sup>. FP is calculated from fuelbed characteristics, defined as “the inherent physical properties of fuels that influence fire behaviour and fire effects”<sup>61</sup>. The FCCS estimates FP using semi-empirical fire behaviour models that incorporate heterogeneous surface fuelbed properties, enabling realistic comparisons among vegetation types<sup>60,61</sup>. The global FP dataset developed by Pettinari and Chuvieco<sup>62</sup>, who applied the FCCS (v3.03.203) to their Global Fuelbed Dataset<sup>63</sup> was used. Simulations were conducted under fixed environmental conditions (Fuel Moisture Scenario D2L2, 0% slope, and a midflame wind speed of 6.4 km h<sup>-1</sup>), ensuring that differences in FP reflect the intrinsic characteristics of vegetation fuelbeds rather than weather variability. The resulting FP values were used as the wildfire vulnerability indicator of fuelbeds in Africa.

A limitation that must be noted is the absence of adaptive capacity as a component of vulnerability. It is considered here to be a site-specific characteristic and, owing to a lack of site-specific information, could not be incorporated into the vulnerability analysis.

## 2.6 Response capacity assessment

Response capacity to environmental risks has been assessed in various ways in the literature. In assessments of invasive alien species risk, for example, national reports on Convention on Biological Diversity implementation have been used as standardised measures of a country's progress toward biodiversity targets<sup>64</sup>. Rød et al.<sup>32</sup>, in assessing natural hazard, evaluated the extent to which hazard was embedded in municipal planning, climate adaptation funding applications and sustainable development plans. Indicators such as the existence of monitoring systems and early warning capacity have also been used, given the role these play in prevention and management of environmental risks<sup>64</sup>. Together these approaches illustrate how a combination of institutional, planning, and operational indicators can be used to characterise a country's capacity to respond to environmental risk.

In this study, a composite indicator approach was adopted to assess national-level response capacity, drawing on this precedent of combining multiple indicator types. Rather than presenting a single aggregated index, which risks obscuring the contribution of individual components, indicators were first examined separately to clarify what each contributes to the overall picture. The three indicators listed below were used:

1. **Hazard monitoring capacity (a)** – measured as the overall maturity level (0–5) of national systems for monitoring and forecasting hydrometeorological hazards. Data were obtained in December 2025 from the Early Warnings for All dashboard of the World Meteorological Organization<sup>65</sup>.
2. **Strategic DRR alignment (b)** – measured as the score (0–1) reflecting the adoption and implementation of national disaster risk reduction (DRR) strategies aligned with the Sendai

Framework, averaged over the most recent five years of reported data. Data were sourced from the UN SDG data portal in December 2025<sup>66</sup>.

3. **NCAP integration** (c)– assessed as a binary indicator (0 or 1) reflecting the existence of a national climate change adaptation plan (NCAP) and whether wildfire is explicitly referenced within it. A total of 24 countries were identified as having national adaptation plans, of which most include references to fire, with a few exceptions<sup>67</sup>.

The composite fire response index was calculated by first normalizing monitoring capacity (a) to a 0–1 scale using the maximum value for the African countries studied and averaging it equally with strategic DRR alignment (b). This average was then adjusted by climate policy integration (c), implemented as a multiplicative modifier (1 + 0.1c) to reflect its relatively limited influence. The final index was subsequently normalized to a 0–1 scale to enable comparison across countries.

Equal weighting is applied to  $a_{norm}$  and  $b$ , while  $c$ , a binary variable (0/1), functions as a modest proportional adjustment (up to + 10%) rather than an independent component. This reflects the assumption that merely referencing fire risk in national climate policy is unlikely to influence response capacity as strongly as operational capabilities captured by  $a_{norm}$  and  $b$ .

$$Response = \left( \frac{a_{norm} + b}{2} \times (1 + 0.1c) \right)_{norm}$$

Sensitivity analysis indicates that this formulation is robust to reasonable variation in weighting assumptions. Varying the magnitude of the  $c$  modifier (0.1–0.5) yields rank correlations (Spearman's) of 0.99, indicating minimal influence on overall rankings. Rankings are also stable under moderate deviations from equal weighting of  $a$  and  $b$  ( $R = 0.98$  at 40:60 and 60:40), with only limited changes at larger deviations ( $R = 0.95$  at 30:70 and 70:30). Overall, the index is relatively insensitive to the treatment of  $c$ , with the balance between  $a_{norm}$  and  $b$  representing the primary, though still limited, source of sensitivity.

## 3. Results

### 3.1 Burned area trends

While total burned area has declined globally, driven largely by reductions of burned area in African Savannas<sup>1</sup>, this trend masks significant variations at the national level. Several countries, particularly in Southern Africa, continue to experience consistently high annual burned area. Figure 3 shows the total annual burned area over a 10-year period (2015–2024) for the upper half of countries with the highest burned area. Namibia, Zambia, Mozambique, South Africa, Zimbabwe, Angola and Botswana rank among the top countries in terms of area burned each year. Among these, Zambia and Mozambique exhibit a decreasing pattern (Supplementary Figure S1a), yet each continues to exceed 25,000 km<sup>2</sup> of burned area annually. Central African countries, including the Central African Republic and the DR Congo, also rank

among the highest in total annual burned area although they see considerably different amounts of burned area annually. In contrast, Northern and Eastern African countries generally record the lowest annual burned area, with the notable exception of Egypt, which has seen an increase over the past five years.

## 3.2 Rock art exposure

The documented distribution of rock art sites across Africa is spatially fragmented and unevenly documented, making it challenging to gain a granular understanding of the density, significance and location of these sites. Nevertheless, the available published literature provides a sufficiently rich dataset to support the objectives of this study. Figure 4 presents the compiled distribution of rock art sites based on the published literature referenced in the methods section, which serves as the basis for identifying risk hotspots by overlaying site distribution with hazard and vulnerability data.

Figure 4 shows the regions that host a significant concentration of rock art, namely North Africa, East Africa and Southern Africa. These regions have rich rock art traditions and denser concentrations of sites, with the typologies of rock art in these regions being highly diverse, ranging from cave art and rock-hewn structures to geoglyphs and engravings on boulders<sup>68</sup>. Beyond these core regions, significant megalithic traditions exist in West Africa. Senegal, The Gambia, Côte d'Ivoire and Nigeria are home to a substantial number of standing stone sites<sup>69</sup>. These West African heritage landscapes remain poorly documented and are consequently absent from the distribution map presented here.

## 3.3 Projected wildfire hazard

Figure 5 shows the ensemble median change in the number of extreme fire weather days (FWIXD) for the near-future (2035–2064) and far-future (2071–2100) periods relative to the near past baseline (1985–2014). The figure illustrates how the frequency of extreme fire weather days exceeding the pre-industrial threshold is projected to change compared with current conditions.

In the near future, the spatial pattern is mixed, with decreases in the number of extreme fire weather days across parts of Central Africa and many mid-latitude regions. Over most of the continent, changes remain relatively small (generally below five additional days), although this signal is not robust across models. In contrast, increases are more evident in parts of North Africa (Algeria, Tunisia, and Morocco) and Southern Africa, where some areas show increases of more than 5 additional extreme fire weather days and others exceed 10 days.

By the far future, the pattern becomes more spatially coherent and more strongly positive in many regions. Areas showing decreases in extreme fire weather days are reduced, while regions with increasing trends expand and intensify. This is especially evident in North and Southern Africa, where robust increases exceed 10 additional extreme fire weather days. Southern African countries and

Madagascar stand out, with large and widespread increases exceeding 15 days relative to the near past period.

### 3.4 Vulnerability

Figure 6 illustrates the spatial distribution of flame length potential (FP), a proxy for fireline intensity and landscape vulnerability to high-intensity wildfires. Across Africa, FP is predominantly moderate, with most vegetated landscapes falling within the 4–6 FP range (light red to orange in Fig. 6), indicating a widespread potential for moderate to high fire intensity. In contrast, the highest FP values ( $> 7$ ), representing the greatest vulnerability to intense wildfire, are concentrated in the Sahel, Somalia, Botswana, South Africa, Namibia, Egypt and Madagascar. Areas with low FP occur primarily in South-western Africa and the Congo Basin. Although these regions exhibit similarly low FP values, they represent different fuelbed types: grass-dominated landscapes in a Desert and Xeric Shrublands biome<sup>70</sup> in South-western Africa, and broadleaf evergreen forests in the Congo Basin. Regions with the highest FP are largely associated with grass-dominated fuelbeds within the Tropical and Subtropical Grasslands, Savannas and Shrubland biome.

It should be noted that the Global Fuelbed Dataset<sup>63</sup> assigns fuel parameters based on combinations of biome and land-cover classifications. The hard edges visible in Figs. 6, particularly in the southwestern part of the continent, reflect a limitation of this approach, as biome boundaries are represented as abrupt transitions, whereas in reality they are ecotones and mosaic habitats that gradually transition between ecosystems<sup>70</sup>. Consequently, the sharp transitions in FP values are a product of the dataset classification and the spatial granularity of the underlying input data.

### 3.5 Response capacity

Figure 7 shows the indicators chosen to represent response capacity of African countries: hazard monitoring capacity, strategic DRR alignment and NCAP integration. The continent shows a diverse degrees and types of response capacities. Only a few countries across the continent have good capacity across the three indicators for response assessed here, these are: Ethiopia, South Africa, Mozambique, Tanzania, Rwanda and Niger. Other countries, such as Kenya, Zambia, Uganda, Senegal and Angola, have well rated hazard monitoring capacity and strategic DRR alignment, but wildfire hazard is not integrated in the NCAP. Countries indicated in grey on the map have not reported having a hazard monitoring capacity. However, this does not necessarily reflect a lack of disaster risk management, as some of these countries have DRR strategies well aligned with the Sendai Framework or have integrated wildfire hazard into their NCAP.

### 3.6 Wildfire pressure and risk

Figure 8 synthesizes the results presented thus far by combining vulnerability and hazard into wildfire pressure levels using a bivariate colour scheme, overlaid with response capacity (yellow circles) and

rock art exposure (hatched area). The bivariate colouring enabled the identification of five wildfire pressure levels representing how projected increases in wildfire-conductive conditions interact with the vulnerability of fuelbeds to sustain fire (the full set of class combinations is presented in the Fig. 8 legend). Within this framework, regions with high vulnerability (6–9) can reach high wildfire pressure levels even under relatively modest increases in hazard (0–5 days), and very high wildfire pressure under greater hazard increases (5–15 days). Conversely, regions with lower vulnerability require greater increases in hazard to reach comparable wildfire pressure levels. This classification reflects the combined influence of hazard and vulnerability, where the same level of projected hazard can result in different wildfire pressure levels depending on the vulnerability of the fuelbed.

Figure 8a presents the near-future scenario, and Fig. 8b presents the far-future scenario of wildfire risk. Comparison of the two shows a shift in the spatial distribution of wildfire pressure over time, with many regions progressing towards higher wildfire pressure levels. Between the near and far future scenarios, the spatial extent of extreme, very high and high wildfire pressure expands, replacing areas previously classified as having moderate wildfire pressure, showing a redistribution of wildfire pressure under future climate conditions.

The spatial distribution of wildfire pressure highlights distinct regional patterns across Africa. The largest increases in wildfire pressure are concentrated in North Africa, Southern Africa and southern Tanzania, regions that also contain high concentrations of recorded rock art sites. Other hotspots of increasing wildfire pressure occur in Madagascar and parts of West Africa, although these regions contain fewer recorded rock art sites.

In contrast, moderate and low wildfire pressure is more broadly distributed across the central latitudes and the Congo Basin, and its spatial extent increases between the near and far future scenarios. The extent of areas with decreasing hazard (shown in grey in Fig. 8) is reduced in the far-future scenario.

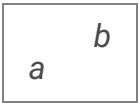


*Figure 8: Bivariate map of hazard and vulnerability overlaid with exposure (hatched polygons) and response capacity (yellow circles) for (a) the near future and (b) the far future. The bivariate colour scheme represents wildfire pressure levels from low to extreme, derived from the combined influence of hazard and vulnerability. Quadrants are annotated with their corresponding level. Countries for which response capacity data were unavailable are presented by a filled in yellow circle. Data underlying this figure are available in the Zenodo repository: <https://doi.org/10.5281/zenodo.21534736>.*

## 4. Discussion

North Africa, Southern Africa, and Madagascar are among the regions projected to undergo substantial changes in wildfire pressure in both the near and far future. This discussion focuses on these hotspots of wildfire risk to rock art, where increases in wildfire pressure are spatially extensive, supported by a

robust signal of change (Fig. 5) and occur in areas known to contain rock art. The discussion also examines broader factors shaping wildfire risk to rock art, including key risk modifiers considered in this assessment, such as limited response capacity, ecosystem shifts and site-scale factors that may further influence risk.

## **4.1 Hotspots of wildfire risk**

### **4.1.1 Southern Africa and Madagascar**

Southern Africa is the region that will see a large increase in wildfire pressure in the near future and a spatial expansion of regions with very high wildfire pressure in the far future. Parts of South Africa, Lesotho, Botswana, Namibia, Zimbabwe, Zambia, Angola, Malawi, eSwatini and Mozambique (dark teal in Fig. 8b) are projected to experience increases of more than 15 days with extreme fire weather conditions while having fuelbed classes with moderate to high vulnerability to intense wildfires. These regions also contain numerous and culturally significant rock art sites, making this transition of particular concern.

Outside of Southern Africa, southern Tanzania and western Madagascar also see an increase from high wildfire pressure in the near future to very high wildfire pressure in the far future. Although no rock art sites are shown on the location map in Fig. 4, western Madagascar warrants attention, as cave rock art sites are known to exist there<sup>71</sup>.

The countries facing these risks differ substantially in their capacity to respond to wildfire. South Africa has one of the more robust wildfire response capacities on the continent and has implemented fire management plans that specifically target rock art sites<sup>72</sup>. Nevertheless, high response capacity does not eliminate risk, as demonstrated by wildfire damage to rock art panels in the Maloti-Drakensberg Park during 2024<sup>13</sup>. Those that have limited to none response capacity in the region such as Lesotho, Botswana, eSwatini and Zambia are likely to fare worse in terms of capacity to adapt and respond to the increasing level of risk. These countries also have a high annual burned area. Given the density and significance of rock art sites in these countries, the projected increase in the risk of intense wildfires warrants urgent attention. These fires could cause substantial damage to rock art, including sites designated as UNESCO World Heritage Sites, and could result in irreversible loss.

### **4.1.2 North Africa**

Similar to Southern Africa, The Nile Basin in Egypt transitions from high wildfire pressure in the near future to very high wildfire pressure in the far future. The Nile Basin hosts a significant number of rock-cut tombs, which, depending on their proximity to vegetation in an otherwise largely barren landscape, face elevated wildfire pressure. Egypt has limited response capacity and has also seen a recent increase in burned area (Fig. 3). A combination of limited response capacity, the increasing wildfire trend, and the number and significance of the rock-cut tombs located in the Nile Basin indicates that there is substantial emerging risk to these sites.

In the rest of North Africa, parts of Morocco, Algeria, and Tunisia (teal in Fig. 8b) transition from moderate wildfire pressure to high wildfire pressure in the far future. These regions are dominated by fuelbeds with relatively low vulnerability to intense wildfires but are projected to experience an additional 5–10 days with extreme fire weather conditions in the near future, with further increases by the far future. Many of these transitions occur in areas containing, or in close proximity to, documented rock art sites. The capacity to prepare for and respond to wildfire varies considerably across these countries. No national early warning systems for hazards were identified for these countries in this assessment (Fig. 7). Furthermore, with the exception of Morocco, wildfire is not explicitly addressed in their NCA, while Tunisia also lacks a formal disaster risk response capacity. These limitations in response capacity are likely to exacerbate the overall level of risk to rock art across this region.

This transition from moderate to high wildfire pressure represents a different conservation challenge, in which more frequent, low-intensity wildfire exposure is unlikely to cause severe thermal damage such as spalling and cracking but will very likely affect the rocks through soot deposition, surface staining, and discolouration.

## 4.2 The role of limited response capacity

Seventeen countries, indicated by filled yellow circles in Fig. 8, lack data across all three response capacity components – meaning no recorded hydrometeorological monitoring and forecasting maturity, no national DRR strategy aligned with the Sendai Framework, and no national climate change adaptation plan explicitly referencing wildfire. They fall into two broad categories of concern: (1) The first is countries facing a very high wildfire pressure with no recorded response capacity. Lesotho is a clear example: it faces very high wildfire pressure yet has no recorded capacity across any of the three components to support the protection of the considerable number of rock art sites it hosts. (2) The second is countries facing high to moderate wildfire pressure where the absence of recorded response capacity and poor documentation of sites (unknown exposure) compounds the level of risk. The countries that fall in this category are Sierra Leone, Guinea-Bissau, Guinea, Ivory Coast, Gabon, Equatorial Guinea, Republic of Congo and DR Congo. While not well documented, this region also hosts megalithic structures<sup>73</sup> and, to a limited extent, rock engravings and paintings<sup>69</sup>. The moderate level of wildfire pressure may seem insignificant, but the combination of no recorded response capacity and limited documentation of rock art sites substantially elevates the risk these sites face.

## 4.3 Biome shifts and dynamic risks

The results presented and discussed in this study assume that fuel characteristics (fuelbed types) remain as they occur at present and do not account for potential future changes. This reflects a broader limitation of vulnerability indicators, as noted by Hinkel<sup>74</sup>, who highlights that such indicators often represent current conditions and may not adequately capture future states. This limitation also applies to this study, as changes in the composition of native vegetation, including ecosystem state shifts and large-scale biome shifts, can occur abruptly in response to gradual changes in climate and external

perturbations such as altered fire regimes<sup>75,76</sup>. These potential changes in vegetation dynamics and their implications for fire regimes are discussed below.

Vegetation changes interacting with climate and land use change have impacted fire regimes across Africa<sup>7</sup>. Increased grass cover in arid regions has introduced fire into areas where fuel was previously insufficient to allow fire spread, such as the arid Karoo in South Africa<sup>2,77</sup>. In contrast, shrub encroachment, increased precipitation, vegetation fragmentation, and cropland expansion have reduced fire activity in many African grasslands and savannas<sup>78,79</sup>. In the future, the extent of savanna and forest biomes in Africa is projected to change significantly, with as much as 45% of areas considered as savannas in 1990 converting to other biomes by 2070<sup>80</sup>. Tropical and subtropical biomes are projected to be the most affected, with tropical rainforests expected to experience a decrease in their potential distribution – a process known as savannisation – shifting towards savanna and grassland biomes under RCP 8.5 scenarios in the 2060–2080 period<sup>81</sup>. It should be noted that this trajectory of future biome shifts remains subject to considerable uncertainty.

The phenomenon of biome shift carries several important implications for fire risk to rock art. First, the dynamic and evolving nature of climate-ecosystem interactions means that future fire regimes are a moving target, subject to uncertainty that static (point-in-time) risk assessments cannot fully capture. Climate-driven changes in vegetation may feedback to climate shifts through shifts in land-atmosphere interactions<sup>82</sup>. Second, regions currently identified as facing low or moderate wildfire pressure on the basis that their present fuelbed type has moderate vulnerability may abruptly shift following ecological or climatic perturbations. Noteworthy in this regard are the bistable savanna zones identified by Aleman et al.<sup>76</sup> areas currently in a savanna state that represent an alternative stable state to forests. This bistable savanna region spans a vast area of the continent, encompassing many countries in the forest-savanna transition zone around central Africa, the majority of which currently hold a moderate vulnerability classification (3–6 FP). Given the inherent instability of these systems and depending on the direction of biome change, wildfire pressure in these areas could shift in either direction.

## 4.4 Site scale factors modulating risk

While the continental-level risk assessment presented in this study provides a broad spatial framework for prioritising attention, risk at the site scale is modulated by a range of factors that the continental analysis cannot capture. These include the shape and orientation of the rock art panel, topography, lithology and the quantity, type and arrangement of adjacent fuel<sup>17,20,83</sup>. In addition to these physical characteristics, moisture content of the rocks during a fire is considered to play a more important role than lithology and topography in the degree of damage fire can cause to rock surfaces<sup>84</sup>.

From a site management perspective, capacity to maintain site management activities such as firebreaks and prescribed burning of vegetation also plays an important role in modulating risk of wildfire damage at rock art sites. Additional fuel near rock art panels in the form of plastic or wooden

boardwalks for accessibility to tourists can increase the risk of damage to rock art panels as has been reported in several cases in Australian<sup>85</sup> and South African rock art sites<sup>86</sup>.

Overall, the risk profiles presented above should be considered most robust when read alongside careful consideration of site-specific factors, including both physical conditions and management activities, which will significantly modulate the actual level of risk in any given context.

## 5. Conclusion

This study assessed climate-driven wildfire risk to African rock art sites integrating fire weather hazard, vegetation characteristics, location of rock art sites and wildfire response capacity. This integrated framework provides a systematic basis for assessing how these interacting factors shape overall wildfire risk.

The results of this study show that, across Africa, extensive areas containing some of the world's richest and most diverse concentrations of rock-art sites are located in regions that frequently experience wildfires. Moreover, these areas are projected to experience a robust and significant increase in extreme fire weather in the near future (2035–2064), with this increase intensifying and expanding geographically in the far future (2071–2100), likely contributing to greater wildfire frequency and severity. Southern Africa will face the largest increase in wildfire risk across a vast area covering many countries. Parts of North Africa will also experience an increase in wildfire risk, with trends in burned area in Egypt already signaling an increase in wildfire activity.

Wildfire poses a major unrecognised threat to rock art sites in Africa, as it can lead to irreversible loss due to soot deposition, flaking or structural collapse. A majority of African countries lack well-adapted management systems to effectively respond to this threat, and a further increase in wildfire incidence is likely to place these already limited capacities under considerable strain.

The projected increase in wildfire risk highlights the need to integrate wildfire hazard into the management and protection of African rock art sites. Proactive measures, including vegetation management, prescribed burning, firebreak maintenance and the appropriate use of visitor infrastructure constructed with non-combustible materials (e.g., stone), will be critical for reducing wildfire risks and safeguarding these irreplaceable cultural resources under future climate conditions.

## Declarations

## Author Contribution

B.T. developed the original idea and designed the study, developed the methodology, conducted the data analysis and data curation, and wrote the original manuscript. T.D.K. and S.A.O. contributed to the development of the methodology and provided critical review and editing of the manuscript. M.L.P. contributed to data curation, supported the development and assessment of the methodology, and

critically reviewed and edited the manuscript. All authors read and approved the final version of the manuscript.

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## Data Availability

Data availability: The datasets generated and/or analysed during the current study are available in the Zenodo repository found here: <https://doi.org/10.5281/zenodo.21534736>.

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## Figures

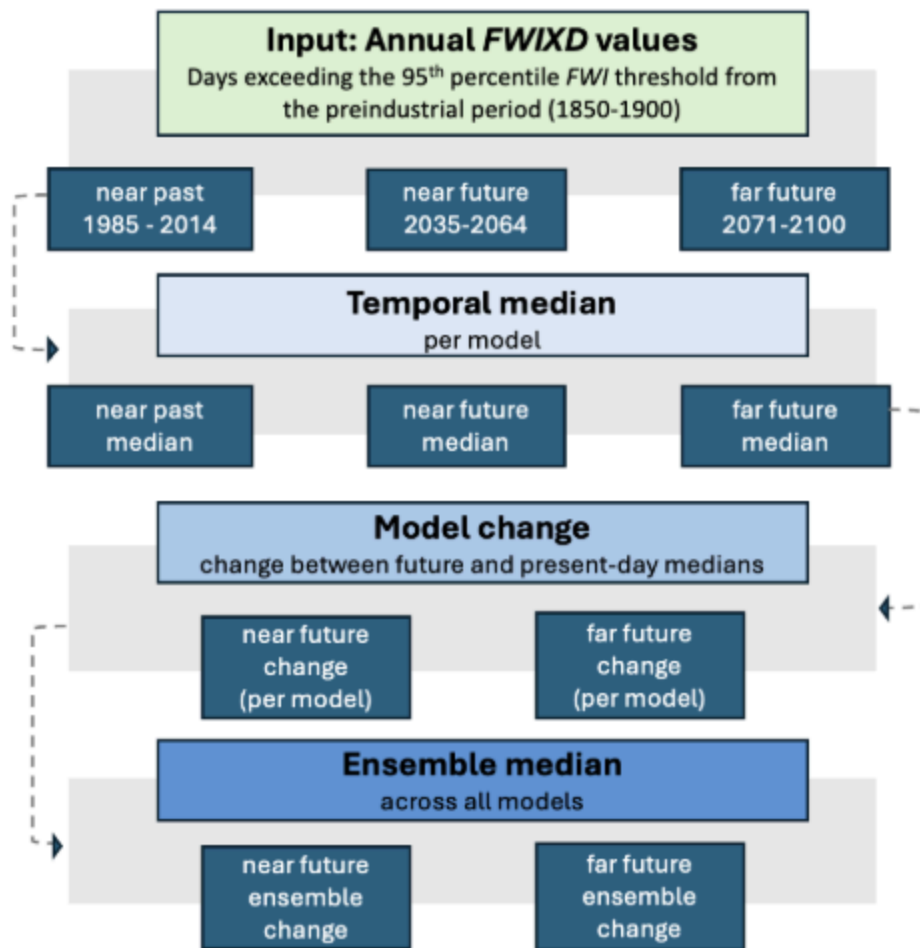


**Figure 2**

*Diagram showing workflow and calculation of fire weather hazard*

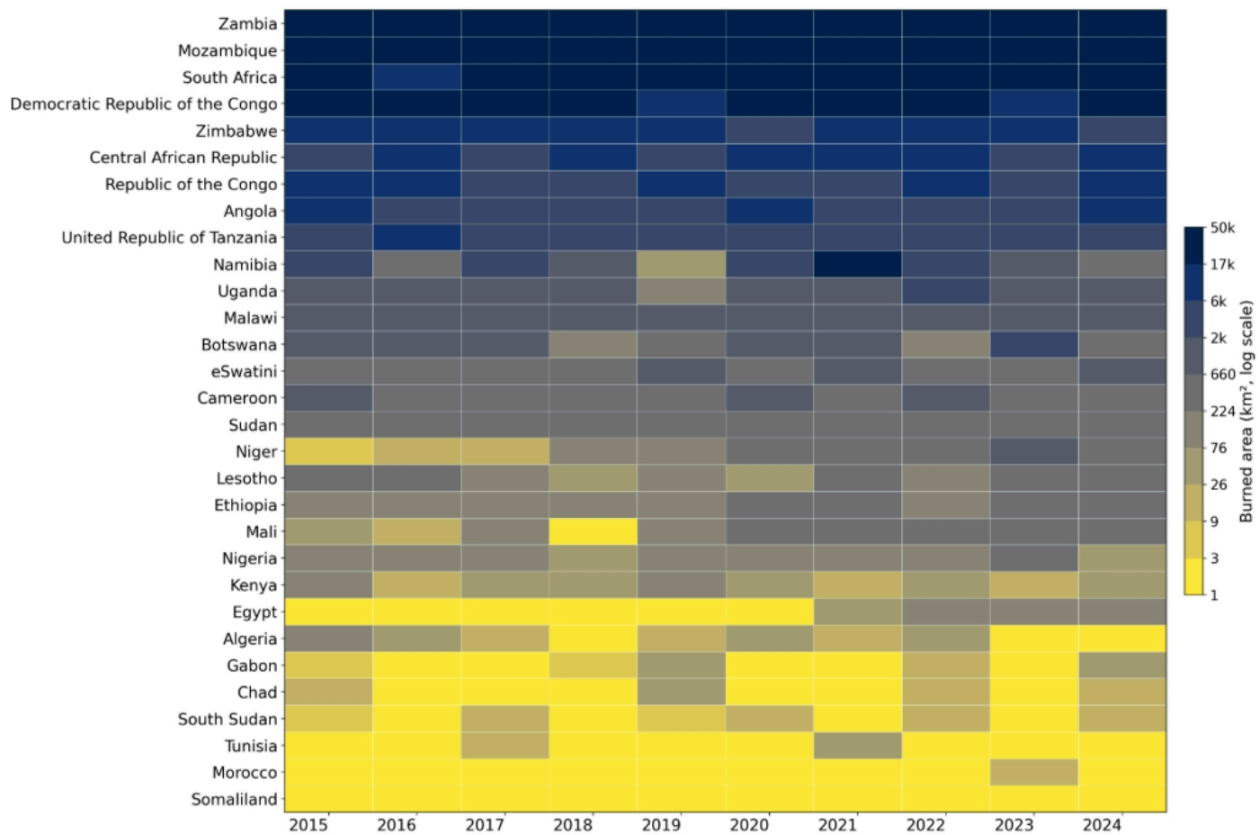


**Figure 3**

*Heat map (2015–2024) of the annual total burned area by country (km<sup>2</sup>) for the 27 highest absolute amounts of total burned area. The z-axis is presented on a logarithmic scale.*

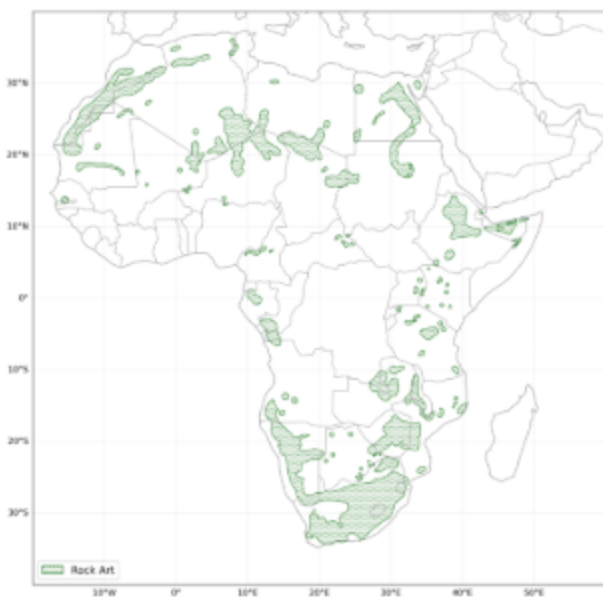


**Figure 4**

*Compiled locations of rock art sites in Africa from sources listed in the methods section.*

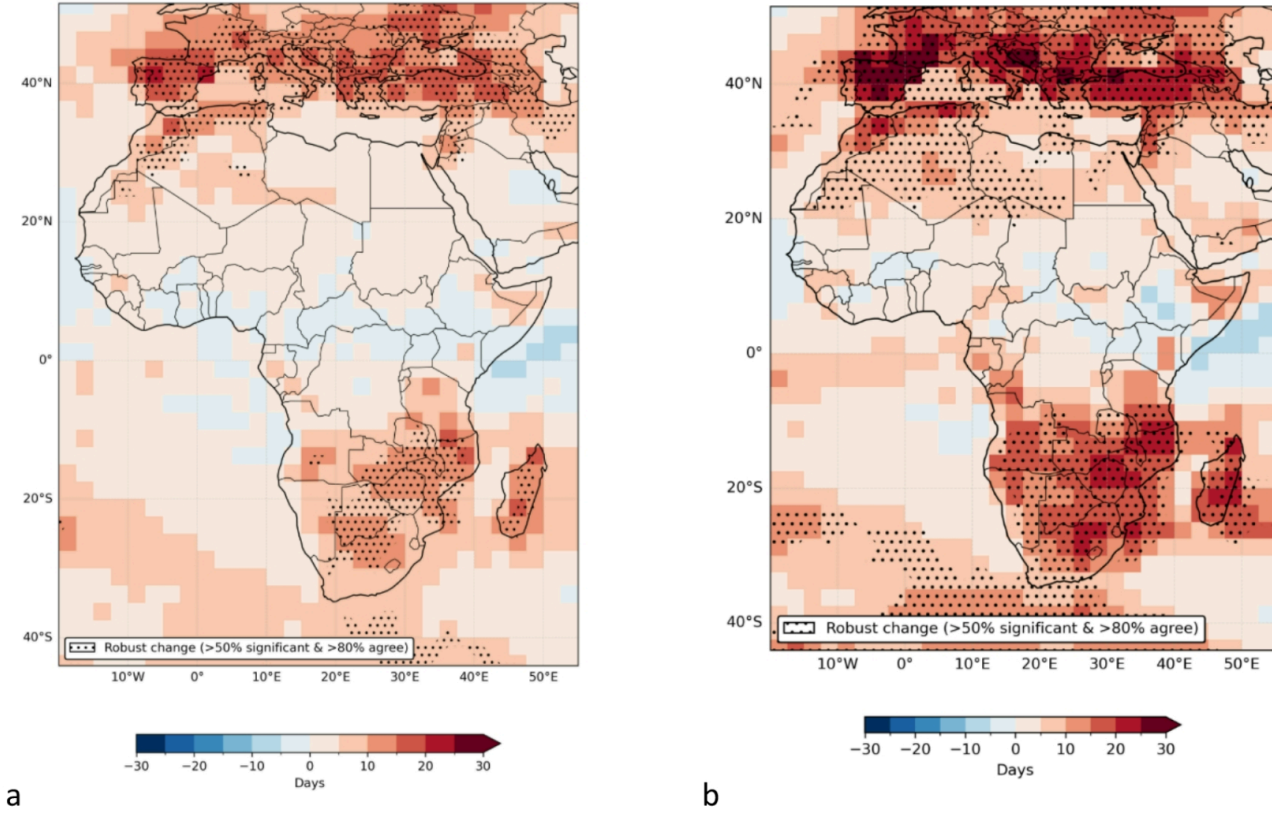


**Figure 5**

*a) Median difference in FWIXD between near future (2035-2064) and near past period (1985-2014), b) Median difference in FWIXD between far future (2071-2100) century and near past period (1985-2014)*

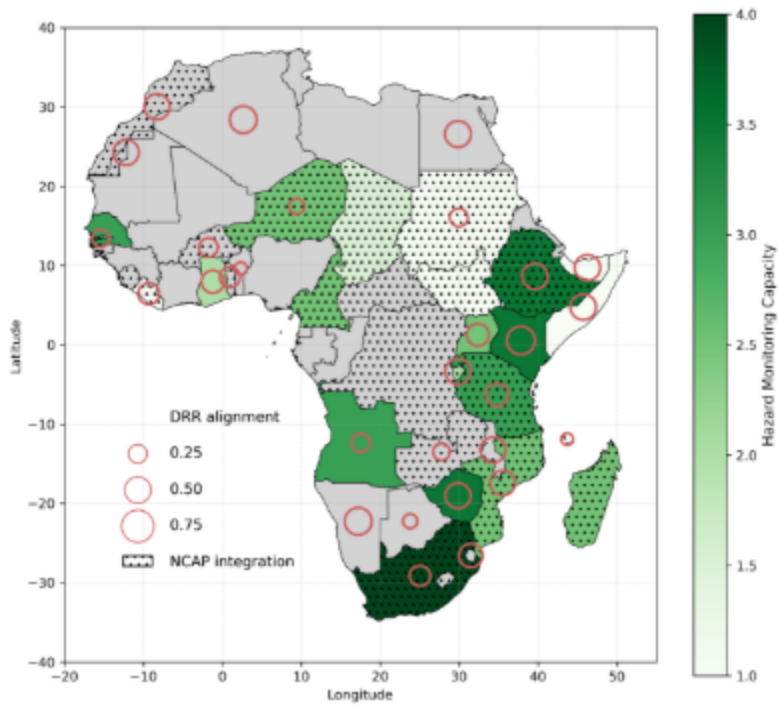


**Figure 7**

Map showing response capacity indicators across Africa. Green shading indicates the rating of national systems for monitoring and forecasting hydrometeorological hazards. Countries in grey have no reported monitoring capacity. Red circles indicate strategic DRR alignment, where circle size corresponds to the strength of alignment with the Sendai Framework. Dot hatching denotes countries that have referenced wildfire in their NACP.

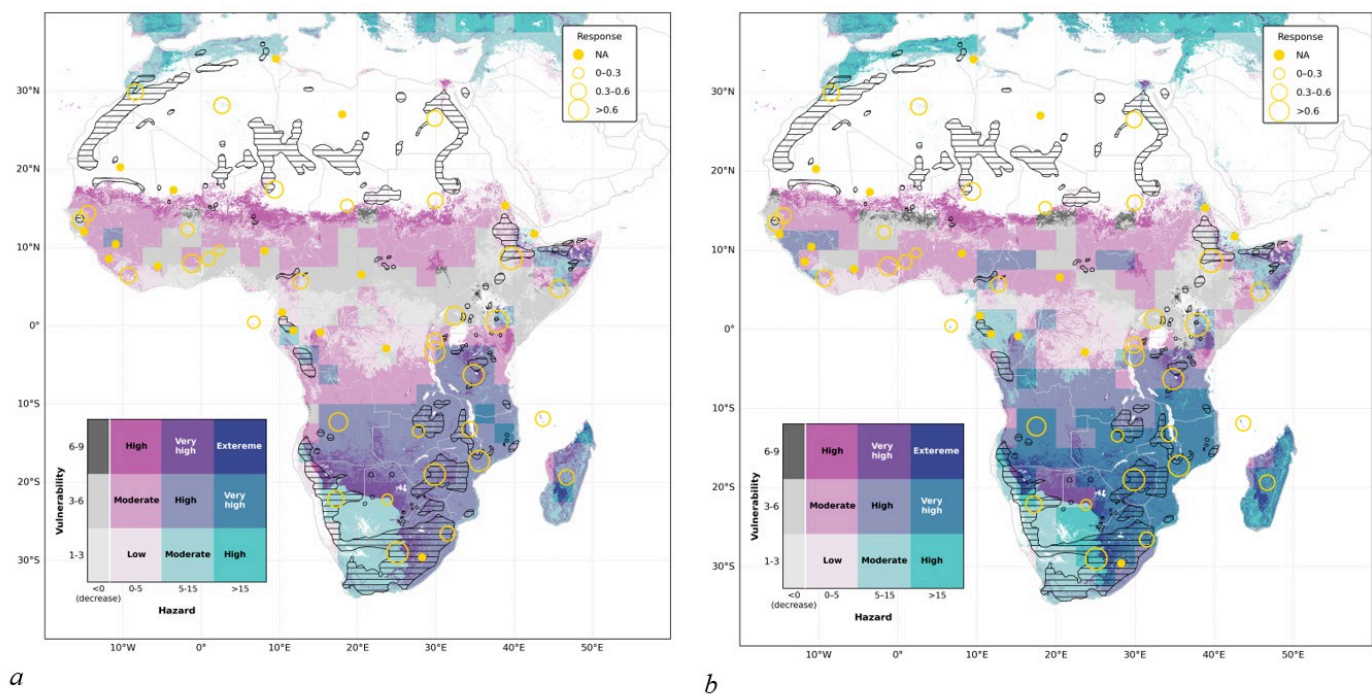


**Figure 8**

*Bivariate map of hazard and vulnerability overlaid with exposure (hatched polygons) and response capacity (yellow circles) for (a) the near future and (b) the far future. The bivariate colour scheme represents wildfire pressure levels from low to extreme, derived from the combined influence of hazard and vulnerability. Quadrants are annotated with their corresponding level. Countries for which response capacity data were unavailable are presented by a filled in yellow circle. Data underlying this figure are available in the Zenodo repository: <https://doi.org/10.5281/zenodo.21534736>.*

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementarymaterial.docx](#)