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Towards integrating paleoecological and traditional knowledge to preserve the Ethiopian Ericaceous belt

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African mountain biomes are social-ecological systems that provide critical ecosystem services but are at risk due to increasing human pressure and climate change. Their conservation require current-day ecological analyses, but also a long-term perspective, integrating local knowledge and paleoecology.

Fire in the Afromontane biome

The Afromontane biome is a globally important biodiversity hotspot (Burgess et al. 2007), supporting the livelihoods of more than 200 million people by providing essential natural resources and ecosystem services (e.g. protection from soil erosion and floods, and water, food and timber provision) (Solomon et al. 2019). The Afromontane biome covers widely scattered mountains extending from Saudi Arabia along the Eastern Arc to Mozambique and South Africa (Fig. 1a). The biome occurs between ca. 2000 to 4000 m asl including several vegetation belts: relatively dry woodland transitioning to wetter woodland from ca. 2000 to 3000 m asl, an Ericaceous belt (EB) above 3200 m asl, and an Afroalpine biome of open shrubland and patchy grassland above 4000 m asl (Bussman 2006). African mountains have been occupied by humans for thousands of years and should be considered socio-ecological systems, wherein human agency is a key element of ecosystem dynamics. Recent studies highlight the importance of local community expertise in successful efforts to protect Afromontane vegetation (Fischer et al. 2021).

The Ericaceous belt is one of the most fragile Afromontane communities, dominated by *Erica arborea* and *E. trimera* stands (Bussmann 2006). It is especially and critically endangered by rising temperatures and unpredictable rains, rapid population growth, and agricultural expansion (Cincotta et al. 2000). *Erica* heathland is highly flammable with relatively low fire-return intervals (5–6 years), but when stands remain unburnt long enough to develop into forest (> 30 years), flammability decreases (Johansson et al. 2018). A fire-return interval between 6 and 30 years creates different degrees of heathland openness, from a dense community (Fig. 1e) to a more open one (Fig. 1f).

Despite recent research on the fire tolerance of the EB, the long-term burning tipping-points controlling *Erica* heathland sustainability are still largely unexplored. Conservation efforts in the EB have traditionally aimed to limit burning practices in protected areas, despite evidence that fire has been used as an agropastoral tool on the African continent for tens of thousands of years and current research suggesting that elimination of burning may result in high-severity fires (Johansson et al. 2018). The Ericaceous belt is one of the ecosystems where fire has long been used by people (Johansson and Granström 2014), and local knowledge and paleoecology therefore need to be considered in conservation planning.

Here we show how information on long-term ecosystem dynamics from the Ethiopian Ericaceous belt in the Bale Mountains National Park (BMNP; Fig. 1b) can be combined with interviews to pastoral communities of the Arsi Mountains National Park (AMNP; Fig. 1b). Both protected areas present similar vegetation and human activities, but AMNP receives less tourism, and traditional cattle and farming management is more widespread. Combining both perspectives will ideally produce an integrated scenario on past vegetation change, as well as a better understanding of local attitudes about the environment in the Ericaceous belt.

Combining past and present burning dynamics

The charcoal, pollen, and stable oxygen isotopic records from Lake Garba Guracha (3950 m asl; Fig. 1d), at the upper limit of the EB in the BMNP, provide information about Holocene fire, vegetation, and moisture availability (precipitation-to-evaporation ratio, P/E; see Bittner et al. 2020 for details on P/E ratio deduced from $\delta^{18}O$; Gil-Romera et al. 2021, 2019; Fig. 2). The data show three periods of *Erica* expansion and high fire activity (Fig. 2I, II, and III). Whether the ignition was human or natural, it is noteworthy that the periods of high fire activity occurred when moisture availability was either low or decreasing (Fig. 2c). This trend might be connected with reducing rainfall amounts, but also with increasing temperatures, as evaporation could have increased.

The first period occurred at 11-10 kyr BP (Fig. 2I), when a sparsely vegetated landscape dominated by Afroalpine taxa was progressively replaced by *Erica*-dominated heathland (Fig. 2b and d). The coeval increase in fire activity and *Erica* expansion at ca. 10.5 cal kyr BP (Fig. 2I) occurred during an overall dry interval. It seems likely that biomass accumulation occurred during the rainy season and supported high fire activity during the dry season. In the second fire-active period, between 8.2 and 5.5 kyr BP (Fig. 2II), the climate was more humid than in the first period, but fire activity and *Erica* biomass also show a degree of co-variability during a progressive dry trend (Fig. 2a–c). In both periods, burning and biomass accumulation established a lead–lag relationship,

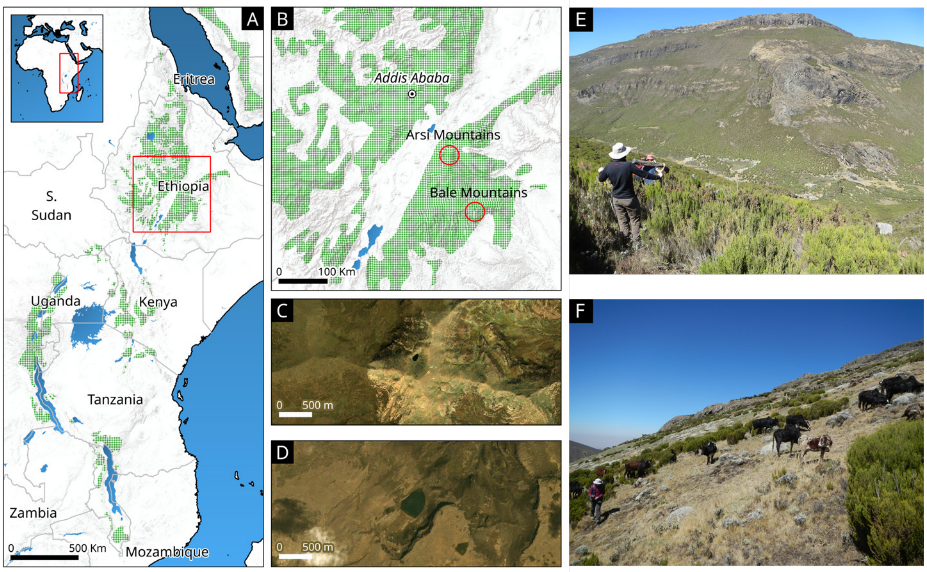

Figure 1: (A) The Eastern Afromontane archipelago; **(B)** Bale and Arsi Mountains National Parks (BMNP and AMNP respectively); **(C)** Haro Kori Lake (4000 m asl); **(D)** Garba Guracha Lake (3950 m asl); **(E)** heathland in Bale and **(F)** in Arsi areas.

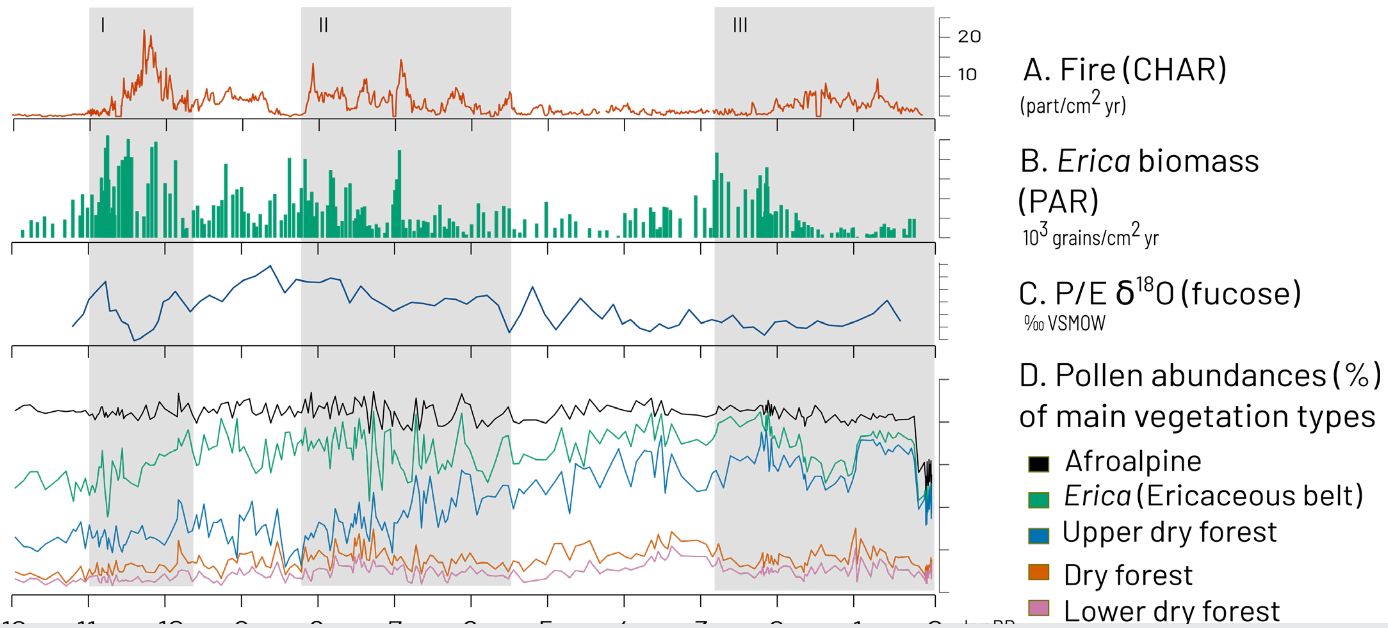

Figure 2: Paleoecological data from Lake Garba Guracha record (3950 m asl, Ethiopia). **(A)** Fire record through charcoal accumulation rate; **(B)** *Erica* abundance inferred from pollen accumulation rates; **(C)** Precipitation/evaporation ratio based on δ[18]O(fucose) isotopes; **(D)** Pollen abundances of the major vegetation zones in BMNP. Charcoal and pollen discussion can be found in Gil-Romera et al. (2019; 2021); more details on δ[18]O(fucose) are given in Bittner et al. (2020). Grey areas I, II, and III reflect the most fire-active periods.

where *Erica* was favored by fire at certain fire-return intervals, and *Erica* biomass fueled subsequent fires (see Gil-Romera et al. 2019 for numerical analyses). The third fire-active period occurred from 2.5 kyr BP to the present (Fig. 2III), under increasingly drier conditions as inferred by the P/E ratio (Fig. 2c). Fire activity was likely less intense than in previous periods, and, although *Erica* was abundant at 2.5 kyr BP (Fig. 2b and d), it decreased as the dry forest of the Afromontane biome extended upslope over the last 2500 years (Fig. 2d). The paleoecological record indicates more biomass burning during the early and mid-Holocene periods, while the EB proved to be resilient under fire frequencies between 4 and 30 years (Gil-Romera et al. 2019).

In light of the long-term environmental context, a meaningful conservation strategy would require understanding recent burning patterns in protected areas, where fire is currently banned. In February 2020, we explored the AMNP (Fig. 1b), which, unlike the BMNP (Fig. 1e), does not have dense heathland areas but rather open short *Erica* shrublands (Fig. 1f). To understand recent fire-vegetation relationships in this region, we interviewed six people from local agro-pastoral communities. Interviewees were between 30 and 40 years old and aware of landscape changes over the last two to three decades. They currently graze goats and cows and have a good knowledge of the recent burning practices in the area. Interviewees agreed that the last time the area experienced regular, large fires, aimed to produce new grass, was 10–15 years ago. Since the designation of the AMNP in 2011, burning has been banned. Two of the interviewees stated that:

"We got educated and therefore most of us do not burn any longer. However, sometimes people burn to keep hyenas away or simply as a tradition, and they send the cattle and the goats to eat the new grass and also the Erica *saplings."*

Interviewees explained that their parents' generation knew a very dense, impenetrable *Erica* landscape with remnants of Afromontane forests up to ca. 3000 m asl in AMNP. Interviewees were also aware that *Erica* plants, as well as grass cover, can return to a relatively dense shrubland within 2 to 4 years after a fire, in agreement with scientific understanding (Johansson et al. 2018). Despite the fact that burning was more frequent 20 to 30 years ago, fire was managed with return intervals of 4–5 years, which enabled the *Erica* heathland to become more dense.

On future integrative research

The evidence from paleoecology and local community knowledge suggests that past burning patterns in the Ethiopian highlands occurred under fire-conducive climates and seasonal biomass accumulations. We also inferred that intermediate fire return intervals, between 4 to 30 years, may have sustained a continuous *Erica* cover. The results suggest that a total fire ban will lead to important changes in EB structure and high-severity fires, given current increasing temperatures and population. Many questions remain about the extent to which local knowledge and recollections of past burning practices match the findings from high-resolution pollen and charcoal records in the area or other fire-information sources, such as remote sensing data. We plan to continue our paleoecological research in the Arsi Mountains by examining other lake-sediment records (e.g. Haro Kori Lake, Fig. 1c) as well as starting new calibration studies including the local knowledge and communities perspectives.

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