S.1 Evaluating different approaches for regional-scale fire activity quantification

In our study, we chose to use z-scores as a meaningful way of comparing deviations from local norms, which is particularly valuable when comparing across sites with different vegetation types and fire regimes, as well as among studies with different methodologies for charcoal quantification (Power et al., 2008). The use of z-scores is a widely accepted and established method in paleo-fire research that has been extensively applied for both global and regional analyses of fire regime changes (Daniau et al., 2010, 2012; Marlon et al., 2008, 2013, 2016; Mooney et al., 2011; Nanavati et al., 2019; Power et al., 2008, 2010b, a). Recent studies, however, have highlighted limitations of z-score scaling, including the distortion of charcoal peaks and the lack of consistency in representing fire absence across sites, particularly in tropical ecosystems where the documentation of both presence and absence is important (Gosling et al., 2021; McMichael et al., 2021). Alternatively, the approach of proportional relative scaling (PRS) proposed by McMichael et al. (2021) is suggested for regions with low or near-absent fire activity, such as Amazonia, as it better captures fire absence by preserving zero values and downweighting the influence of records characterized by rare fire events. Compared to simple relative scaling (e.g., rescaling between 0 and 100), PRS is indicated to perform better by minimizing the impact of extreme minimum or maximum values often driven by outliers.

Here, we present a comparison of methods used to derive regionalized information on past fire activity from microcharcoal data in sediment records. The compared approaches include the z-score standardization method proposed by Blarquez et al. (2014), PRS as per McMichael et al. (2021), and a modified version of PRS applying the same base period used for z-score calculations (0.2–21 ka, PRS.bp). Although the use of a base period is not specified in McMichael et al. (2021), we introduced this adjustment to ensure consistency across methods. We compare the resulting PRS and PRS.bp curves with those produced using z-scores and briefly discuss the differences among them.

S.2 Materials and methods

z-score rescaling. The z-score standardization follows the methodology described in Power et al. (2008) and Blarquez et al. (2014) using the *paleofire* R package, which involves (Eq. S1) rescaling values using a minimax transformation; (Eq. S2) homogenization of variance using the Box-Cox transformation; and finally (Eq. S3) rescaling values to z-scores.

(Eq. S1) Minmax transformation:

$$c_i' = (c_i - c_{min})/(c_{max} - c_{min})$$

where c_i' is the minimax-transformed value of the i^{th} sample in a particular record, c_i, and c_{max} and c_{min} are the maximum and minimum values of the given record.

(Eq. S2) Box-Cox transformation:

$$c_i^* = \begin{cases} ((c_i' + \alpha)^\lambda - 1)/\lambda & \lambda \neq 0 \\ \log(c_i' + \alpha) & \lambda = 0 \end{cases}$$

where c_i^* is the transformed value, λ is the Box-Cox transformation parameter and α is a small positive constant (0.01). The final step consists in the rescaling of the transformed data as z-scores, so all sites have a common mean and variance.

(Eq. S3) z-score rescaling:

$$z_i = \left(c_i^* - \overline{c_{(BP)}^*} \middle| sd_{(BP)}^*\right)$$

where z_i is the final z-score rescaled value of the sample c_i^*, calculated considering the minmax-rescaled and Box-Cox transformed value over the defined base period (here, 21-0.2 ka), , $\overline{c_{(BP)}^*}$, and the standard deviation over the same interval, $sd_{(BP)}^*$.

Proportional relative scaling. The herein applied PRS follows the approach described by McMichael et al. (2021), with an optional modification to incorporate a base period (BP). Calculations were performed by modifying the pfTransform function of *paleofire* R package (Blarquez et al., 2014), implementing the following rationale:

(Eq. S4) Proportional relative scaling:

$$c_i^* = \left({}^{c_i}/_{c_{max(BP)}} \times 100\right) \times \left({}^{f}/_{\mathrm{N}}\right)_{(BP)}$$

where c_i is the charcoal value of the i^{th} sample, c_{max} is the maximum value of the given record, f represents the number of samples in the record containing charcoal (*i.e.*, measurement > 0), and N is the total number of samples in the series. If a base period BP is defined, the maximum value, c_{max}, and the frequency of samples containing charcoal are calculated only for that period. Otherwise, the full series is used as per McMichael et al. (2021). However, differently from McMichael et al. (2021), we represent the resulting composite data as curves using the same parameters applied for z-scores in order to compare both methods.

S.3 Results and discussion

Our comparisons show that despite changes in the amplitude of variability, all regions hold mostly coherent patterns of changes and a similar temporal structure. However, some key differences also arise. Although all composites for NNeo indicate increased fire activity between 18 and 13 ka and during the LGM for CEB, z-scores and PRS.bp suggest a stronger rise, while PRS shows only a mild increase (Fig S1a,d). The use of base period produces very similar trends between both methods, which is particularly important when including records with peak values outside our time of interest. Moreover, variabilities during the Pleistocene are more sensitive to site-specific data, due to the low availability of records.

On the other hand, in Amazonia, although the overall temporal patterns are similar across methods, a key divergence is observed: both PRS and PRS.bp suggest higher fire activity during the LGM and part of the deglaciation compared to the Holocene, whereas z-scores indicate the opposite trend. In this case, z-scores seem more consistent with the known long-term fire history in the region. Several Amazonian records spanning Pleistocene ages suggest higher fire activity during the Holocene (Blaus et al., 2024; Bush et al., 2004; Colinvaux et al., 1997; Fontes et al., 2017; Hermanowski et al., 2012). An exception is southwestern Amazonia, where high charcoal concentrations occur during the Pleistocene, followed by a decline in the late Holocene as rainforest expanded (Burbridge et al., 2004).

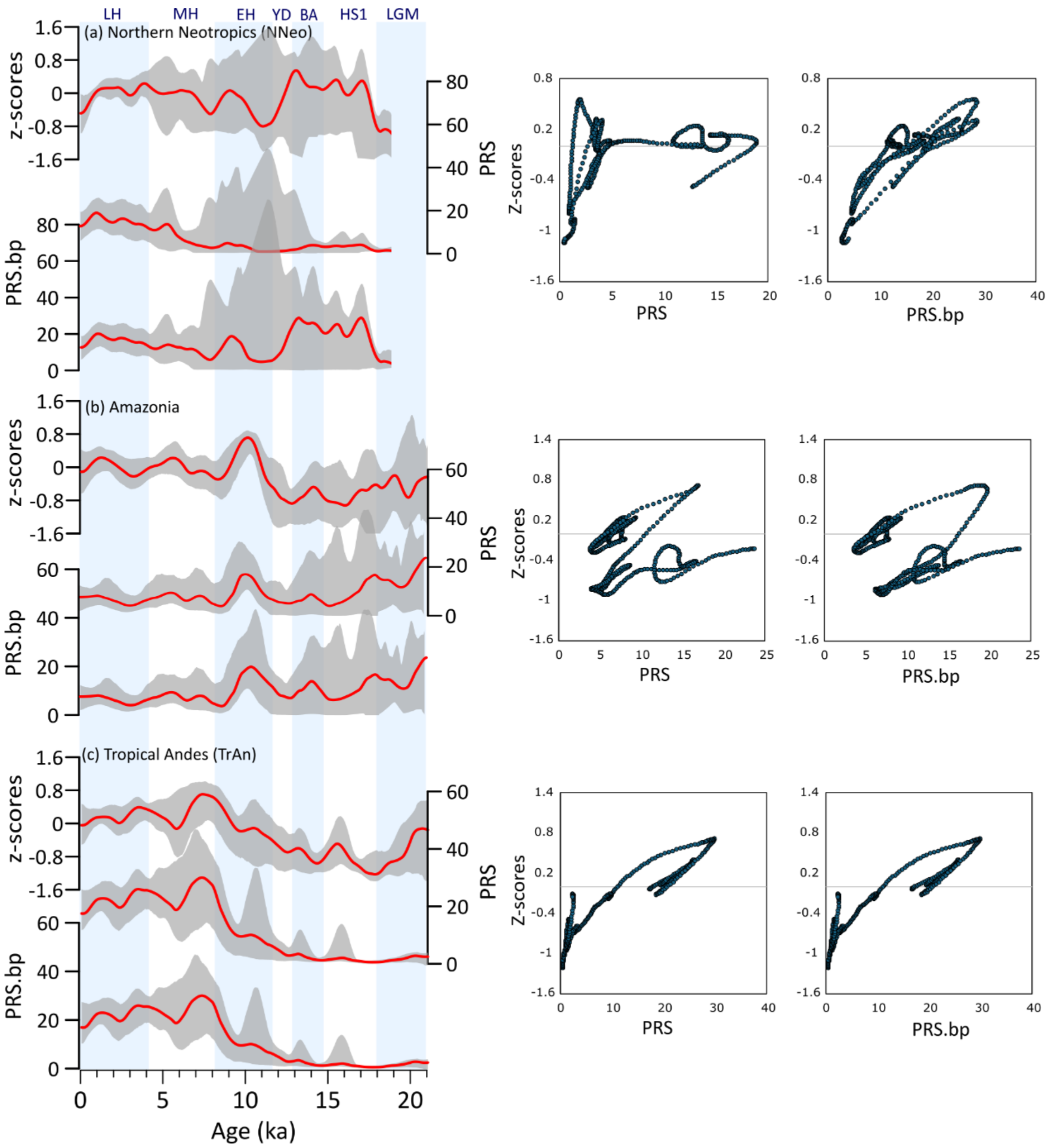

Fig. S1. Comparison of charcoal influx data transformed into z-scores with proportional relative scaling (PRS) and proportional relative scaling with a 0.2 – 21 ka base period (PRS.bp). All curves use pre-bin half width of 40 yr and window half width smoothing of 1000 yr.

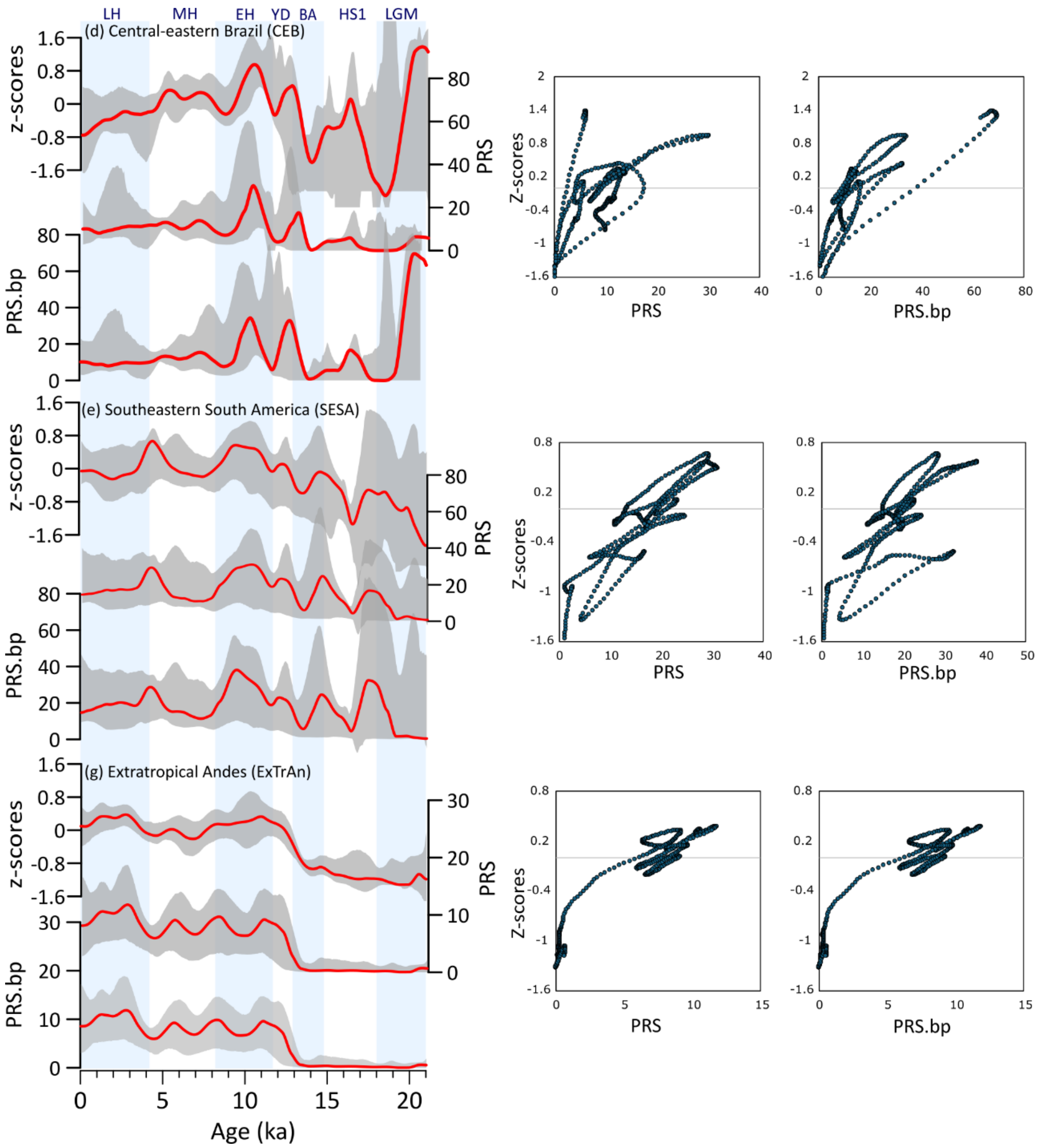

Fig S1. Continued.

Given that Amazonia exhibited important discrepancies between methods and is the region in which PRS is likely to best perform due to its rare frequency of fire events, we tested both z-scores and PRS.bp with multiple settings by applying combinations of sizes for bin half-window (binhw: 1500, 1000, 500, 300, and 40 years) and smoothing half-window (hf: 3000, 2000, 1500, 1000, and 400 years) (Fig. S2).

Testing several parameters for Amazonia shows that PRS.bp is more sensitive to binhw choices in comparison to z-scores, with Holocene base levels increasing systematically with larger bin sizes (Fig. S2). Notably, while for binhw of 40 and 300, Pleistocene values are usually higher than those of the Holocene, the opposite is produced by applying binhw of 500, 1000 and 1500 years (Fig S2b). In contrast, z-scores remain stable across different settings, consistently showing higher Holocene fire levels and no systematic variation linked to bin size.

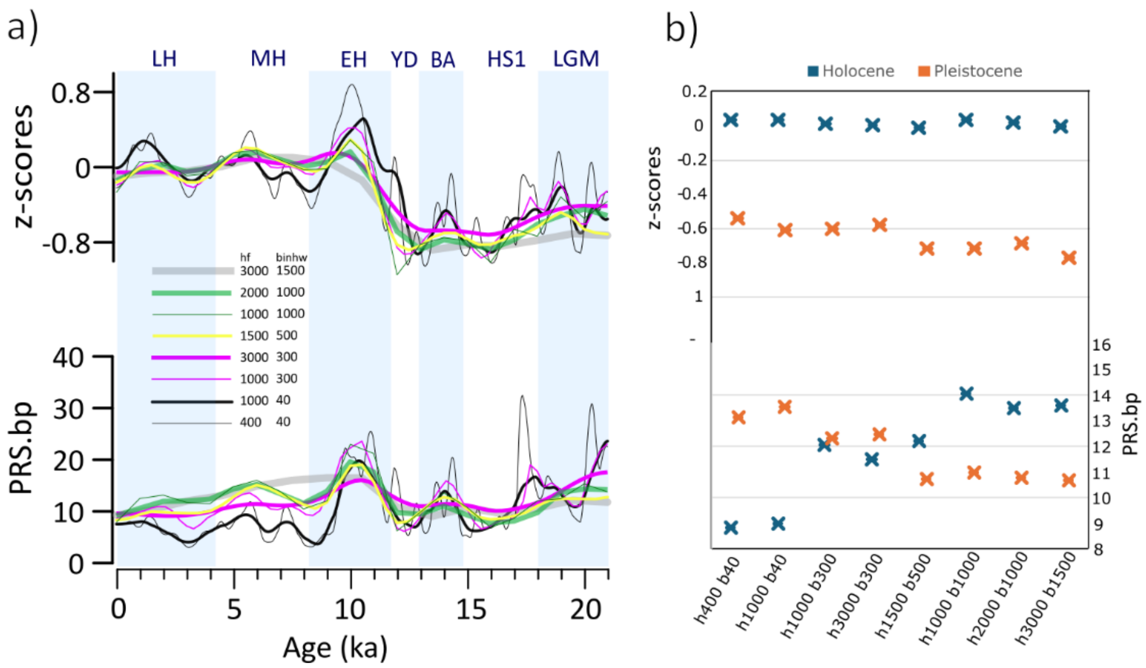

Fig. S2. (a) Charcoal influx composites for Amazonia using z-scores and proportional relative scaling (PRS.bp; base period: 0.2–21 ka), applying different parameters for smoothing window half-width (hf) and pre-bin half width (binhw) lengths in years. **(b)** average composite values for the Holocene and Pleistocene considering the same parameters used.

S.4 Final remarks

Considering these observations, z-scores appear to be more stable and better suited for capturing long-term trends in fire activity. While PRS seems promising, particularly for regions such as Amazonia where fire activity is rare, it still requires further testing. For example, its performance across different regions and time spans, as well as its sensitivity to variations in base periods and binning parameters, remains to be fully assessed. Therefore, we find strong justification for using z-scores as a well-tested and reliable method in our study, where fire regimes vary markedly across both regions and periods.

S.5 Code availability

The analyses were primarily performed using code from already developed R packages “paleofire”, “Neotoma” and “rcarbon”. However, the specific scripts used, based on these packages, can be found on GitHub at https://github.com/tkakabane/APcomp

S.6 References

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