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On the scaling and standardization of charcoal data in paleofire reconstructions

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Abstract

Understanding the biogeography of past and present fire events is particularly important in tropical forest ecosystems, where fire rarely occurs in the absence of human ignition. Open science databases have facilitated comprehensive and synthetic analyses of past fire activity, but charcoal datasets must be standardized (scaled) because of variations in measurement strategy, sediment type, and catchment size. Here, we: i) assess how commonly used metrics of charcoal scaling perform on datasets from tropical forests; ii) introduce a new method called proportional relative scaling, which down-weights rare and infrequent fire; and iii) compare the approaches using charcoal data from four lakes in the Peruvian Amazon. We found that z-score transformation and relative scaling (existing methods) distorted the structure of the charcoal peaks within the record, inflating the variation in small-scale peaks and minimizing the effect of large peaks. Proportional relative scaling maintained the structure of the original non-scaled data and contained zero values for the absence of fire. Proportional relative scaling provides an alternative scaling approach when the absence of fire is central to the aims of the research or when charcoal is infrequent and occurs in low abundances.

Highlights

- Proportional relative scaling is a new methodology for comparing fire histories across sites
- Proportional relative scaling is most useful in systems where fire is rare or absent, whereas current methodologies are geared towards systems with high fire frequency.

Keywords: Charcoal, data standardization, fire activity, paleofire, scaling, z-score

Introduction

Basic categorizations of natural systems as being fire-prone or fire-resistant are reflected in evolved traits (e.g., Uhl & Kauffman 1990). Humans commonly introduce and manipulate fire in ecosystems and can radically rebalance that biogeography of traits (e.g., Uriarte et al. 2016). Because moist closed canopy tropical forests are, for the most part, too wet to burn naturally (Bush et al. 2008, Malhi et al. 2014), most plant species are especially susceptible to fire (Uhl & Kauffman 1990). Humans have inhabited and used fire in these closed canopy tropical forests for millennia,

which has undoubtedly shaped the biogeography of many species and functional traits in modern systems (Roberts et al. 2017, van der Sande et al. 2019).

Quantifying fire histories, i.e., determining patterns of past fire activity, has become an integral part of tropical paleoecology (e.g., Bush & Silman 2007, Power et al. 2013). The importance of establishing past fire frequency and the amount of biomass burning is evident based on studies of ecological responses to modern fires. A single fire can radically alter the relative abundances of Amazonian rainforest trees, and systems that have burned two or three times within a decade resulted

in an almost complete species turnover and incipient savannization (Barlow & Peres 2008). Local variability in fuel availability, human population density (reflecting potential ignition sources), and droughts would all create a spatial and temporal mosaic of fire effects (e.g., Marlon 2020). Thus, quantifying the spatial and temporal patterns of past fires (hereafter paleofires) is particularly important for understanding modern biogeographic patterns and local scale ecological processes in tropical forests.

The Global Charcoal Database (Power et al. 2010a), or Global Paleofire Database (paleofire.org), has been established as a repository of charcoal datasets used to facilitate large-scale syntheses of past fire activity (Power et al. 2008, Marlon et al. 2009, Brücher et al. 2014, Marlon et al. 2016). The sediment type, catchment size, and charcoal metric varies across sites in the database (e.g., Marlon et al. 2016), resulting in measurements that can often vary by thirteen orders of magnitude (Power et al. 2010a, Brücher et al. 2014). Scaling methods are therefore needed to standardize these data and allow inter-site comparisons (e.g., Marlon et al. 2008, Power et al. 2008, Brücher et al. 2014, Marlon et al. 2016).

Two scaling metrics commonly used for standardization of charcoal datasets are z-score transformations (Marlon et al. 2008, Power et al. 2008, Power et al. 2010a, Marlon et al. 2013, Power et al. 2013) and relative scaling (McMichael et al. 2012, Valencia et al. 2018). Both approaches scale the charcoal data for each lake relative to the values within the lake, overcoming the issue of variations in catchment size or measuring strategies. The z-score approach commonly includes a Box-Cox transformation, with z-scores calculated on the transformed values (Brücher et al. 2014). The z-score transformations reduce the influence of outliers while maximizing small-scale variation in the dataset (Marlon et al. 2016). It does not, however, retain a consistent value that represents the absence of fire across sites. Relative scaling, which is based on the minimum and maximum values in the charcoal dataset, has been used primarily in tropical regions in studies where assessing the absence of fire across regions is as important as detecting its presence (e.g., McMichael et al. 2012, Valencia et al. 2018). Relative scaling, however, has the potential to artificially inflate small-scale variance in settings that truly contain very little to no charcoal, such as wet tropical systems. For example, a lake that has a maximum charcoal abundance of $0.05 \text{ mm}^3/\text{cm}^3$, and an adjacent lake with a maximum value of $10 \text{ mm}^3/\text{cm}^3$, would be scaled to the same value of 1 using relative scaling.

In the wet tropical forests of the Amazon, many lake sediment records contain frequent or abundant charcoal (e.g., Bush & Silman 2007, Power et al. 2013, Bush et al. 2016), while others do not (Bush et al. 2007b, Schiferl et al. 2017, Nascimento et al. 2019, Åkesson et al. 2020). Here we show how both the z-score and relative scaling approaches can be problematic when interpreting datasets with very little charcoal. We also present an alternative methodology for scaling and standardizing charcoal datasets that builds on

the relative scaling approach but down-weights rare charcoal that occurs in low abundances. Our simple scaling method, termed proportional relative scaling, may prove useful when research aims are to compare the absence or near absence of fire across sites or to compare peak magnitudes of fire activity between sites.

Methods

A case study: lake sediment records in the Peruvian Amazon

Four reconstructions of past fire activity, based on charcoal fragments extracted from lake sediments collected within the state of Madre de Dios in the Peruvian Amazon (Bush et al. 2007b, Bush et al. 2007a) (Fig. 1), were used as a case study to compare scaling approaches. The four lakes (Gentry, Parker, Vargas, Werth) are all roughly the same size, lack riverine or fluvial inputs, and lie within ca. 60 km of each other (Bush et al. 2007a). Though similar in environment and physical characteristics, the four lakes have starkly contrasting fire histories because of localized human influence in the region (Bush et al. 2007b, Bush et al. 2007a).

The charcoal quantified in these four lake sediment records was processed and analyzed using the same standardized methodology (Bush et al. 2007a,b). It is also important to note here that the charcoal analyst (Claudia Listopad) was consistent among these four reconstructions, and that the charcoal fragments recovered from all four sites were analyzed with the same microscopes, using the same calibrations. Thus, the differences in the measured charcoal quantities (non-scaled data are in units of mm^2/cm^3) reflect true differences in the amounts of charcoal recovered and are not a result of varying laboratory processing techniques, methodologies, analyst abilities, or microscope calibrations.

The sediment record from Lake Gentry spans the last 6500 years and contains brief intervals of maize cultivation that began around 3700 calibrated years before present (hereafter cal yr BP) and ended ca. 500 cal yr BP (Bush et al. 2007a,b). The sediment record from Lake Parker spans ca. 7900 years and contains no evidence of cultivation (Bush et al. 2007a,b). Lakes Gentry and Parker contain the highest overall abundances of charcoal ($0 - 34 \text{ mm}^2/\text{cm}^3$) and experienced more frequent fires (72 out of 103 total samples at Lake Gentry, and 180 out of 234 total samples at Lake Parker) compared with the other two lakes (Fig. 2a). Lake Vargas spans ca. 8000 years and has no evidence of cultivation, though sedimentation stopped between 7200 and 2500 cal yr BP (Bush et al. 2007a,b). Charcoal abundances were typically much lower in Lake Vargas ($0 - 17 \text{ mm}^2/\text{cm}^3$) compared with Lakes Gentry and Parker, and fire occurrence was also less frequent (10 out of 25 samples; Fig. 2a). Lake Werth spans the last ca. 3100 years, has no evidence of cultivation, and has the lowest charcoal abundances ($0 - 0.29 \text{ mm}^2/\text{cm}^3$) and fire recurrence (2 out of 86 samples) of any of the four records (Bush et al. 2007a,b; Fig. 2a). The 'Data

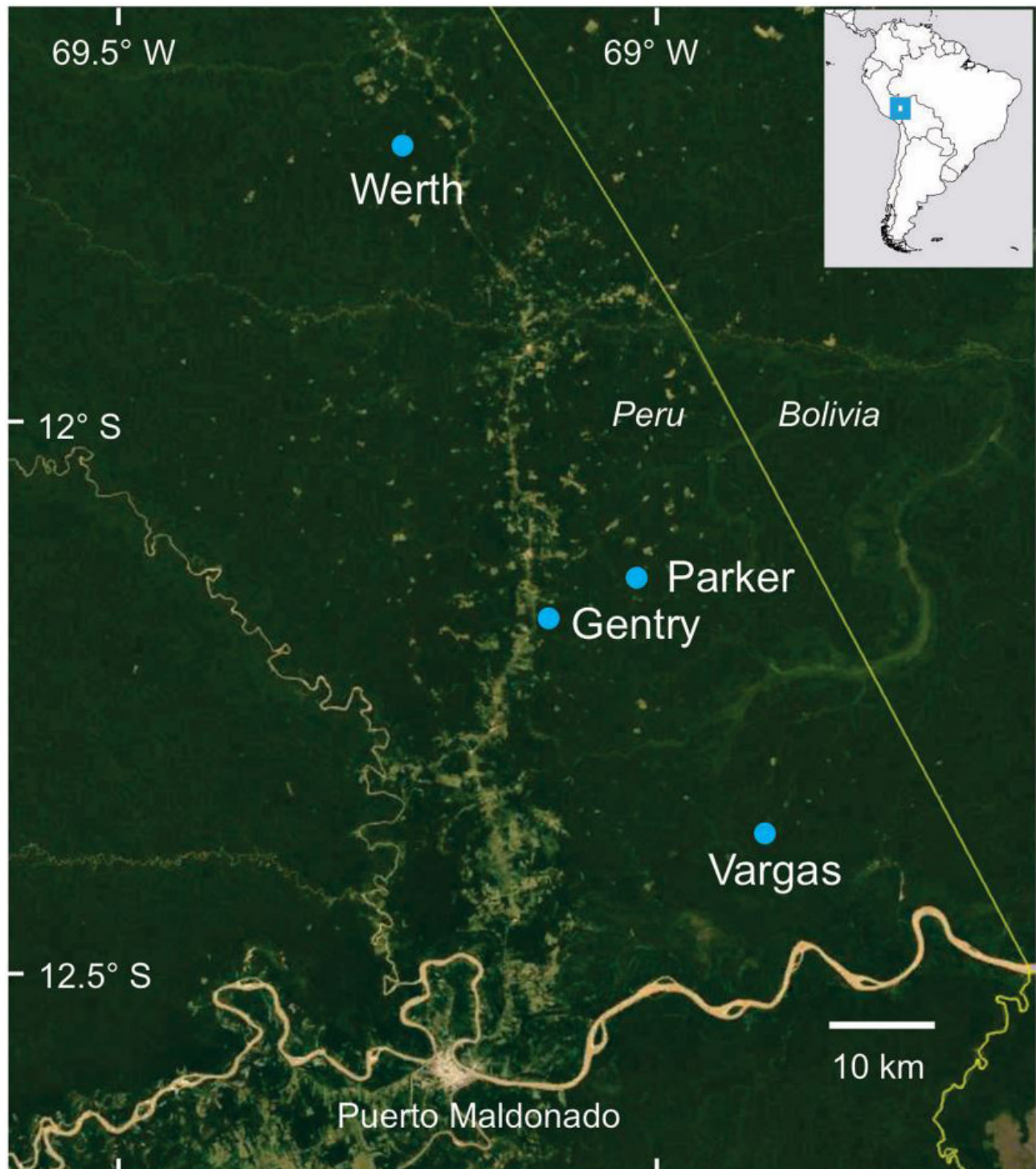


Fig. 1. Map of Lakes Gentry, Parker, Vargas, and Werth in southeastern Peru. The four lakes are shown as blue circles. The background is from Google Earth imagery captured in 2020. The dark green background shows the extent of lowland Amazonian rainforest in the region. The city of Puerto Maldonado lies on the Madre de Dios River. Part of the TransAmazon Highway (30C) runs north out of Puerto Maldonado, past Lakes Gentry and Werth, and into Rio Branco, Brazil. Yellow line indicates the Peru-Bolivia border.

sources' section contains links to the charcoal data used in these studies.

We applied the z-score transformation, relative scaling, and our new approach of proportional relative scaling (Table 1) to the charcoal data from Lakes Gentry,

Parker, Vargas, and Werth. The z-score transformation scales an individual charcoal measurement (c') based on the mean (\bar{c}') and standard deviation ($\sigma_{c'}$) of minimax and Box-Cox^u transformed charcoal data (Table 1). The relative scaling takes an individual charcoal

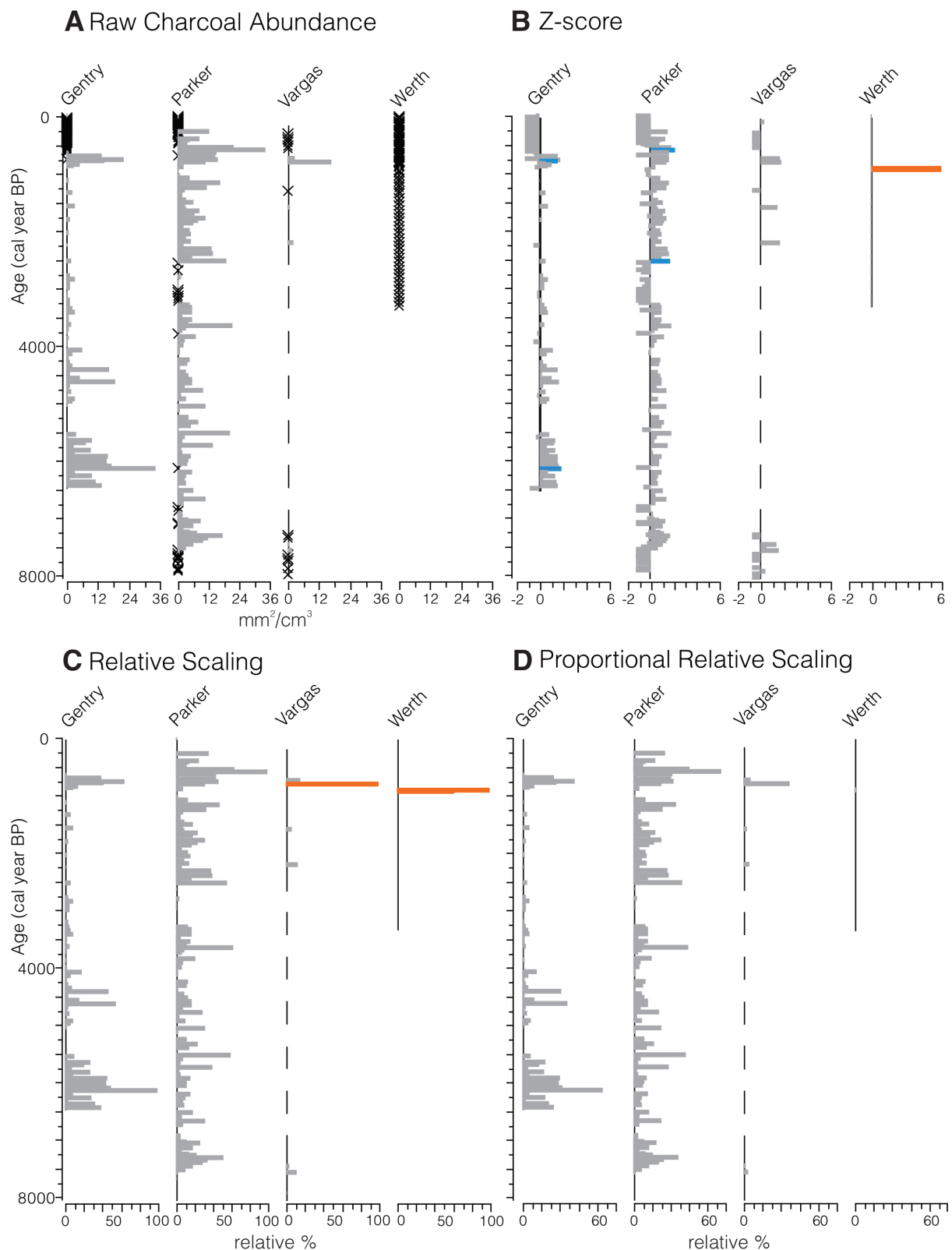


Fig. 2. Charcoal data from Lakes Gentry, Parker, Vargas, and Werth in southeastern Peru, shown as both raw data and an array of scaling methods: A) raw charcoal data (non-scaled), B) z-score scaling, C) relative scaling, D) proportional relative scaling of charcoal data. Red bars indicate where a scaling method has inflated the influence of the measurement, and blue bars indicate where a scaling method has decreased the influence of a measurement. Black Xs in panel A indicate charcoal sampling effort. Dashed line on Lake Vargas indicated a hiatus in the record (no data).

measurement (c_i), divides it by the maximum charcoal measurement found within the core (c_{max}), and multiplies by 100 (Table 1). Because relative scaling is based on the minimum and maximum values within a series, it gives the same result as the minmax transformation ($(c_i - c_{min}) / (c_{max} - c_{min})$) when the minimum value in the series is 0. The proportional relative scaling takes the same formula as relative scaling, but then multiplies the outcome by the proportion of samples in the

record containing charcoal, i.e., the number of samples containing charcoal (f) out of the total number of samples analyzed (N) (Table 1). Links to the outputs of these scaling approaches can be found in the 'Data sources' section.

We also constructed a regional composite of fire activity across the four lakes (Gentry, Parker, Vargas, and Werth) using the z-score approach and the proportional relative scaling approach. The composites of fire activity were generated for the last 2000 years, which is the overlapping time period of all four records. The median temporal resolution of pollen samples within the lakes was 56, 11, 58, and 70 years for Lakes Gentry, Parker, Vargas, and Werth, respectively. Based on this, composites of proportional relative scaling (i.e., running medians of scaled values) and z-score scaling were performed at 60-year temporal resolution. We also showed the spread of values (boxplots) for proportional relative scaling in 200-year bins throughout the 2000-year timespan. All analyses were conducted using the 'stats' and 'paleofire' (Blarquez et al. 2014) packages for R (R Development Core Team 2013).

Table 1. Scaling approaches commonly used to standardize charcoal data, including the new methodology of proportional relative scaling. c_i = a single charcoal measurement within a series, c_{μ} = mean of all charcoal measurements in the series, c_{σ} = standard deviation of all charcoal measurements in the series, c_{max} = the maximum value of all charcoal measurements in the series, f = the number of samples in the series containing charcoal (measurement > 0), N = the total number of samples in the series. Where char is listed as c' in the z-score method, these charcoal measurements have undergone the minmax and Box-Cox transformations (Power et al. 2010a).

| Scaling method | Formula |
|-------------------------------|---|
| z-score | $char_{zscore} = \frac{c'_i - c'_{\mu}}{c'_{\sigma}}$ |
| relative scaling | $char_{scaled} = \frac{c_i}{c_{max}} * 100$ |
| proportional relative scaling | $char_{pscaled} = \left(\frac{c_i}{c_{max}} * 100 \right) * \frac{f}{N}$ |

Results

All lakes had a minimum non-scaled value of 0 (i.e., an absence of charcoal in at least one sample of the series; Table 2). By definition, the absence of charcoal remained at 0 for the relative scaling and proportional scaling methods, and the z-score approach had varying degrees of negative numbers representing fire absence (Table 2, Fig. 2b). The maximum value of non-scaled charcoal was ca. 35 mm²/cm³ at Lakes Gentry and Parker, which was approximately twice the maximum amount found at Lake Vargas (17 mm²/cm³), and

Table 2. Results of three scaling methods (z-score, relative scaling, proportional relative scaling) applied to charcoal datasets from Lakes Gentry, Parker, Vargas, and Werth located in the Peruvian Amazon. The units of non-scaled values are mm²/cm³. For proportional relative scaling (prop relative scaling), values in parentheses indicate the number of samples containing charcoal out of the total number of samples, corresponding with f/N in the formula (Table 1).

| Lake | Scaling method | minimum | maximum | range |
|--------|---------------------------------|---------|---------|-------|
| Gentry | non-scaled | 0 | 34.8 | 34.8 |
| Gentry | z-score | -1.24 | 1.92 | 3.16 |
| Gentry | relative scaling | 0 | 100 | 100 |
| Gentry | prop relative scaling (72/103) | 0 | 69.9 | 69.9 |
| Parker | not scaled | 0 | 34.6 | 34.6 |
| Parker | z-score | -1.27 | 2.11 | 3.38 |
| Parker | relative scaling | 0 | 100 | 100 |
| Parker | prop relative scaling (180/234) | 0 | 76.9 | 76.9 |
| Vargas | not scaled | 0 | 17.1 | 17.1 |
| Vargas | z-score | -0.73 | 1.78 | 2.51 |
| Vargas | relative scaling | 0 | 100 | 100 |
| Vargas | prop relative scaling (10/25) | 0 | 40 | 40 |
| Werth | not scaled | 0 | 0.29 | 0.29 |
| Werth | z-score | -0.15 | 6.44 | 6.60 |
| Werth | relative scaling | 0 | 100 | 100 |
| Werth | prop relative scaling (2/86) | 0 | 2.33 | 2.33 |

significantly higher than the maximum amount found at Lake Werth ($0.3 \text{ mm}^2/\text{cm}^3$, Table 2).

The scaling method altered the structure of the true maximum peak heights between lakes. For example, the non-scaled maximum charcoal amount is $34.8 \text{ mm}^2/\text{cm}^3$ at Lake Gentry, compared with $0.29 \text{ mm}^2/\text{cm}^3$ at Lake Werth. The z-score scaling transformed these two measurements of charcoal to 1.92 and 6.44, respectively, making the magnitude of the scaled charcoal peak in Lake Werth much greater than in Lake Gentry (Table 2, Fig. 2). By definition (Table 1), relative scaling transformed the two maximum charcoal measurements in the Lakes Werth and Gentry records to have equivalent peak size (Table 2, Fig. 2). Both of these approaches distorted the structure of peak height compared with the non-scaled data. The proportional relative scaling down-weighted the maximum peak height based on the rarity of charcoal in the record, maintaining structure in the peak heights (Table 2, Fig. 2).

The composite records generated by the z-score and proportional relative scaling approaches differed in their overall trends from 2000 to 600 cal yr BP (Fig. 3). The highest median value, using either the 60-year running median or the 200-year binned medians, occurred from ca. 800–600 cal yr BP with proportional relative scaling (Fig. 3a). This peak was also present in 60-year running mean of z-score values, though there was an even larger peak at ca. 1660 cal yr BP (Fig. 3b). The non-scaled (raw) data show that the charcoal peaks from 800–600 cal yr BP are represented across all lakes, whereas the high abundances of charcoal at ca. 1660 cal yr BP are not (Fig. 2a). The small-scale variation that occurred in charcoal abundances from 2000–1200 cal yr BP (Fig. 3a) is also amplified using the z-score scaling (Fig. 3b). The large variation (i.e., potential ‘outliers’) seen from 600–400 cal yr BP (Fig. 3a), however, had a reduced magnitude with the z-score scaling approach (Fig. 3b).

Discussion/Conclusions

Because of the large differences in lake size, watershed topography, local vegetation, and charcoal quantification methods, charcoal data need to be scaled, or standardized, so that direct comparisons of relative biomass burning can be made between sites (e.g., Marlon et al. 2016 and references within). The three scaling methods (z-score, relative scaling, proportional relative scaling) compared here have differential effects on the charcoal dataset from Lakes Gentry, Parker, Vargas, and Werth (Figs. 2–3). Our results demonstrate that the best method of charcoal data scaling will depend on the research question being addressed and the quality of the datasets. Chronological (un)certainty of the age model, changes in sedimentation rates, and changes in sampling effort throughout a core can affect any of the scaling methods. We also suggest considering these factors during the selection of sites to be used in any paleofire synthesis, regardless of the choice of scaling method.

The z-score scaling method highlights broad trends and anomalies in past fire activity synthesized on global, continental and sub-continental scales

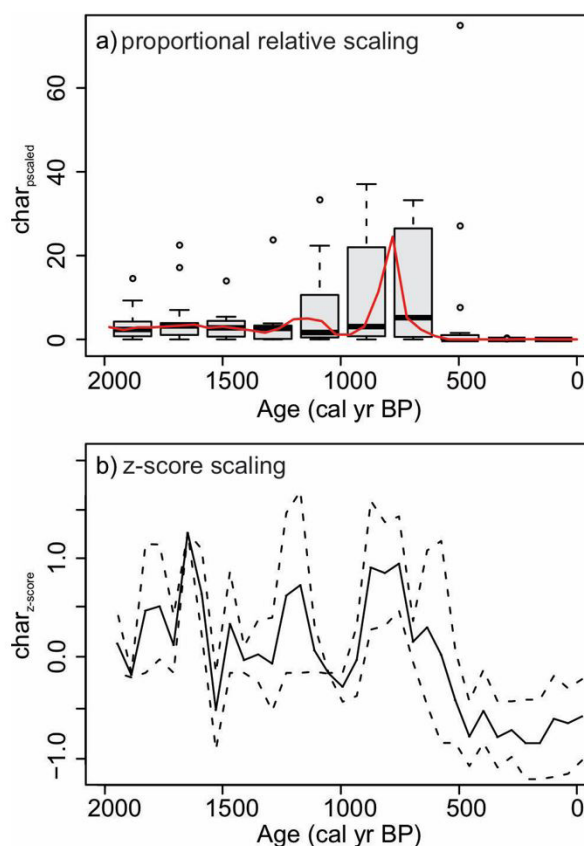


Fig. 3. Composite records of fire activity for Lakes Gentry, Parker, Vargas, and Werth in the Peruvian Amazon for the last 2000 years generated using a) proportional relative scaling and b) z-score scaling. In (a) the red line represents a 60-year running median through the time series, and box and whisker plots show the spread of scaled charcoal values in 200-year time bins. In (b) the solid line is the 60-year mean z-score, and dashed lines are 95% confidence intervals.

(Power et al. 2008, Marlon et al. 2013, Brücher et al. 2014, Blarquez et al. 2015, Marlon et al. 2016). Z-score scaling is the basis of the functions used to synthesize composite charcoal records in the ‘paleofire’ R package (Blarquez et al. 2014). It is also used in programs (e.g., CharAnalysis) containing algorithms for signal-to-noise decomposition to detect true fire events from background charcoal influx within a record (e.g., Higuera et al. 2011). ‘Background’ charcoal was originally thought to result primarily from the constant in-washing of particles derived from the surrounding terrestrial environment (Clark & Patterson 1997). Recent analyses, however, suggest that ‘background’ charcoal represents biomass burning at the regional or landscape scale (Marlon et al. 2016 and references within, Loughlin et al. 2018).

In regional analyses, z-score scaling is typically performed in settings where fire is a natural landscape process, such as in temperate regions (e.g., Blarquez et al. 2015), or where fire frequency is high due to long-term human occupation (e.g., Vanni ere et al. 2016). It has less commonly been used for regional analyses in

tropical settings (Power et al. 2010b, Maezumi et al. 2015). In tropical systems, some paleofire records contain very little charcoal whereas nearby sites contain frequent charcoal fragments, and this heterogeneity can occur within a single watershed (e.g., Bush et al. 2007b; Figs. 1-2). The z-score scaling technique is used to increase the visibility of small-scale variation, and reduce the influence of large-scale outliers (Marlon et al. 2016) (Figs. 2-3). As a result, z-score scaling artificially increases the maximum charcoal peak heights in sites where there are low abundances or infrequent recurrences of charcoal. This inflation is easily seen in the records of Lakes Vargas and Werth, where the height of the largest charcoal peak scales equal to or greater than Lakes Gentry and Parker, even though they contained significantly less charcoal (red peaks in Fig. 2, Table 2). The reduced influence of the large charcoal peaks (blue peaks in Fig. 2) was also noted in the z-score composite of Lakes Gentry, Parker, Vargas, and Werth (Fig. 3).

In some instances, research aims are to compare periods of fire absence. By definition, z-scores do not keep measurements of the absence of fire standard between sites (Tables 1-2, Figs. 2-3). When assessing the absence of fire has been central to the aims of the research, relative scaling has been used to make inter-site comparisons (McMichael et al. 2012, Valencia et al. 2018). While allowing for the standardization of fire absence, relative scaling has the same artificial inflation of the small charcoal abundances seen at Lakes Werth and Vargas as the z-score scaling (Fig. 2, Table 2). The proportional relative scaling approach shows the same relative trends in medians as z-score scaling, maintains a standard value for the absence of fire (0), and also maintains the structure of the magnitude of peak heights relative to the raw (unscaled) data (Figs. 2-3, Table 2).

We used the frequency of samples containing charcoal (i.e., where the charcoal measurement is > 0) to scale the data (Tables 1-2). We used the frequency metric because the variance in catchment size and measurement metrics makes scaling by means, medians or percentiles impossible. Lake sediments containing a low frequency of samples containing charcoal (e.g., Lake Werth) typically also have low abundance measurements (Bush et al. 2007b; Åkesson et al. in revision, Bush et al. 2007a, Nascimento et al. 2019). These low-abundance, low-frequency charcoal measurements highlight the need for down-weighting in inter-site comparisons (Fig. 2). Proportional relative scaling is useful when the maximization of small-scale variability achieved with the z-score approach artificially inflates fire peaks or variability amongst records (Figs. 2-3).

We suggest that proportional relative scaling provides a charcoal data standardization technique that is useful when research aims to integrate sites where past fire occurrence may be rare or absent, and assess past fire-free periods within paleoecological records. This metric will thus be particularly useful in wet tropical environments or extratropical settings with low fire frequencies, and will facilitate more

nuanced understandings of the role of past fire in shaping modern ecosystems.

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Author Contributions

CNHM and BMH conceived the ideas, designed methodology, and compiled and analysed the data; CNHM led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Data Accessibility Statement

All data are available from the Dryad Digital Repository (doi:10.5061/dryad.nzs7h44r0). Please note that the charcoal data for Lakes Gentry and Parker as listed in the Global Paleofire Database (www.paleofire.org) are not correct (as of May 2020). We have notified the database owners. Please use the datasets provided in Dryad until the issue is resolved.

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