Discussion of : Statistical models for use of palaeosol magnetic properties as proxies for palaeorainfall

May 20, 2014

Scripps Institution of Oceanography
Maggie Avery

Grand Challenges

#5 Environmental Magnetism, Dust and Rainfall:

Rock and mineral magnetic techniques can be used to study the formation, transportation, deposition and post-depositional alteration of magnetic minerals as they respond to changes in environmental conditions. Environmental magnetism has contributed to research in Earth science and has found applications in physics, chemistry and biological sciences including research on pollution, climate change, and iron biomineralization (see comprehensive review by Liu et al. 2012). While magnetic properties are quick to measure, deciphering the environmental implications remains a challenge requiring a detailed understanding of a range of complex measurements. The MagIC database has been designed to accommodate the wide range and enormous volume of measurements generated in a typical environmental magnetism study.

Background

Relationship between magnetic susceptibility (χ) and mean annual precipitation (MAP) in soils

- Systematic variations in the concentration and grain size of the magnetic minerals in the sediment produces a systematic variation in χ.
- Magnetic minerals form in-situ through the release of Fe by weathering which then oxidizes and crystallizes.
- In modern soils the degree of magnetic enhancement is associated with climate, especially MAP (within ~300 mm/yr to ~1500 mm/yr) – as well as: temperature, soil water capacity, evaporation, etc.

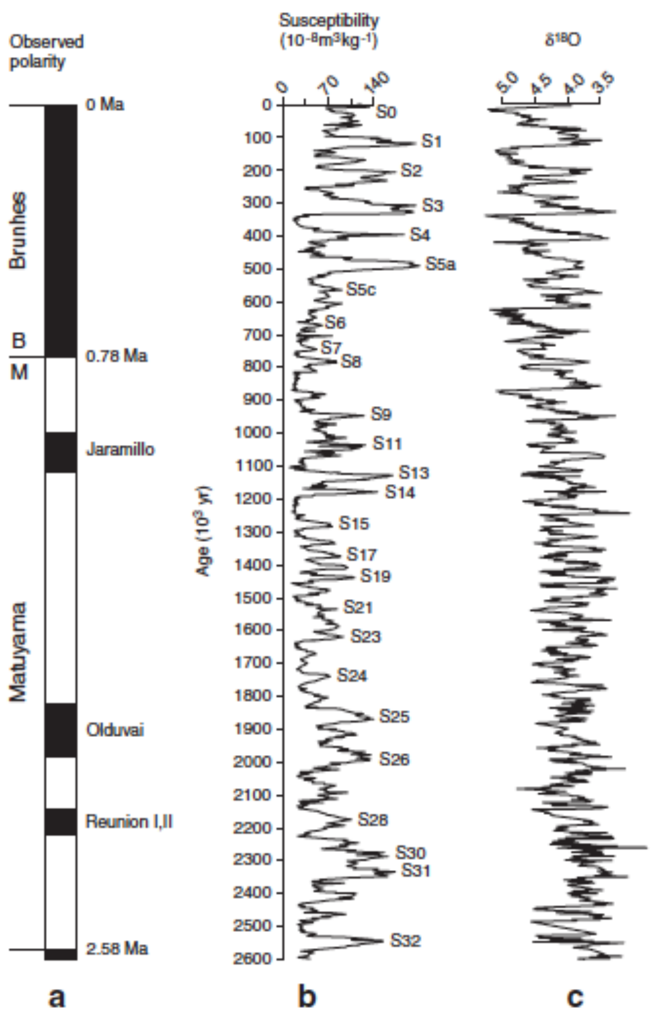
Background

By quantifying the relationship between modern climate and the magnetic properties of recent soils, it may be possible to make paleoclimate predictions.

- **Climofunction,** φ

The present is the key to the past!

Background



Maher and Possolo (2013)

Fig. 1. Stratigraphic, palaeomagnetic and magnetic records for the Chinese Loess Platea(Lingtai), and the deep-sea oxygen isotope record from ODP677 (Shackleton et al.,1990).

S0,…,S32 denote palaeosol units.

Palaeomagnetic chronology drawn from the geomagnetic polarity timescale of Cande and Kent (1995).

Records from ODP677 redrawn from Han et al. (2011).

Background

Heslop and Roberts (2013)

> "Quantitative prediction requires full assessment of the uncertainties associated with predictions."

Global and Planetary Change 110 (2013) 379–385

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

ELSEVIER

Calculating uncertainties on predictions of palaeoprecipitation from the magnetic properties of soils

David Heslop *, Andrew P. Roberts

Research School of Earth Sciences, Australian National University, 0200 Canberra, ACT, Australia

Background

Heslop and Roberts (2013)

- Used discrimination intervals to judge the predictive power of climofunction
  - Uncertainty in the location of the true regression line relating MAP and χ
  - Uncertainty in the ability of the parameter χ to make prediction of MAP
    - i.e. non-zero misfit between measured data and predictions from the estimated regression. Such variability results from pedogenic process: two soils with same MAP may have slightly different magnetic properties

Background

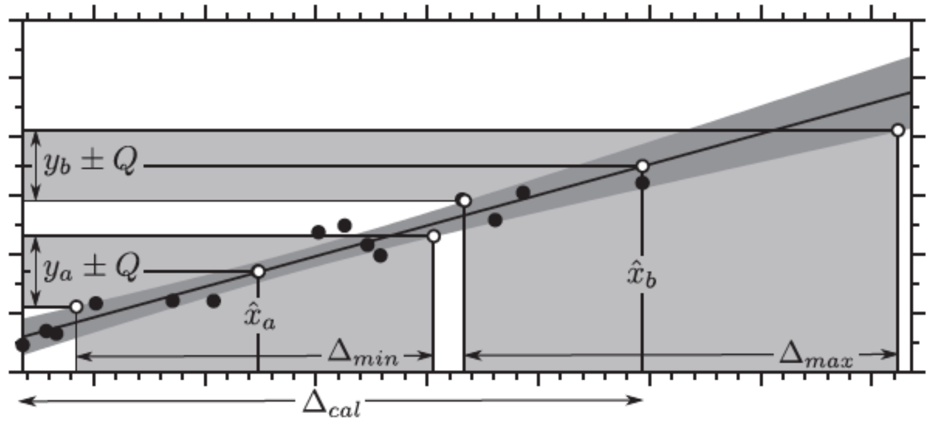


Fig. 2. For the illustrated example data set, y_a yields the narrowest possible discrimination interval at given values of α and P. The width of this discrimination interval is defined as Δ_{min}. In contrast, y_b produces the widest possible discrimination interval associated with a point estimate, $\hat{x}_b$, which still lies within the interval of the calibration data. The width of this discrimination interval is defined as Δ_{max}. To simplify comparison, Δ_{min} and Δ_{max} can be expressed as ratios with respect to the width of the calibration data interval on which the regression is based, Δ_{cal}.

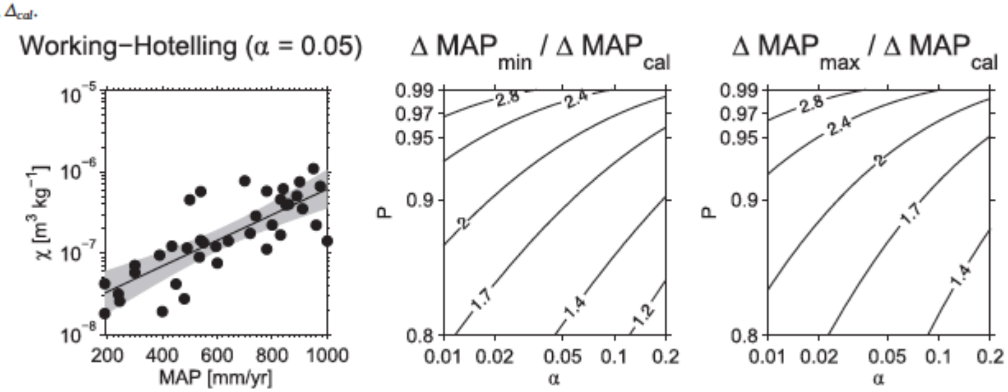


Fig. 3. (left) The Mali χ versus MAP data set of Balsam et al. (2011) shown with its corresponding regression model (line) and 95% Working and Hotelling (1929) confidence band (shaded). (middle) Contours of $\Delta MAP_{min}/\Delta MAP_{cal}$ as a function of α and P. The top-left and bottom-right corners of the plot represent the most stringent and lowest confidence scenarios, respectively. All of the tested cases produce ratios greater than unity, which indicates that the width of the narrowest possible discrimination interval spans a range of MAP values wider than the data on which the regression model is based. (right) Contours of $\Delta MAP_{max}/\Delta MAP_{cal}$ as a function of α and P.

Background

Heslop and Roberts (2013)

- Found: existing climofunctions have associated uncertainties that are so large that their predictions are **invalid**
- Paleoprecipitation reconstructions must be treated with extreme caution

Today's paper of discussion

Global and Planetary Change 111 (2013) 280–287

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

ELSEVIER

Statistical models for use of palaeosol magnetic properties as proxies of palaeorainfall

CrossMark

B.A. Maher [a,*], A. Possolo [b]

[a] Centre for Environmental Magnetism & Palaeomagnetism, Lancaster Environment Centre, University of Lancaster, LA1 4YQ UK
[b] Statistical Engineering Division, Information Technology Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA

Authors

- Barbara A. Maher – Centre for Environmental Magnetism & Palaeomagnetism, Lancaster Environment Centre, Lancaster University
  - Research interests: environmental magnetism and paleomagnetism, the application of magnetic methods to environmental processes and problems.
- Antonio Possolo – Chief of the Statistical Engineering Division, Information Technology Laboratory, NIST
  - Ph.D. in statistics from Yale, 1983
  - Professional interests: spatial statistics, point processes, environmental remote sensing, measurement uncertainty, and foundations of probability theory and of statistical inference

Major Assumptions

- Climofunctions don’t vary with time
- An error-in-variables formulation of the uncertainty of climofunctions is a more appropriate measure of the uncertainty in predictions of paleoprecipitation than the discrimination intervals Heslop and Roberts (2013) used
- Interpret the estimated expected value of MAP as a long-term average

Outline of the paper

- Introduction
- Material and methods
  - Great Plains of the United States - temperate
  - Chinese Loess Plateau & Russian Steppe - temperate
  - Mali: Timbuktu to Bamako - tropical
  - Morocco: Rabat to Taouz - tropical
- Results and discussion
- Conclusions

Errors-in-variables formulation

- Both MAP and χ (or $R=\chi_e/\chi_p$) have non-negligible observational errors

- $\mu_i = \varphi(\rho_i)$, $R_i = \rho_i + D_i$, $MAP_i = \mu_i + E_i$
  - μ is the **value of MAP expected to prevail over the long-term (100s of years)**
  - φ is the climofunction
  - ρ is the true χ_e/χ_p (rather than observed R)
  - D and E are the measurement errors – assumed to be independent Gaussian random variables, zero mean, and $u(R_i)$ and $u(MAP_i)$ standard deviations
  - i=1,…,m the number of data points

- You fit φ to the data by minimizing:

$$\sum_{i=1}^{m} \left(\frac{R_i - \rho_i}{u(R_i)}\right)^2 + \left(\frac{\mathrm{MAP}_i - \varphi(\rho_i)}{u(\mathrm{MAP}_i)}\right)^2.$$

Errors-in-variables formulation

- Minimize to solve for the slope (β) and intercept (α) of φ – when climofunction is linear
- Goal is to estimate the expected value of MAP corresponding to a given measured value of soil magnetic enhancement, and not to predict an individual (30-year average) observation of MAP to correspond with the measured enhancement
- Use a non-parametric bootstrap to estimate uncertainties on slope and intercept estimates, and to estimate a confidence band (narrowest band that fully covers say 95% of the bootstrap resamples)

Great Plains, United States

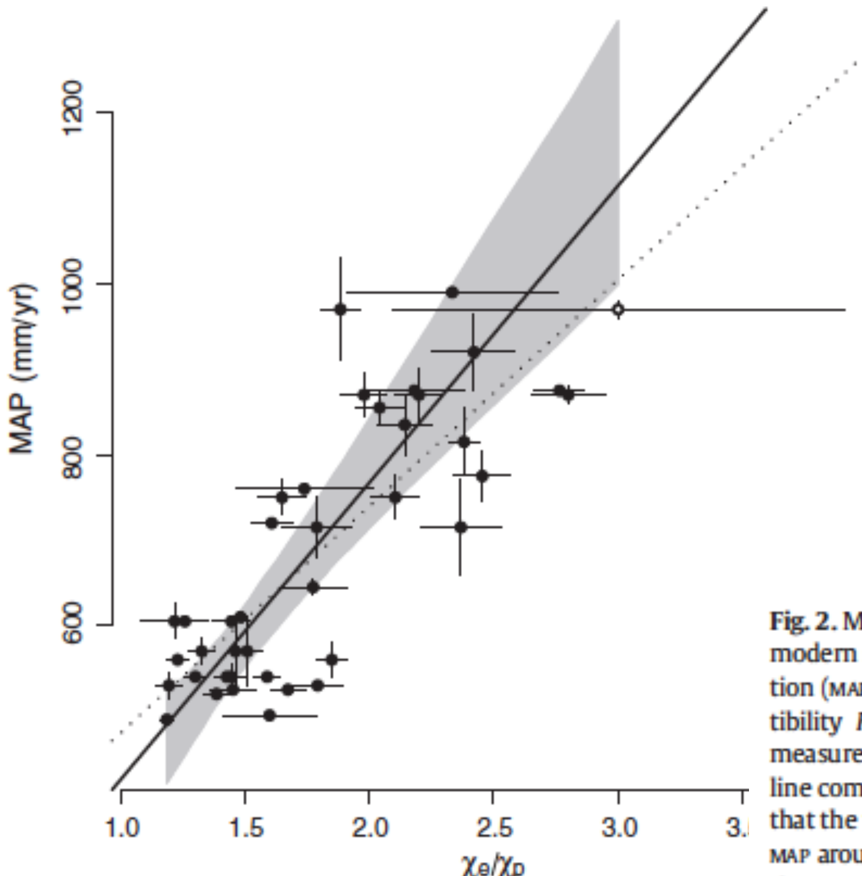


Table 1
Estimates of slope and intercept of the climofunction for the Great Plains of the United States. The estimate of the intercept α produced by the errors-in-variables model is 71 mm/yr, and the estimate of the slope β is 348 mm/yr. The data point whose value of R is close to 3, marked in Fig. 2) with a small white dot inside its circle, exerts considerable leverage upon the ordinary least squares line. Since the corresponding value of $u(R)$ is very large, under the errors-in-variables model its "pull" upon the line weakens considerably, leading to an appreciably steeper line (solid line in Fig. 2).

(mm/yr)	α	$u(\alpha)$	β	$u(\beta)$
Ordinary least squares	209	57	265	31
Errors-in-variables	71	16	348	11

Fig. 2. Mean annual precipitation (MAP) versus susceptibility enhancement for samples of modern soil from the Great Plains of the United States. Values of mean annual precipitation (MAP, of rain per year) plotted against values of the enhancement in magnetic susceptibility $R = \chi_e/\chi_p$. The thin line segments represent plus or minus one standard measurement uncertainty. The dotted line is the conventional least squares regression line computed neglecting the standard measurement uncertainties, and in fact assuming that the values of R have negligible uncertainty relative to the dispersion of the values of MAP around the line. The solid line is the errors-in-variables line that takes into account the stated measurement uncertainties. The shaded area (in grey) is a simultaneous 95% confidence band for the expected value of MAP corresponding to each value of R. The point marked with a small white dot, whose abscissa is $R = 3$, is discussed in the caption of Table 1.

Chinese Loess Plateau and Russian steppe

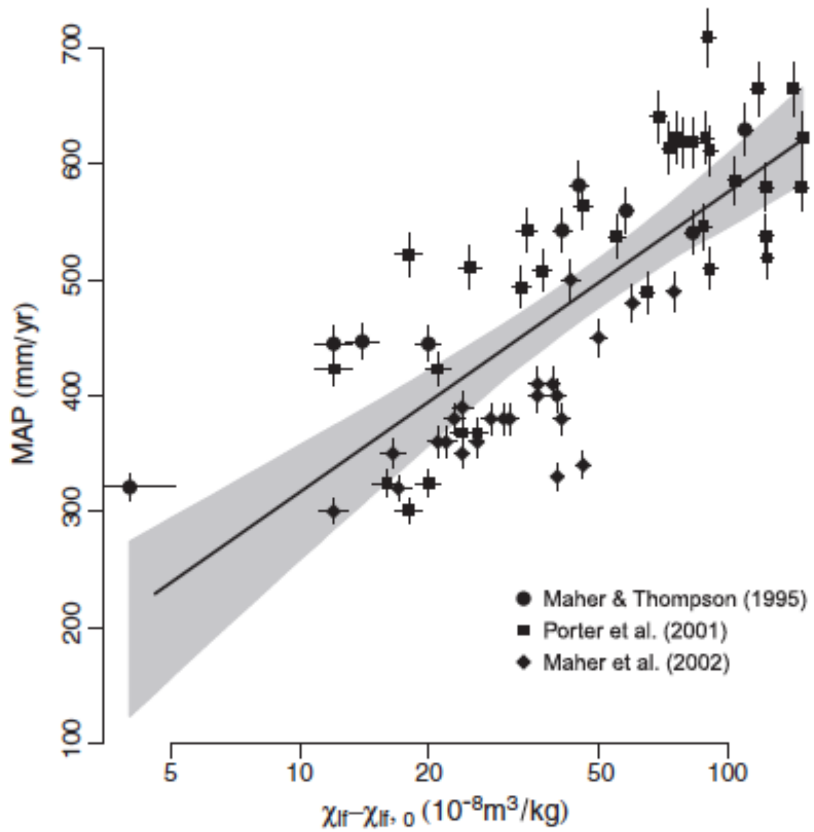


Fig. 3. Mean annual precipitation (MAP) versus magnetic susceptibility enhancement for samples of modern soil from the Chinese Loess Plateau and from the Russian steppe. Values of mean annual precipitation (MAP, mm of rain per year) plotted against values of magnetic susceptibility enhancement, χ_{lf}-$\chi_{lf,0}$. Note that the horizontal axis has a logarithmic scale. The fitted line minimises the criterion in Eq. (2): the intercept is 57.7 mm/yr (with a standard uncertainty of 46.0 mm/yr), and the slope is 112.5×10^8 mm kg yr^{-1} m^{-3} (with a standard uncertainty of 11.9×10^8 mm kg yr^{-1} m^{-3}). The shaded area (in grey) is a simultaneous 95% confidence band for the expected value of MAP corresponding to each value of the magnetic susceptibility enhancement.

Log scale because predictor is log(χ), so the minimization criterion is different, but process is the same.

Non-linear climofunction

Model the climofunction with a three-parameter logistic curve instead of straight line:

$$\mu = \frac{\alpha}{1 + exp\left(\frac{\beta - log\chi}{\gamma}\right)},$$

- α is an asymptote MAP approaches for increasing χ
- β is the centre of symmetry of the curve
- ϒ is the scale of the deviations between values of log χ and β

Mali Transect

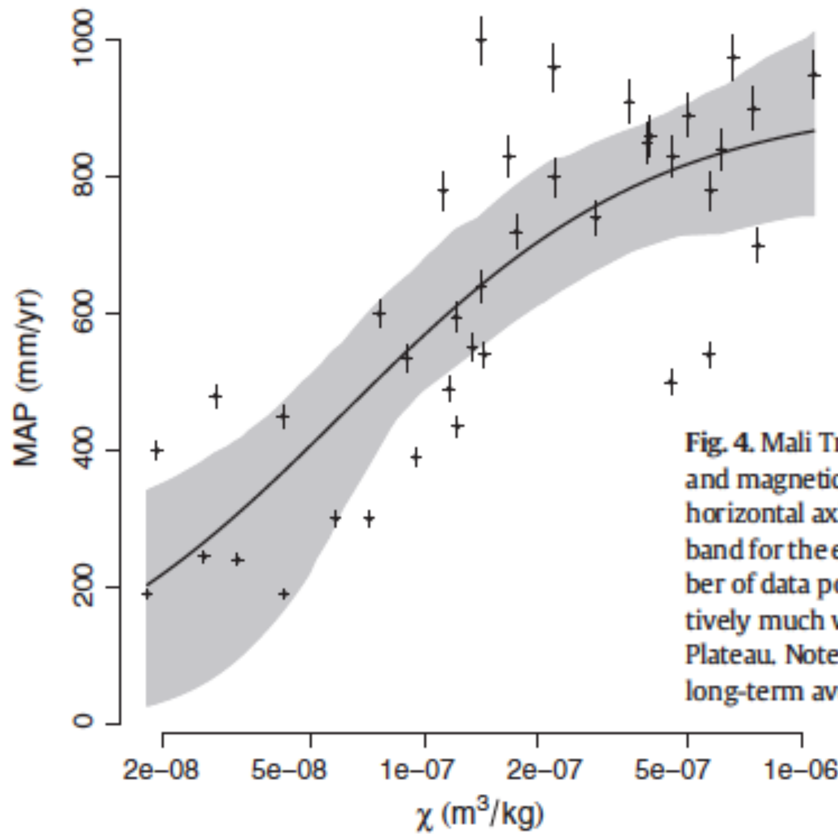


Table 2
Estimates of parameters of logistic climofunctions for Mali and Morocco transects, and associated standard uncertainties (STD. UNC.). In both cases, the climofunction is of the form $\mu=\alpha/[1+\exp\{(\beta-\log\chi)/\gamma\}]$, and σ is the standard deviation of the error map−μ. The predictions likely are meaningful only for the portion of the curve that is approximately linear, that is, for values of log χ close to β (relative to γ)).

	Mali	
	Estimate	Std. unc.
α(mm/yr)	912.000	96.000
β	−16.600	0.268
γ	0.965	0.289
σ(mm/yr)	142.000	16.700

Fig. 4. Mali Transect: mean annual precipitation (MAP) versus χ. Relationship between MAP and magnetic susceptibility χ and corresponding logistic model. Note that the scale of the horizontal axis is logarithmic. The shaded area (in grey) is a simultaneous 95% confidence band for the expected value of MAP corresponding to each value of χ. The fairly small number of data points, and their substantial dispersion, lead to a confidence band that is relatively much wider than the band for the model fitted to the data from the Chinese Loess Plateau. Note that this band depicts the uncertainty associated with the fitted curve (the long-term average values of MAP), not the dispersion of the individual 30-year averages.

Log scale

Morocco Transect

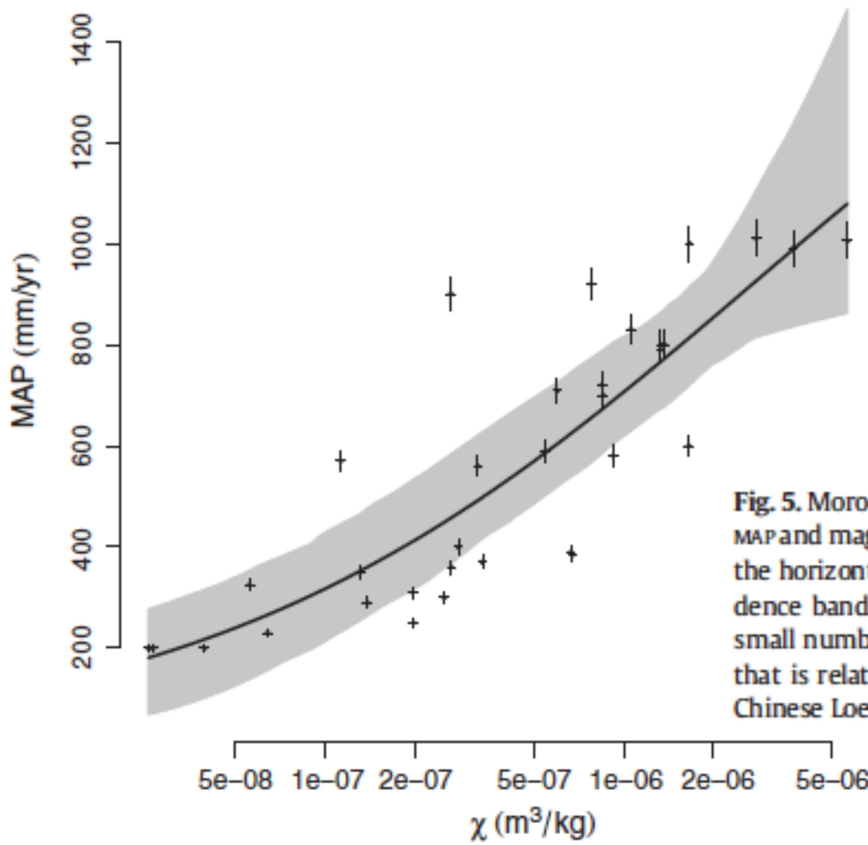


Table 2
Estimates of parameters of logistic climofunctions for Mali and Morocco transects, and associated standard uncertainties (STD. UNC.). In both cases, the climofunction is of the form $\mu=\alpha/[1+\exp\{(\beta-\log\chi)/\gamma\}]$, and σ is the standard deviation of the error map−μ. The predictions likely are meaningful only for the portion of the curve that is approximately linear, that is, for values of log χ close to β (relative to γ)).

		Morocco	
		Estimate	Std. unc.
α(mm/yr)		1840.0	1170.000
β		−12.8	2.610
γ		2.1	0.768
σ(mm/yr)		140.0	17.800

Fig. 5. Morocco Transect: mean annual precipitation (MAP) versus χ. Relationship between MAP and magnetic susceptibility χ and corresponding logistic model. Note that the scale of the horizontal axis is logarithmic. The shaded area (in grey) is a simultaneous 95% confidence band for the expected value of MAP corresponding to each value of χ. The fairly small number of data points, and their substantial dispersion, lead to a confidence band that is relatively much wider than the band for the model fitted to the data from the Chinese Loess Plateau.

Appling statistical model to paleosols to predict MAP

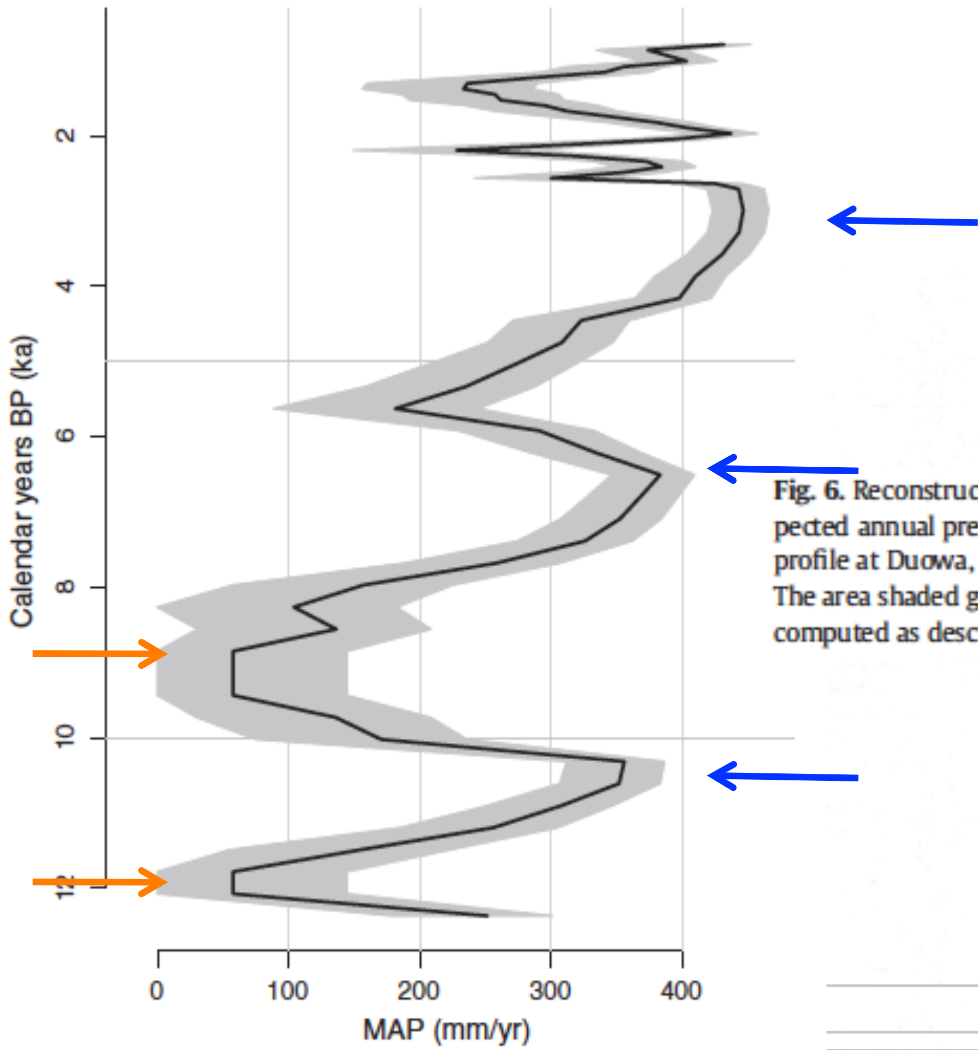


Fig. 6. Reconstruction of the mean annual precipitation (MAP) at Duowa. Estimates of expected annual precipitation (MAP, of rain per year) plotted against age for the stratigraphic profile at Duowa, Qinghai Province, at the western margins of the Chinese Loess Plateau. The area shaded grey is a 95% simultaneous confidence band for the whole reconstruction, computed as described towards the end of Section 2.2.

Conclusions

Trustworthiness of χ measurements as a proxy for rainfall depends on:

- Demonstration and quantization of association between χ and rainfall in modern soils
- Understanding of pedogenesis
- Suitable normalization
- **Evaluation of the uncertainties**

To evaluate the uncertainty of the estimates of paleorainfall estimate longterm averages of yearly rainfall, as opposed to the comparatively short-term 30-year averages.

Characterized the uncertainty associated with a reconstruction of the Holocene paleorainfall record at Duowa, using a climofunction derived from samples from the CLP and The Russian steppe. Although non-negligible, this uncertainty is sufficiently small to confirm changes in intensity of the East Asian monsoon during the Holocene.

Comments on Heslop and Roberts (2013)

Their analysis doesn't apply to these examples because:

- Their analysis applies to "inverse" linear regression models homogeneous variance and Gaussian errors in only one variable
- They used tolerance intervals instead of confidence intervals
- The target here is the expected value of MAP, not individual values of MAP comparable to those used to estimate the climofunction

Questions Raised

- What different questions are Heslop and Roberts (2013) and Maher and Possolo (2013) asking, and which is more appropriate?
- Can we quantify all of the sources of uncertainty?
- With how much caution do we need to treat paleoprecipition models?
- Should I be learning R?

Thanks

- News:
  - The MagIC workshop was good time. Thank you to the organizers.
  - Congratulations Dr. Geoff Cromwell!