Supporting Information for

Mapping key soil micronutrients across the Tibetan Plateau

Huangyu Huo[1,2], Xiling Gu[1,2], Jiayi Li[1,2], Shanshan Yang[1], Yafeng Wang[1*], Jinzhi Ding[1*]

[1]State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China.

[2]University of Chinese Academy of Sciences, College of Resources and Environment, Beijing 100049, China.

**Corresponding to:* Jinzhi Ding (jzding@itpcas.ac.cn), Yafeng Wang (yfwang@itpcas.ac.cn)

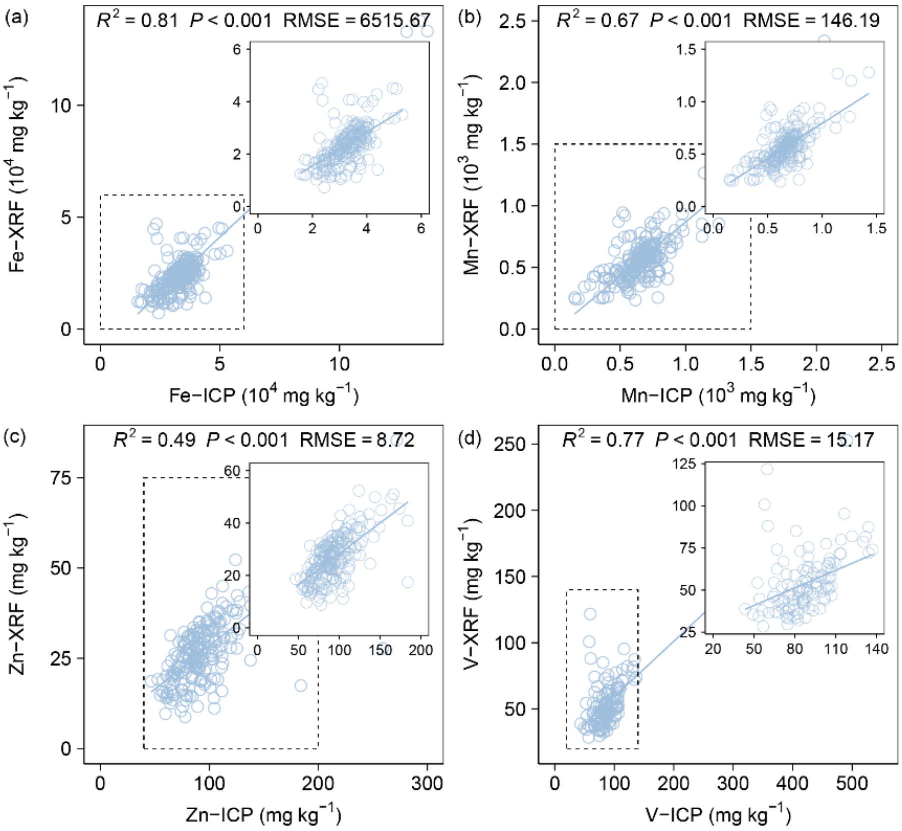

Figure S1. Comparison between laboratory-based third-generation XRF and ICP-MS measurements for four soil micronutrients (Fe, Mn, Zn, and V).

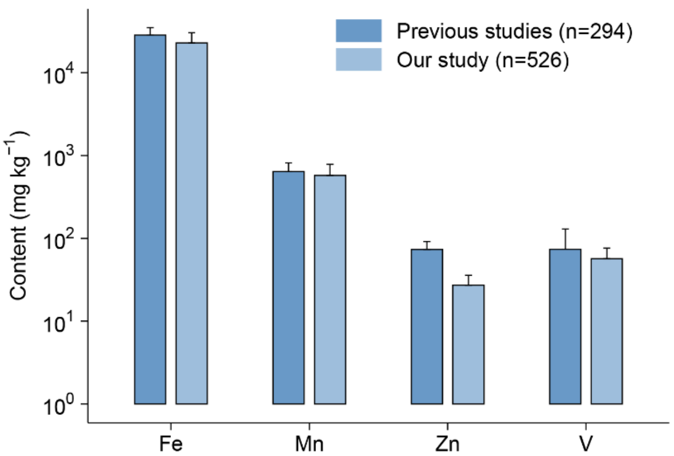

Figure S2. Comparison of mean soil micronutrient contents (Fe, Mn, Zn, and V) between this study and previous studies (Yang et al., 2020; Sheng et al., 2012; Cheng et al., 1993) on the Tibetan Plateau. Bars represent mean values, and error bars indicate one standard deviation.

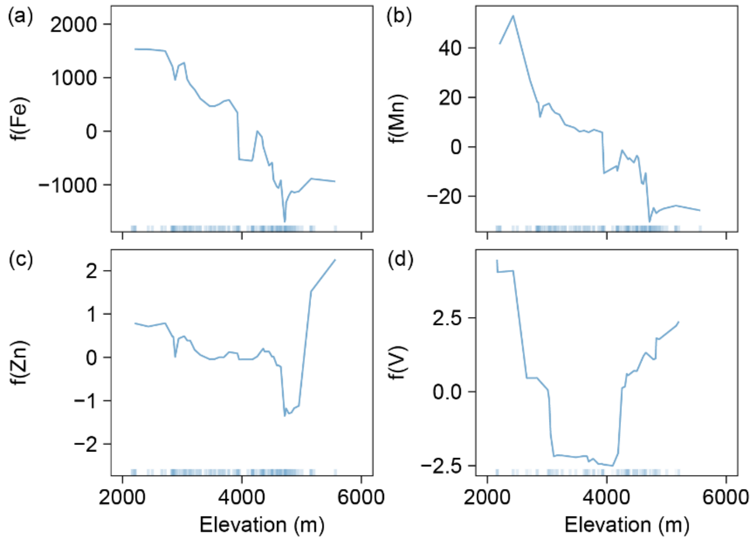

Figure S3. Nonlinear responses of soil micronutrient contents (Fe, Mn, Zn, and V) to elevation estimated with accumulated local effects (ALE). The short ticks (rugs) beneath each graph indicate the distribution density of the samples along the elevation axis.

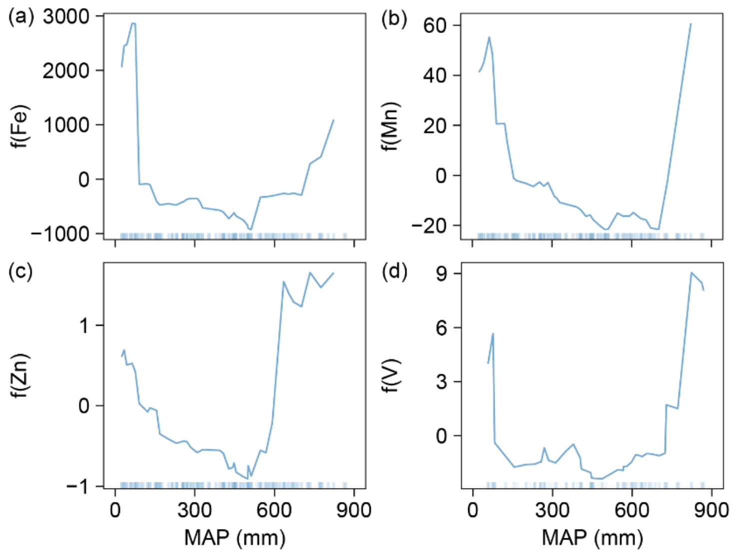

Figure S4. Nonlinear responses of soil micronutrient contents (Fe, Mn, Zn, and V) to mean annual precipitation (MAP) estimated with accumulated local effects (ALE). The short ticks (rugs) beneath each graph indicate the distribution density of the samples along the MAP axis.

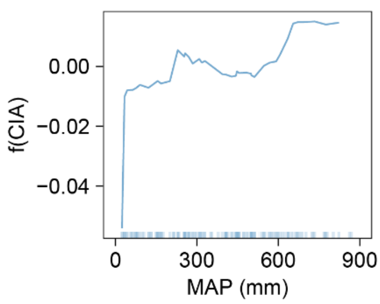

Figure S5. Nonlinear responses of the chemical index of alteration (CIA) to mean annual precipitation (MAP) estimated with accumulated local effects (ALE). The short ticks (rugs) beneath each graph indicate the distribution density of the samples along the MAP axis.

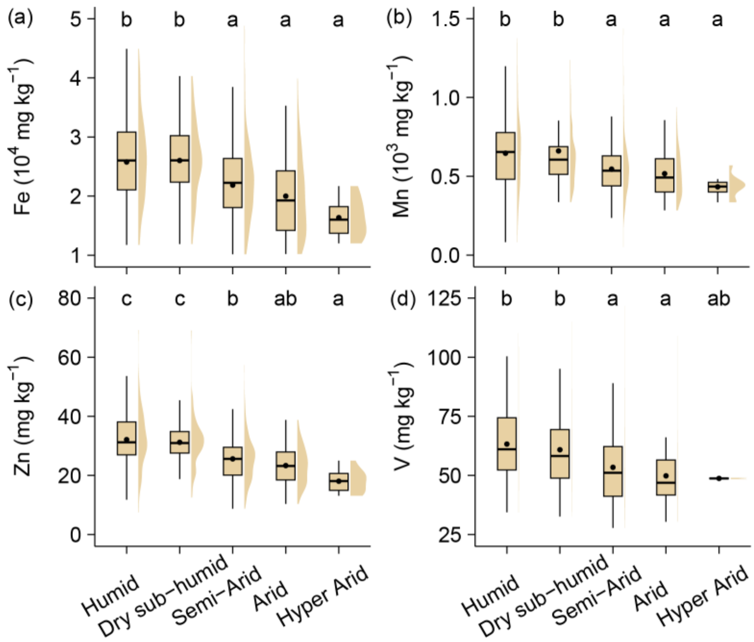

Figure S6. Variability of soil micronutrients (Fe, Mn, Zn, and V) in the Tibetan Plateau with drought gradient. Drought classes follow the Trabucco et al., 2018: Humid (AI > 0.65), Dry sub-humid (0.50 ≤ AI ≤ 0.65), Semi-arid (0.20 ≤ AI < 0.50), Arid (0.03 ≤ AI < 0.20), and Hyper-arid (AI < 0.03).

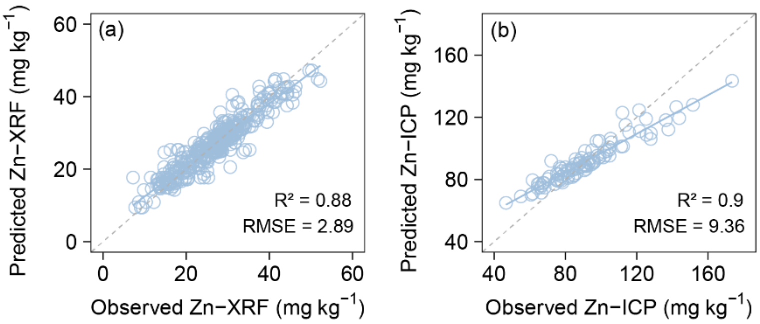

Figure S7. XRF-based observed values are highly correlated with the XRF-based predicted values (a), and the ICP-MS-based observed values are also highly correlated with the ICP-MS-based predicted values (b).

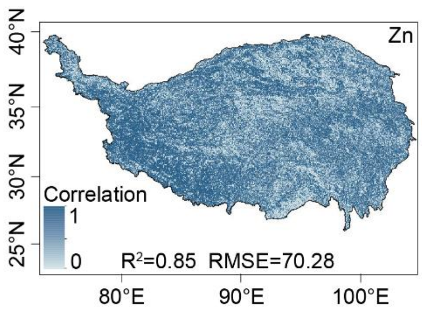

Figure S8. Spatial correlation maps of Zn contents before and after calibration of XRF measurements against ICP-MS. The strong consistency confirming that the calibration adjusted absolute contents but did not alter the large-scale spatial patterns of this element.

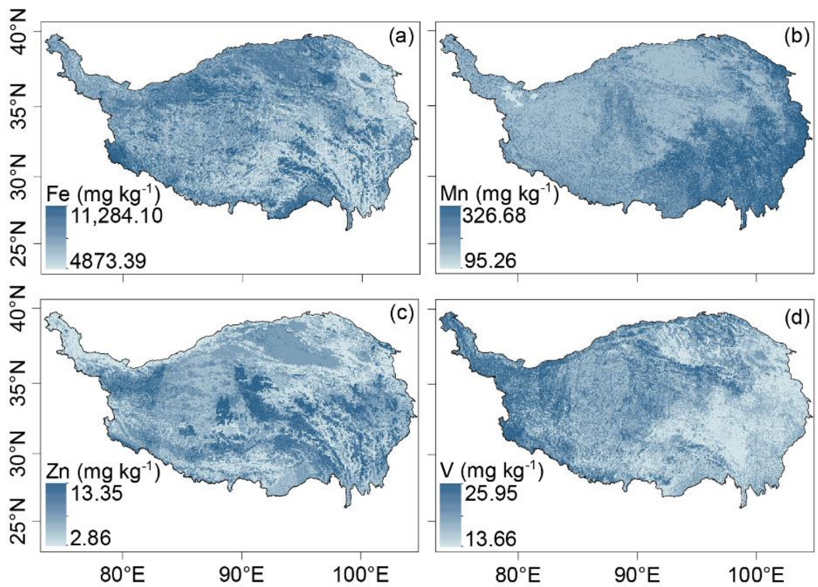

Figure S9. Spatial uncertainty of soil micronutrients (Fe, Mn, Zn, and V) predictions across the Tibetan Plateau, expressed as standard deviation of per-tree predictions in the random forest; units in mg kg^{-1}.

Table S1. Examples of large-scale geochemical surveys using XRF (alone or combined with ICP-based methods).

Programme	Sample analysis	Source
Geochemical Mapping of Agricultural and Grazing Land Soil in Europe (GEMAS)	All samples were analysed for 52 chemical elements after an aqua regia extraction, 41 by **XRF** (total).	(Reimann et al., 2014)
National Geochemical Survey of Australia (NGSA)	Sample analysis has started for 60+ elements/parameters using mainly X-rayfluorescence (**XRF**) and (reaction cell) inductively coupled plasma-mass spectrometry (ICP-MS) at Geoscience Australia.	(Caritat et al., 2011)
Africa Soil Information Service (AfSIS)	A 10% subset of samples will be subjected to a wide range of tests, including extractable nutrients, soil carbon using thermal combustion, total element analysis using total **X-ray fluorescence spectroscopy**, mineralogy using X-ray diffraction spectroscopy, particle size analysis and soil stability using laser diffraction spectroscopy, water holding capacity, and engineering properties.	IUGS Commission on Global Geochemical Baselines
China Geochemical Baselines Project (CGB)	Seventy-six elements are determined by ICP-MS/AES following 4-acid digestion and by **XRF** following fusion as the backbone methods combined with another 10 methods.	IUGS Commission on Global Geochemical Baselines
A soil geochemical survey of India	The samples were analyzed for 23 elements by **X-ray fluorescence spectrometry**.	IUGS Commission on Global Geochemical Baselines
Geochemical Baseline Survey of the Environment (G-BASE) of the British Geological Survey (BGS)	All chemical analyses are done at the BGS laboratories in Keyworth with **x-ray fluorescence spectrometry (XRFS)** being the principal analytical method for stream sediments and soils, and inductively coupled plasma (ICP) spectrometry the main method for surface waters.	(Johnson et al., 2004)
TellusNI	Topsoil samples were analysed by **X-ray fluorescence (XRF)** for a range of major and trace elements.	(Johnson et al., 2004)
FOREGS Geochemical Atlas of Europe	Five techniques, **WD-XRF**, ICP-MS, TOC, Hg analyzer and AR/ICP-AES, were applied for analyses of the subsoil samples.	(Yao et al., 2011)
Institute of Geophysical and Geochemical Exploration (IGGE)	Seven techniques including **XRF**, ICP-MS, ICP-AES, AFS, AES, VOL and COL were applied in IGGE methods for the determination of 71 elements in composite samples	(Yao et al., 2011)
Multi-element geochemical mapping in Southern China	According to the aforementioned requirements, ICP-MS, **XRF**, and ICP-AES were adopted to analyze most of the elements.	(Cheng et al., 2014)
Geochemical Atlas of Cyprus	Samples were analysed for over 60 elements by aqua regia ICP-MS and INAA at Actlabs, Australia and Canada. Major elements were analysed by **XRF** and CS-analyser, and soluble ions by ion chromatography at the GSD laboratories, Lefkosia.	(Cohen et al., 2011)

Table S2. Descriptive statistics of micronutrients from various studies (in milligrams per kilogram).

	This study				China (CNEMC, 1995)	Global (Bowen, 1979)	UCC (Taylor et al., 1995)
	Mininum	Maxinum	Mean	Median	Mean	Mean	Mean
Fe	3,339.62	54,877.54	22,864.30	22,661.92	29,400	40,000	35,000
Mn	51.05	1,833.82	576.74	551.01	583	600	600
Zn	7.53	69.19	27.24	27.12	74.20	50	71
V	27.83	121.70	56.99	54.33	82.7	90	53

Table S3. Uncertainty parameters of the random forest model (RF).

	R^2	RMES
Fe	0.76	3782.57
Mn	0.65	96.28
Zn	0.77	4.05
V	0.39	1494

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