Response to Reviewer #1

The manuscript resubmitted has made some improvements according to my previous comments. However, the key analysis still has not been revised. I reiterate my comments and suggestions and also provide several questions for this version. Please see my concerns below.

[Response] We appreciate the reviewer's continued effort in evaluating our manuscript. We have carefully re-examined each of the earlier comments, including those reiterated in this round, and conducted substantial, targeted revisions to directly and comprehensively address the reviewer's concerns.

In this version, we have:

Revised figures and expanded the Supplementary Information to improve transparency, statistical interpretability, and data usability. In response to concerns about the uncertainty of XRF-derived micronutrient contents and the potential use of data, we updated Figure R1 to present the calibration performance of XRF against ICP-based measurements for the retained elements, and we substantially expanded the Supplementary Information to report complete calibration diagnostics (including R^2 and RMSE). Importantly, to ensure that the released dataset contains only high-confidence micronutrient variables, we retained only those elements showing acceptable and reproducible prediction quality (Fe, Mn, Zn, and V) and removed Cu, Mo, and Ni due to relatively insufficient calibration performance. These revisions enable users to evaluate uncertainty explicitly and determine data suitability for specific applications. Moreover, the analytical workflow adopted here is consistent with established practice in large-scale geochemical baseline and mapping programmes worldwide (**Table R1**), where XRF is commonly used as a high-throughput backbone method for soils, often complemented by ICP-based measurements for multi-element determination, calibration, validation, or targeted subsets (e.g., GEMAS, NGSA, CGB, G-BASE, TellusNI).

Clarified methodological rationale and resolved ambiguities in the analytical workflow. First, we specified our proportional (area-weighted) sampling strategy, stating that the number of sampling sites assigned to each ecosystem type, including croplands, was approximately proportional to its areal extent across the Tibetan Plateau, with the goal of achieving a plateau-wide and regionally representative characterization of surface-soil micronutrients across dominant ecosystem types. Second, we added a clear description of the prediction grid resolution (1 km), which matches the spatial resolution of the environmental covariates used in the RF modelling.

Explicitly acknowledged limitations and provided guidance for appropriate use of the dataset. Specifically, we clarified the interpretational boundaries of cropland-related analyses by noting that croplands occupy only a small fraction of the Tibetan Plateau and are represented by a limited number of samples under our area-weighted sampling reminder; We also added an uncertainty map (**Figure R3**) and related discussion to address spatially uneven sampling, emphasizing that model estimates in sparsely sampled western regions (such as parts of the Changtang Plateau and Ngari) are supported by fewer observations and should be interpreted more cautiously.

We believe these revisions directly address the core scientific concerns raised and significantly strengthen the manuscript. Detailed, point-by-point responses to each comment are provided below.

[Comment 1] For the XRF analysis, I still think this method has a large uncertainty for micronutrient concentrations in soils. As shown in Figure R1, most of these elements had a very weak prediction ("not strong correlations"). I agree that the spatial patterns of these elements analyzed by XRF and ICP-MS can be similar, but as a dataset, the exact concentrations are more important. That means other scientists would directly use these exact concentrations to further work. Unfortunately, the XRF results cannot do this. So, I strongly suggest authors to analyzing all their samples using ICP-OES or ICP-MS. Otherwise, I cannot recommend such dataset to be published.

[Response] We state the calibration results presented in Figure R1 do not support the reviewer's conclusion that "most elements had very weak prediction". Among the examined elements, Fe ($R^2 = 0.81$), Mn ($R^2 = 0.67$), Zn ($R^2 = 0.49$), and V ($R^2 = 0.77$) exhibit clear and statistically significant linear relationships with ICP measurements, demonstrating moderate to strong correlation. The increased dispersion observed at low contents reflects known limitations of XRF near detection thresholds, rather than method failure.

Moreover, our analytical strategy follows established practice in large-scale geochemical mapping, where XRF is commonly used for determination of total/major-element composition, while ICP-based methods are commonly employed in parallel for complementary measurements (e.g., extracted fractions, waters, or elements requiring lower detection limits) and, where appropriate, for inter-method comparison and validation. In addition to GEMAS and NGSA, similar XRF-based workflows have been implemented in other regional/national baseline programmes (e.g., BGS G-BASE in the UK, the FOREGS Geochemical Atlas of Europe, and the Global Geochemical Baselines framework). These precedents support the robustness and suitability of using XRF with targeted ICP verification for plateau-scale geochemical datasets (**Table R1**).

It is also important to emphasize that micronutrient data from the Tibetan Plateau are extremely scarce, owing to its vast geographic extent, logistical difficulty, and harsh environmental conditions. To our knowledge, this work represents the first large-scale and systematic effort to map micronutrient distributions across the Plateau, providing an urgently needed data foundation for ecological, biogeochemical, and Earth system research. The spatial micronutrient information therefore constitutes a meaningful scientific contribution.

Furthermore, the primary scientific purpose of this dataset is to characterize spatial patterns, ecological gradients, and multivariate relationships across the Plateau, rather than to provide ultra-precise quantification of element contents at the individual-sample

level. For these objectives, XRF-derived contents, supported by calibration, cross-validation, and transparent uncertainty reporting, provide reliable and ecologically interpretable information.

Regarding the reviewer's suggestion to analyze all samples using ICP-OES or ICP-MS, such an approach is neither realistic nor necessary. Our dataset includes 1,660 topsoil samples collected from 526 locations, to my knowledge, one of the densest soil sampling efforts ever conducted on the Tibetan Plateau. Full ICP re-analysis of all samples would be expensive, time-consuming, and is not standard practice for large-scale regional geochemical surveys. XRF combined with targeted ICP calibration is the accepted approach for datasets of this scope.

In response to the reviewer's concern, we have taken two major steps to further strengthen the dataset: (1) We retain only those micronutrients for which XRF demonstrates acceptable and reliable prediction quality. Cu, Mo and Ni have been removed from the released dataset due to their relatively insufficient calibration performance. This ensures that only high-confidence micronutrient variables (Fe, Mn, Zn, and V) are included. (2) We provide calibration statistics for the retained elements, including R^2, and RMSE, in the revised Supplementary Information (**Figure R1**). This allows users to fully assess data quality and appropriate use scenarios.

Table R1. 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)
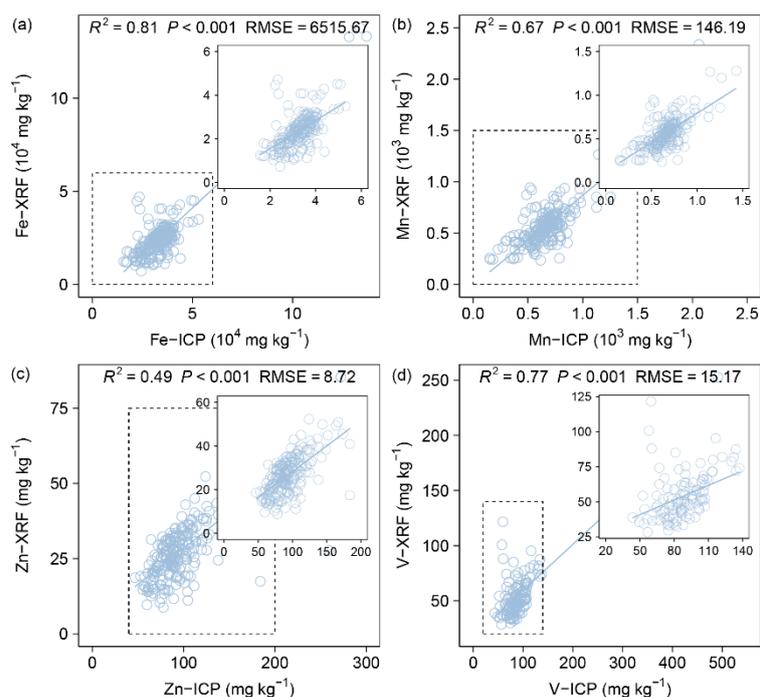
Figure R1. Comparison between laboratory-based third-generation XRF and ICP-MS measurements for four soil micronutrients (Fe, Mn, Zn, and V).

[Comment 2] I do not agree that farmland is not important on the TP. You cannot assess its importance just according to the proportion in China. In contrast, the importance of agriculture is increasingly underscored. So, only 12 samples cannot well represent the distribution of micronutrients studied. More sites with more samples should be considered. Otherwise, the statistical results (e.g., Figure S7) are not reliable.

[Response] We agree that croplands, although limited in extent, play an increasingly important role in certain regions. Our study does not intend to downplay this importance. Instead, our sampling framework was designed to represent the spatial distribution of ecosystem types across the plateau, rather than to evaluate cropland systems in isolation.

To clarify, croplands on the Tibetan Plateau occupy less than 2% of the total land area, as shown in **Figure R2**. Because our sampling design followed a proportional, area-weighted scheme, the number of cropland samples is necessarily small. **Figure R2** demonstrates that the sampling frequency (dots) closely matches the actual areal proportions (bars) for each ecosystem type, indicating that the sampling is representative at the regional scale. Thus, the limited number of cropland samples

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reflects the underlying land-cover structure of the TP rather than insufficient sampling effort. The purpose of including cropland samples in our study is to enable ecosystem-type comparisons in micronutrient contents, not to produce a high-resolution assessment of cropland micronutrient distributions. For such comparative analyses, the available cropland samples are adequate.

In response, we have added explicit statements on (i) the proportional sampling strategy as follows: *"Our field sampling followed a proportional, area-weighted design, whereby the number of sampling sites allocated to each ecosystem type was approximately proportional to its areal extent across the Tibetan Plateau. This design aims to provide a plateau-wide, regionally representative characterization of surface-soil micronutrients across dominant ecosystem types."* (Lines 71-74 on Pages 3-4).

(ii) the interpretational boundaries of cropland-related analyses as follows: *"Because croplands occupy a very small fraction of the Plateau and are represented by a limited number of samples in our area-weighted design, cropland-related results should be interpreted primarily as a cross-ecosystem contrast at the plateau scale. Users addressing cropland-specific questions are advised to use these values with caution and, where possible, complement them with targeted cropland sampling or independent field observations."* (Lines 379-383 on Page 17).
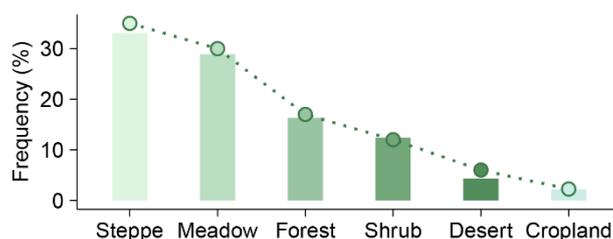

Figure R2. Areal proportions of ecosystem types (bars) versus sampling point frequency distribution (dots) across corresponding ecosystems. Similar bar and dot heights indicate that the sampling is proportionally representative.

[Comment 3] Now, I see the sampling method, particularly the soil depth. Still, I do not think 0-10 cm is a good choice to analyze element concentrations in all land uses.

As I mentioned last time, in forest soils, this depth may only include soils in organic layer, but in grasslands, it may include those in mineral layer. In farmlands, this depth also represents mixed layer due to the tillage. This disparity must result in significant difference in element concentrations among the different land uses. More importantly, I do not agree that forests and farmlands are not important just because of their relatively smaller area than steppes and meadows. One of the dataset importance lies in its wide application for more scientific questions. The scientific way to collect samples is to consider the soil development or tillage, particularly in forest and farmland soils.

[Response] The use of fixed-depth surface sampling (e.g., 0-10 cm or 0-20 cm, depending on land use) is widely adopted in large-scale soil monitoring and cross-ecosystem comparisons. This practice is consistent with major soil mapping frameworks that report properties at standard depth intervals (e.g., the GlobalSoilMap specifications adopted by SoilGrids and used for harmonisation in WoSIS), as well as regional geochemical surveys such as GEMAS. Soil horizons differ across ecosystems, whereas fixed depths provide a consistent, comparable reference layer representing the biologically active surface zone. The ecological differences among organic-rich forest soils, mineral grassland soils, and tilled agricultural soils are therefore not methodological artifacts, but rather the intended ecological signals that enable meaningful comparison among land uses. Importantly, our study aims to compare ecosystem-wide patterns, not to reconstruct soil profile development within each land use type. For such cross-ecosystem comparisons, fixed-depth sampling provides the most robust and widely used approach. For Tibetan soils, the 0-10 cm interval mainly correspond to mineral horizon in alpine vegetation (more than 80% of the region), and the plough layer in farmlands (<2%). These differences reflect real ecological and pedogenic variation among ecosystems.

Regarding forests and farmlands, we do not consider these ecosystems unimportant. Their lower sample numbers simply reflect their limited spatial extent on the Tibetan Plateau. As shown in **Figure R2**, sampling frequency matches the areal proportion of each ecosystem, ensuring proportional representativeness.

We have added text clarifying the rationale for fixed-depth sampling. (Lines 81-85 on Page 4). Users are advised to consider these factors when applying the dataset: *"the reported contents represent a fixed-depth (0-10 cm) surface layer, which may correspond to different dominant horizons among land uses (organic-rich surface in some forests, mineral topsoil in grasslands/meadows, and the plough layer in croplands)."* (Lines 375-377 on Page 17). We also provide uncertainty information for the retained elements in the Supplementary Information to support appropriate interpretation, particularly for low contents close to detection limits.

[Comment 4] In this study, most of the sampling sites are located in the southern, northern, and eastern TP, but not in the western TP (Figure 1), while the prediction results included the whole TP (Figure 7). Although RF method is widely used and has a relatively good results, the lack of key variables in these western regions must cause errors of the predictions. Moreover, I do not find the design of the grid range for the prediction. This difference (e.g., 100 * 100 m, 500 m * 500 m) will cause different uncertainties for the results, particularly for the TP with such a large area. This study only has 500+ sites, and I think this limitation will lead to an uncertain result.

[Response] The lower sampling density in the western Tibetan Plateau primarily reflects severe accessibility constraints rather than shortcomings in the sampling design. Large parts of the region (including areas within the Changtang Plateau and Ngari) are sparsely inhabited, remote, and subject to access restrictions, and extensive areas occur at very high elevations (often >5,000 m), where fieldwork is highly challenging and large-scale sampling is often impractical. Consequently, sampling cannot be conducted in many of these zones. Despite these constraints, our dataset still includes more than 500 sites across the 2.6-million-km^2 Plateau, representing one of the most extensive soil sampling efforts ever achieved in this environment.

Regarding prediction across the Plateau, Random Forest (RF) models were trained using climatic, topographic, vegetation, and soil covariates that provide full environmental coverage. RF operates in environmental space, enabling prediction in

environmentally similar but geographically unsampled regions. Importantly, model performance was strong, with cross-validation results showing R^2 values of 0.77-0.88 cross the retained micronutrients (Fe, Mn, Zn, and V). These metrics indicate that the model captures the major relationships between micronutrient contents and environmental predictors and generalizes well to unsampled region.

In the revised manuscript, we provide an uncertainty map (**Figure R3**) and added related disscussion about limited sampling in the western plateau: *"Large regions in the west (including parts of the Changtang Plateau and Ngari) are sparsely inhabited and difficult to access, with extensive high-elevation terrain and access restrictions that constrain fieldwork. Consequently, model estimates in these areas are supported by fewer observations and should be interpreted with greater caution. We therefore recommend that users consider the accompanying uncertainty layer when applying the gridded products, especially for analyses focusing on the western Plateau or on fine-scale local interpretation."* (Lines 364-369 on Page 17). We also added a clear description of the prediction grid resolution (1 km), which matches the resolution of the environmental covariates. This grid size affects the spatial visualization detail but not the underlying RF model performance.
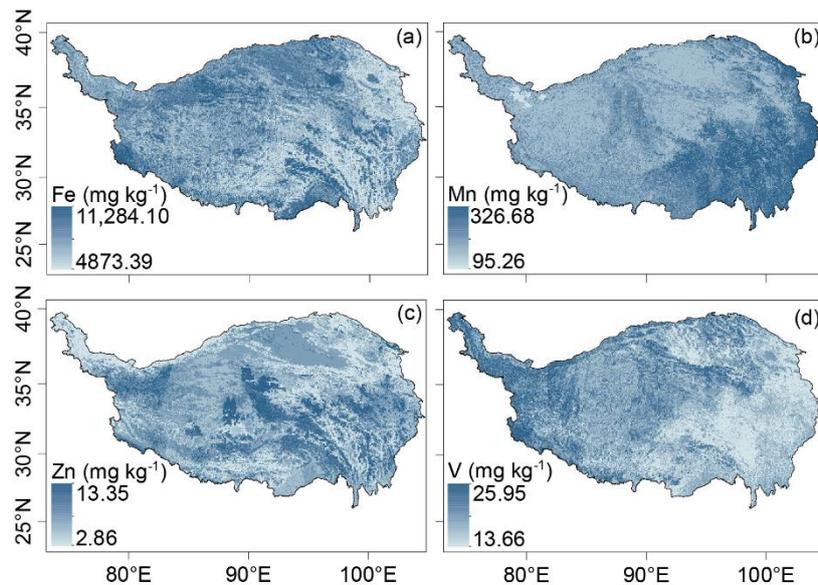

Figure R3. Spatial uncertainty of soil micronutrients (Fe, Mn, Zn, and V) predictions across the Tibetan Plateau, expressed as standard deviation of per-tree predictions in

the random forest; units in mg kg^{-1}.

[Comment 5] For the CIA (Lines 95-98), there are several elements (e.g., Al, Na, K) or their oxides that need to be analyzed. But, how to obtain these data? If using these element concentrations, was still XRF used? If so, how about the precision of the analysis for these elements?

[Response] The oxide data required for CIA calculation (Al_2O_3, CaO, Na_2O, and K_2O) were obtained from the laboratory XRF measurements which directly provide major oxides as weight percentages (wt.%) for all samples. These oxide data were converted to molar proportions, and CIA was calculated following the established method of Fedo et al. (1995).

In this study, CIA is employed as an environmental proxy to characterize relative chemical weathering intensity and its spatial variability, rather than for absolute geochemical mass-balance calculations. Both the CIA formulation and the use of XRF-derived major oxide data are not newly developed in this work, but are widely adopted in existing soil, sediment, and global geochemical databases. Major oxide (total) data used for CIA were obtained from laboratory XRF analysis, consistent with the analytical workflows adopted in large-scale geochemical surveys such as NGSA and GEMAS. Laboratory XRF is a standard technique for major oxide determination and is fully adequate for resolving spatial gradients in CIA (Potts, 1987; Ogasawara et al., 2018; Nesbitt & Young, 1982). The analytical precision of the XRF measurements is sufficient for CIA-based environmental interpretation, particularly when the index is applied comparatively across sites and environmental gradients. Standard QA/QC procedures, including replicate analyses and certified reference materials, were applied to ensure data reliability. These clarifications have been added to the revised manuscript. (Lines 114-117 on Page 6).

[Comment 6] In Figure R10, what is the standard for the elevation division? For example, in the range of 1000-3500 m, there are different land uses. You put all these

data together to make elevation comparison. This is not reasonably. Why did you use specific elevation data to make the analysis?

[Response] First, we need to clarify that the elevation classes used in the original Figure R10 (1000-3500 m, 3500-5000 m, and >5000 m) were not arbitrarily defined. They follow the official 1:1,000,000 physiognomic regionalization standard of China (Zhou et al., 2009), which is widely applied to delineate major geomorphic belts on the Tibetan Plateau. These elevation zones correspond to distinct transitions in climate conditions, weathering intensity, soil-forming processes, and vegetation patterns. Thus, the elevation division is not arbitrary but based on a nationally recognized geomorphological framework.

As the reviewer mentioned, the binning elevation into broad classes may obscure continuous trends and may be confounded by differences in land-use/vegetation composition within a given elevation range. To address this concern, we did not use elevation "division" in the revision. Instead, we analyze elevation as a continuous variable and quantify its relationship with micronutrient contents using Accumulated Local Effects (ALE) derived from the Random Forest model (**Figure R4**). ALE provides the marginal response of each micronutrient to elevation while accounting for correlations and interactions with other predictors (e.g., climate, vegetation, soil covariates, and lithology), and therefore avoids the arbitrariness of elevation binning.
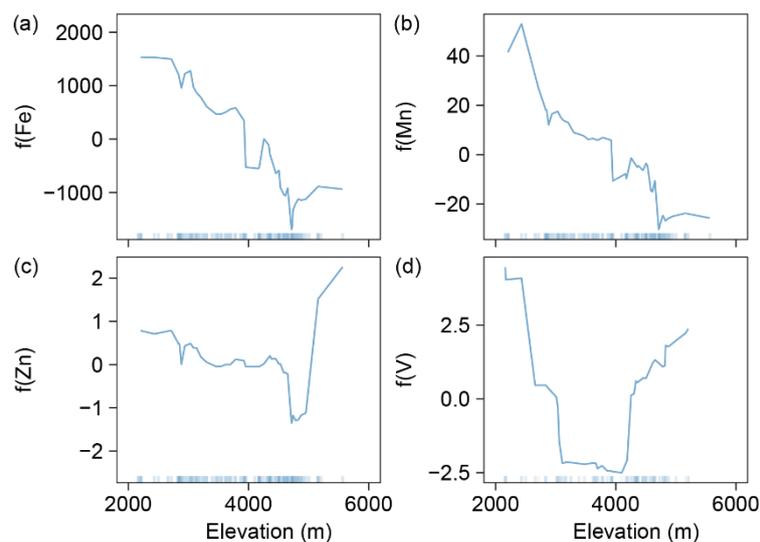

Figure R4. Nonlinear responses of soil micronutrient contents (Fe, Mn, Zn, and V) to

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.

[Comment 7] Additionally, in Figure R11, this kind of analysis cannot directly find the relationships between element concentrations and MAT or MAP.

[Response] Thank you for this comment. To address this concern, we quantify the climate-micronutrient relationships using Accumulated Local Effects (ALE), which is a model-interpretation approach suitable for Random Forests and other non-linear models. ALE estimates the marginal response of micronutrient contents to MAT (or MAP) while accounting for the joint distribution and interactions with other predictors, and it avoids extrapolation issues common in partial dependence when predictors are correlated.

Accordingly, we replaced the previous visualization with two new figures: **Figure R5** (ALE responses to MAT) and **Figure R6** (ALE responses to MAP). These figures directly show the nonlinear response curves of Fe, Mn, Zn, and V along continuous MAT/MAP gradients, with rug plots indicating sample density to help interpret the support of the data across the climate ranges.
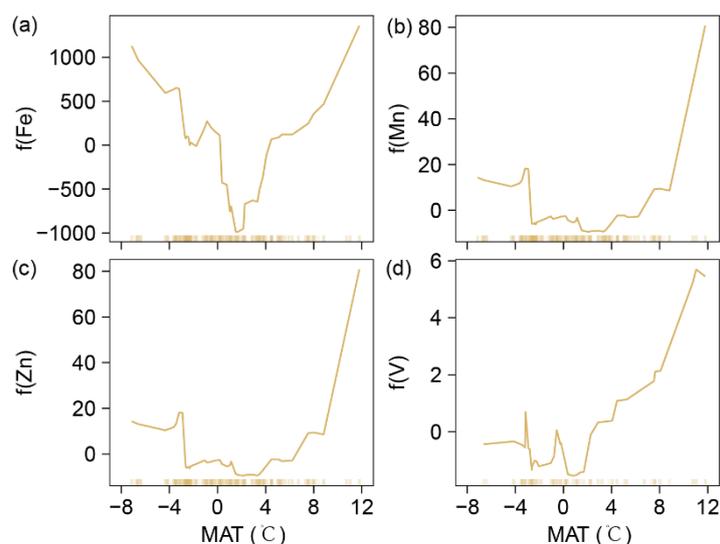

Figure R5. Nonlinear responses of soil micronutrient contents (Fe, Mn, Zn, and V) to mean annual temperature (MAT) estimated with accumulated local effects (ALE). The

short ticks (rugs) beneath each graph indicate the distribution density of the samples along the MAT axis.

Figure R6. 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.
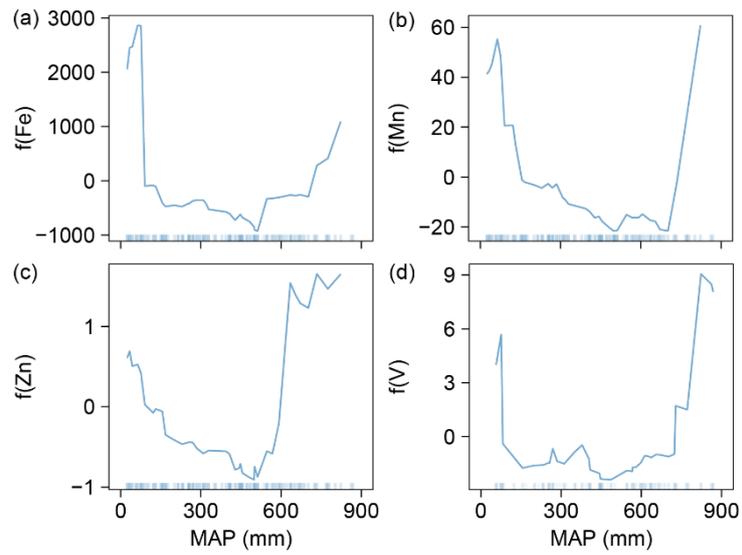
Response to Reviewer #2

Huo and coauthors present a dataset of seven elements derived from 1660 samples from 526 sites across the Qinghai-Tibetan Plateau. This dataset covers different vegetation types and different lithological classes, offering a valuable map for the Tibetan Plateau soil micronutrients. However, I am a little bit confused with the simultaneously adopted methods for measuring soil micronutrients (i.e., XRF, ICP-MS) and the manuscript can be improved by condensing the results and optimizing the structure of discussion. In addition, I have also had several other concerns on the current manuscript that may help further improve the manuscript. Please find my comments and suggestions below.

[Response] Thank you very much for your positive assessment and constructive suggestions regarding the clarity of the measurement strategy and the organization of the manuscript. In response, we have carefully revised the manuscript and provided detailed, point-by-point replies to each comment. We believe that these revisions have substantially improved the clarity and overall quality of the work, and hope that the revised version meets the reviewer's expectations.

Regarding the methods used to measure soil micronutrients, we adopted a two-step analytical strategy to ensure data reliability. First, all 1,660 topsoil samples collected from 526 sampling locations were air-dried, sieved (2 mm), and analyzed in the laboratory using a third-generation X-ray fluorescence (XRF) spectrometer. All soil micronutrient data reported in this study are based on these laboratory XRF measurements. Second, to independently validate the XRF-derived contents, a subset of 218 samples was randomly selected and re-analyzed using inductively coupled plasma-mass spectrometry (ICP-MS), a widely accepted reference method for elemental analysis (Simon, 2005). The XRF and ICP-MS measurements showed strong and significant correlations, demonstrating that the XRF data provide reliable quantification of soil micronutrients. Detailed explanations and validation results are provided in our response to Comment 12. Other related issues are addressed in the point-by-point responses below.

Notely, the use of XRF alone or in combination with ICP for calibration and validation has been widely and successfully applied in large-scale regional and national geochemical surveys, e.g., BGS G-BASE in the UK, the FOREGS Geochemical Atlas of Europe, and the Global Geochemical Baselines framework, the GEMAS project and the National Geochemical Survey of Australia, supporting the robustness and suitability of our approach (**Table R1**).

[Comment 1] L7: Soil micronutrients supply --> Soil micronutrient supply.

[Response] Comment accepted.

[Comment 2] L11-12: Can you specify the soil property, actually, soil micronutrient also belongs to soil properties.

[Response] We have specified that soil attributes include pH, soil organic carbon, and soil texture, and replaced the term "soil properties" with "soil covariates" to clearly distinguish predictors from response variables. (Line 11 on Page 1).

[Comment 3] L12: graze disturbance or grazing disturbance?

[Response] We have standardized the terminology to "grazing disturbance" throughout the manuscript.

[Comment 4] L15-16: climate-related weathering intensity? What is this? You have mentioned climate and weathering proxy earlier (L11-12).

[Response] Here weathering intensity is represented by specific proxy variable that are climate-controlled, consistent with the previously mentioned variables. To avoid confusion, we rephrased the statement as follows: *"Key results reveal that pronounced regional heterogeneity is driven primarily by weathering intensity with secondary modulation from climate and topography covariates."* (Lines 14-16 on Page 1).

[Comment 5] L17: southeastern/southern plateaus or southeastern/southern plateau?

[Response] We have revised the wording to "southeastern/southern plateau" to refer to the southeastern/southern part of the Tibetan Plateau.

[Comment 6] Introduction: Please show the importance of measuring soil micronutrients in the Qinghai-Tibetan Plateau.

[Response] Thank you for this valuable suggestion. In the revised manuscript, we have strengthened the motivation by highlighting the Tibetan Plateau as a uniquely important yet underrepresented region for soil micronutrient research. In the updated Introduction below, sentences shown in italics have been newly added to emphasize the regional significance of the Tibetan Plateau:

As essential yet trace-level components of living systems, micronutrients (e.g., Fe, Mn, Zn, and V) sustain fundamental ecological processes, including photosynthesis (Fe, Mn; Fischer et al., 2015; Schmidt et al., 2020), respiration (Fe; Dallman, 1986), enzymatic/redox functions (Zn, V; Hänsch et al., 2009), and biological nitrogen fixation (V; O'Hara, 2001). Crucially, micronutrient gradients in soils propagate through trophic chains, directly influencing human nutrition and health; deficiencies exacerbate global malnutrition burdens (Fageria et al., 2002; White et al., 2005). Despite their pivotal role in ecosystem stability and food security (Presteele et al., 2016; Stehfest et al., 2019), critical knowledge gaps persist regarding the distribution patterns and drivers of soil micronutrients from regional to global scales.

The Tibetan Plateau represents a uniquely important yet underrepresented region for addressing these knowledge gaps. As the high-altitude landmass and the most extensive alpine permafrost region at low to mid-latitude (Yao et al., 2012), the Tibetan Plateau supports vast areas of cold- and nutrient-limited ecosystems, where plant productivity, microbial activity, and biogeochemical cycling are particularly sensitive to micronutrient availability (Han et al., 2022; Tian et al., 2019). In such environments, micronutrients may act as co-limiting or even primary limiting factors alongside nitrogen and phosphorus, yet their spatial distributions and environmental controls remain poorly quantified (Dong et al., 2023; Pan et al., 2024). Moreover, the Tibetan Plateau is experiencing rapid climate change characterized by accelerated warming and increasing moisture availability, which is expected to fundamentally alter soil

weathering regimes, redox conditions, and mineral-organic interactions (Yu et al., 2024; Cheng et al., 2024). Without robust baseline assessments of soil micronutrients, it remains difficult to evaluate how ongoing climate change may reshape nutrient limitation patterns and ecosystem functioning across high-altitude regions.

Soil micronutrient supply originates from coupled physicochemical weathering and biological mediation, critically regulated by local climate and topography (Ochoa-Hueso et al., 2020; Hartmann et al., 2023). In cold-arid high-altitude regions, particularly the Tibetan Plateau, extreme environmental interactions govern micronutrient cycling. Cryogenic processes such as glacial erosion and freeze-thaw cycles, accelerate physical bedrock weathering to mobilize lithogenic micronutrient reservoirs, while aridity concurrently constrains chemical weathering and elemental release (Mu et al., 2020; Mu et al., 2016). Low temperatures suppress biological turnover and synergize with aridity to compromise pedogenesis through clay deficits and diminished mineral reactive sites, thereby reducing elemental retention capacity (Dijkstra et al., 2004). *The combined effects of these opposing processes jointly determine the overall abundance and spatial heterogeneity of soil micronutrients across alpine soils, likely differing from the patterns of soil micronutrients observed in temperate and tropical regions.*

Despite the ecological significance of soil micronutrient, our understanding of their spatial distribution and controlling factors across the Tibetan Plateau remains limited. Previous studies have been largely confined to localized transects or site-specific investigations (e.g., the Heihe River Basin and the Tibetan Plateau Highway), offering limited spatial coverage and representativeness, and providing insufficient insight into how climate, vegetation, topography and lithology jointly regulate micronutrient patterns at the regional scale (Zhang et al., 2012; Guan et al., 2017; Bu et al., 2016). To address these knowledge gaps, we conducted a large-scale field investigation across the Tibetan Plateau, establishing 526 sampling sites distributed across representative temperature and moisture gradients. The sampling design encompassed the plateau's

dominant vegetation types and lithological classes. Using this dataset, we analyzed distribution patterns and key controlling factors for four essential micronutrients (Fe, Mn, Zn, V). We then applied a Random Forest algorithm to generate high-resolution spatial distribution maps of these micronutrients, representing the first comprehensive quantification at this scale and resolution.

[Comment 7] L42: understudied?

[Response] The related sentence has been updated as follows: *"Despite the ecological significance of soil micronutrient, existing studies on soil micronutrients across the plateau are largely confined to localized transects or site-specific investigations (e.g., the Heihe River Basin and the Tibetan Plateau Highway), offering limited spatial coverage and representativeness."* The term "understudied" has been removed from original sentence.

[Comment 8] L42-43: what is the meaning?

[Response] Our intention was to highlight that existing studies on soil micronutrients over the Tibetan Plateau are mostly based on site-specific observations or linear transect sampling (e.g., along a river valley or highway corridor). Such transects cover a narrow environmental and geographic range and therefore provide limited spatial representativeness, making it difficult to infer plateau-wide distribution patterns and controlling factors. We have rewritten this sentence to clarify the meaning: *"Despite the ecological significance of soil micronutrient, our understanding of their spatial distribution and controlling factors across the Tibetan Plateau remains limited. Previous studies have been largely confined to localized transects or site-specific investigations (e.g., the Heihe River Basin and the Tibetan Plateau Highway), offering limited spatial coverage and representativeness, and providing insufficient insight into how climate, vegetation, topography and lithology jointly regulate micronutrient patterns at the regional scale."* (Lines 52-56 on Page 3).

[Comment 9] L44: I am confused, what are the knowledge gaps?

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[Response] In the revised manuscript, we have clarified the specific knowledge gaps regarding soil micronutrients on the Tibetan Plateau. These gaps include: (1) Limited spatial coverage: previous studies have mostly focused on localized transects or site-specific investigations, which cannot represent the spatial heterogeneity of the plateau. (2) Insufficient understanding of environmental controls: the combined influences of climate, topography, lithology, and biotic factors on micronutrient distributions remain poorly quantified at the regional scale. (3) Lack of high-resolution, large-scale quantification: comprehensive spatial patterns and predictive mapping of key micronutrients across the entire plateau have not been reported. We have revised the Introduction to explicitly state these gaps as follows: *"Despite the ecological significance of soil micronutrient, our understanding of their spatial distribution and controlling factors across the Tibetan Plateau remains limited. Previous studies have been largely confined to localized transects or site-specific investigations (e.g., the Heihe River Basin and the Tibetan Plateau Highway), offering limited spatial coverage and representativeness, and providing insufficient insight into how climate, vegetation, topography and lithology jointly regulate micronutrient patterns at the regional scale (Zhang et al., 2012; Guan et al., 2017; Bu et al., 2016). To address these knowledge gaps, we conducted a large-scale field investigation across the Tibetan Plateau, establishing 526 sampling sites distributed across representative temperature and moisture gradients. The sampling design encompassed the plateau's dominant vegetation types and lithological classes. Using this dataset, we analyzed distribution patterns and key controlling factors for four essential micronutrients (Fe, Mn, Zn, V). We then applied a Random Forest algorithm to generate high-resolution spatial distribution maps of these micronutrients, representing the first comprehensive quantification at this scale and resolution."* (Lines 52-62 on Page 3).

[Comment 10] L62-63: 15 m transect makes me confused, please tell the rationale to do this.

[Response] Each site was established as a $10*10 \, m^2$ quadrat, and soil samples were collected at three positions along the diagonal (0 m, midpoint, and end of the diagonal,

approximately 0 m, 7.1 m, and 14.1 m). This sampling design allows us to capture spatial heterogeneity within the plot while maintaining a standardized framework across all sites. The previously stated "15 m transect" referred to the approximate length of the quadrat diagonal and has now been revised as follows: *"At each site, we established a 10*10 m² quadrat and collected triplicate soil samples along the diagonal at three positions (0 m, 7.1 m, and 14.1 m; 0-10cm depth), corresponding to the start, midpoint, and end of the quadrat diagonal. This design allows sampling across the spatial heterogeneity within each plot while maintaining a standardized sampling framework."* (Lines 78-81 on Page 4).

[Comment 11] L63-65: This statement might be supported by https://doi.org/10.1007/s11104-017-3376-9 and other related papers.

[Response] Thank you for the helpful reference. we have added the suggested citation (Du et al., 2017) and additional relevant reference (Cardon et al., 2013) to support the rationale that the 0-10 cm layer represents a biologically active surface horizon closely linked to plant uptake and microbially mediated nutrient cycling.

[Comment 12] L70-77: I am confused with the analysis procedures; how many soil samples were reanalyzed by ICP-MS? 218 vs.1600? L93-94 should also show it clearly. Moreover, I am not sure about the measurement method of XRF analysis, and the authors have also showed that there are large uncertainties for these data (L70-84; L345-353)

[Response] To ensure the reliability of soil micronutrient measurements, we adopted a two-step analytical strategy. First, all 1,660 topsoil samples collected from 526 sampling locations were air-dried, sieved (2 mm), and analyzed in the laboratory using a third-generation X-ray fluorescence spectrometer (XRF). All micronutrient data reported in this study are based on these laboratory XRF measurements. Second, to independently validate the XRF-derived concentrations, a subset of 218 samples was randomly selected and re-analyzed using inductively coupled plasma-mass spectrometry (ICP-MS), a widely accepted reference method for elemental analysis

(Simon, 2005).

Among the examined elements, Fe ($R^2 = 0.81$), Mn ($R^2 = 0.67$), Zn ($R^2 = 0.49$), and V ($R^2 = 0.77$) exhibit clear and statistically significant linear relationships with ICP measurements, demonstrating moderate to strong correlation (**Figure R1**). The increased dispersion observed at low contents reflects known limitations of XRF near detection thresholds, rather than method failure. Moreover, our analytical strategy follows established practice in large-scale geochemical mapping, where XRF is commonly used for high-throughput determination of total/major-element composition, while ICP-based methods are commonly employed in parallel for complementary measurements (e.g., extracted fractions, waters, or elements requiring lower detection limits) and, where appropriate, for inter-method comparison and validation. In addition to GEMAS and the NGSA, similar XRF-based workflows have been implemented in other regional/national baseline programmes (e.g., BGS G-BASE in the UK, the FOREGS Geochemical Atlas of Europe, and the Global Geochemical Baselines framework). These precedents support the robustness and suitability of using XRF with targeted ICP verification for plateau-scale geochemical datasets (**Table R1**). (See Comment 1, #1)

We have revised the Methods section (original L70-77 and L93-94) to clearly distinguish the total number of samples analyzed by XRF (n = 1,660) from the subset used for ICP-MS validation (n = 218), and to clarify the role of each method in the analytical framework. (Lines 87-92 on Page 4). The discussion of uncertainties associated with XRF measurements has also been revised to emphasize that these uncertainties were explicitly assessed and constrained through independent ICP-MS validation. (Lines 347-359 on Pages 16-17).

[**Comment 13**] L95-96: How did the authors measure these oxides?

[**Response**] The major-element oxides required for calculating CIA (Al_2O_3, CaO, Na_2O, and K_2O) were obtained from the laboratory XRF measurements performed on the air-

dried and sieved soil samples. (Lines 114-117 on Page 6).

[Comment 14] L97-98: Because the authors have abbreviated the chemical index of alteration in L95, so it should use CIA here instead, please also check other places.

[Response] We have checked the entire manuscript and updated all relevant occurrences to ensure consistent usage.

[Comment 15] L135: Soil micronutrient content.

[Response] We have revised "Soil micronutrients contents" to "Soil micronutrient content".

[Comment 16] L148-150: Is it possible to show the statistical difference for Mn among different land use types, rather than merely showing which one is the largest and which one is the lowest. Please also condense the descriptions for other micronutrients.

[Response] Thank you for your suggestion. We have revised the main text as follows: *"Soil micronutrient content (Fe, Mn, Zn, and V) varied significantly among different vegetation types (Fig. 3). Fe contents were highest in shrub and forest ecosystems, with mean values of 26,264.11 mg·kg^{-1} and 26,090.66 mg·kg^{-1}, respectively, significantly exceeding values observed in desert (19,762.66 mg·kg^{-1}) and steppe ecosystems (19,852.37 mg·kg^{-1}) by 31-33%. Similarly, Mn contents were significantly higher in forest (703.22 mg·kg^{-1}) than in shrub (606.33 mg·kg^{-1}), meadow (591.59 mg·kg^{-1}), desert and steppe ecosystems (both below 510 mg·kg^{-1}). Zn demonstrated a strong vegetation-dependent variability, with forest (32.00 mg·kg^{-1}) exhibiting the highest values and steppe (22.94 mg·kg^{-1}) and desert (21.95 mg·kg^{-1}) the lowest, shrub and cropland were intermediate and not significantly different from forest or meadow. V also varied among vegetation types, with forest being significantly higher than meadow and steppe, and shrub significantly higher than steppe, whereas cropland and desert displayed intermediate levels."* (Lines 165-173 on Page 8).

[Comment 17] L176-205: Please also show the statistical difference among different lithological classes.

[Response] Thank you for your suggestion. We have revised the main text as follows: *"Lithological class exerted a significant influence on the distribution of several soil micronutrients (Fig. 4). Fe contents differed among lithological classes, with soils derived from acidic metamorphic rocks showing the highest mean value 25,252.72 mg·kg⁻¹ and being significantly higher than soils developed from acidic igneous rocks (20,830.15 mg·kg⁻¹) and fluvial facies rocks (21,910.22 mg·kg⁻¹), whereas carbonate (24,260.96 mg·kg⁻¹), eolian facies (23,902.77 mg·kg⁻¹), and clastic sedimentary rocks (23,157.66 mg·kg⁻¹) exhibited intermediate levels and were not significantly different from either group. A similar pattern was observed for Mn, where acidic-metamorphic-drived soils (658.37 mg·kg⁻¹) were significantly higher than acidic-igneous-drived soils (530.45 mg·kg⁻¹) and fluvial-facies-drived soils (560.91 mg·kg⁻¹), with the remaining lithologies showing intermediate values. Zn also varied among lithologies, with the highest mean content in acidic metamorphic rocks (30.79 mg·kg⁻¹), which was significantly higher than acidic igneous rocks (25.27 mg·kg⁻¹) and fluvial facies rocks (25.10 mg·kg⁻¹), while eolian facies, clastic sedimentary, and carbonate rocks did not differ significantly from acidic metamorphic rocks or the lower group. For V, acidic-metamorphic-derived soils (63.67 mg·kg⁻¹) were significantly higher than fluvial facies, acidic igneous, and clastic sedimentary derived soils, whereas eolian facies rocks and carbonate rocks showed intermediate levels and were not significantly different from acidic metamorphic rocks or the lower group."* (Lines 182-194 on Page 9).

[Comment 18] L332-333: Lack references.

[Response] we have added references documenting that climate-change-driven drought can reduce the availability and plant uptake of micronutrients such as Fe and Zn (Moreno-Jimenez et al., 2019; Bista et al., 2018).

Bista, D. R., Heckathorn, S. A., Jayawardena, D. M., Mishra, S., and Boldt, J. K.: Effect of drought and carbon dioxide on nutrient uptake and levels of nutrient-uptake proteins in roots of barley, American Journal of Botany, 107, 1401-1409, https://doi.org/ 10.1002/ajb2.1542, 2018.

Moreno-Jimenez, E., Plaza, C., Saiz, H., Manzano, R., Flagmeier, M., and Maestre, F. T.: Aridity and reduced soil micronutrient availability in global drylands, Nature Sustainability, 2, 371-377, https://doi.org/10.1038/s41893-019-0262-x, 2019.

[Comment 19] For the discussion, I would like to see the discussion on the differences among vegetation types and among lithological classes, consistent with the results described by the authors earlier.

[Response] Following your suggestion. In the revised manuscript, we have reorganized and expanded the Discussion to include two subsections:

(i) vegetation-type effects on micronutrient patterns. *"The vegetation-type contrasts likely reflect ecosystem controls on topsoil (0-10 cm) geochemistry. These contrasts are consistent with ecosystem-mediated controls on topsoil geochemistry, where denser vegetation generally enhances near-surface nutrient cycling through greater biomass inputs, rhizosphere processes, and organic matter accumulation (Hinsinger, 2000). Increased organic inputs and reactive organo-mineral associations can promote retention of Fe, Mn, and Zn and, indirectly, V that is often associated with Fe-bearing phases (Lehmann et al., 2015). In contrast, arid steppe and desert systems typically exhibit weaker soil development and lower organic inputs, reducing reactive surfaces and binding sites for micronutrients, resulting in lower surface pools (Kabata-Pendias, 2010). Cropland tends to show intermediate levels, likely reflecting mixing within the plough layer and partial homogenization of surface concentrations (Alloway, 2008)."* (Lines 263-270 on Pages 13-14).

(ii) lithological controls on micronutrient variability: *"Lithological class imposes a first order control on surface soil micronutrient variability (Fig. 4), consistent with the well-established role of parent material in determining baseline micronutrient pools through differences in primary mineral assemblages and weathering products. In our dataset, acidic metamorphic-derived soils are consistently enriched in Fe, Mn, Zn, and V relative to several other lithologies, whereas acidic igneous and fluvial facies*

substrates tend to show lower contents, with carbonate, eolian facies, and clastic sedimentary rocks generally occupying intermediate levels. Such contrasts are expected where lithology governs not only the supply of Fe and Mn-bearing minerals but also the abundance of secondary oxides and clay surfaces formed during pedogenesis, which strongly influence trace-element retention and depletion intensity at regional scales (Lara et al., 2018; Spinola et al., 2022). The coherent behaviour of V alongside Fe is also mechanistically plausible because vanadate is efficiently retained by Fe and Mn oxides, making V distributions closely coupled to the abundance and reactivity of these mineral phases (Abernathy et al., 2022; Larsson et al., 2017)." (Lines 271-280 on Page 14).

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