

1 **Water availability creates global thresholds in multidimensional soil**
2 **biodiversity and functions**

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35

36 **Abstract**

37 Soils support an immense portion of Earth's biodiversity and maintain multiple
38 ecosystem functions which are essential for human well-being. Environmental
39 thresholds are known to govern global vegetation patterns, but it is still unknown
40 whether they can be used to predict the distribution of soil organisms and functions
41 across global biomes. Using a global field survey of 383 sites across contrasting
42 climatic and vegetation conditions, here we showed that soil biodiversity and functions
43 exhibited pervasive nonlinear patterns worldwide and are mainly governed by water
44 availability (precipitation/potential evapotranspiration). Changes in water availability
45 resulted in drastic shifts in soil biodiversity (bacteria, fungi, protists and invertebrates)
46 and soil functions including plant-microbe interactions, plant productivity, soil
47 biogeochemical cycles, and soil carbon sequestration. Our findings highlight that
48 crossing specific water availability thresholds can have critical consequences for the
49 provision of essential ecosystem services needed to sustain our planet.

50

51 **Introduction**

52 Soils are the foundation of terrestrial ecosystems, supporting the delivery of multiple
53 ecosystem services that benefit human societies, from food production to carbon
54 sequestration^{1,2}. Furthermore, soils are home to a myriad of soil organisms ranging
55 from bacteria to invertebrates^{2,3}. However, these vital components of soil are
56 increasingly endangered by a variety of environmental disturbances, including natural
57 processes such as drying and warming and anthropogenic pressures such as nutrient
58 loading^{4,6}. Mounting evidence suggests that the ecosystem's responses to
59 environmental changes are not always gradual, and that ecosystems sometimes undergo
60 abrupt changes, highlighting the unpredictability of the ecological consequences. For
61 example, recent studies have reported temperature thresholds associated with dramatic
62 declines in fungal decomposers⁷ and ecosystem respiration⁴, as well as water
63 availability thresholds linked to abrupt reductions in multiple structural and functional
64 ecosystem attributes in arid regions⁵. However, those works have largely focused on a
65 single ecosystem attribute (e.g., organism^{5,7} or function^{4,7}) or environmental gradient
66 (e.g., temperature⁴) or accounted for specific environmental conditions (e.g., drylands
67⁵). In the field of biogeography, a global perspective that considers contrasting
68 vegetation and climate types can sometimes reframe our understanding derived from
69 local scales to identify more general environmental drivers^{8,9}. Here, we understand
70 thresholds as points in an environmental gradient where soil biodiversity or function
71 abruptly changes its value (discontinuous threshold or break point) or its relationship
72 with that environmental gradient (continuous threshold)⁵. In this context, a unimodal
73 (or hump-shaped) relationship between soil biodiversity and environmental stress may
74 be expected, where moderate stress promotes community species diversity through
75 niche release and mitigation of competitive exclusion or predation, but extreme
76 pressure would hinder the development of all taxa¹⁰⁻¹². If these thresholds are preserved
77 across soil biodiversity and functions, they may be footprints of complex underlying
78 processes involving ecosystem feedbacks that may produce abrupt responses to climate
79 forcing¹³. In other cases, they may arise from inherent nonlinear mechanisms of
80 ecosystems, which are usually disregarded in the ecological literature¹⁴. In any case,
81 unraveling the existence of these environmental thresholds on a global spatial scale and
82 carefully discussing the underlying mechanisms^{15,16} would help develop more effective
83 strategies to address ongoing climate change.

84 Here, we evaluated the presence of environmental thresholds on the distribution of
85 multiple soil biodiversity and functions across global terrestrial ecosystems. Instead of
86 adopting the most commonly used meta-analysis methods that are affected by
87 heterogeneity in soil sampling and analytical methods^{17,18}, we conducted a global
88 standardized field survey across 383 sites from six continents, representing various
89 climates (arid, temperate, tropical, continental, and polar) and vegetation types (forests,
90 grasslands, and shrublands) (Fig. 1). To the best of our knowledge, until now, no global
91 study has been conducted using standardized observational approaches to evaluate
92 environmental thresholds on the distribution of multiple soil biodiversity and functions
93 worldwide. In this study, we obtained plot-level information on the richness of 12 soil
94 taxa across trophic levels, including bacteria, fungi, protists and invertebrates
95 (Supplementary Table 1). We used species richness (i.e., the number of zero-radius
96 operational taxonomic units [zOTUs] generated using the marker-gene sequencing
97 methods) as our metric of diversity. We also obtained data for a suite of 12 proxy soil
98 functions (i.e., stocks and processes) that correspond to key components of ecosystem
99 services—water regulation, nutrient cycling, organic matter (OM) decomposition, plant

100 biomass production and plant-microbe interactions including pathogen control and
101 mutualism (Supplementary Table 2). These variables measure either “true” soil
102 functions (that is, rates and availabilities) or key attributes/processes that constitute core
103 ecosystem functions that are both fundamental and quantifiable^{3,19}. For example,
104 available nitrogen (N) and phosphorus (P) are nutrients that frequently limit the primary
105 production and carbon storage in terrestrial ecosystems²⁰. Soils are a significant
106 reservoir of carbon, storing more than that held in vegetation and the atmosphere
107 combined, and thus play an important role in global carbon cycling²¹. Importantly,
108 these functions are more influenced by soil organisms. In this context, we hypothesize
109 that potential abrupt changes in soil biodiversity and functions are linked to specific
110 environmental factors, such as temperature⁶, water availability⁵, and/or climatic
111 seasonality²².

112 **Results and Discussion**

113 Our results found pervasive nonlinear relationships between broad environmental
114 gradients and multiple groups of soil biodiversity and functions worldwide. Of the
115 multiple environmental variables assessed, we found water availability to be the most
116 important driver, generating a series of discrete thresholds associated with abrupt
117 changes in soil biodiversity and functions. These abrupt changes in soil biodiversity
118 were speculated to be related both directly to water limitation and indirectly to changes
119 in plant productivity and even shifts in vegetation²³. Furthermore, abrupt decreases in
120 soil functions associated with reduced water availability occurred sequentially in three
121 phases characterized by abrupt declines in plant-microbe interactions, plant
122 productivity and soil biogeochemical cycles, and finally soil carbon contents. Overall,
123 the interplay between the direct effects of water limitation and the indirect effects of
124 vegetation shift governed the response behavior of soil biodiversity and functions to
125 environmental changes. It is worth mentioning that while our study does not cover the
126 entire environmental spectra found on Earth, it represents a large fraction of the planet’s
127 environmental variability from arid to mesic ecosystems (Fig. 1), with a greater
128 resolution at the arid end⁵. We acknowledge that the abrupt changes found in this study
129 do not necessarily mean that these effects will translate into time; this is a future
130 research question to be solved by future studies based on temporal experiments.

131 ***Consistent effect of water availability on soil biodiversity***

132 We first discovered that a wide range of environmental variables exhibited pervasive
133 significant thresholds related to abrupt changes in soil biodiversity across global biomes
134 of various vegetation and climate types (Extended Data Figs. 1-2, Supplementary Fig.
135 1). Biodiversity at multiple trophic levels is interconnected through the soil food web
136²⁴, as confirmed by this study (Spearman ρ ranges 0.2–0.7, Supplementary Fig. 2),
137 indicating that they may respond to environmental changes in similar ways but in
138 different orders. To evaluate the importance of different environmental variables in
139 controlling the abrupt change in soil biodiversity, we used the term “conservative” or
140 “convergent” when referring to a specific environmental factor that presents the most
141 adjacent threshold in soil biodiversity (see Methods for rationale). Our results show that
142 water availability presented the most convergent threshold values (i.e., the smallest
143 variability) across the diversity of all measured soil taxa (Extended Data Fig. 3).
144 Specifically, abrupt changes (or reductions) in soil biodiversity at multiple trophic
145 levels occurred at a small range of water availability levels of ~0.2–0.4 (Fig. 2a). When
146 crossing a water availability level of ~0.3, a potential systemic shift would occur for
147 the diversity of all groups (soil multidiversity hereafter) (Fig. 2a). The importance of

148 water availability in explaining the distribution of soil biodiversity is further supported
149 by a random forest analysis (Extended Data Fig. 4).

150 Most taxa displayed a hump-shaped pattern along the water availability gradient
151 (Fig. 2a). We speculated that such a uniform pattern across multiple groups of soil taxa
152 is attributed to their eco-physiological fitness to water limitation and the associated
153 nutrient availability. Ultimately, water availability is crucial to the survival and
154 functionality of living organisms, including the eukaryotic and prokaryotic taxa studied
155 in this study²⁵. Soil taxa depend on distinct optimal ranges of water availability,
156 deviating from this range would impede their growth and survival^{25,26}. Although we
157 should not assume a mechanistically simple relationship between microbial biomass or
158 growth rate and diversity^{11,27}, moderate water stress (approaching the optimum from
159 the right side of the curves, Fig. 2a) could reduce the biomass or growth rate of
160 dominant taxa, thereby freeing up more niches or alleviating competitive exclusion or
161 predation, both of which contribute to soil biodiversity^{11,12}. In the face of strong
162 environmental stress (crossing the optimum and proceeding to extreme drought, Fig.
163 2a), however, most soil taxa no longer survive shortages, for example, in water and
164 nutrient availability. As evidence for the above assertion, our results further show a
165 hump-shaped relationship between soil heterotrophic respiration and water availability,
166 with a threshold of 0.32 (Fig. 3i). Some soil organisms, such as Excavata and
167 Chlorophyta, did not follow this uniform pattern (Fig. 2a), which could be associated
168 with their different eco-physiological features. For example, some members of
169 Chlorophyta (i.e., green algae) establish symbiotic relationships with fungi to form
170 lichens that generally prefer arid conditions²⁸.

171 The observed abrupt reductions in soil biodiversity could also be linked to
172 reductions in plant productivity and essential soil nutrient availability when water
173 availability declines to approximately 0.4 (Fig. 3d–g). This notion was supported by
174 decreases in soil fine texture (% of clay and silt; Fig. 2b), porosity (Fig. 3l), and the
175 stability of soil aggregates⁵, which affect the soil's capacity to sustain inorganic
176 nutrients and microbial access to water, nutrients and oxygen in soil pores²⁶. In this
177 regard, our results further show that larger eukaryotic taxa (mostly acting as primary
178 decomposers of plant inputs³) were more sensitive to water stress than were smaller
179 prokaryotic bacteria (acting as nutrient miners by activating nutrients from the soil),
180 which may have also been linked with abrupt changes in plant community composition
181 and soil biogeochemical cycles²⁹. As water availability decreased to the dry end that
182 sustains forest and grassland, vegetation shifted to stress-avoidant shrub species
183 (Supplementary Fig. 3), which are better adapted to the infertile soil conditions and
184 seasonal droughts characterizing these environments^{5,16}. Accordingly, the soil
185 communities shift from larger primary decomposers that preferably degrade high-
186 quality detritus (e.g., nutrient-enriched litter and foliage) to smaller nutrient miners that
187 are less picky for N/P-limited shrub detritus^{30,31}. In addition, larger soil taxa (e.g.,
188 Nematoda and Cercozoa in Fig. 2a) are more affected by changes in soil physical
189 connectivity for movement and access to resources in soil pores^{26,32}, while bacterial
190 diversity is primarily controlled by soil chemical properties such as soil pH¹⁰. Soil
191 physical properties are more sensitive to decreasing water availability than soil pH (Figs.
192 2b and 3j), which may also contribute to the shift in soil biodiversity under dry
193 conditions.

194 Our analyses further revealed that climatic variables influenced soil biodiversity in
195 a nonlinear way, possibly through changes in water availability. Climate change affects

196 global water availability through changes in seasonal precipitation and evaporation³³.
197 Consistently, we reported statistically inverse relationships between water availability
198 and increased seasonal variation in both precipitation (that is, PSEA, Spearman $\rho =$
199 -0.25 , $P < 0.05$) and temperature (that is, TSEA, Spearman $\rho = -0.29$, $P < 0.05$)
200 (Supplementary Fig. 4). Accordingly, our results showed that high seasonal variations
201 in precipitation and temperature were also correlated with threshold behaviors in soil
202 biodiversity (Extended Data Figs. 1-2), which may be driven by abrupt reductions in
203 water availability (Extended Data Fig. 5). Together with previous studies^{33,34}, our
204 results call for more attention to the effect of extreme intra-annual climate seasonality
205 on soil biodiversity rather than focusing solely on interannual climate changes.

206 *Cascading effect of water availability on soil functions*

207 Tipping into the response of individual soil functions to environmental gradients, we
208 also found pervasive nonlinear manners and identified environmental thresholds at
209 which these functions abruptly changed (Extended Data Figs. 6-7 and Supplementary
210 Fig. 5). Using a random forest algorithm, the results revealed that water availability was
211 among the most important environmental drivers influencing multiple individual soil
212 functions, ranking first in five out of twelve cases (i.e., plant productivity, soil organic
213 carbon, pathogen control, soil saprobes, and chitin degradation) and second in another
214 four cases (i.e., soil water holding capacity, soil nitrate, soil respiration and mutualism)
215 (Extended Data Fig. 8).

216 Our study demonstrated that, when specific thresholds of water availability were
217 exceeded, a sudden reduction occurred in all individual soil functions, except for
218 porosity (Fig. 3). Interestingly, the responses of soil functions to water stress could be
219 categorized into three distinct phases, which were characterized by orderly and abrupt
220 changes in three sets of soil functional variables (Fig. 3). The soil functional changes
221 under water limitation commenced with a marked reduction in positive plant-microbe
222 interactions when water availability dropped below levels of 0.5–0.7 (Fig. 3a-c). The
223 observed decline in the relative abundance of soil saprobes (Fig. 3a) may be due to the
224 sudden decrease in the quality of plant litter inputs (leaf nitrogen content⁵) into the soil,
225 leading to reduced substrate availability for soil decomposers. The abrupt decline in
226 plant mutualism (Fig. 3b) could be linked to abrupt alterations in plant community
227 composition^{23,29}. This notion was further supported by the sharp decrease in the effect
228 of pathogen control (Fig. 3c), which could be attributed to the vacancy of niches that
229 were originally occupied by pathogen competitors and the fact that pathogenic fungi
230 are more adept at surviving in dry conditions^{5,35}. Ecosystem stability and resistance to
231 drought are positively correlated with soil saprobes and negatively related to plant
232 symbionts and pathogens^{35,36}. Therefore, the shift to a pathogen-dominated soil fungal
233 community may occur due to weakened positive plant-microbe interactions under
234 increasingly arid conditions²³, exacerbating the adverse effects on ecosystem stability.

235 As water availability continued to decrease to levels of ~ 0.3 – 0.4 , we further
236 noticed an abrupt decline in plant productivity and soil biogeochemical cycles. The
237 reductions in plant productivity could be attributed to the weakening of positive plant-
238 microbe interactions identified above (Fig. 3a–d). The biogeochemical changes
239 included abrupt reductions in soil nutrient transformation (including inorganic nitrate,
240 ammonium and phosphorus) and a sharp decline in organic matter (OM) decomposition,
241 characterized by chitin degradation and soil heterotrophic respiration (Fig. 3e–i). The
242 observed reductions in soil available nutrients linked to decreased plant-derived organic
243 inputs into the soil, which were driven by the abrupt reduction in plant productivity (Fig.

244 3d) and by the sharp decline in the relative abundance of soil saprobes (Fig. 3a). This
245 was further supported by the decrease in OM decomposition, which is the primary
246 source of readily-available inorganic nutrients in soil³⁷. The available N and P are good
247 surrogates of soil nutrient availability for soil organisms¹⁹. Accordingly, our results
248 showed that there were sharp declines in the diversity of most soil organisms, especially
249 larger-size eukaryotic taxa, when water availability dropped to the level of abrupt
250 reductions in soil inorganic nutrients (Fig. 2a). Other changes observed at this level of
251 water availability include a decline in soil water holding capacity (Fig. 3i), which was
252 a key driver affecting the soil's capacity to store soluble inorganic nutrients³⁸.

253 With a further decrease in water availability below 0.25, a sharp decline in the soil
254 carbon sink was ultimately detected (Fig. 3k). The reductions in soil carbon content
255 could be attributed to a decrease in the diversity of soil taxa (Fig. 2a), which are crucial
256 for maintaining ecosystem functioning and soil fertility³. In addition, drastic reductions
257 in soil nutrients (Fig. 3e–g), which are essential for plant productivity and soil carbon
258 storage²⁰, may have contributed to the reduction in soil organic carbon content. The
259 drastic reduction in the terrestrial carbon sink adds to other abrupt changes that occurred
260 under drier conditions, such as the decline in plant cover (Fig. 2b) and species richness
261⁵, implying that most plant species may not survive shortages of both water and
262 nutrients once this threshold of water availability is crossed.

263 **Conclusions**

264 By presenting pervasive nonlinearity in multiple soil taxa and functions along gradual
265 changes in broad environmental gradients, our results greatly extend the current
266 framework of abrupt shifts for terrestrial ecosystems. We identified a series of water
267 availability threshold values associated with abrupt declines in soil biodiversity starting
268 from larger eukaryotic organisms to smaller prokaryotic bacteria. Additionally, we
269 found that soil functions under water stress undergo a three-phase disruption,
270 characterized by abrupt declines in plant-microbe interactions, plant productivity and
271 soil biogeochemical cycles, and soil organic carbon content. Furthermore, we propose
272 that such threshold behaviors are governed both directly by water stress and indirectly
273 by vegetation shifts along the way. Overall, our global survey highlights the
274 fundamental importance of water availability in governing soil biodiversity and
275 functions worldwide and suggests that further water limitations are likely to shift the
276 ecological functions provided by soil organisms and may potentially result in ecosystem
277 collapse in some cases.

278 **Methods**

279 **Field survey and soil sample collection**

280 The global field survey aimed to cover a wide range of environmental contexts, soil
281 biodiversity, and functions. To achieve this goal, a total of 383 soil samples were
282 collected from natural sites across all continents except Antarctic, to include globally
283 distributed regions that span a wide range of climatic and vegetation types. Coordinates
284 for each site were recorded *in situ* with a portable GPS, and vegetation type was
285 annotated on-site based on the dominant vegetation. Specifically, the surveyed locations
286 encompassed tropical, temperate, continental, polar, and arid regions, including
287 grasslands, shrublands, forests, and moss heaths (ecosystems entirely covered by soil
288 mosses). It provides a good representation of the most common environmental
289 conditions found on Earth, with the mean annual precipitation and temperature, and
290 plant cover ranging between 17 and 2161 mm, -6.7°C and 29.2°C , and 0.1% and 100%,

291 respectively. The range of estimated environmental variables can be found in Extended
292 Data Fig. 1. This method has been used in previous global studies, which have shown
293 its effectiveness in biome classification^{3,39}.

294 Between 2016 and 2019, we conducted a sampling campaign specifically designed
295 to evaluate soil biodiversity and functions at the plot level. A representative plot was
296 established at each site, reflecting the vegetation present in that area. To ensure
297 consistency and minimize confusion arising from sampling annual communities at
298 different times of the year or years, we focused only on perennial plant species^{19,39}. To
299 account for spatial heterogeneity in the plot, five soil cores (the uppermost ~10 cm
300 depth with surface litter removed) were collected from both under the dominant
301 perennial plant species (e.g., trees, shrubs, grasses) and in open areas devoid of
302 perennial vegetation¹⁹, and then were homogenized into a composite soil sample
303 (weighing over 250 g) in the field. We selected topsoil because it is the most commonly
304 used depth in comparable studies and is typically biologically the most active in terms
305 of plant roots, microbial biomass, and nutrient pools³⁹. After field sampling, the soils
306 were sieved (< 2 mm) in laboratory and separated into two portions: one portion was
307 air-dried for one-month and stored for soil biochemical analyses, and the second portion
308 was immediately frozen at -20 °C for molecular analyses. We do not expect seasonality
309 to affect our results, as global patterns in nutrient availability are expected to be more
310 consistent over time, and seasonality is known to have a reduced impact on large scale
311 patterns in ecology⁴⁰.

312 **Environmental context**

313 In this study, we represented the environmental context with a range of variables that
314 included climatic factors, such as the temperature and precipitation, biological factors,
315 such as plant cover and productivity, as well as soil physical property and chemical
316 conditions, such as soil fine texture and pH. These variables were chosen due to their
317 significance as environmental predictors of soil biodiversity and functions, and the
318 ability to influence their responses to environmental change^{3,5,39}. The cover of
319 perennial vegetation was measured *in situ* at each site using the line-intercept method
320¹⁹. Soil properties were determined using standardized protocols¹⁹. In brief, for all soil
321 samples, pH was measured with a pH meter in a 1:2.5 mass:volume suspension of dry
322 soil and deionized water, and salinity was measured with a conductivity meter in a 1:5
323 mass:volume suspension. Soil fine texture, which is defined as the percentage of clay
324 + silt, was determined using a simplified method combining sieving and sedimentation
325 steps⁴¹. Soil pH and fine texture ranged between 3.77 and 9.54, and 0.49% and 88.22%,
326 respectively.

327 We obtained climatic data from the Worldclim database (www.worldclim.org) at a
328 1 km resolution⁴². Specifically, mean annual temperature (MAT) and temperature
329 seasonality (TSEA, defined as the standard deviation of the monthly mean temperatures
330 expressed as a percentage of the annual mean temperature) as well as precipitation
331 seasonality (PSEA, defined as the coefficient of variation of the monthly precipitation
332 estimates expressed as a percentage of the annual mean precipitation) were extracted.
333 For assessing climatic water availability, the aridity index (precipitation/potential
334 evapotranspiration) was used instead of mean annual precipitation, as it reflects the
335 balance between water received by the land surface (precipitation) and that demanded
336 by the atmosphere (potential evapotranspiration, PET, calculated using the FAO
337 Penman-Monteith equation⁴³). This is a widely used water-availability related metric
338 at a global scale⁵. The Global Potential Evapotranspiration database (V3)⁴³, which is

339 based on interpolations provided by WorldClim ⁴⁴, was used to estimate water
340 availability, with values ranging from 0.01 to 2.12 in this study.

341 **Soil diversity measures**

342 In this study, the diversity of soil taxa, including bacteria, fungi, protists, and
343 invertebrates, was measured using an Illumina MiSeq platform for amplicon
344 sequencing. Soil DNA was extracted with the Powersoil DNA Isolation Kit (MoBio
345 Laboratories) following the manufacturer's instructions. The 16S rRNA gene for
346 bacteria and the 18S rRNA gene for eukaryotes were sequenced using the 341F/805R
347 ⁴⁵ and Euk1391f/EukBr ⁴⁶ primer sets, respectively. The bioinformatic analysis were
348 performed using a combination of QIIME ⁴⁷, USEARCH ⁴⁸, and UNOISE3 ⁴⁹. The
349 sequences were clustered into soil phylotypes – zero-radius operational taxonomic
350 units (zOTUs) – at a 100% identity level. The representative sequences of zOTUs were
351 annotated against the SILVA (16S rRNA gene)⁵⁰ and PR2 and SILVA (18S rRNA
352 gene)⁵¹ databases. Before estimating the richness of soil organisms, the zOTU
353 abundance tables were rarefied at 10,000 (for bacteria) and 4,000 (for eukaryotes)
354 sequences per sample to ensure an even sampling depth within each group of soil
355 organisms. Protists were defined as eukaryotic taxa, except fungi, Metazoa
356 (invertebrates and vertebrates), and vascular and non-vascular plants (Streptophyta).
357 Algae were classified as protists in this study. Fungal guilds were characterized using
358 the FUNGuild ⁵².

359 Here, we employed species richness, which represents the number of phylotypes,
360 as a measure of soil diversity since it is widely used and straightforward ³⁹. We used the
361 zOTU tables to estimate the richness of 12 of the most common prokaryotic and
362 eukaryotic taxa found in our soil samples: bacteria, fungi, protists (Apicomplexa,
363 Cercozoa, Ciliophora, Chlorophyta, Excavata, Ochrophyta, Oomycota) and
364 invertebrates (Arachnida, Nematoda, Rotifera). To generate a composite diversity index
365 (i.e., multidiversity), we normalized the richness of each taxon to a 0-1 scale using the
366 formula $(\text{rawDiversity} - \min(\text{rawDiversity})) / (\text{max}(\text{rawDiversity}) - \min(\text{rawDiversity}))$
367 and then calculated the mean value ³. Nevertheless, we acknowledge that quantification
368 of soil invertebrate biodiversity using sequencing techniques may have limitations, as
369 larger soil organisms may be underrepresented by this approach ³.

370 **Soil functions**

371 This study included 12 surrogates of soil functions that are regulated by soil organisms
372 and are associated with a diverse range of ecosystem services. These surrogates include
373 aboveground plant productivity (estimated using satellite data to measure average plant
374 biomass), soil carbon storage (evaluated by measuring the content of total soil organic
375 carbon), soil water regulation (measured using soil water holding capacity and porosity),
376 organic matter decomposition (evaluated using an enzyme related to chitin degradation,
377 the proportion of saprotrophic fungi, and soil heterotrophic respiration), nutrient
378 cycling (assessed by measuring the contents of soil Olsen-P, ammonium and nitrate),
379 and plant-microbe interactions (evaluated by mutualism and pathogen control). These
380 variables measure either “true” functions (e.g., element cycling) or key
381 properties/processes (e.g., soil enzyme activity), which together provide a good proxy
382 for biogeochemical cycles, productivity, and the buildup of terrestrial ecosystems ^{3,19}.
383 We discussed the ecological significance of these variables individually below and in
384 the Supplementary Table S2.

385 Plant productivity is of great importance in regulating the functioning of terrestrial

386 ecosystems, given that nearly all aboveground and belowground life forms rely on it as
387 their ultimate source of energy, directly or indirectly^{3,53}. To quantify plant productivity,
388 we used the Normalized Difference Vegetation Index (NDVI) from the Moderate
389 Resolution Imaging Spectroradiometer aboard NASA's Terra satellites
390 (<https://modis.ornl.gov/data.html>) at a resolution of 250 m, which provides a global
391 measure of vegetation greenness across Earth's landscapes, serving as a proxy of
392 photosynthetic activity and vegetation distribution⁵⁴. Here, we obtained averaged
393 NDVI values obtained from the month before, during, and after the sampling dates of
394 the surveyed plots. Previous work has shown that the choice of productivity period
395 should not alter our results³.

396 Other eleven soil functions listed above, except for plant productivity, were
397 analyzed with air-dried soil samples. Previous studies have found that air drying and
398 further storage of soils does not appreciably alter the functions of interest in this study,
399 and these methods are commonly used when analyzing physical and chemical soil
400 properties in natural terrestrial ecosystems worldwide¹⁹. Furthermore, it is also
401 important to note that most of the sampled soils were collected when they were in a dry
402 state, minimizing the potential bias induced by our drying treatment^{3,19}.

403 Soil water regulation was assessed through the measurement of two important soil
404 physical properties, namely soil water holding capacity and soil porosity. Soil water
405 holding capacity – the amount of water that a given soil can retain – is relevant to
406 several aspects of soil water management⁵⁵ and crucial in determining aboveground
407 plant productivity via regulating plant-water provision^{56,57}. On the other hand, soil
408 porosity – the percentage of the soil volume occupied by pore spaces – is an important
409 physical property that controls various key soil hydrological properties, including water
410 storage capacity and infiltration^{58,59}. Soil water holding capacity was determined in the
411 lab using the funnel method³⁸. Soil porosity was quantified as $100 \times (1 - (\text{bulk density}/\text{particle density}))$, where bulk density was measured for each sample using the
412 cylindrical core method³⁸, and particle density was estimated using a constant value of
413 2.65 g/cm^3 .
414

415 Regarding soil nutrient cycling, we obtained the availability of inorganic N
416 (ammonium and nitrate) and P (Olsen P) from K_2SO_4 and NaHCO_3 (pH: 8.5) extracts,
417 respectively, for all samples, using colorimetric assays¹⁹. The contents of available N
418 and P are reliable indicators of their availability to plants and microorganisms in
419 terrestrial ecosystems globally¹⁹. Soil organic C (SOC) is a significant terrestrial carbon
420 reservoir and plays a crucial role in atmospheric CO_2 sequestration^{60,61}. SOC
421 concentration was determined in ball-milled soils by dry combustion, gas
422 chromatography and thermal conductivity detection Thermo Flash 2000 NC soil
423 analyzer (ThermoFisher Scientific, Waltham, Massachusetts, USA), after the removal
424 of carbonates by acid fumigation¹⁹. Soil organic C varied from 0.45 to 378.1 g/kg in
425 this study. Extracellular enzymes are responsible for the breakdown of organic matter
426⁶², and β -N-acetylglucosaminidase (NAG) provides a major source of mineralizable
427 nitrogen in the soil by catalyzing chitin breakdown to amino sugars⁶³. The activity of
428 NAG was measured using the fluorometry method from 1 g of soil⁶⁴.

429 Soil heterotrophic respiration is an important process that contributes to carbon
430 losses through the decomposition of litter, detritus and soil organic matter by soil
431 microorganisms, and it plays a crucial role in the global carbon cycle⁶⁵. The estimation
432 of soil heterotrophic respiration was carried out using a high-throughput colorimetric
433 method (Microresp⁶⁶). Dried soil samples were incubated at 20° C for 10 hours (short-

434 term incubation). Soils were then transferred to the 96-well deep microtiter plates by
435 adding approximately 0.5–1 g soil per well. The soil moisture was adjusted to 60% of
436 its water-holding capacity using sterile deionized water, which is optimal for microbial
437 activity³. First, the soil samples were pre-incubated for 5 hours in growth chambers
438 under dark conditions, while being covered with polyethylene film to prevent soil
439 drying and allow gas exchange. Our approach aims to allow the microbial community
440 to settle after the initial disturbance⁶⁷ and to avoid rapid initial CO₂ flush as a
441 consequence of rewetting dry soils (i.e., Birch effect⁶⁸) without compromising the re-
442 adaptation of microbial communities to new incubation conditions⁶⁹. Subsequently, the
443 samples were incubated for 5 hours with colorimetric detection plates. The Microresp
444 protocol utilizes a CO₂ detection solution containing cresol red indicator dye, which
445 changes due to the pH variation that occurs when respired CO₂ reacts with the
446 bicarbonate of the detection solution. The absorbance of the detection plate was
447 measured immediately before and after use at 595 nm. To ensure accuracy, three
448 analytical replicates were performed per sample, and the average of these replicates per
449 assay temperature was used as the observed potential respiration rate for each sample.

450 Plant roots interact closely with beneficial symbionts (arbuscular and
451 ectomycorrhizal fungi) that enhance nutrient acquisition and pathogens that cause root
452 necrosis or plant death^{36,70}. In this study, plant-microbe interactions were evaluated by
453 considering mutualism and pathogen control. Mutualism specifically refers to the
454 relationship between plant and mycorrhizal fungi, which provide benefits to both
455 partners, and was quantified by determining the relative abundance of mycorrhizal
456 fungi in overall fungal community. Pathogen control, on the other hand, refers to the
457 ability of an ecosystem to reduce the incidence of fungal diseases⁷⁰, and was calculated
458 as the inverse of the relative abundance of soil-borne fungal phytopathogens in overall
459 fungal community.

460 **Statistical analyses**

461 **Partial correlations**

462 Partial correlations were used to assess the relationships among individual variables in
463 soil biodiversity or environmental context, with the two-sided Spearman's *rho* (ρ) used
464 as the measure of strength and direction of the association. We used a false discovery
465 rate approach to determine adjusted P values to control for spurious correlations (false
466 positives). The statistical analysis was conducted using the R package 'psych'⁷¹.

467 **Threshold identification**

468 In this study, we employed the Akaike information criterion (AIC) in two steps to
469 identify the most suitable model that describes the relationship between soil
470 biodiversity/functional attributes (y) and environmental gradients (x)⁵. The first step
471 involved fitting linear and nonlinear models, including quadratic (the simplest case of
472 nonlinear trend) and generalized additive models (GAM, more complex trend through
473 smoothing parameters), to the data⁵. The linear model is the null hypothesis that
474 assumes a gradual x-y relationship, while a lower AIC value for either nonlinear model
475 implies the presence of a threshold point.

476 In the second step, we tested for the presence of threshold only when nonlinear
477 regressions were a better fit to the data. We considered a threshold as the point in x
478 where y changes abruptly its value (discontinuous threshold or break point) or its
479 relationship with x (continuous threshold). In the latter case, the incidence of abrupt

480 change in slope is regarded, but also more subtle and continuous changes that may
481 involve high degree polynomials (usually better fitted by GAM models where changes
482 in the slope do not involve a breakpoint of a sudden change but indicate a point of
483 maximum curvature). Both cases, despite being continuous, are still thresholds and may
484 indicate important information for management: the value of x signaled is the most
485 obvious point where one should stop assuming the previous x - y relationship.

486 In this study, we examined both continuous and discontinuous thresholds, which
487 involved evaluating the performance of three threshold models. Continuous thresholds
488 can be effectively detected using segmented regression (i.e., a linear regression that
489 modifies its slope at the threshold) or more complex GAM regression. On the other
490 hand, discontinuous thresholds require an overall change in both intercept and slope,
491 and can be well-fitted to either step (i.e., a linear regression that changes only the
492 intercept at the threshold) or a combination of step and segmented regressions (called
493 segmented, which involve changes in both intercept and slope at the threshold). All
494 these models, except for GAM, generate a threshold value as part of their parameters.
495 The best model among segmented, step, and segmented regressions was chosen using
496 the AIC values. If GAM regression was found to be the best model compared to
497 threshold models, the threshold yielded by segmented regression was reported to
498 indicate the point of maximum curvature of the regression. Detailed AIC values for
499 each regression model are provided in Supplementary Table 3.

500 Threshold detection is sensitive to influential points or outliers. We used the
501 Mahalanobis distance method to remove outliers (points scoring a Mahalanobis
502 distance higher than 12^{72}) and restricted the search of threshold to the 0.05 and 0.95
503 quantiles of x gradient. We performed 1000 bootstrap samplings on each case to
504 identify a set of 1000 plausible thresholds for each case and obtained the mean value as
505 the final threshold. To further test whether the identified threshold significantly affected
506 the slope and/or intercept of the fitted regressions, we bootstrapped linear regressions
507 at both sides of the threshold and used the unpaired two-sided Mann-Whitney U test to
508 compare the slopes. In almost all cases where nonlinear regressions were the better fit,
509 we found significant differences in slopes of both sides of the threshold (Extended Data
510 Figs. 2 and 7). This approach followed the method in ref. [5]. We used the `chngt`⁷³ and
511 `gam`⁷⁴ packages in R to fit nonlinear regressions.

512 **Convergence of environmental thresholds**

513 We evaluate the conservatism or convergence of environmental variables in driving
514 abrupt changes in soil biodiversity by measuring the variability of the threshold values
515 identified. A smaller variability indicates a higher conservatism of environmental
516 factors, or a higher convergence of corresponding identified thresholds. The underlying
517 assumption is that when a series of thresholds detected across soil biodiversity converge
518 within a narrow range of a given environmental gradient, there is a fundamental and
519 insurmountable difference separating responses of soil biodiversity. This may be due to
520 strong convergence in environmental limits, such as a physiological trigger that is equal
521 across soil taxa, or due to interactions across ecological dimensions typical of feedback
522 that amplify responses to the environmental factor, such as low carbon leading to low
523 decomposition, low fungal diversity, and even less decomposition and less carbon¹⁶.
524 The threshold variability is evaluated using the average variation degree (AVD)⁷⁵,
525 which quantifies the deviation degree from the mean of identified environmental
526 threshold of multiple groups of soil taxa. In this respect, only those soil taxa that
527 respond nonlinearly to a given environmental factor are included in estimating the

528 threshold variability for that environmental factor. The AVD is calculated using the
529 following equation:

$$530 \quad a = \frac{\sum_i^n |t_i - \bar{t}|}{\delta * n}$$

531 where a is the variation degree, t_i is the threshold identified for ecosystem attribute i ,
532 n is the number of ecosystem attributes that respond nonlinearly to a given
533 environmental factor, and \bar{t} and δ is the average value and standard deviation of all
534 thresholds identified across ecosystem attributes, respectively.

535 **Data availability**

536 All the materials, raw data, and protocols used in the article are available upon request
537 and without restriction, and all data that support the main findings of this study will be
538 made publicly available in Figshare⁷⁶ upon publication.

539 **Code availability**

540 The data in this study were analyzed with publicly available tool packages in R and
541 the figures were produced with R. The R code used in the analysis presented in this
542 paper is available in Figshare⁷⁶.

543 **Acknowledgments**

544 Y.F. is supported by National Natural Science Foundation of China (42177297), CAS
545 Strategic Priority Research Program (XDA28010302), and Knowledge Innovation
546 Program of Chinese Academy of Sciences (ISSASIP2205). M.D.-B. acknowledges
547 support from the Spanish Ministry of Science and Innovation for the I+D+i project
548 PID2020-115813RA-I00 funded by MCIN/AEI/10.13039/501100011033. M.D.-B. is
549 also supported by a project of the Fondo Europeo de Desarrollo Regional (FEDER) and
550 the Consejería de Transformación Económica, Industria, Conocimiento y
551 Universidades of the Junta de Andalucía (FEDER Andalucía 2014-2020 Objetivo
552 temático “01 - Refuerzo de la investigación, el desarrollo tecnológico y la innovación”)
553 associated with the research project P20_00879 (ANDABIOMA). F.T.M. is supported
554 by Generalitat Valenciana grant CIDEGENT/2018/041 and the Horizon Europe
555 program of the European Union (SOILGUARD, Grant Agreement number 101000371).
556 MB acknowledges funding from Spanish Ministry of Science and Innovation through
557 a Ramón y Cajal Fellowship (# RYC2021-031797-I). C.C. is supported by the European
558 Commission under the Marie Skłodowska-Curie Grant Agreement No. 702057
559 (DRYLIFE). The survey of dryland areas was supported by the European Research
560 Council (BIODESERT project, Grant Agreement number 647038).

561 **Author contributions**

562 M.D.-B., M.B., and Y.F. developed the original ideas. F.T.M., M.D.-B., and B.K.S.
563 provided the original data. M.D.-B., F.T.M., B.K.S., T.S.-S., L.G.-V., and J.W. contributed
564 to lab analyses. J.Z., Y.F., M.B., M.D.-B., and C.C. conducted statistical analyses. J.Z.,
565 Y.F., and M.D.-B. wrote the first draft of the manuscript, and all authors contributed
566 substantially to revisions.

567 **Competing interests**

568 The authors declare no competing interests.

569 **Figure legends**

570 **Fig. 1 | Map showing locations of the 383 soil sampling sites included in this study.**
571 Sites are colored based on the Köppen climate classification of biomes ⁷⁷. Map is
572 displayed using the Robinson projection.

573 **Fig. 2 | Nonlinear relationships between water availability and the diversity of soil**
574 **taxa as well as other environmental factors.** The y axes represent the diversity of
575 multiple groups of soil taxa and the multidiversity of all of the groups (a) and other
576 environmental properties that are influenced by water availability (b). Regression
577 models represent the linear regressions before and after the water availability threshold.
578 Black dashed lines represent the smoothed trend fitted by a generalized additive model,
579 and blue solid lines represent the linear fits at both sides of each threshold. Inset
580 numbers and vertical dashed lines describe the water availability threshold identified.

581 **Fig. 3 | Relationships between soil functions and water availability.** Threshold
582 values of water availability were identified for (a) soil saprobes, (b) plant-mycorrhizal
583 mutualism, (c) plant-pathogen control, (d) plant productivity, contents of soil (e) nitrate,
584 (f) ammonium, and (g) available phosphorus, (h) enzyme activity of chitin degradation,
585 (i) soil heterotrophic respiration rate, (j) soil water holding capacity, and (k) content of
586 soil organic carbon. The relationship between (i) soil porosity and water availability
587 was better fitted by a linear regression over nonlinear model. Many functional variables
588 are log-transformed to improve normality. The rest of the information is the same as
589 Fig. 2.

590 Reference

- 591 1 Amundson, R. *et al.* Soil and human security in the 21st century. *Science* **348**,
592 1261071 (2015).
- 593 2 Bardgett, R. D. & van der Putten, W. H. Belowground biodiversity and ecosystem
594 functioning. *Nature* **515**, 505–511 (2014).
- 595 3 Delgado-Baquerizo, M. *et al.* Multiple elements of soil biodiversity drive
596 ecosystem functions across biomes. *Nat. Ecol. Evol.* **4**, 210–220 (2020).
- 597 4 Johnston, A. S. A. *et al.* Temperature thresholds of ecosystem respiration at
598 a global scale. *Nat. Ecol. Evol.* **5**, 487–494 (2021).
- 599 5 Berdugo, M. *et al.* Global ecosystem thresholds driven by aridity. *Science*
600 **367**, 787–790 (2020).
- 601 6 Wang, C. *et al.* The temperature sensitivity of soil: microbial biodiversity,
602 growth, and carbon mineralization. *ISME J.* **15**, 2738–2747 (2021).
- 603 7 Feng, Y. *et al.* Temperature thresholds drive the global distribution of soil
604 fungal decomposers. *Glob. Chang. Biol.* **28**, 2779–2789 (2022).
- 605 8 Jarzyna, M. A. & Jetz, W. Taxonomic and functional diversity change is scale
606 dependent. *Nat. Commun.* **9**, 2565 (2018).
- 607 9 Martiny, J. B., Eisen, J. A., Penn, K., Allison, S. D. & Horner-Devine, M. C.
608 Drivers of bacterial β -diversity depend on spatial scale. *Proc. Natl. Acad. Sci. U.S.A.* **108**,
609 7850–7854 (2011).
- 610 10 Fierer, N. & Jackson, R. B. The diversity and biogeography of soil bacterial
611 communities. *Proc. Natl. Acad. Sci. U.S.A.* **103**, 626–631 (2006).
- 612 11 Bastida, F. *et al.* Soil microbial diversity–biomass relationships are driven
613 by soil carbon content across global biomes. *ISME J.* **15**, 2081–2091 (2021).
- 614 12 Zwerschke, N., Bollen, M., Molis, M. & Scrosati, R. A. An environmental stress

- 615 model correctly predicts unimodal trends in overall species richness and
616 diversity along intertidal elevation gradients. *Helgol. Mar. Res.* **67**, 663–
617 674 (2013).
- 618 13 Scheffer, M. *et al.* Early-warning signals for critical transitions. *Nature*
619 **461**, 53–59 (2009).
- 620 14 Qi, Y., Xu, M. & Wu, J. Temperature sensitivity of soil respiration and its
621 effects on ecosystem carbon budget: nonlinearity begets surprises. *Ecol.*
622 *Modell.* **153**, 131–142 (2002).
- 623 15 Huang, J. P., Yu, H. P., Guan, X. D., Wang, G. Y. & Guo, R. X. Accelerated
624 dryland expansion under climate change. *Nat. Clim. Change* **6**, 166–171 (2016).
- 625 16 Berdugo, M., Vidiella, B., Sole, R. V. & Maestre, F. T. Ecological mechanisms
626 underlying aridity thresholds in global drylands. *Funct. Ecol.* **36**, 4–23 (2022).
- 627 17 van den Hoogen, J. *et al.* Soil nematode abundance and functional group
628 composition at a global scale. *Nature* **572**, 194–198 (2019).
- 629 18 Phillips, H. R. P. *et al.* Global data on earthworm abundance, biomass,
630 diversity and corresponding environmental properties. *Sci. Data* **8**, 136 (2021).
- 631 19 Maestre, F. T. *et al.* Plant species richness and ecosystem multifunctionality
632 in global drylands. *Science* **335**, 214–218 (2012).
- 633 20 Wieder, W. R., Cleveland, C. C., Smith, W. K. & Todd-Brown, K. Future
634 productivity and carbon storage limited by terrestrial nutrient availability.
635 *Nat. Geosci.* **8**, 441–444 (2015).
- 636 21 Liang, C., Amelung, W., Lehmann, J. & Kastner, M. Quantitative assessment of
637 microbial necromass contribution to soil organic matter. *Glob. Chang. Biol.*
638 **25**, 3578–3590 (2019).
- 639 22 Guerra, C. A. *et al.* Blind spots in global soil biodiversity and ecosystem
640 function research. *Nat. Commun.* **11**, 3870 (2020).
- 641 23 Hagedorn, F., Gavazov, K. & Alexander, J. M. Above- and belowground linkages
642 shape responses of mountain vegetation to climate change. *Science* **365**, 1119–
643 1123 (2019).
- 644 24 Soliveres, S. *et al.* Biodiversity at multiple trophic levels is needed for
645 ecosystem multifunctionality. *Nature* **536**, 456–459 (2016).
- 646 25 Stevenson, A. *et al.* Is there a common water-activity limit for the three
647 domains of life? *ISME J.* **9**, 1333–1351 (2015).
- 648 26 Moyano, F. E., Manzoni, S. & Chenu, C. Responses of soil heterotrophic
649 respiration to moisture availability: An exploration of processes and models.
650 *Soil Biol. Biochem.* **59**, 72–85 (2013).
- 651 27 Willig, M. R. Biodiversity and productivity. *Science* **333**, 1709–1710 (2011).
- 652 28 Liu, Y. R. *et al.* Global diversity and ecological drivers of lichenised soil
653 fungi. *New Phytol.* **231**, 1210–1219 (2021).
- 654 29 Lu, M. & Hedin, L. O. Global plant-symbiont organization and emergence of
655 biogeochemical cycles resolved by evolution-based trait modelling. *Nat. Ecol.*
656 *Evol.* **3**, 239–250 (2019).
- 657 30 Harris, J. Soil microbial communities and restoration ecology: facilitators
658 or followers? *Science* **325**, 573–574 (2009).

- 659 31 Montane, F., Romanya, J., Rovira, P. & Casals, P. Aboveground litter quality
660 changes may drive soil organic carbon increase after shrub encroachment into
661 mountain grasslands. *Plant Soil* **337**, 151–165 (2010).
- 662 32 Keiluweit, M., Gee, K., Denney, A. & Fendorf, S. Anoxic microsites in upland
663 soils dominantly controlled by clay content. *Soil Biol. Biochem.* **118**, 42–50
664 (2018).
- 665 33 Konapala, G., Mishra, A. K., Wada, Y. & Mann, M. E. Climate change will affect
666 global water availability through compounding changes in seasonal
667 precipitation and evaporation. *Nat. Commun.* **11**, 3044 (2020).
- 668 34 He, D. *et al.* Diversity and co-occurrence network of soil fungi are more
669 responsive than those of bacteria to shifts in precipitation seasonality in
670 a subtropical forest. *Soil Biol. Biochem.* **115**, 499–510 (2017).
- 671 35 Liu, S. E. *et al.* Phylotype diversity within soil fungal functional groups
672 drives ecosystem stability. *Nat. Ecol. Evol.* **6**, 900–909 (2022).
- 673 36 van der Heijden, M. G. A. *et al.* Mycorrhizal fungal diversity determines
674 plant biodiversity, ecosystem variability and productivity. *Nature* **396**, 69–
675 72 (1998).
- 676 37 Delgado-Baquerizo, M. *et al.* Decoupling of soil nutrient cycles as a function
677 of aridity in global drylands. *Nature* **502**, 672–676 (2013).
- 678 38 Maestre, F. T. *et al.* Grazing and ecosystem service delivery in global
679 drylands. *Science* **378**, 915–920 (2022).
- 680 39 Delgado-Baquerizo, M. *et al.* Changes in belowground biodiversity during
681 ecosystem development. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 6891–6896 (2019).
- 682 40 Zhang, K., Delgado-Baquerizo, M., Zhu, Y. G. & Chu, H. Space is more important
683 than season when shaping soil microbial communities at a large spatial scale.
684 *mSystems* **5**, e00783–00719 (2020).
- 685 41 Kettler, T. A., Doran, J. W. & Gilbert, T. L. Simplified method for soil
686 particle-size determination to accompany soil-quality analyses. *Soil Sci. Soc.
687 Am. J.* **65**, 849–852 (2001).
- 688 42 Fick, S. E. & Hijmans, R. J. WorldClim 2: new 1 - km spatial resolution climate
689 surfaces for global land areas. *Int. J. Climatol.* **37**, 4302–4315 (2017).
- 690 43 Zomer, R. J., Xu, J. & Trabucco, A. Version 3 of the global aridity index and
691 potential evapotranspiration database. *Sci. Data* **9**, 409 (2022).
- 692 44 Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G. & Jarvis, A. Very
693 high resolution interpolated climate surfaces for global land areas. *Int. J.
694 Climatol.* **25**, 1965–1978 (2005).
- 695 45 Fierer, N. *et al.* Cross-biome metagenomic analyses of soil microbial
696 communities and their functional attributes. *Proc. Natl. Acad. Sci. U.S.A.*
697 **109**, 21390–21395 (2012).
- 698 46 Ramirez, K. S. *et al.* Biogeographic patterns in below-ground diversity in New
699 York City’s Central Park are similar to those observed globally. *Proc Biol
700 Sci* **281** (2014).
- 701 47 Caporaso, J. G. *et al.* QIIME allows analysis of high-throughput community
702 sequencing data. *Nat. Methods* **7**, 335–336 (2010).

- 703 48 Edgar, R. C. Search and clustering orders of magnitude faster than BLAST.
704 *Bioinformatics* **26**, 2460–2461 (2010).
- 705 49 Edgar, R. C. UPARSE: highly accurate OTU sequences from microbial amplicon
706 reads. *Nat. Methods* **10**, 996–998 (2013).
- 707 50 Quast, C. *et al.* The SILVA ribosomal RNA gene database project: improved data
708 processing and web-based tools. *Nucleic Acids Res.* **41**, D590–D596 (2013).
- 709 51 Guillou, L. *et al.* The Protist Ribosomal Reference database (PR2): a catalog
710 of unicellular eukaryote small sub-unit rRNA sequences with curated taxonomy.
711 *Nucleic Acids Res.* **41**, D597–D604 (2013).
- 712 52 Nguyen, N. H. *et al.* FUNGuild: An open annotation tool for parsing fungal
713 community datasets by ecological guild. *Fungal Ecol.* **20**, 241–248 (2016).
- 714 53 Yang, G., Wagg, C., Veresoglou, S. D., Hempel, S. & Rillig, M. C. How soil
715 biota drive ecosystem stability. *Trends Plant Sci.* **23**, 1057–1067 (2018).
- 716 54 Pettorelli, N. *et al.* Using the satellite-derived NDVI to assess ecological
717 responses to environmental change. *Trends Ecol. Evol.* **20**, 503–510 (2005).
- 718 55 Horne, D. J. & Scotter, D. R. The available water holding capacity of soils
719 under pasture. *Agr. Water Manage.* **177**, 165–171 (2016).
- 720 56 Sala, O. E., Parton, W. J., Joyce, L. A. & Lauenroth, W. K. Primary production
721 of the central grassland region of the United States. *Ecology* **69**, 40–45 (1988).
- 722 57 Grizzetti, B., Langanova, D., Liqueste, C., Reynaud, A. & Cardoso, A. C.
723 Assessing water ecosystem services for water resource management. *Environ.*
724 *Sci. Policy* **61**, 194–203 (2016).
- 725 58 Helalia, A. M. The relation between soil infiltration and effective porosity
726 in different soils. *Agr. Water Manage.* **24**, 39–47 (1993).
- 727 59 Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A. & Nosalewicz, A. Soil porosity
728 and water infiltration as influenced by tillage methods. *Soil Tillage Res.*
729 **89**, 210–220 (2006).
- 730 60 Schmidt, M. W. *et al.* Persistence of soil organic matter as an ecosystem
731 property. *Nature* **478**, 49–56 (2011).
- 732 61 Jackson, R. B. *et al.* The ecology of soil carbon: pools, vulnerabilities, and
733 biotic and abiotic controls. *Annu. Rev. Ecol. Evol. Syst.* **48**, 419–445 (2017).
- 734 62 Sinsabaugh, R. L. *et al.* Stoichiometry of soil enzyme activity at global
735 scale. *Ecol. Lett.* **11**, 1252–1264 (2008).
- 736 63 Ekenler, M. & Tabatabai, M. A. β -Glucosaminidase activity as an index of
737 nitrogen mineralization in soils. *Commun. Soil. Sci. Plan.* **35**, 1081–1094
738 (2004).
- 739 64 Bell, C. W. *et al.* High-throughput fluorometric measurement of potential soil
740 extracellular enzyme activities. *J. Vis. Exp.* **81**, e50961 (2013).
- 741 65 Heimann, M. & Reichstein, M. Terrestrial ecosystem carbon dynamics and climate
742 feedbacks. *Nature* **451**, 289–292 (2008).
- 743 66 Campbell, C. D., Chapman, S. J., Cameron, C. M., Davidson, M. S. & Potts, J.
744 M. A rapid microtiter plate method to measure carbon dioxide evolved from
745 carbon substrate amendments so as to determine the physiological profiles of
746 soil microbial communities by using whole soil. *Appl. Environ. Microbiol.* **69**,

- 747 3593–3599 (2003).
- 748 67 Bloem, J., Hopkins, D. W. & Benedetti, A. *Microbiological methods for*
749 *assessing soil quality*. (CABI, 2005).
- 750 68 Fraser, F. C. *et al.* On the origin of carbon dioxide released from rewetted
751 soils. *Soil Biol. Biochem.* **101**, 1–5 (2016).
- 752 69 Dacal, M., Bradford, M. A., Plaza, C., Maestre, F. T. & Garcia-Palacios, P.
753 Soil microbial respiration adapts to ambient temperature in global drylands.
754 *Nat. Ecol. Evol.* **3**, 232–238 (2019).
- 755 70 Yuan, J. *et al.* Predicting disease occurrence with high accuracy based on
756 soil macroecological patterns of Fusarium wilt. *ISME J.* **14**, 2936–2950 (2020).
- 757 71 Revelle, W. psych: procedures for psychological, psychometric, and
758 personality research. *R package v 2.3.3* (2022).
- 759 72 Filzmoser, P., Maronna, R. & Werner, M. Outlier identification in high
760 dimensions. *Comput. Stat. Data An.* **52**, 1694–1711 (2008).
- 761 73 Fong, Y. *et al.* chngpt: estimation and hypothesis testing for threshold
762 regression. *R package v 2022.4–6* (2021).
- 763 74 Hastie, T. gam: generalized additive models. *R package v 1.20* (2020).
- 764 75 Xun, W. B. *et al.* Specialized metabolic functions of keystone taxa sustain
765 soil microbiome stability. *Microbiome* **9**, 35 (2021).
- 766 76 Zhang, J. *et al.* Water availability creates global thresholds in
767 multidimensional soil biodiversity and functions,
768 <<https://doi.org/10.6084/m9.figshare.20004335>> (2023).
- 769 77 Kottek, M., Grieser, J., Beck, C., Rudolf, B. & Rubel, F. World map of the
770 Koppen-Geiger climate classification updated. *Meteorol. Z.* **15**, 259–263 (2006).
- 771
- 772

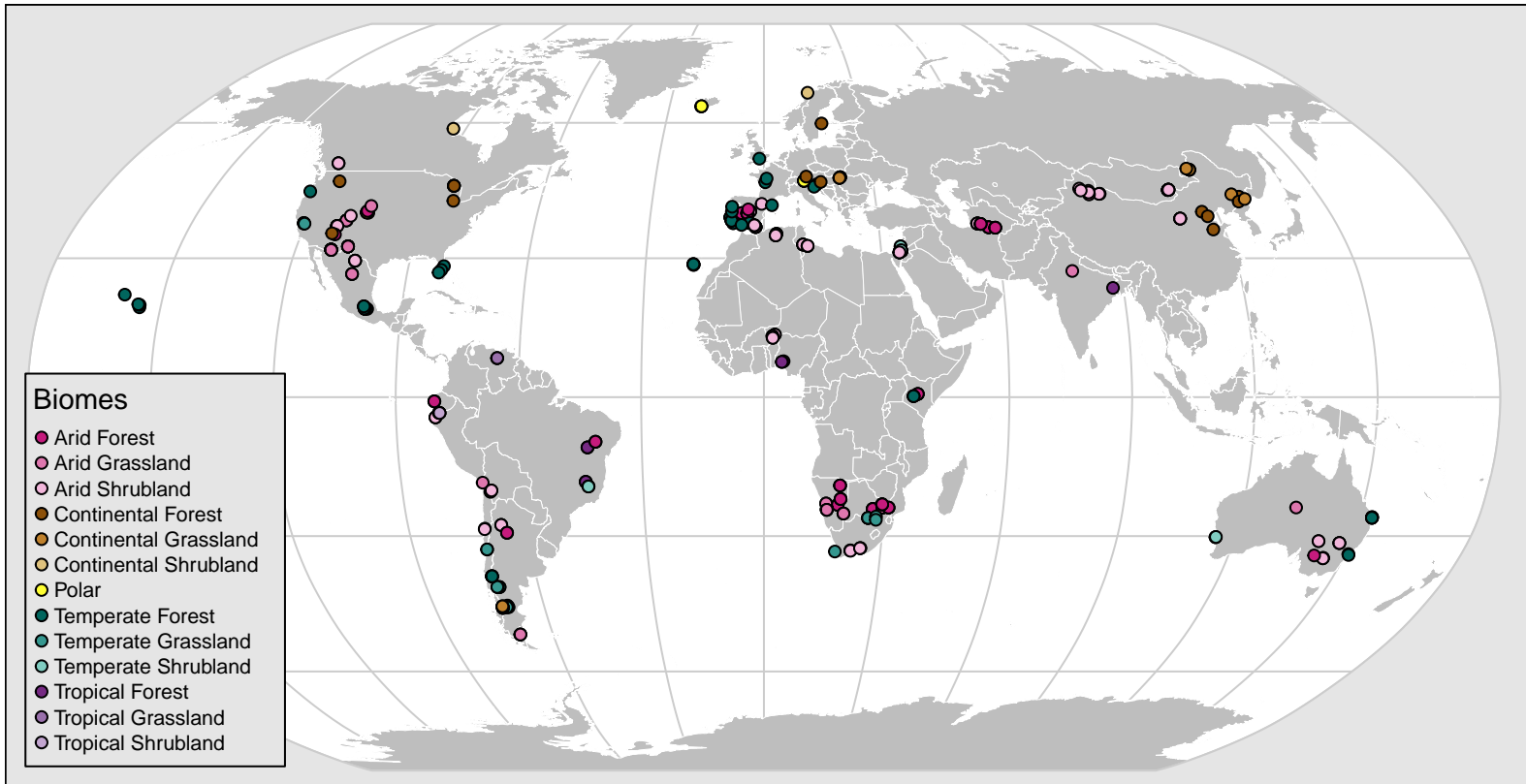
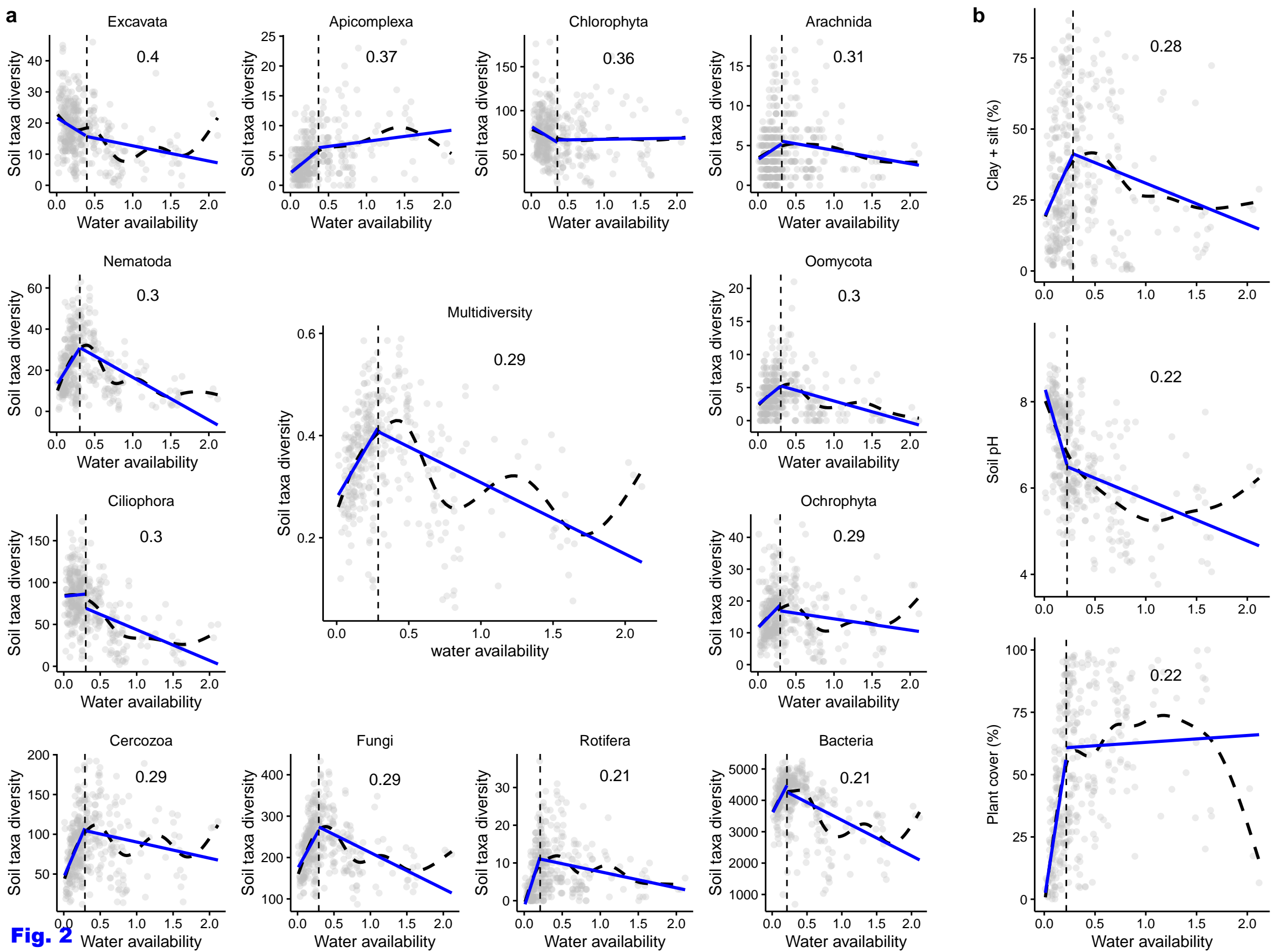


Fig. 1



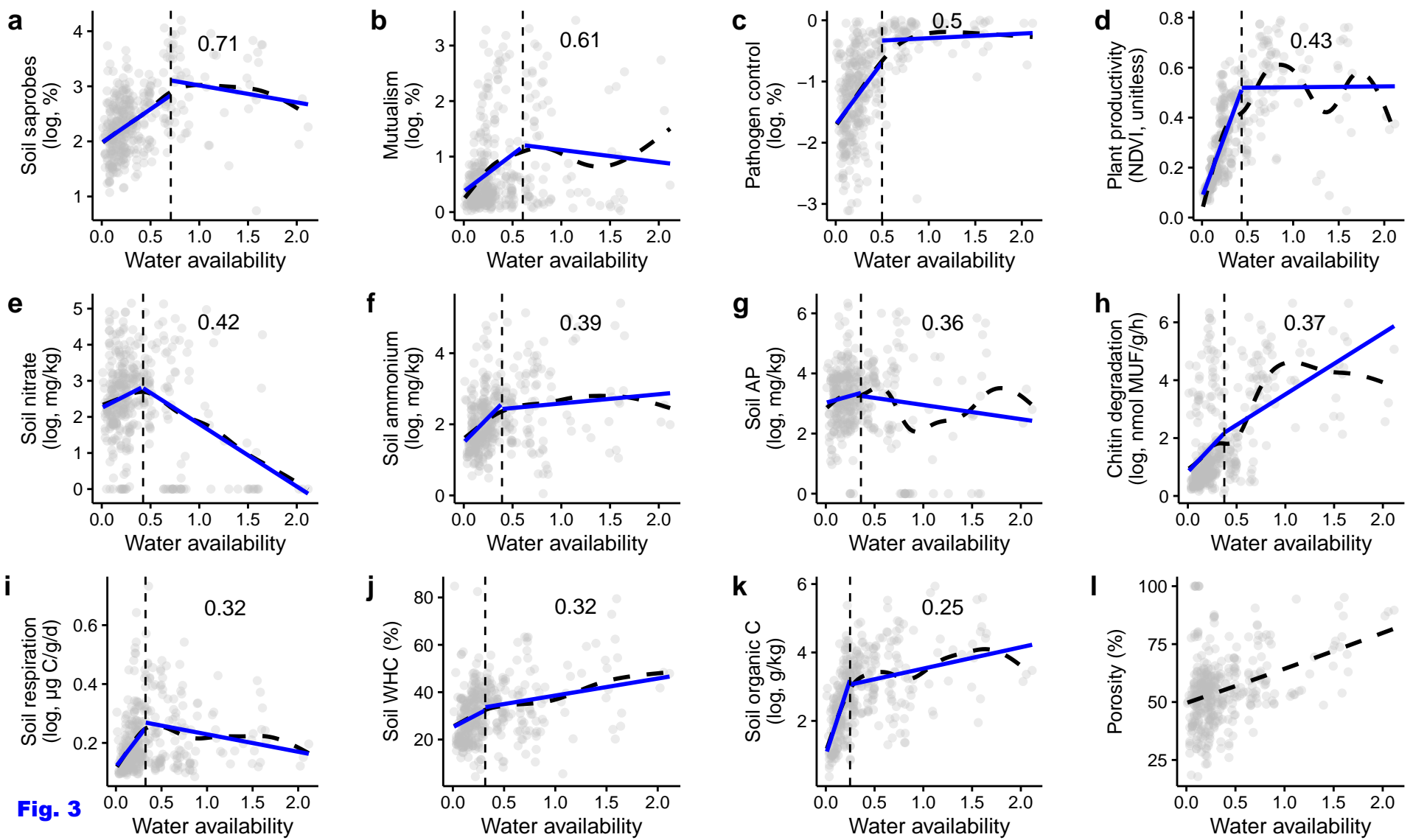


Fig. 3