

# Global patterns of geo-ecological controls on the response of soil respiration to warming

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## Article

**Keywords:** Temperature Sensitivity, Soil Properties, Vegetation Traits, Plant Growth Conditions, Soil Development

**Posted Date:** February 24th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-147557/v1>

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1 **Global patterns of geo-ecological controls on the response of soil respiration to warming**

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5

6 **Abstract**

7 **While soil respiration is known to be controlled by a large range of biotic and abiotic**  
8 **factors, its temperature sensitivity in global models is largely related to climate**  
9 **parameters. Here, we show that temperature sensitivity of soil respiration is primarily**  
10 **controlled by interacting soil properties and only secondarily by vegetation traits and**  
11 **plant growth conditions. Temperature was not identified as a primary driver for the**  
12 **response of soil respiration to warming. In contrast, the non-linearity and large spatial**  
13 **variability of identified controls stress the importance of the interplay among soil,**  
14 **vegetation and climate parameters in controlling warming responses. Global models**  
15 **might well predict current soil respiration, but not future rates because they neglect the**  
16 **controls exerted by soil development. Thus, to accurately predict the response of soil**  
17 **respiration to warming at the global scale, more observational studies across**  
18 **pedogenetically diverse soils are needed rather than focusing on the isolated effect of**  
19 **warming alone.**

20

21 **Background**

22 With implemented climate policies struggling to limit global warming to an average of less  
23 than 1.5 °C<sup>1</sup>, elucidating the response of an adapting ecosphere to warming is more and more

24 important. Understanding soil C dynamics is key to this because it directly determines a large  
25 portion of future net greenhouse gas (GHG) emissions from terrestrial ecosystems<sup>2</sup>.  
26 Soils are considered net sinks for C with current net sequestration estimated at 1 Pg C yr<sup>-1</sup><sup>3</sup>.  
27 This is only a minor part of the continuous exchange of C between soil and atmosphere due to  
28 C input to soils through plants and release of C through soil respiration, approximately balanced  
29 at annual fluxes of 58 - 80 Pg C yr<sup>-1</sup><sup>4-6</sup>. Rising global temperatures are expected to lead to  
30 significantly higher decomposition rates of soil C and thus CO<sub>2</sub> release from soils<sup>7,8</sup>, largely  
31 because of more energy available for microbial decomposer communities<sup>9</sup>. However, despite  
32 its importance, the response of soil C to warming is still one of the great uncertainties in global  
33 carbon cycling<sup>10</sup>. Great uncertainties are related to the effect of warming on vegetation, C  
34 input<sup>11</sup> across different soil depths<sup>12</sup>, microbial responses<sup>13</sup>, and estimates for losses of soil C  
35 the arctic plus high latitudes<sup>14</sup> and tropical plus low latitudes<sup>15</sup>.  
36 While the temperature sensitivity of soil carbon has been long studied<sup>10,16</sup>, only now ecosystem  
37 models begin to implement mechanistic controls of microbial soil respiration in response to  
38 climate and soil changes<sup>17,18</sup>. One issue is that soil properties, often crucially related to subsoils,  
39 are hidden from air and space borne sensing techniques that do not “see” soils. Therefore,  
40 statistical models are needed to better represent relationships between microscopic and  
41 macroscopic processes, especially on broader scales<sup>19,20</sup>. Furthermore, most of our mechanistic  
42 understanding of soil processes and warming is derived from studies in temperate zones; their  
43 numbers simply dwarf the number of studies in boreal and tropical ecosystems (see Figures S1  
44 and S2). Due to the nature of small-scale studies with often homogenous soil and environmental  
45 properties, a holistic, global assessment on factors controlling soil respiration, except for basic  
46 variables that integrate various processes at once (i.e. clay content) has not been done yet<sup>16</sup>.  
47 Soil is not mechanistically represented in global ecosystem models, but is rather given a mostly  
48 budgetary function. Thus, future global soil greenhouse gas emissions might be critically

49 misrepresented under changing environmental conditions. For example, global climate and  
50 ecosystem models<sup>21,22</sup> dealing with warming focus on GHG fluxes from environments where  
51 climatic and hydrological barriers are the key controls to limit C decomposition<sup>23</sup>. However,  
52 these climate and hydrology driven, geochemically speaking “young”, soil systems do not  
53 represent soil conditions found for the largest part of globally relevant soil C stocks<sup>24</sup>. The  
54 majority of soil C is stored in geochemically more complex and weathered soil systems, where  
55 soils have developed over millennia and the biosphere adapted to warmer conditions over  
56 millions of years of evolution<sup>25</sup>. Hence, soils in every (geo-)climatic zone will likely show very  
57 different responses in respirations to warming due to their different, soil type dependent,  
58 properties and drivers<sup>26</sup>. To the best of our knowledge, previous models of soil  $Q_{10}$  took the  
59 average air temperature as main predictor for soil  $Q_{10}$ .<sup>27-29</sup> Thus, the global representation of  
60 soils and GHG emissions from them with their drivers and controls are not well represented in  
61 earth system models (ESMs) and  $Q_{10}$  is still treated as an average value over all climate zones  
62 and state-of-the-art in CMIP5 models to consider temperature sensitivity in soil<sup>29-32</sup>. By using  
63 highly averaged values of temperature sensitivity of soil C<sup>28,33-36</sup> that do not represent the  
64 underlying processes<sup>16</sup>, or by focusing on selected climatic drivers, current earth system and  
65 climate models unintentionally neglect the variability of crucial biogeochemical factors  
66 altering the response of soils to climate forcing<sup>37</sup>. Doing so introduces large biases and  
67 uncertainties in global estimates of future C emissions from soils.

68 Here, we brought together large and small-scale controls that have been identified as key  
69 variables to explain the soil respiration response to warming - expressed as soil  $Q_{10}$  - at the  
70 global scale and used machine learning techniques to identify the most important groups of  
71 explaining variables for soil  $Q_{10}$ . More specifically, we combined experimental results with a  
72 large database on climate, vegetation and soil related parameters (further called *best data*  
73 approach) as proxies of soil respiration influencing factors under warming<sup>38,39</sup> (Table S3).

74 While  $Q_{10}$  of soil respiration is not a mechanistic depiction of soil C response, it can be  
75 interpreted as a phenomenological response of multiple instantaneous processes that differ  
76 across geo-climatic and land use settings<sup>38,39</sup> and is widely used in global scale ecosystem  
77 models. We compiled 3400 observations from 560 soil warming studies conducted from 1971  
78 to 2018 with incubation lengths of several days to more than three years from all major climate  
79 and land use combinations (see methods & Figure S2). For our analyses, we concentrated on  
80 climate zones in which rich plant-soil interactions occur and excluded regions with bare soils  
81 (polar and non-polar (semi-)deserts and high alpine environments) for which not enough data  
82 to train models and/or global maps of independent predictors were available. Then, we (i) built  
83 linear and non-linear predictive models for soil  $Q_{10}$ , (ii) derived the relative importance of the  
84 derived groups of explaining variables for SRRW and (iii) determined the changing importance  
85 of the identified controls in different climate systems and land use zones using partial  
86 dependence analyses (Figures 1 & 2). To assess the validity of our interpretation and the  
87 robustness of our models, we have repeated i-iii by using only predictors of SRRW derived  
88 from global datasets, further referred to as the *generalized data* approach (Table S4 & Table  
89 S6).

90

## 91 **Results & Discussion**

### 92 *Predicting soil $Q_{10}$ and its controls*

93 Our model satisfactorily predicted soil  $Q_{10}$  across all included systems for both the *best data*  
94 and the *generalized data* approach (Figures 1a & S3a), showing to the best of our knowledge,  
95 for the first time how the temperature sensitivity of heterotrophic soil respiration is driven by  
96 a combination of soil properties, vegetation and climate interactions at the global scale.  
97 Similarly to previous assessments of soil  $Q_{10}$  at the regional scale<sup>40</sup>, non-linear model  
98 approaches ( $R^2 = 0.18 - 0.46$ ; RMSE 0.58 - 0.72) greatly outperformed linear models ( $R^2 =$   
99 0.07 - 0.08; RMSE 0.76 - 0.77) (Table S6). Both the *best data* and *generalized data* model

100 approaches performed similarly in explaining the variability in temperature sensitivity of soil  
101 respiration ( $R^2 = 0.46$ ) and with reasonable uncertainty (relative RMSE = 24 %). Only a relative  
102 small part of soil  $Q_{10}$  was directly controlled by plant growth conditions (11.6%) as well as  
103 evapotranspiration and precipitation (12.6%). In contrast, a much larger share of soil  $Q_{10}$   
104 variability was controlled by soil properties (63.1%) (Figure 1b). Interestingly, climate and  
105 vegetation variables were more intercorrelated and their effects on soil  $Q_{10}$  were not clearly  
106 separable (Table S3).

107  
108 [Figure 1 about here]

109  
110 *Global patterns of controls on soil  $Q_{10}$*

111 Our analyses also revealed an extremely high variability in the controlling factors for soil  
112 respiration (Figure 1c). Vegetation and climate related parameters like growth conditions and  
113 evapotranspiration had a strong influence at both extreme ends of their respective range of  
114 values, which represent climatic extremes; As a general trend, climate was a strong control at  
115 lower temperatures, low precipitation or higher evaporation (Figures 1c, 2). This is likely  
116 related to the lack of mineral stabilization of C in these colder climate zones<sup>41</sup> leading to a  
117 faster response of microorganisms to warming, and hence a decomposition of labile C once  
118 temperature barriers are released<sup>42</sup>. Notably, temperature was not a separate dominant control  
119 on SRRW and climatic variables in general exert little influence in environments with more  
120 moderate climate; moreover, temperature ceases to influence soil  $Q_{10}$  in warmer climate zones.  
121 In contrast, a wide range of biotic and abiotic soil variables controlled the variability of soil  
122  $Q_{10}$  across their full range of values, resulting in the observed high heterogeneity. This  
123 dominance of soil variables is most likely because of the variety of parent materials that soils  
124 develop from and the various stages of weathering across the globe that affect plant growth and  
125 C stabilization. In cold climates, soils show low reactivity due to climatic barriers to chemical

126 soil weathering<sup>16</sup>. Plant litter, and not microbially processed or mineral associated C, is often  
127 the main source of energy for microorganisms under these cold conditions. In temperate  
128 climates, soils have generally higher chemical reactivity and high C stabilization potential,  
129 thereby diversifying potential C sources for microorganisms. This diversification of energy  
130 sources can lead to very variable competitive strategies driving carbon use efficiency<sup>43</sup> and  
131 thus soil  $Q_{10}$ <sup>42</sup>. In tropical climates, chemical weathering has depleted many soils of reactive  
132 minerals and reduced C stabilization potential, leading to a reduction in the variety of C  
133 resources.

134 Hence, strategies for an efficient recycling of nutrients from litter back into plants are  
135 prevailing<sup>26,44</sup>. The implementation of all identified controls in our model resulted into a  
136 spatially highly variable map of soil  $Q_{10}$  (Figure 2a,b) and a similarly diverse map of relative  
137 uncertainty of prediction (Figure 2c,d). More specifically, in arctic and boreal environments,  
138 where temperature is a major barrier for decomposition of labile C, soil  $Q_{10}$  was particularly  
139 high across all major land use systems. In contrast, soil  $Q_{10}$  was highly variable in temperate  
140 zones where local soil development drives C stabilization and thus responsiveness to warming.  
141 Lastly, soil  $Q_{10}$  was generally lowest in tropical environments where soils are deeply weathered  
142 and C accessibility is driven by litter quality. Deviations from this general pattern were tied to  
143 local variations in climatic, topographic and biogeochemical soil conditions (Table S9). Our  
144 uncertainty map (Figure 2c,d) shows high spatial variability especially in data poor regions of  
145 the (sub)tropics or in regions with highly diverse soil landscapes (temperate and tropical  
146 zones). We explain this with the fact that in data poor regions the model cannot be trained to  
147 the same degree as in data-rich regions due to a lack of data and precision for both response  
148 and independent variables. In regions of highly developed soils, our results point at the  
149 importance of considering local soil development and land use history for predicting SRRW,  
150 because these can differ greatly from one geo-climatic region to the next leading to varying

151 model complexity and strength of predictors (see figure 1) that is not fully captured at the global  
152 scale. In summary, our analyses allowed for predicting global patterns of soil Q<sub>10</sub> with  
153 reasonable uncertainty at a much higher accuracy and spatial variability than comparable  
154 approaches using climatic and vegetation variables alone<sup>27,28,40,45</sup> across major climate zones  
155 in which forests, grasslands and agricultural land use appears. Nevertheless, a larger share of  
156 variability in soil Q<sub>10</sub> remained unexplained (about 55%). We relate this lack of identifiability  
157 to the coarse spatial and temporal resolution of global key datasets, where information on local  
158 heterogeneity is lost, paired with a lack of accurate data from data poor regions (i.e. mountains,  
159 boreal zones, wetlands, tropics). Furthermore, global studies and predictions are in parts driven  
160 by completely different parameters than comparable regional studies, due to the different  
161 resolution and data availability<sup>46</sup>. A large number of local to regional scale controls on soil Q<sub>10</sub>  
162 and microbial decomposition processes exist (i.e. land management) that cannot be represented  
163 currently through proxy variables at the global scale<sup>39</sup>.

164  
165 [Figure 2 about here]

#### 166 *CO<sub>2</sub> release from soils in the decades to come*

167 Our study showed much higher and more variable temperature sensitivity of respiration than  
168 comparable ecosystem-level assessments<sup>27</sup>. Soil Q<sub>10</sub> predicted by our model was on average  
169  $33 \pm 10 \%$  higher than compared to soil Q<sub>10</sub> in climate driven models<sup>28</sup>. Our results are  
170 consistent with, and can help explain, the predicted reduced uptake of C in soils by the end of  
171 the 21<sup>st</sup> century<sup>47,48</sup>. As has been demonstrated before<sup>49</sup>, boreal and temperate climate zones of  
172 the northern hemisphere showed increased C release from soils with changing temperature and  
173 precipitation while soils of the southern hemisphere showed only limited responses and tropical  
174 soils even less. However, based on our results, we would predict that in colder environments,  
175 warming will create over time a more reactive soil matrix, similar to those found in temperate  
176 climates. Examples for the expected changes in arctic soils are for example, higher rock-



177 derived nutrient release due to (bio-) chemical weathering, higher potential to stabilize carbon  
178 with minerals, thicker soils for higher water retention capacity and larger rooting zones<sup>50-52</sup>. It  
179 is thus likely that in many of these changed future soils of arctic, antarctic or alpine  
180 environments, plant productivity will increase, C stabilization through various mineral related  
181 physico-chemical mechanisms<sup>53</sup> will improve and microbial communities will respond to the  
182 changed climatic conditions with, for example, higher carbon use efficiency<sup>43</sup>. Greening and  
183 weathering are likely to compensate some of the projected soil C loss from thawing and  
184 regressing permafrost<sup>54</sup> losses through additional C sequestration and create new terrestrial C  
185 sinks in higher latitudes. However, recent studies show<sup>36</sup> that it is unreasonable to assume that  
186 these processes can fully compensate for the additional release of C from soils. Plant growth is  
187 limited by more than atmospheric parameters, and weathering leading to nutrient release or C  
188 stabilization potential is slow and on decadal timescales<sup>55</sup>. Warming in the next decades could  
189 lead to an additional C release from soil that is equal to all other current anthropogenic C  
190 emissions.

191 A warming climate, however, will ultimately lead to lower SRRW in boreal zones in the long  
192 term, as plant-soil systems become more adapted to warming<sup>56</sup> with arctic soil systems  
193 becoming more similar to boreal or even temperate systems if climate change is progressing as  
194 predicted<sup>57</sup>. Predicting these contrasting trends of soil Q<sub>10</sub> in changed soil landscapes requires  
195 earth-system models to incorporate soil development trajectories as a control for future C fluxes  
196 and account correctly for the carbon flux between soil and atmosphere<sup>58</sup>. Indeed, in order to  
197 estimate C fluxes further into the future, a more mechanistic approach is needed that includes  
198 processes like soil formation (i.e. accelerated soil formation in arctic due to warming and  
199 increased weathering) or soil degradation (i.e. in the tropics due to land use change and erosion)  
200 to accurately predict the future warming response of these dynamic systems.

201  
202 **Take home message - A call for action**

203 Our results illustrate how complex the interplay and strengths of controlling factors for soil Q<sub>10</sub>  
204 can be at global scales. First, using a large range of independent variables to predict soil Q<sub>10</sub> in  
205 heterogeneous ecosystems, we confirm that controls on soil C responses to climate change are  
206 drastically different between climate zones and environmental settings, limiting the  
207 transferability of experimental and mechanistic knowledge on soil processes across geo-  
208 climatic zones. Second, almost all variables showed spatially varying influence on soil Q<sub>10</sub>,  
209 meaning that soil Q<sub>10</sub> is highly non-linear and multifactorial. Lastly, from poles to the equator,  
210 temperature has not been identified as the main driving factor for soil Q<sub>10</sub>. While temperature  
211 was certainly a limiting and controlling factor for biological activity in high latitudinal  
212 environments, soil Q<sub>10</sub> was increasingly stronger related to biogeochemical and physical soil  
213 conditions than to warming *per se* in mid and lower latitudes. Thus, large changes to the soil C  
214 cycle will occur through a warming induced feedback loop that is more strongly controlled by  
215 changing soil parameters and development due to better conditions for chemical weathering  
216 than by temperature itself. Our study, focusing on soil development related variables shows  
217 which key controls have to be considered in ESMs besides warming to understand and predict  
218 a changing terrestrial C sink versus source by the end of the 21<sup>st</sup> century. Lastly, improving our  
219 mechanistic understanding of the effects of developing soil characteristics in different climate  
220 zones and ecosystems, especially in tropical regions, is required before soil respiration  
221 responses to warming can be accurately projected into the future.

222

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480  
481 **Acknowledgements**

482 Further financial support has been given by: ETH Zurich and the German Research Foundation  
483 (DFG, Project No. 387472333). Special thanks goes to Heather Maclean for language  
484 proofreading.

485  
486 **Author contributions**

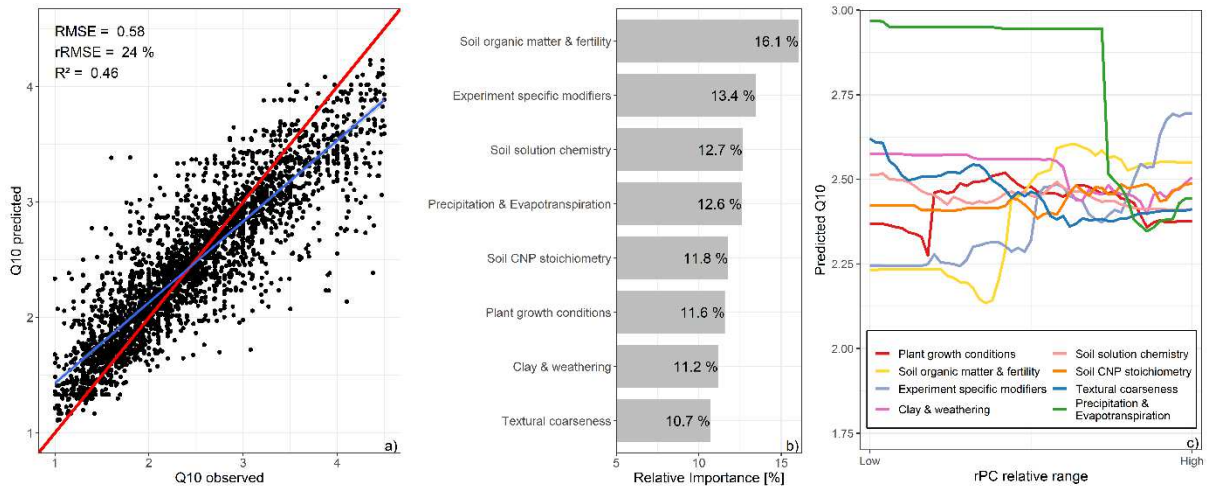
487 SD designed the research. DH conducted the data assembly and statistical analyses. DH and  
488 SD processed the data. All authors interpreted the data and contributed to the writing of the  
489 paper.

490  
491 **Supplementary Information**

492 Supplementary Information, including source data information, a documented and annotated R  
493 code of all applied statistics as well as a database containing all input data files is linked to the  
494 online version of the paper at [www.nature.com/nature](http://www.nature.com/nature).

495  
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497 **Figures**  
 498

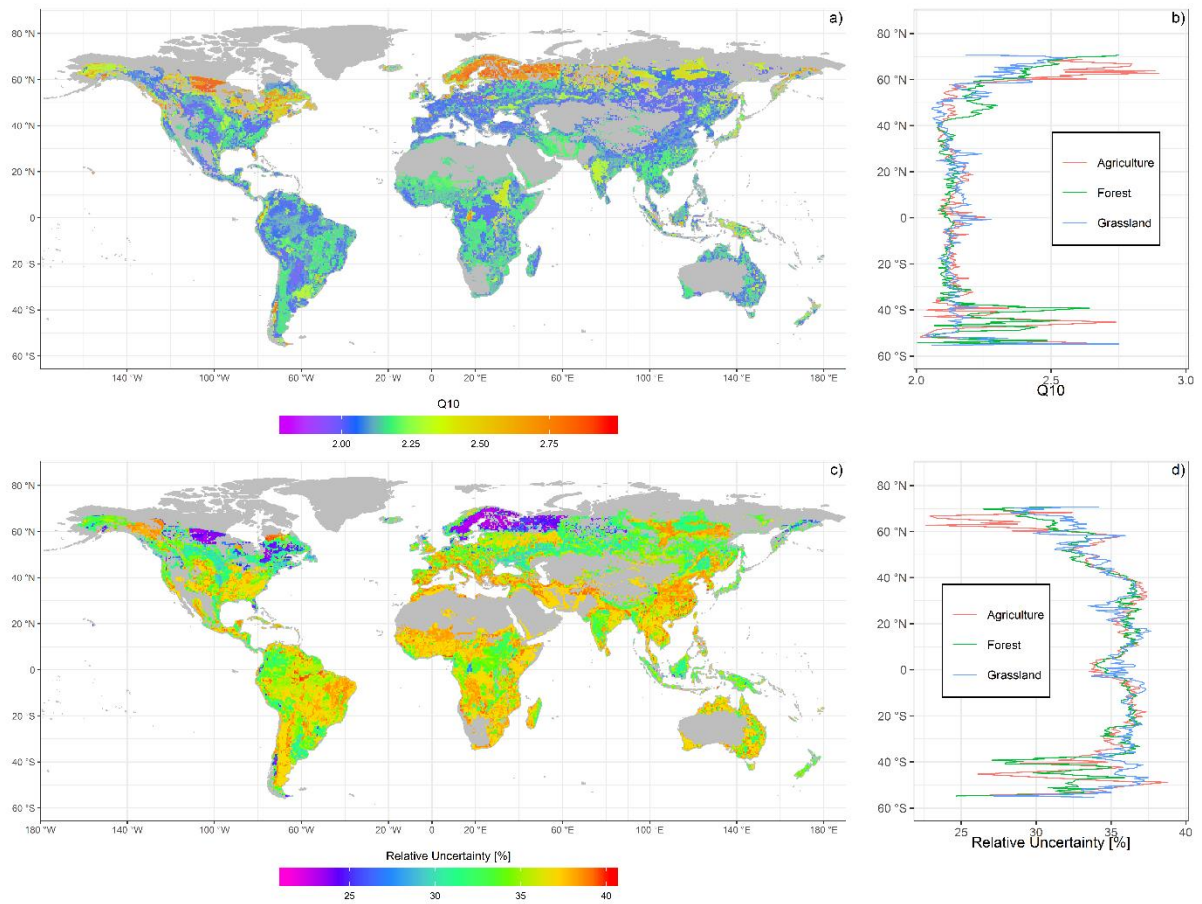


499

500 **Figure 1.** Predictions for soil  $Q_{10}$ , expressed as  $Q_{10}$  of soil respiration, (panel a, best data approach, random forest  
 501 model) show a good fit across the complete data range. An assessment of the relative importance of rPCA derived  
 502 variables (panel b) shows the dominance of the sum of soil parameters on the prediction over climate and  
 503 vegetation related and experiment specific modifiers. Partial dependence plots (panel c) illustrate the variable  
 504 effect of identified controls on averaged soil  $Q_{10}$ .



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**Figure 2.** Map of the predicted average soil  $Q_{10}$  for terrestrial, non-desert environments (a), and the averaged

510

latitudinal  $Q_{10}$ -pathway for different major land-use types (b), aggregated at 0.25° latitudinal resolution, and the

511

corresponding distribution of relative uncertainty (c & d) (see methods section “Global soil  $Q_{10}$  mapping for

512

details and uncertainty).

513

514 **Online only methods section**

515 **Statistical analysis. Basics.** Statistical analysis was performed in R<sup>59</sup> Version 3.4.1 with  
516 additional packages (Table S8). For all statistical tests, a significant level of  $p < 0.05$  was used.  
517 A documented and annotated R code of all applied statistics as well as a database containing  
518 all input data.

519  
520 **Database assembly and pre-processing.** Global  $Q_{10}$  data of soil basal respiration was  
521 collected from existing scientific databases<sup>60</sup> and published laboratory and field studies (for a  
522 full overview of all included studies, see supplementary data file “Q10\_Database“ and  
523 “Q10\_Database References”). The biggest part of soil  $Q_{10}$  values were taken from the Global  
524 Database of Soil Respiration Data (SRDB)<sup>60</sup>, together with information about the experiment  
525 temperatures. All compiled information from the database were counterchecked with the  
526 reported values of the original reference and duplicate  $Q_{10}$  values for the same temperature  
527 ranges were removed to keep only the temperature range related to the original study.  
528 Furthermore, web-based search engines like Google Scholar, ResearchGate or Web of Science  
529 were examined with catchphrases like “(laboratory/field measured) temperature sensitivity of  
530 SOC decomposition” or “soil  $Q_{10}$  (for laboratory/field experiments)” and added to our  
531 database. In total, data from 67 laboratory studies and from 493 field studies were compiled  
532 located between 68 °N to 43 °S and 176 °E to 156 °W (Fig. S1).

533 In our compiled database, soil  $Q_{10}$  data in these studies were taken from temperature ranges -5  
534 - +50 °C, conducted from 1971 to 2018 with incubation lengths of several days to more than  
535 three years. We constrained our study to observations of topsoil samples (weighted averages  
536 for 0-30cm soil depth) and excluded studies that targeted autotrophic soil respiration. Reported  
537  $Q_{10}$  in these studies represent the average soil  $Q_{10}$  during the length of the experiment and are  
538 considered as soil basal respiration.

539 The included soil  $Q_{10}$  data was tested for fulfilling normal distribution using the Shapiro-Wilk  
540 Normality Test<sup>61</sup> and for fulfilling homogeneity of variances with the Fligner-Killeen Test<sup>62</sup>.  
541 Comparability of soil  $Q_{10}$  and to avoid introducing potential biases was tested in several ways.  
542 To identify experiment specific influencing factors (measures taken by the experimentalist, see  
543 figure A2) we used one-way Analysis of Variances (ANOVA)<sup>63,64</sup> and in case of significant  
544 rejection of the statistical requirements for ANOVA, using the Kruskal-Wallis Test<sup>65</sup>, to test  
545 for differences in soil  $Q_{10}$  between (i) lab and field studies, (ii) studies reporting explicitly  
546 heterotrophic respiration vs. mixed respiration where remnants of autotrophic respiration  
547 cannot be excluded, (iii) sequential vs. parallel warming of soils and (iv) explicit pre-treatments  
548 of the samples vs. non-treated samples. Results of this test indicated only minor differences  
549 between the above compared studies (Figure S2). Furthermore, we evaluate the effect size of  
550 the applied Kruskal-Wallis test pairs to show the strength of the analysed relationship of  
551 statistical significant differences between sub-groups of the database. We computed the effect  
552 size as follows<sup>66</sup>:

$$\eta^2(H) = (H - k + 1)/(n - k) \quad (1)$$

555 where H is the test statistic, n is the number of observations and k is the number of groups in  
556 the model.

557 The analyses revealed that among all pairs, only grouping by climate zone has a strong effect  
558 on  $Q_{10}$  differences between subgroups. Other pairings, including the division of lab vs. field  
559 derived  $Q_{10}$  did not show a significant effect size (Table S2). Additionally, we tested our model  
560 performance on a data-rich and environmentally diverse region (Continental Europe,  
561 Scandinavia and the British Isles) using the same independent predictor variables and model  
562 structures as for the global approach, but predicting SRRW with only subsets of the data: one  
563 prediction where we use both field and lab data (n = 786) combined, and one prediction each  
564 where we used only lab (n = 237) or field data (n=549). Our results (Figure S3) show that no

565 difference in model performance or potential bias can be observed based on the origin of parts  
566 of our data. Hence, we continued with a unified dataset for all other analyses, but included  
567 these experiment specific criteria in our later modelling approach as a confining factor (see  
568 methods section “statistical analyses”, results in tables S3-S5 and figure 1).

569 From the compiled  $Q_{10}$  data, values  $<1$  and  $>4.5$  were excluded from further analysis, as (i) we  
570 want to represent natural conditions that follow current paradigm, namely that soil basal  
571 respiration increases with incubation temperatures<sup>27</sup> and (ii) that  $Q_{10} >4.5$  are the result of the  
572 decomposition of large amounts of poorly decomposed, isolated organic matter (litter, roots<sup>67</sup>)  
573 in litter layers or de-frosting former permafrost soils. Furthermore, including these values  
574 would lead to inaccuracy in calculation with exponential equations<sup>68</sup>. These criteria led to the  
575 exclusion of 8% of the compiled observations (262 observations), resulting in a total of 3413  
576 observations remaining across all major land use (grassland, cropland, forest and wetland) for  
577 the boreal, temperate, subtropical and tropical climate zones of the northern and southern  
578 hemisphere used in this study (Figure S2).

579  
580 **Included independent variables.** To analyse the influence of soil properties, vegetation and  
581 climate parameters on  $Q_{10}$ , five climatic and vegetation as well as eight soil parameters were  
582 selected as independent variables. These parameters were used for all further statistical  
583 analyses. Where available, we used high-resolution local data taken from the included studies  
584 directly, resulting in our “*best data*” dataset. Where local studies did not include all the desired  
585 independent variables, global datamaps and satellite remote sensing data were used to fill gaps  
586 in climate and soil properties (Table S3). Note that values of pH  $<3$  were replaced with a pH =  
587 3, due to the fact that soils with a pH  $< 3$  do not occur in the ecosystems investigated in this  
588 study<sup>69</sup> and are an artefact created during the assembly of the original dataset (best data  
589 approach: 9 datapoints replaced; generalized data approach: 0 datapoints replaced). Note that  
590 these global datamaps of independent controls show variable spatial resolutions ranging from

591 250m - 0.5° and represent averages over 1-30 years (see Table S1 for details). To assess the  
592 potential impact of spatially highly variable data in our analyses, we used the data in the highest  
593 available resolution and did not transformed the data to match resolutions. In addition, to  
594 represent potential controls that result from the interaction of soil parameters with climate and  
595 vegetation, a series of interaction terms were included. Organic carbon/organic nitrogen/total  
596 phosphorus ratios were included to represent effects of nutrient stoichiometry in soils<sup>70</sup>. Clay  
597 content/mean annual temperature ratios were included to represent soil weathering and changes  
598 in mineral surface area<sup>71</sup>. Base saturation/clay content and potential cation exchange capacity  
599 (CEC)/clay content as well as base saturation/CEC ratios were used to assess mineral surface  
600 charge effects. Base saturation / pH ratios were used to assess soil acidity effects. Mean annual  
601 precipitation (MAP) / Potential evapotranspiration (PET) and PET/normalized vegetation  
602 index (NDVI) ratios were used to assess plant productivity as well as precipitation and  
603 evapotranspiration related effects<sup>72</sup>.

604 The resulting dataset of independent variables is not inclusive for all experimentally identified  
605 controls (i.e. variability of microbial decomposers and their strategies are not included)<sup>73,74</sup>.  
606 However, key criteria for their selection in our modelling exercise was availability as global  
607 datasets to fill data gaps of the metadata of the included warming studies. Furthermore, all  
608 included variables stand in a causal relationship for controlling biological processes and C  
609 cycling between soils and atmosphere and vary across a large range of possible values (Table  
610 S1) that represent the majority of conditions in which biological processes take place in soils  
611 (i.e. very acidic, to very basic, very low and very high temperatures, etc.). This compilation of  
612 empirical data was selected to bridge a crucial gap from experimental finding to  
613 implementation of soil processes into earth system models.

614  
615 **Statistical analysis. Rotated principal component analysis.** To increase the identifiability of  
616 larger groups of controls and to reduce the number of independent variables that are

617 autocorrelated, we used rotated principal component analysis (rPCA), performed for both our  
618 *best data* model building (Table S3) as for our *generalized data* approach (Table S4) and  
619 interpreted the loading of each principal component according to their underlying relevance as  
620 a controlling factor for SRRW. To minimize multicollinearity effects, the Variance Inflation  
621 Factor (VIF) was estimated for all independent predictor variables and maximal VIF was  
622 eliminated until all independent variables possessed a  $VIF < 5$ . As rotation method and to  
623 minimize multicollinearity, variance maximizing (VARIMAX) was used. The selection of an  
624 optimal number of principal components was done on the basis of the Kaiser-Guttman rule and  
625 limited to principal components with an Eigenvalue  $> 1$ . This resulted in 8 rotated principal  
626 components (rPC), identifying the eight most important groups of explaining variables for  
627 SRRW (Table S3).

628  
629 **Statistical analysis. Predictive modelling.** To build and identify the best model for predicting  
630 soil  $Q_{10}$  and using the results of the rPCA analyses, regression modelling was conducted  
631 including four different linear and four different non-linear regression types. Linear regression  
632 included models without (LM) and with (LEAPS) stepwise selection<sup>75</sup> as well as models such  
633 as least angle regression (LARS)<sup>76</sup> and Elastic Net (ENET)<sup>77</sup> that use a penalizing term to the  
634 regression coefficients of those variables with minor influence on the prediction<sup>78</sup>. Non-linear  
635 regressions included the tree- and rule-based (=representing the path of partitioned  
636 regression(s) by using distinct if-then rules to create prediction models)<sup>77</sup> models random forest  
637 (RF)<sup>79</sup> and boosted tree model (BOOSTED)<sup>80</sup>, as well as model bagged tree (BAGGED)<sup>81</sup> and  
638 cubist (CUBIST)<sup>82</sup>. All models, except for the LM linear regression and the BAGGED model,  
639 have built-in feature selection procedures and were tuned individually, to increase the accuracy  
640 and control the complexity of the models<sup>78</sup>. As part of the tuning process, the following steps  
641 have been taken: LEAPS models were trained for the maximal number of variables. For  
642 penalizing models, penalty terms for feature reduction (i.e. lowering the effect of less important

643 variables on the final linear equation) varied between 0 and 0.1 in 0.01 steps. The RF models  
644 were constrained by setting the maximum number of allowed trees to 1000. The number of  
645 included predictors were set to the maximum number of possible predictors divided by three<sup>83</sup>.  
646 BOOSTED were trained with a minimum of 10 to a maximum of 100 trees with 1-7 nodes, a  
647 shrinkage factor of 0.01 or 0.1 and a maximum size of 5. To train the CUBIST models, 1-9 by  
648 2 neighbours and 1, 5, 10, 50, 75 and 100 communities were used. For all models, Monte-  
649 Carlo-cross-validation<sup>84</sup>, with 100 repeated data resamples and a ratio of 80 % training to 20  
650 % validation data were used to assess the uncertainty of model structures and prevent over-  
651 fitting. Root mean square error of cross-validation (RMSE) and R<sup>2</sup> were estimated for all tuned  
652 models and used to analyze the residual variance and accuracy of the models<sup>85</sup> and as a criterion  
653 for ranking model performance (Table S5). For an easier interpretation of the uncertainty of  
654 estimated SRRW, relative root means square error (rRMSE) was estimated by dividing the  
655 absolute error by the global mean of Q<sub>10</sub>. Random Forest regressions resulted in the best model  
656 performance within one-standard error of minimal RMSE<sup>86</sup> and were used for all further  
657 analyses of variable importance. Furthermore, residual plots for the global best model (Figure  
658 4S) and the three data-rich examples of continental Europe (Figure S3) were created. All  
659 residual plots show random patterns, indicating a good fit of the used random forest models for  
660 the global and the European models.

661  
662 **Statistical analysis. Assessing variable importance.** To estimate the influence of the  
663 identified rPC variables for predicting Q<sub>10</sub>, we assessed variable importance using permutation  
664 variable importance measurements (PVIM) through the variable importance tool implemented  
665 in R caret package<sup>87</sup> for the model with the highest accuracy and prediction quality (Random  
666 Forest RF). Briefly, to assess the error of prediction in the model, the PVIM method calculates  
667 the mean square error for every given regression tree with out-of-bag estimates<sup>79,88</sup>. The  
668 resulting measure of variable importance of RF models represents the influence of the predictor

669 variables on the model results<sup>89</sup>. For better comparability all independent controls in our  
670 models<sup>90</sup>, the included independent rPC control variables were normalized on a scale of 0-  
671 100% to represent relative importance for the model outcome.

672  
673 **Statistical analysis. Partial dependency of controls.** Partial dependence analyses using the R  
674 package pdp<sup>91</sup> were used to test effects between predicted Q<sub>10</sub> and independent controls across  
675 the whole range of possible values that were included in the RF modeling. Briefly, the method  
676 results in a statement about the global relationship of an independent variable to the predicted  
677 across the whole range of all potential values by removing and averaging out the effect of other  
678 independent controls and isolating the effect of the targeted independent variable(s)<sup>80</sup>. In  
679 contrast to the assessment of the relative importance of an independent variable overall, partial  
680 dependence analyses and their visual representations (partial dependence plots, PDP) can  
681 illustrate the average marginal effect of one or more independent variables on the predicted  
682 outcome of a machine learning model<sup>80</sup> across a specific range of values. For example, a PDPs  
683 can show whether the relationship between the predicted variable and an independent control  
684 is linear, monotonic or complex<sup>92</sup>. The shape and knickpoints of the PDP curve can then be  
685 used to interpret and identify areas where an independent has a particular strong and direct  
686 effect on the predicted, and where its control is rather indirect, for example through influencing  
687 other independent variables. For simpler interpretation of the PDPs x-axis from low to high,  
688 the curves of rPCs with dominant negative loading (best data approach: rPC1, rPC7; Table S3)  
689 were reversed.

690 As an example in our study, PDPs illustrate that precipitation and evapotranspiration has a  
691 weak effect and control on Q<sub>10</sub> at lower ranges, but a stronger effect at higher ones (Figures  
692 1c). As the loading of our rPC variable “precipitation and evapotranspiration” is not mixed  
693 with other controls (Table S3, S4), the PDP allows a direct interpretation of the variable’s



694 value. In contrast, temperature has a complex relationship to the predicted soil  $Q_{10}$ , mostly  
695 through affecting plant growth conditions, experimental setup and weathering.

696  
697 **Statistical analysis. Global soil  $Q_{10}$  mapping.** A map of the global distribution of soil  $Q_{10}$ ,  
698 expressed as  $Q_{10}$  of soil basal respiration and a corresponding map of the relative uncertainty  
699 of prediction (Figure 2) was derived using our *best data* rPCA structure and scores (Table S4)  
700 and a RF model with the included global climate, vegetation and soil datasets (Table S1) that  
701 we used to build our *generalized data* model of soil  $Q_{10}$ . Using the datasets of the *generalized*  
702 *data approach*, we calculated factor maps based on the primary input variables for our 8 rPC  
703 scores for each according raster cell before using them to calculate a spatial explicit map of  
704 global soil  $Q_{10}$ . In consequence, the resulting map corresponds in quality to the results of our  
705 RF model results without experiment specific modifiers as explanatory variables (Table S7;  $R^2$   
706 = 0.42, RMSE 0.61). For this mapping exercise at a global scale, input variables were run at a  
707  $0.5^\circ$  resolution and later aggregated at  $0.25^\circ$  latitudinal resolution to derive a mean  $Q_{10}$  value  
708 separately for major land use systems at the respective latitude. Land use was derived using the  
709 2015 ESA CCI-LC<sup>93</sup> land cover maps (300m original resolution) and summarized to  
710 agriculture, forest and grassland systems. We excluded those areas from our prediction where  
711 (i) data in any of the required predictors was missing, (ii) land use was different to the  
712 aggregated land use systems listed above or (iii) areas where located in climate zones which  
713 were not targeted by our model (polar and non-polar (semi-) deserts). Predictors that were  
714 available at a higher resolution were resampled using geostatistics to match a  $0.5^\circ$  resolution.  
715 The resulting map's averages shows significant differences for distinct USDA and WRB<sup>94</sup> soil  
716 orders across climate zones and land use systems (Table S9). To assess the uncertainty related  
717 to the creation of the map due to resampling of data and unexplained variability not captured  
718 by the rPC scores we run the model also at a finer resolved  $1 \text{ km}^2$  grid or those areas where  
719 input variables were available at this higher resolution. This analysis revealed an overall

720 uncertainty of our global soil Q<sub>10</sub> map averaging at 27.4 +/- 10 %. The corresponding map of  
721 relative uncertainty of prediction was built by displaying standard deviation/divided by the  
722 mean of prediction based on the results of our final random-forest model with standard  
723 deviation related to the range of possible predictions based on the build-up of the used decision  
724 tree after 500 model runs.

725

## 726 **Caveats**

### 727 *The “real” controls and the influence of experimental modifications*

728 The identification of variables for regression models, including their importance and  
729 dependency assessments, are highly dependent on the range in which the included variables  
730 can vary. In our global model design, we addressed this by including independent variables  
731 that vary across a large range of possible values in which biological processes take place and  
732 which represent the majority of conditions that can occur in soils (Table S1). To assess the  
733 validity of our interpretation and the robustness of our models, we repeated all statistical  
734 analyses that involve independent predictors by using data only derived from global datamaps,  
735 further referred to as the *generalized data* approach (Table S4 & Figure S3). An approach that  
736 excluded experiment specific modifiers (Table S7) generally yielded in less performance than  
737 fully parameterized models, but differences were marginal ( $R^2 = 0.03 - 0.42$ ; RMSE 0.61 -  
738 0.79). Together with our analyses of potential biases in the database that yielded negative  
739 results (Figure S2) this suggests that experimental and climatic conditions, if made comparable  
740 across larger gradients, do not exceed the control of soil variables on soil Q<sub>10</sub>.

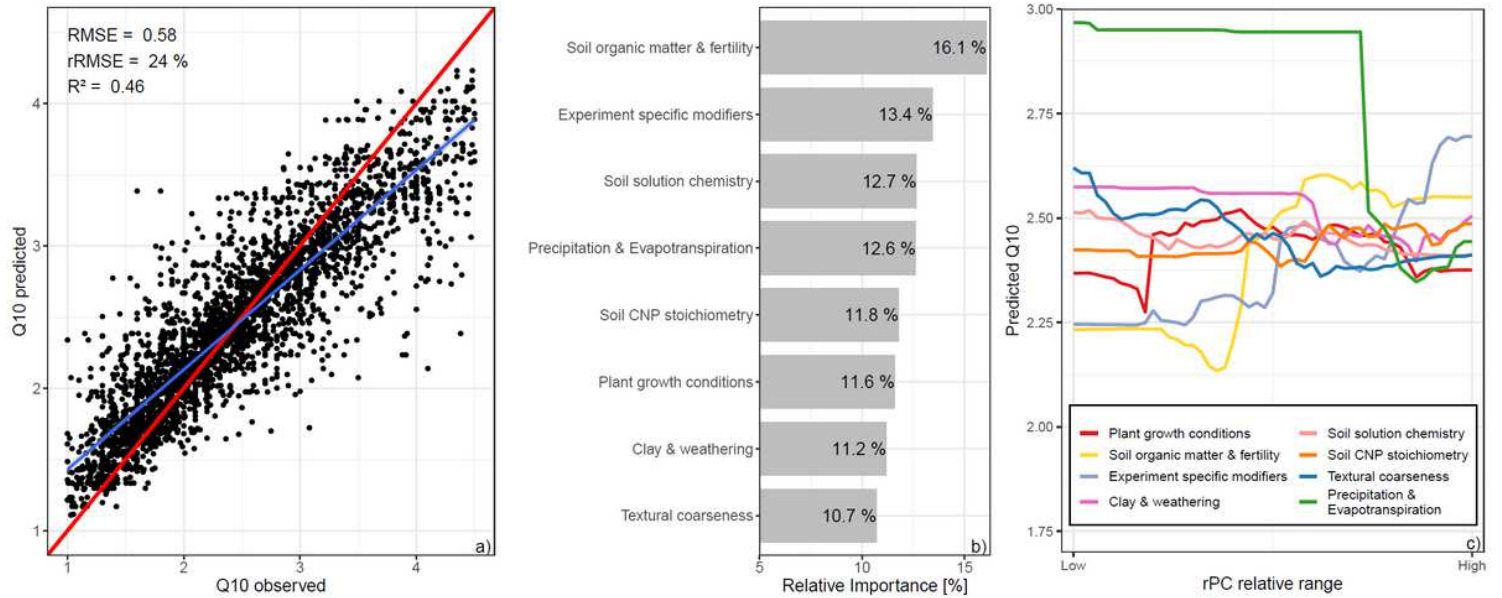
741

### 742 *Spatial autocorrelation*

743 Building our predictive models of soil Q<sub>10</sub> (Figures 1a 3Sa), we tested for and quantified spatial  
744 autocorrelation of modelled residuals using Moran I test<sup>95</sup>. Results indicated only a minor  
745 influence of spatial autocorrelation for all linear models (Moran I = ca. 0.3 for all models).

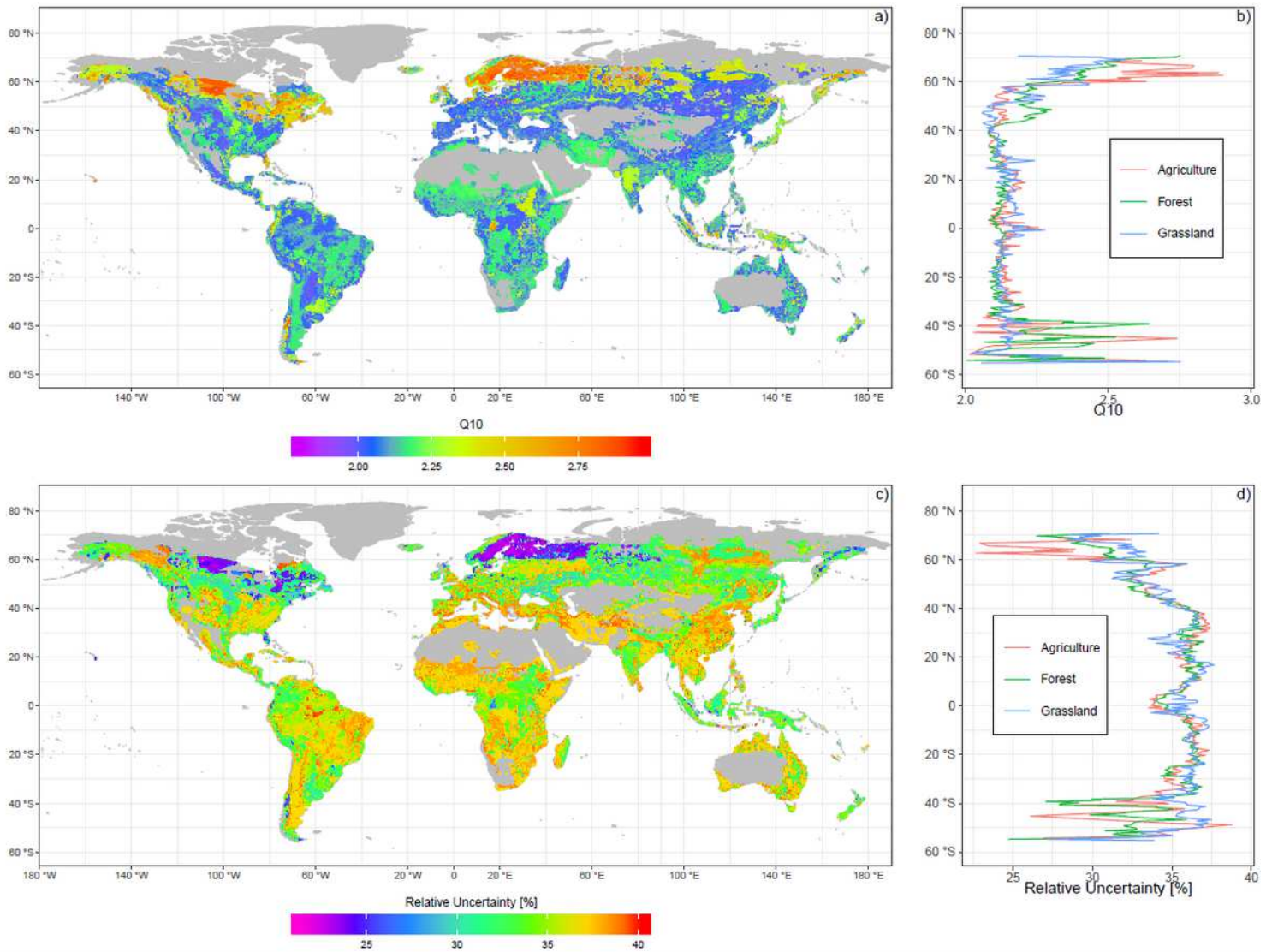
746 Further corrections taking into account spatial variability and the accuracy of geographic  
747 coordinates<sup>96</sup> in the modelling structure of the linear models showed no improvement. In  
748 combination with the good results of the machine learning models (Table S6 & S7), we  
749 interpret these results as supportive to our finding that the relationship of soil Q<sub>10</sub> and the  
750 included independent controls are primarily non-linear.

# Figures



**Figure 1**

Predictions for soil Q10, expressed as Q10 of soil respiration, (panel a, best data approach, random forest model) show a good fit across the complete data range. An assessment of the relative importance of rPCA derived variables (panel b) shows the dominance of the sum of soil parameters on the prediction over climate and vegetation related and experiment specific modifiers. Partial dependence plots (panel c) illustrate the variable effect of identified controls on averaged soil Q10.



**Figure 2**

Map of the predicted average soil Q10 for terrestrial, non-desert environments (a), and the averaged latitudinal Q10-pathway for different major land-use types (b), aggregated at 0.25° latitudinal resolution, and the corresponding distribution of relative uncertainty (c & d) (see methods section “Global soil Q10 mapping for details and uncertainty”). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors

## Supplementary Files

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- [SupplementaryFiguresandTablesRev2.pdf](#)
- [SupplementarydataannexSRRWannotatedcodeanonimized.R.txt](#)

- [SupplementarydataannexSRRWDatabaseanonymized.xlsx](#)
- [SupplementaryQ10DatabaseReferences.pdf](#)