

1 **Title:**

2 Identifying knowledge gaps on simultaneous above- and belowground organism responses to global
3 change.

4

5 **Running title:**

6 Above-belowground global change

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22 invertebrates, vertebrates

23

24 **Abstract**

25 Global change affects all terrestrial organisms regardless if they live above or below the ground. Even
26 though they are strongly linked by various direct and indirect interactions, organisms can respond very
27 differently to global change stressors, due to different features of above- and belowground compartments.
28 Many different organism groups have shown declines in diversity, abundance or biomass which goes
29 hand in hand with the loss of important ecosystem services. However, to date, the extent to which above-
30 and belowground organisms are studied simultaneously in global change research has not systematically
31 been studied. This makes it difficult to assess knowledge gaps and research deficits in this area. Here we
32 present a systematic literature overview on well-covered research areas and knowledge gaps on how
33 global change stressors affect above- and belowground organisms in terrestrial ecosystems. We found an
34 underrepresentation of tropical areas and non-agricultural ecosystems, like wetlands and deserts. For
35 global change stressors we identified knowledge gaps on many aspects, including non-agricultural
36 pollutants, extreme weather events, and direct exploitation, while we overall observed a strong focus on
37 invertebrates compared to other organism groups. Many combinations of organism groups and stressors
38 were poorly or not at all covered. Our results regarding study design and focal biodiversity metrics
39 suggest a lack of studies investigating future scenarios as well as direct linkages of organism presence
40 with ecosystem functioning. Closing the knowledge gaps that we identified will be the key to lift our
41 knowledge from how single groups respond to global change to how whole communities and ecosystems
42 will be altered. This knowledge could not only significantly improve conservation measures but might
43 also offer relevant economic and societal benefits via agricultural advancements and provision of
44 ecosystem services.

45

46 **Introduction**

47 All terrestrial organisms are directly or indirectly affected by different kinds of biotic or abiotic stressors
48 (IPBES, 2019). Global change comprises many stressors like land use, climate change, pollution, or
49 biotic stressors (Jaureguiberry et al., 2022; Hald-Mortensen, 2023; Sala et al., 2000) all of which affect
50 biodiversity across the globe (Jaureguiberry et al., 2022; Hald-Mortensen, 2023; Pereira et al., 2024).
51 There are widespread patterns of biodiversity decline in response to global change stressors across many
52 taxa, for example insects (Sánchez-Bayo & Wyckhuys, 2019), vertebrates (Maxwell et al., 2016),
53 microbes (Wu et al., 2022) and plants (Midolo et al., 2019; Vellend et al., 2017). Each loss of species
54 might even be enhanced by the co-extinction of affiliated species (Koh et al., 2004). Biodiversity loss
55 goes hand in hand with the loss of ecosystem stability (Hautier et al., 2015) and important ecosystem
56 functions (Cardinale et al., 2012; Lefcheck et al., 2015; Soliveres et al., 2016) which are directly linked
57 to essential ecosystem services for humans like nutrient cycling, pollination, or pest control (IPBES,
58 2019).

59 To gain a comprehensive understanding of ecosystem functioning, it is necessary to look at different
60 organism groups which are driving the respective ecosystem functions (Soliveres et al., 2016). Common
61 examples are earthworms as indicators for nutrient cycling (Scheu, 2003; Z. Wang et al., 2026), plants
62 for primary production (Shaw et al., 2002), bees for pollination (Biesmeijer et al., 2006; Connelly et al.,
63 2015), predatory arthropods for agricultural pest control (Bianchi et al., 2006; Dainese et al., 2019) or
64 mycorrhizal fungi for plant growth (Wurzburger & Clemmensen, 2018). In recent years, research focus
65 in ecology has started to shift from investigating single ecosystem functions to simultaneously studying
66 multiple ecosystem functions (Balvanera et al., 2014; Delgado-Baquerizo et al., 2016) to more
67 comprehensively assess global-change impacts on ecosystems (Giling et al., 2019; Jing et al., 2015).

68 In ecological research, terrestrial ecosystems have been historically separated in two compartments and

69 therefore also two different study subjects: the aboveground and the belowground world (Bardgett,
70 2018). As a result, organisms inhabiting these different compartments were often studied independently
71 of each other (Cameron et al., 2019), including their specific focal ecosystem functions like
72 decomposition or pollination (Klein et al., 2006; Potapov et al., 2022). Studies on belowground
73 organisms are still underrepresented compared to aboveground studies, though they have experienced
74 increased attention in the past decades (Cameron et al., 2019; Geisen, Briones, et al., 2019; Geisen, Wall,
75 et al., 2019). This is also the case for studies that investigate interactions between both compartments
76 (Bardgett, 2018). Additionally, we know that above- and belowground biodiversity do not necessarily
77 match (Cameron et al., 2019). Despite these differences, above- and belowground compartments and
78 their organisms are closely linked by various direct and indirect interactions and interdependencies
79 (Bardgett & Wardle, 2010; Scheu, 2001; Wardle et al., 2004, 2005). For example, belowground
80 organisms play a major role in decomposition and the nutrient cycle (Parker, 2010; Potapov et al., 2022)
81 which is one of the determining factors of plant growth which in turn shapes habitats and resource
82 availability for aboveground organisms (Bardgett & Wardle, 2010). While some direct interactions, like
83 predation, can be more easily observed, more indirect ones are harder to quantify like the recruitment of
84 aboveground predators by plants enhanced by symbiotic belowground fungi (Rasmann et al., 2017). This
85 results in complex interaction systems between above- and belowground compartments, with multiple
86 different organisms and types of interactions being involved (Barber & Soper Gorden, 2015; Deyn &
87 Putten, 2005; Heinen et al., 2018).

88 These complex interaction systems can be altered by global change in multiple different ways. Climate
89 change, for example, has been shown to alter above-belowground food webs leading to changes in the
90 carbon cycle (Koltz et al., 2018; Manlick et al., 2024), while belowground invasion of earthworms was
91 reported to impact aboveground invertebrate communities (Jochum et al., 2022). Although above- and

92 belowground organisms are closely linked, their response to global change might differ as stressors can
93 alter the two compartments in different ways and intensities (Aguirrebengoa et al., 2020; E. Gao et al.,
94 2023; Le Provost et al., 2021), due to many differences in aspects like microclimate or structural
95 composition (Bardgett & Wardle, 2010; Van der Putten et al., 2001). Aboveground compartments are
96 expected to be differently affected by climate change than belowground compartments (García-García et
97 al., 2023), which could lead to imbalances between above- and belowground foodwebs (Thakur, 2020).
98 The same stressors can have different effects depending on the focal organism, ecosystem or habitat type
99 (Bartley et al., 2019; Le Provost et al., 2021; Cozim-Melges et al., 2024). Outside of ecological
100 experiments, in the real world, it is rarely just a single stressor that affects and alters ecosystems, but
101 multiple different stressors impacting systems via different mechanisms and with different intensities
102 (Orr et al., 2020). Depending on whether they act in isolation or combined with others, stressor impact
103 can vary (Rongstock et al., 2026). These challenges obstruct our understanding of how global change
104 stressors affect organisms, ecosystem functions and ecosystem services now and in the future.

105 Therefore, it is important to simultaneously study both above- and belowground organism responses to
106 global change stressors to gain a comprehensive and realistic picture of how global change affects
107 ecosystems (Cameron et al., 2019; Deyn & Putten, 2005). However, to date, the extent to which above-
108 and belowground organisms are studied simultaneously in global change research has not systematically
109 been studied although this subject has increased in attention rapidly. This makes it difficult to assess
110 knowledge gaps and research deficits in this area.

111 A common approach to address issues like this is the “systematic map” method (e.g., Chausson et al.
112 (2020), Mazor et al. (2018), Medeiros et al. (2024)), which follows a standardised protocol (Haddaway
113 et al., 2018b) to receive a comprehensive and representative subset of studies on a specific topic or
114 research area. Here, we conducted a “systematic map” literature search to identify the distribution of

115 research areas and knowledge gaps on how global change stressors affect above- and belowground
116 organisms (plants excluded) in terrestrial ecosystems. More specifically, we investigated the literature
117 focus and gaps regarding ecosystem types, global change stressor identity and combinations, taxonomic
118 groups, research approach (experimental vs. observational), biodiversity metrics studied. Our work
119 represents the first systematic assessment of how above- and belowground organisms are simultaneously
120 studied under global change and will help to focus future research efforts towards closing the knowledge
121 gaps to enable more comprehensively assessing global change impacts on the biodiversity and the
122 resulting functionality and stability of terrestrial ecosystems

123

124 **Material and Methods**

125 *Benchmark publications and search term*

126 To identify relevant peer-reviewed studies combining above- and belowground organisms under global
127 change stressors in terrestrial ecosystems, we conducted a systematic map based on the ROSES protocol
128 for systematic maps (Figure S1) (Haddaway et al., 2018b). We chose this protocol as it is commonly
129 used in the field of ecology to quantify knowledge distribution (Ashe-Jepson et al., 2024; Chausson et
130 al., 2020). We started by defining three key elements that must be included in our target studies:
131 aboveground organisms, belowground organisms, and at least one global change stressor. In this study,
132 the term “organism” does not include plants. Plants were excluded because an assignment to either above-
133 or belowground organisms is often unfeasible due to the above- and belowground linkage by plant shoot-
134 and root system. We selected 15 studies that composed a diverse and representative selection of targeted
135 studies to use them as benchmark publications (hereafter: benchmarks, Table S1). They were received
136 from basic web searches, or were already familiar literature to experts in this field. Search string creation
137 started by scanning titles, keywords and abstracts of all benchmarks for cooccurring and topic
138 distinguishing terms. All benchmarks included terms for investigated organisms, global change stressors
139 and specifically mentioned that above and belowground compartments were investigated. Therefore, we
140 also structured our search term in these three segments: organisms, global change stressors and above-
141 and belowground compartments. We started by integrating all search terms used in our benchmark
142 studies to the respective segments. Organism terms were in most cases based on the same taxonomic
143 level within certain groups. Invertebrates for example were most often mentioned on order level, while
144 vertebrates were most often mentioned on class or subclass level. Therefore, we added scientific and
145 common terms for all missing taxonomic groups on the respective levels. The same procedure was used

146 for functional group terms like “detritivore” or “pollinator”. Global change stressors were collected by
147 screening commonly used literature on global change effects on ecosystems (IPBES, 2019; Jaureguiberry
148 et al., 2022; Hald-Mortensen, 2023). Additional terms and synonyms for above- and belowground
149 compartments were obtained from basic web searches. This resulted in the final search string presented
150 in Table S2, which extracted all of our benchmarks. We conducted our literature search through the Web
151 of Science (WoS) service due to its common use in the field of literature reviews and meta analyses on
152 similar topics (Beaumelle et al., 2021; Côté et al., 2016; Jaureguiberry et al., 2022). Additionally, the
153 WoS free access and the ability to process long and complex search terms contributed to our choice. We
154 used the Web of Science Core Collection as the source database and selected publication title, keywords,
155 and abstract as searchable fields. We limited our search to studies that were published before 01.01.2025,
156 assigned to either the WoS category “Ecology” or “multidisciplinary sciences”, as all our benchmarks
157 were from one of these categories, and English language due to limited capacity. To exclude non peer-
158 reviewed studies and books, we considered only the WoS document types “Article” and “Review
159 Article”. Studies were extracted on January 29th, 2025. Additionally, we added four pre-screened studies
160 that fitted our inclusion criteria (Figure S1).

161 *Inclusion criteria and article screening*

162 For article screening, we defined inclusion and exclusion criteria for investigated organisms, global
163 change stressors, and study design (Table S3) based on the PICOS (**P**opulation, **I**ntervention,
164 **C**omparator, **O**utcome, **S**tudy design) schema (Hosseini et al., 2024; Pullin & Stewart, 2006), as it
165 reflects the structure of our target studies well. Population referred to the investigated organisms, and
166 had to include above- and belowground organisms from multiple genera or higher taxonomic levels.
167 Studies that only included aquatic organisms, plants or a single species were excluded, due to absence of

168 distinct above- and belowground organisms. At least one global change stressor or driver had to be used
169 as an explanatory variable to fulfil the inclusion criteria as intervention. No criteria were defined for the
170 comparator, as it was not relevant for our research question. For outcome, we did not define any criteria
171 either and included all possible outcomes, regardless of positive, negative or neutral effects of
172 explanatory variables. Considering study design, we could only consider studies that were published in
173 English. Studies on pure aquatic ecosystems were excluded due to incomparability with terrestrial
174 ecosystems. However, periodically or partially flooded ecosystems like swamps were included. Only
175 observational and experimental setups were included, while theoretical simulations, modelling studies,
176 and meta-analyses were excluded. Synthesis studies that combined data from different studies were
177 checked for co-occurring data with other studies from our literature dataset. In the case of co-occurring
178 data, we checked if the respective studies used different analyses or variables and thereby obtained unique
179 findings. Only synthesis studies with findings going beyond those of studies focusing on a smaller data
180 subset were accepted. Based on our defined criteria in the PICOS schema (Table S3), we screened all
181 studies from our literature search in three steps (title, abstract, full text) following the screening procedure
182 (Figure S1) proposed by Haddaway et al. (2018a). The number of accepted and rejected studies in each
183 step is shown in Figure S1. Screening was performed by only one person to avoid bias through different
184 interpretations of inclusion and exclusion criteria. At the full text screening stage, 14 studies out of 298
185 (6 %), which were not fully accessible for us, were excluded.

186 For all included studies, the following information was extracted: studied countries, ecosystem types,
187 organism groups, stressor aspects, biodiversity metrics, and study approach (Table S4). For a detailed
188 description of how this information was extracted and processed for analysis, please refer to the
189 supporting information.

190 **Results & Discussion**

191 *General findings*

192 In total we extracted 2963 studies through our Web of Science database search. After the full screening
193 process, we ended up with 178 accepted studies from 58 different journals (Figure S1; for the full list of
194 all 178 accepted studies, please refer to the supporting information). The most common journals were
195 “Agriculture ecosystems & environment” with 15 studies followed by “European journal of soil biology”
196 and “Pedobiologia” with 13 studies each. The earliest study from our dataset was published in 1993
197 (Figure 1a). Until 2007, only very few ($n = 13$) studies were published. From then on, the frequency
198 increased to about five studies per year. In 2015, there was a sudden increase to about ten studies per
199 year with an inclining trend up to 2025. This correlates with the rising awareness for ecosystem
200 multifunctionality in the literature (e.g., Balvanera et al. (2014), Delgado-Baquerizo et al. (2016), Jing et
201 al. (2015), Soliveres et al. (2016)). The only exceptions are the years 2020 to 2021 with fewer studies
202 compared to previous years, which could be an effect of the Covid-19 pandemic. Afterwards, an all time
203 high of 15 studies per year was reached in 2023 and topped by 22 studies in 2024.

204

205 *Geographical distribution*

206 The 178 studies were carried out in 45 different countries covering all continents (Figure 1c). The most
207 studied countries were the United States of America (29 studies; 16 %), Germany (19; 11 %), France
208 (14; 8 %), the United Kingdom (13; 7 %) and China (12; 7 %). Ten studies (6 %) were carried out in
209 greenhouses or laboratory setups and therefore not assigned to a country. Overall, North America and
210 Western Europe were the regions with the highest study density. By contrast, Africa (6 studies, 3 %) and
211 Arabia (no studies) seem to be relatively underrepresented. Most studies (80 %) took place in countries

212 with temperate or subtropical climates. Countries in the tropics were the focus of 19 % of studies and
213 two studies (1 %) took place in polar zones.

214 In comparison to the GDP per country assessed by the World Bank (2026) it becomes evident that
215 countries with high GDP were more often chosen as study locations than countries with lower GDP. Note
216 that our map in Figure 1c displays the country where the study took place, which may differ from the
217 country of funding. However, we assume a strong geographic correspondence of study location and
218 funding. We expect that research funding and focus will be closely linked to the GDP of the respective
219 country, leading to fewer studies in lower-income countries. This is likely to be one of the main reasons
220 why less than 20 % of studies from our dataset took place in the tropics, as many countries in the tropics
221 show a lower GDP than countries in temperate regions (*World Bank Open Data*, 2026). A general
222 underrepresentation of tropical regions in ecological studies was already observed by Collen et al. (2008)
223 and Clarke et al. (2017). Considering the versatile differences between temperate and tropical regions,
224 including seasonal change, or lack thereof, climatic and geographical conditions, it is evident that global
225 change impacts these regions differently (IPBES, 2019; IPCC, 2023). This increases the importance of
226 comprehensive research on global change in above-belowground systems in all parts of the world. This
227 underrepresentation of especially tropical regions is alarming as it can be assumed that these regions will
228 be ecologically and economically more vulnerable to global change than temperate regions (IPBES,
229 2019; IPCC, 2023).

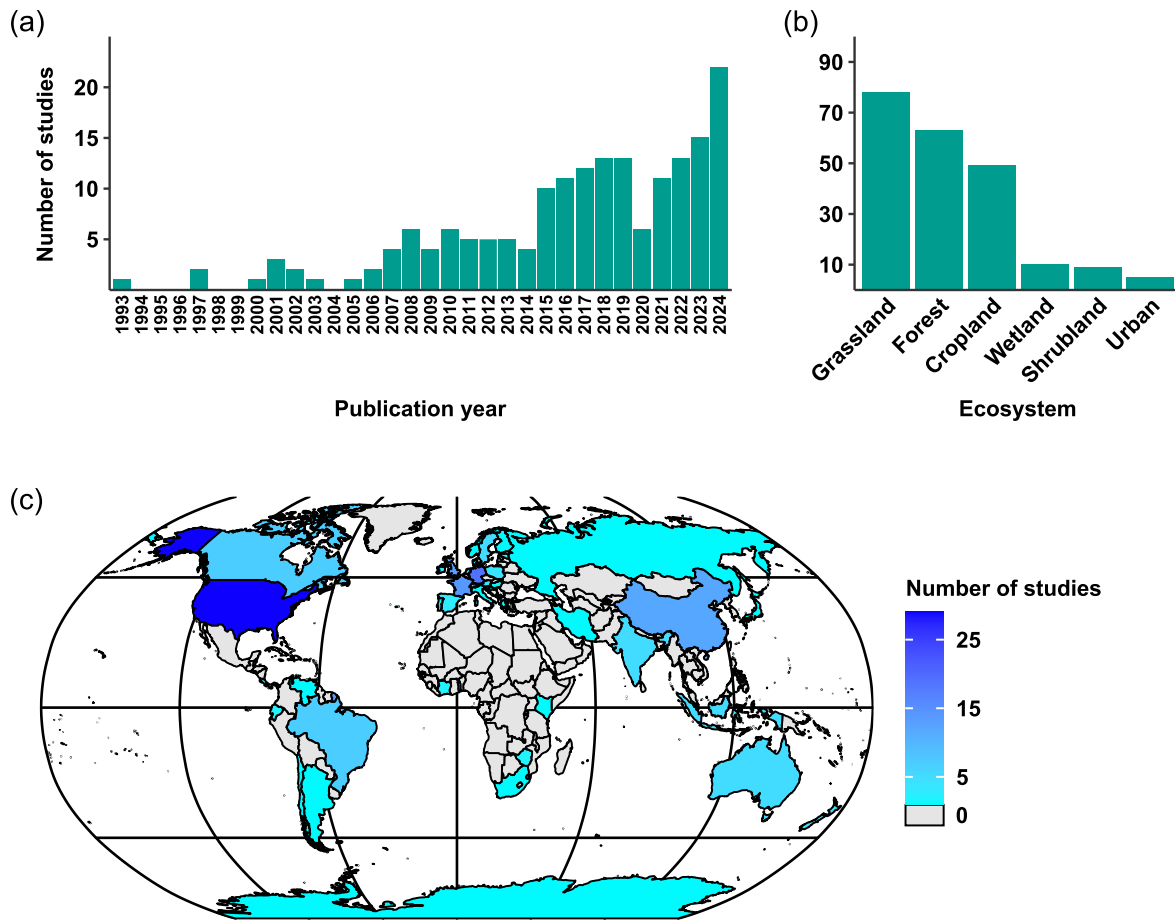
230 In our dataset, grasslands were the most-studied ecosystem with 79 (44 %) studies, closely followed by
231 forests (63, 35 %) and croplands (49, 28 %) (Figure 1b). Wetlands, shrublands, and urban ecosystems
232 were only studied 10 times or less (< 6 %) each and thereby show a clear separation to the three most-
233 studied ecosystems. We recorded no studies on desert ecosystems. Ecosystem coverage in our data
234 largely matches their global share of terrestrial area presented by Sayre et al. (2020). Note that our

235 definition of grasslands differs from Sayre et al. (2020) as we include all habitats that contain any form
236 of grassland, ranging from huge grasslands in the north of China (Bai et al., 2023; E. Gao et al., 2023; L.
237 Wang et al., 2019) to heterogeneous habitats like savannas (Chikorowondo et al., 2018) or small
238 grassland strips next to croplands (Jowett et al., 2024; Pelosi et al., 2024). Therefore, we assume an
239 estimated global land cover share of 40% by grasslands (Suttie et al., 2005), which matches with the
240 number of studies in grasslands from our dataset.

241 High land cover share will impact study ecosystem choice, however the aspects that have contributed to
242 these high land cover shares in the first place might be as relevant. One central aspect will be the
243 economic relevance, since all three most-studied ecosystems provide indispensable direct economic
244 benefits through goods like food, fodder, or wood (O'Mara, 2012; Suttie et al., 2005) and indirect benefits
245 provided by ecosystem services like pollination, CO₂ storage, or recreation (Bengtsson et al., 2019;
246 FOREST EUROPE, 2026). Wetlands, shrublands, urban and desert ecosystems contribute to or cover a
247 notable share of these ecosystem services (Gómez-Baggethun & Barton, 2013; N. T. Taylor et al., 2017;
248 Zedler & Kercher, 2005). However, they might not in all cases have comparable direct economic benefits.
249 This also contributed significantly to the conversion of wetlands to agricultural land (Fluet-Chouinard et
250 al., 2023; Rijksen & Persoon, 1991). In particular deserts are considered “low productivity” ecosystems
251 (Hadley & Szarek, 1981) which is associated with the negative connotations of the term “desertification”
252 in an ecological context (Le Houérou, 1996; UNCCD, 2026). As a result, deserts might be unappealing
253 study objects to researchers and funders. Additionally, many deserts are located in countries with a low
254 GDP, which were overall underrepresented as study countries. Regardless of the reasons, the lack of
255 knowledge on simultaneous above- belowground organism responses to global change represents a gap
256 that needs to be closed, since desertification will continue and more ecosystems will convert to desert
257 ecosystems (UNCCD, 2026). The same applies to urban ecosystems as their area will expand with

258 ongoing urbanization (United Nations, 2025). Therefore, it will become even more relevant to investigate
259 these systems to learn how to manage them and understand the underlying mechanisms of degradation
260 and potentially also restoration. Contrasting patterns can be observed for wetlands as their area is
261 shrinking making it all the more important to study them to prevent them from disappearing and maintain
262 their role in ecosystem function and service provision. In the context of global change, it is essential to
263 study a diverse selection of regions and ecosystems, as stressor identity and their respective impacts may
264 differ between them (Bowler et al., 2020).

265



266

267 **Figure 1.** Temporal and geographical coverage of studies investigating simultaneous above- and
 268 belowground organism responses to global change (total studies $n = 178$). **(a)** Number of published
 269 studies per year, retrieved from our literature search in the WoS core collection database. **(b)** Number
 270 of studies carried out per ecosystem type. Multiple ecosystems can be assigned to single studies. **(c)**
 271 Global distribution of studies on sovereign state level. This refers to sample and data origin not author
 272 or institutional affiliation. Multiple countries can be assigned to single studies. Darker colors indicate
 273 higher number of studies, while gray indicates countries without studies. Studies without direct
 274 connection to ecosystems (laboratory setups: $n=10$) are not displayed here.

275

276

277 *Stressors*

278 The most studied stressor category in our dataset (Figure 2a) was land use with 131 (74 %) studies,
279 followed by biotic stressors (63; 30 %), climate change (54; 35 %) and pollution (9; 5 %). The rate of
280 increase of studies on land use, biotic stressors and climate change seemed to be similar until 2014. From
281 2014 on, the number of studies on land use showed a much stronger rate of increase compared to the
282 number of studies on biotic stressors and climate change, which remained stable. For studies dealing with
283 pollution, only one study was recorded until 2008. After that, the number of studies only increased
284 slightly with approximately one study every two years.

285

286 To better understand why each category was investigated how often and in which combinations, it is
287 necessary to look at the respective aspects which form the stressor categories (Figure 2c). Land-use
288 consisted of the largest number of aspects, while biotic stressors and climate change shared the same
289 amount of aspects in our dataset, which is, as expected, reflected in total studies per category. The two
290 most investigated stressor aspects were habitat transformation (29 %) and eutrophication (33 %), both
291 assigned to land use. They are very often investigated together with other aspects, irrespective of stressor
292 category. Water availability and temperature change, both associated with climate change, were the
293 second most studied aspects with inclusion in 22 % of studies from our dataset. They are most often
294 studied simultaneously, while being more rarely studied together with other aspects compared to habitat
295 transformation and eutrophication. Biotic stressor aspects have only a few co-occurrences. Instead, they
296 are more frequently investigated in combination with aspects of land use. Pollution only consists of a
297 single aspect. Across categories, the least often studied aspects were mulching (3 %), pests (3 %) and

298 storms (1 %).

299

300 Although we observe a strong focus on land use, we still find many land-use aspects that were not often
301 studied (Figure 2c). For example mulching, burning, and urbanization were each only considered by less
302 than 6 % of the total studies. This fragmentation of land use into many diverse stressor aspects is likely
303 to be a result of the many different forms of land use, which are also closely linked to the respective
304 ecosystems. Urban and cropland ecosystems, for example, are both a result of anthropogenic land use
305 (Hobbs et al., 2009), yet they are very different ecosystems with different stressor aspects playing key
306 roles, like light pollution in urban ecosystems and pesticides in cropland (Geiger et al., 2010; Jones &
307 Leather, 2012; Moretto & Francis, 2017; Venter et al., 2016). In particular, agriculture involves a variety
308 of stressor aspects that are closely linked with the type of agricultural use (McLaughlin & Mineau, 1995).
309 Given the complexity of land-use aspects and their possible interactions, further research into these
310 hitherto little-studied aspects is necessary.

311 In our dataset, climate change is mainly composed of two major climatic aspects: temperature change
312 and water availability, which both have been studied frequently in our dataset (Figure 2c). However,
313 considering their central role as climatic aspects, they show unexpectedly little overlap with aspects of
314 other categories. Especially the low number of studies which investigated the interactive effect of climate
315 change and biotic stressors on above-belowground organisms, contrasts with the direct link between
316 climate change and biodiversity loss (Smith et al., 2018) and the success of biological invasions (Dukes
317 & Mooney, 1999; Walther et al., 2009). Additionally, extreme weather events that are not included in
318 temperature change or water availability, for example storms or floods, are underrepresented. Extreme
319 weather events have shown to significantly impact terrestrial organisms (Maxwell et al., 2019) and even
320 change whole food webs (Byrnes et al., 2011). Considering that weather extremes will become more

321 frequent in the future (IPCC, 2023), it becomes all the more important to fill this knowledge gap (Jentsch
322 et al., 2007).

323 We also identified knowledge gaps for interactions between biotic stressors, since they were most often
324 studied together with land-use or climate change aspects, but not with each other (Figure 2c). A closer
325 look into our dataset suggests that two different patterns could explain this. Invasions and pests were
326 commonly combined with other aspects to investigate potential mutualistic or antagonistic interactions
327 (e.g., Kutyniok & Müller (2013), Lu et al. (2015)), while biodiversity loss was most often seen as a
328 secondary stressor aspect caused by another aspect. This was especially prominent for habitat
329 transformation causing declines in plant biodiversity (e.g., Aguiar et al. (2022), Potapov et al., (2024)).
330 What is striking is that, although biotic stressors had co-occurrences with many different aspects,
331 simultaneous investigations of biotic stressors and pollution were absent.

332 In our dataset, studies on pollution (eutrophication and pesticides excluded here, as we assigned them to
333 land-use) were generally scarce (Figure 2a). All pollution studies exclusively investigated direct effects
334 of soil pollution on above- and belowground earthworms or, in one case, fungi. We found no studies that
335 investigated the simultaneous effect of pollution on different taxonomic orders or trophic groups. Mostly
336 heavy metal pollution was investigated, with the exception of two studies on coal mining residues
337 (Emmerling & Paulsch, 2001) and alkaline waste (Butt & Briones, 2017). Studies on pollution types such
338 as microplastic, pharmaceuticals, light, sound or air pollution were absent in our dataset. One possible
339 reason for this could lie in the diverse and complex pathways via which pollutants affect above- and
340 belowground organisms, which might be difficult to investigate. Soil pollutants, for example, can affect
341 soil organisms via many different direct and indirect pathways (Beaumelle et al., 2021; Rusek &
342 Marshall, 2000). For aboveground organisms, pathways seem even more complex, such as pollution
343 transfer from soil to aboveground systems via plants (Joubert et al., 2024) or change of soil and vegetation

344 parameters (Brändle et al., 2001). Airborne pollutants are also likely to be a threat, as they can affect
345 pollinators directly or indirectly (Duque & Steffan-Dewenter, 2024). Particularly given these complex
346 mechanisms, we argue that more studies on these systems will be needed to gain a comprehensive
347 understanding of the diverse effects of pollution on combined above-belowground biodiversity.

348 Direct exploitation is mentioned in the IPBES report (2019), Maxwell et. al (2019) and many other
349 sources, as one of the central stressors of worldwide terrestrial biodiversity loss. However, aspects of
350 direct exploitation are only sparsely represented in our dataset, as logging, which we included in forest
351 management, was only recorded rarely, while any forms of hunting or poaching were not recorded at all.
352 There might be a simple explanation for this, as mainly larger organisms, especially vertebrates, are
353 hunted, and thereby directly affected (Dias et al., 2019; Milner-Gulland & Bennett, 2003). Due to the
354 lack of direct hunting pressure on belowground organisms and such effects only being indirect, studies
355 on the simultaneous hunting effects on above- and belowground organisms seem very niche. However,
356 direct exploitation of aboveground organisms will affect above- and belowground organisms through
357 indirect pathways by affecting food webs and trophic interactions (O'Connor et al., 2024; Schmitz et al.,
358 2000) or change of ecosystem properties by removal of ecosystem engineers (Ceballos et al., 1999;
359 Dalbeck et al., 2007; Waldram et al., 2008). We therefore emphasize that further studies on the indirect
360 effects of direct exploitation, particularly hunting, are needed to gain insights into how different
361 organisms respond and how other stressors might interact with direct exploitation.

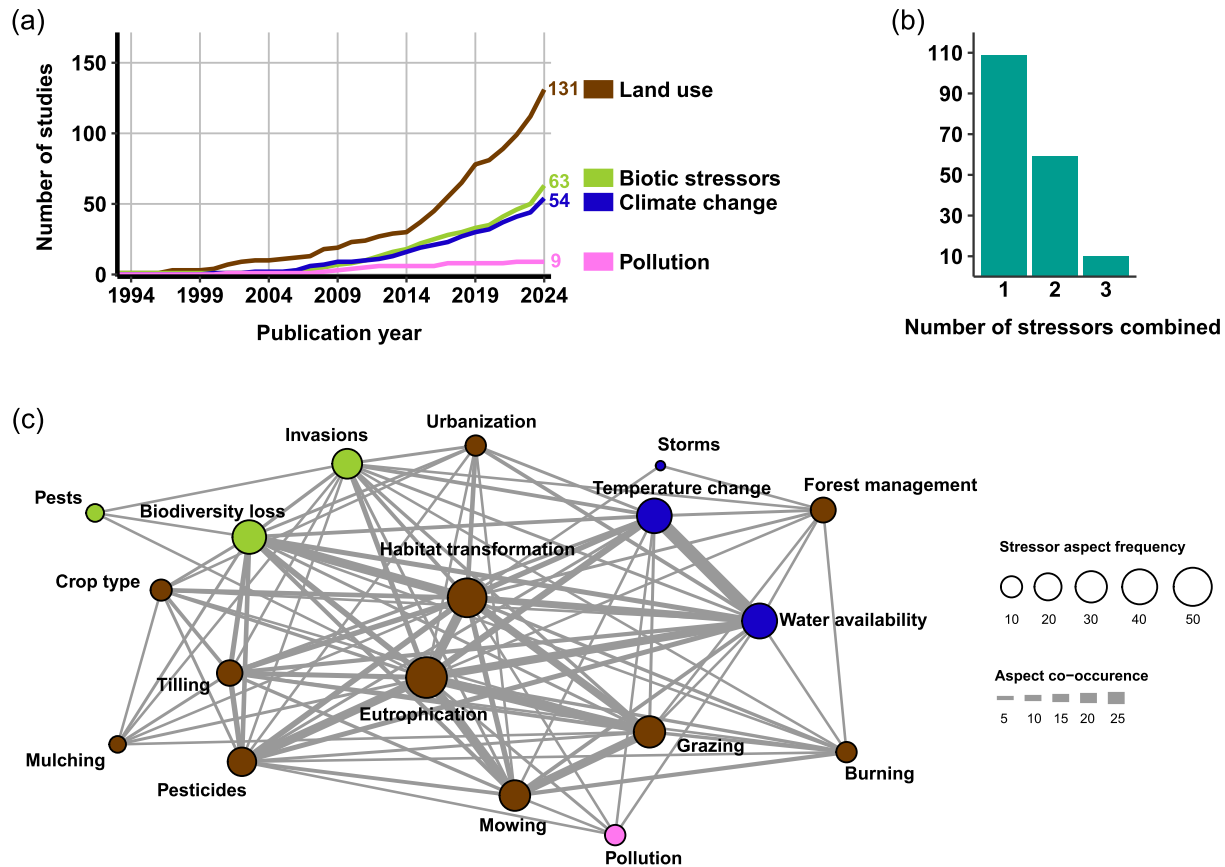
362

363 In addition to the relative importance of these global change stressors in the literature, we assessed how
364 many studies focused on single stressors versus two or more (Figure 2b). In our dataset, 109 studies (60
365 %) investigated impacts of only a single stressor category, while 59 (33 %) of studies included a second
366 category and only ten (6 %) studies combined three stressor categories. Combinations of all four

367 categories were absent.

368 Similar patterns were also observed for the number of full-factorial two-stressor studies on insects
369 (Kaunisto et al., 2016) and the number of experimental studies on soil biota and processes that
370 investigated multiple global change stressors (Rillig et al., 2019). This suggests that there is only sparse
371 information on the relative strength of multiple stressors let alone or their interactive effects on
372 organisms. Understanding the different types of interactions between stressors is crucial to evaluate their
373 impact on real world ecosystems, as these interactions have shown to be additive in the case of soil
374 functioning (Rillig et al., 2023) but also neutral or antagonistic interactions have been reported
375 (Holmstrup et al., 2010; Rongstock et al., 2026; Yue et al., 2017). Given that Earth's ecosystems are
376 rarely affected by only a single stressor, but rather by several of them simultaneously (Bowler et al.,
377 2020), there is an urgent need for further studies on the effects of multiple stressors on above-
378 belowground organisms. Without sufficient research on stressor interactions, predictions on future
379 responses of terrestrial systems to global change are at best inaccurate, threatening to result in poor policy
380 and conservation measures.

381



382

383 **Figure 2.** Visualisation of investigated stressors, stressor aspects and their combinations from studies
 384 on simultaneous above- and belowground organism responses to global change (total studies $n = 178$).
 385 **(a)** Cumulative number of studies per global change stressor (land use, biotic stressors, climate change,
 386 pollution) over time. Studies that included multiple stressors, were counted as one record for each
 387 stressor included. Total number of studies per stressor are displayed on the right. **(b)** The frequency of
 388 studies incorporating single vs multiple global change stressors affecting above- and belowground
 389 organisms. **(c)** Co-occurrence node plot of stressor aspects. Stressor aspects of the stressor categories
 390 shown in (a) are represented by the same color code. Node size (area) represents stressor aspect
 391 frequency among total studies, while thickness of links represents the number of co-occurrences of
 392 stressor aspects in studies. Arrangement of nodes is based on optimal visibility.

393 *Organism groups*

394 Next, we assessed which taxa dominated the literature on above-belowground organism responses to
395 global-change impacts (Figure 3a). The most frequently studied organism group were invertebrates with
396 aboveground invertebrates being included in 158 studies (89 %) of total studies and belowground
397 invertebrates in 146 (82 %). Both showed a synchronous exponential increase in studies over time. The
398 next most frequently studied groups were belowground fungi (58; 33 %) and belowground bacteria (44;
399 25 %). The earliest studies including belowground fungi or bacteria were published in the early 2000s
400 with a strong increase in studies from 2014 on. Their aboveground counterparts showed a weaker increase
401 with 27 studies (15 %) investigating aboveground fungi and 10 (6 %) aboveground bacteria. Vertebrates
402 were the least studied group in our dataset overall, with the earliest study dating back to 2006.
403 Aboveground vertebrates were included in 17 (10 %) of our studies, while belowground vertebrates
404 appeared only in one study (<1 %). Most vertebrate-including studies focused on birds and bats while
405 other mammals, reptiles and amphibians were only studied by Delgado-Baquerizo et al. (2018), Hilpold
406 et al. (2018) and Roos et al. (2023).

407 Given the rising attention on arthropods in the context of global change and biodiversity loss (Sánchez-
408 Bayo & Wyckhuys, 2019; Thomas et al., 2004; Wagner, 2020), it is not surprising that the majority of
409 studies from our dataset included invertebrates. However, there are more reasons that make studying
410 invertebrates attractive. Sampling and recording of invertebrates is often very time and cost efficient
411 compared to the other organism groups discussed here, as they are highly abundant and can often be
412 sampled with basic methods, like sweepnetting or pitfall traps. Additionally, many invertebrate groups
413 are commonly used as indicators for ecosystem services, like pollination, decomposition or pest control
414 (Bianchi et al., 2006; Biesmeijer et al., 2006; Parker, 2010). The synchronous increase of above- and
415 belowground invertebrates (Figure 3a) suggests that they are often studied together. Studying the same

416 taxonomic group above- and belowground rather than different groups could be generally attractive, as
417 it allows for better comparability of above- and belowground responses and does not require additional
418 taxonomic or methodological expertise on other groups.

419 However, this pattern was not observed for bacteria and fungi. Here we find a synchronous increase of
420 both groups belowground, while the aboveground counterparts act differently (Figure 3a). A possible
421 explanation lies again in the applied methods to study these groups, as bacteria and fungi were often
422 investigated together in our dataset as part of a soil microbiome analysis (Blanchet et al., 2016; Holly et
423 al., 2009). Biochemical and molecular methods like metabarcoding, enabling analyses of bacteria and
424 fungi from the same soil sample with only minor methodological adjustments (Geisen, Briones, et al.,
425 2019; Knight et al., 2018), are probably one of the main reasons for the synchronous increase. This is
426 also supported by the observed increase of studies on belowground bacteria and fungi from 2014 on, as
427 these methods became standards not long ago (Philippot et al., 2012). In our dataset, studies on
428 aboveground bacteria and fungi were diverse, investigating for example plant associated endo- or
429 epiphytic taxa (Durand et al., 2017), plant pathogens (Quintanilla-Tornel et al., 2016) or aboveground
430 fungi sporocarps (Pestaña & Santolamazza-Carbone, 2011), while studies including belowground
431 bacteria and fungi mostly focused on microbial biomass and diversity as indicators for ecosystem
432 services, such as nutrient cycling (e.g., Allen et al., (2014), Blanchet et al., (2016)). Irrespective of above-
433 or belowground habitats, bacteria and fungi are complex and diverse groups (Tedersoo et al., 2014;
434 Torsvik et al., 2002), which play important roles in ecosystem functioning, as pathogens (Whipps, 2001),
435 symbionts (A. F. S. Taylor & Alexander, 2005) or decomposers (Delgado-Baquerizo et al., 2020;
436 Hättenschwiler et al., 2005). Especially prominent are their interactions with plants (Lee et al., 2012;
437 Partida-Martinez & Heil, 2011), but also direct interactions within bacteria and fungi or with other
438 groups, like invertebrates, have to be considered (Douglas, 2015; Vega et al., 2009; Whipps, 2001).

439 Additionally, both represent essential parts of the total terrestrial biomass (Bar-On et al., 2018). However,
440 this ecological importance and taxonomic as well as functional diversity was not reflected in the number
441 of studies here, especially for aboveground bacteria and fungi, suggesting that many interactions with
442 different groups and also responses to global change stressors have been poorly studied.

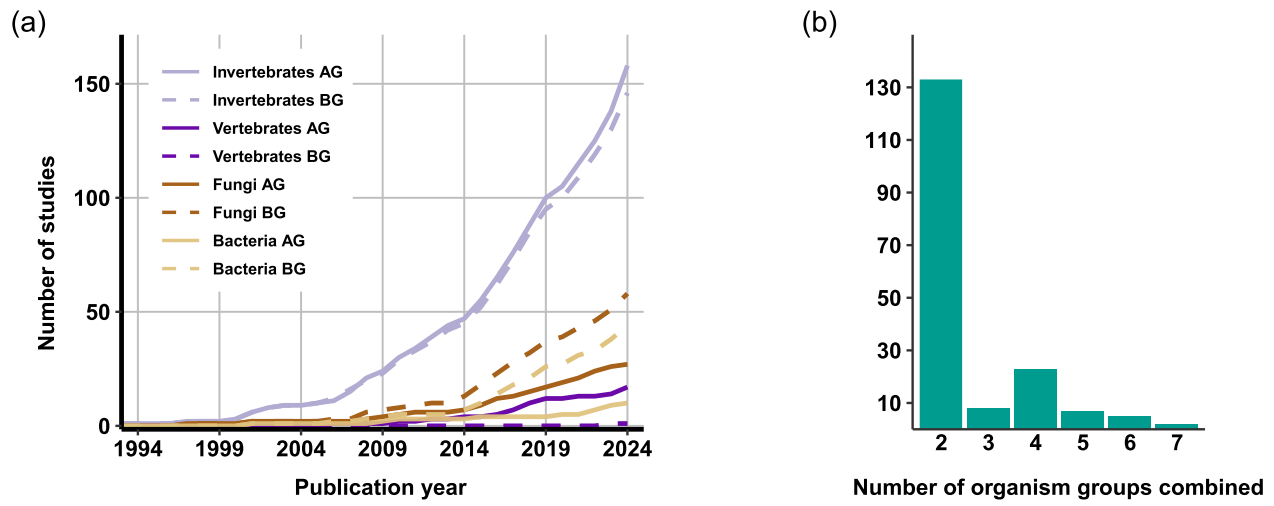
443 The same can be assumed for the least often studied group in our dataset which were vertebrates (Figure
444 3a). That almost all studies on vertebrates focused on aboveground taxa is not surprising, as most
445 vertebrate taxa live aboveground (Anthony et al., 2023; Measey, 2006), which also makes them easier to
446 observe. However, this might point to insufficient information for evaluating the responses of
447 belowground vertebrates (Böhm et al., 2013), although belowground vertebrates take part in important
448 ecosystem services like pest control and nutrient cycling (Dooren et al., 2024; Gervais et al., 2010) or act
449 as ecosystem engineers (Ceballos et al., 1999). For aboveground vertebrates, the main focus on birds and
450 bats is likely to be a result of their common use in literature as indicators for ecosystem services like pest
451 control, seed dispersal, or pollination (Medellín et al., 2000; Wenny et al., 2011; Whelan et al., 2008).
452 Additionally, the development of acoustic monitoring methods made the monitoring of birds and bats
453 more time and cost efficient (Allen-Ankins et al., 2023; Gibb et al., 2019; Sugai et al., 2019). For other
454 taxa, more elaborate methods like personal observations or camera traps have to be carried out, often in
455 even larger areas. This results in a general underrepresentation of most mammals, amphibians and
456 reptiles in many ecological assessments (Meiri et al., 2023; Moss et al., 2022; Tinya et al., 2023), even
457 though they play important roles in ecological networks (Davic & Welsh Jr., 2004; Godó et al., 2022;
458 Whiles et al., 2006). Given the observed declines of vertebrate species (Beebee & Griffiths, 2005;
459 Ceballos & Ehrlich, 2002), we emphasise that more studies on vertebrates, especially mammals, reptiles
460 and amphibians, will be needed to understand trends and possible effects of their disappearance.

461 As for the stressors, we also assessed how frequently studies focused on more than two organism groups

462 (compared to the two which are, by definition, the minimum for inclusion in our literature search). The
463 majority (133; 75 %) of studies from our dataset investigated only two organism groups (Figure 3b).
464 Second most often were combinations of four different organism groups (23; 13 %). Studies including
465 three, five, six or seven groups each account for less than 5% of the studies in our dataset. Studies that
466 combined all eight groups were not recorded.

467 The frequent combination of groups with their respective above-belowground counterparts, without
468 including other organism groups, likely is one factor behind the observed focus on only two organism
469 groups per study (Figure 3b). Additionally, the underrepresentation of many groups, due to elaborate
470 sampling or analysis methods, is also likely to play a role. The frequent combination of above-
471 belowground invertebrates with belowground fungi and bacteria (17 out 23 studies; 74 %) results in more
472 studies investigating four instead of three groups. Of the 45 (25 %) of studies that included more than
473 two organism groups, one third are syntheses that include several datasets. Many of these datasets belong
474 to large-scale projects, like the “Biodiversity Exploratories” (Fischer et al., 2010) or the BASE project
475 (Bissett et al., 2016) which offer a framework for collaboration and synthesis. This underlines the
476 extensive effort underlying the combination of multiple methods and expertises required to
477 simultaneously investigate multiple above-belowground organism groups. However, this effort is needed
478 as different groups can respond very differently to global change stressors (L. Gao et al., 2024; Lawton
479 et al., 1998; Simons et al., 2017). It has been shown that the diversity of single taxonomic groups is not
480 necessarily a good predictor for other groups (Billeter et al., 2008; Thomas et al., 2004). Additionally, it
481 is not only the groups themselves that are affected by global change, but also the interactions between
482 them (Tylianakis et al., 2008). This interplay between multiple different organism groups is crucial for
483 ecosystem functioning (Duffy et al., 2007; Soliveres et al., 2016) and thereby also for ecosystem services
484 (IPBES, 2019; Millennium Ecosystem Assessment, 2005). In order to assess the impact of global change

485 on ecosystems, we must therefore focus on uncovering how entire communities and interaction networks
486 will be affected. The key objectives for achieving this are to improve existing or develop novel methods
487 to reduce the effort required for sampling or analysis and foster cooperative synthesis projects to link
488 expertises on different organism groups above and below the ground
489



490

491 **Figure 3.** Visualisation of investigated organism groups and their combination from studies on
 492 simultaneous above- and belowground organism responses to global change (total studies $n = 178$). **(a)**
 493 Cumulative number of studies on different above- and belowground organism groups over time. All
 494 studies include at least one aboveground and one belowground organism group. Each organism group
 495 per study was counted as a single record. Colors represent taxonomic assignment, while linetype
 496 differentiates between above- and belowground groups (AG: aboveground, solid line; BG: belowground,
 497 dashed line). **(b)** Frequency of studies per number of investigated organism groups within each study
 498 (total studies $n = 178$).

499 *Combination of stressors and organisms*

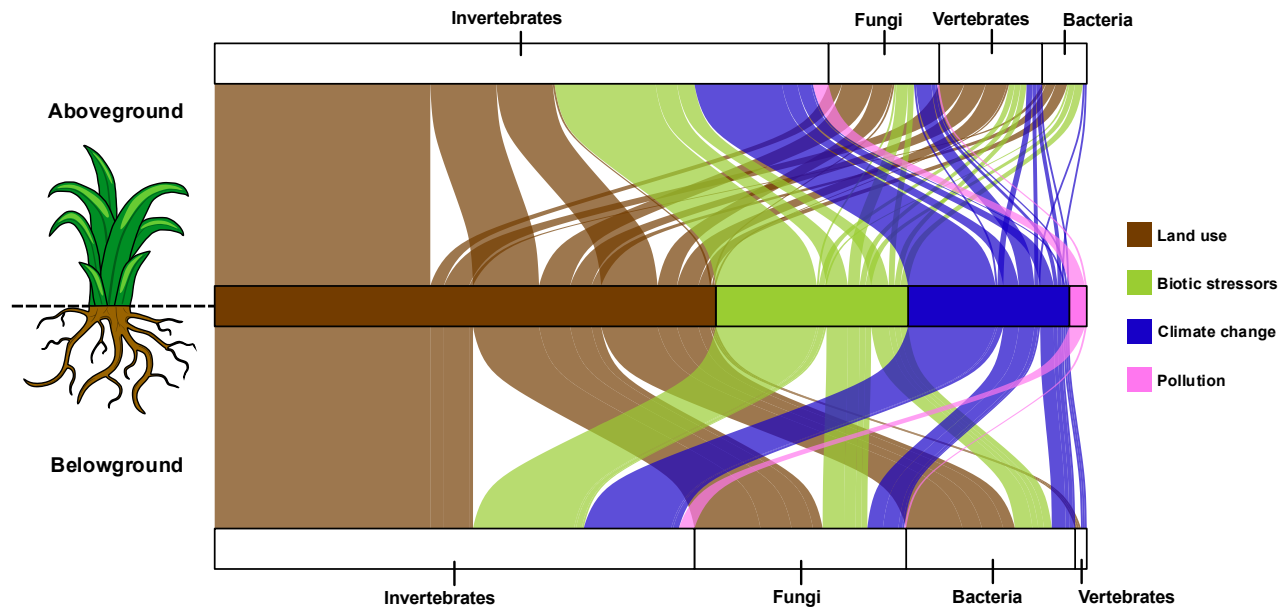
500 To visualise which organism groups were combined with each other and with which stressors, we created
501 an alluvial diagram (Figure 4). All organism groups were most often studied in combination with land-
502 use stressors. The second most common combination for almost all groups were climate change and
503 biotic stressors, in about equal shares. Aboveground bacteria were an exception here, as combinations
504 with climate change were much less common than combinations with biotic stressors. Pollution was only
505 combined with above-belowground invertebrates and fungi, with the majority of studies focusing on
506 invertebrates. Within all stressor categories, invertebrates were the most frequently studied group. In
507 most cases, above- and belowground invertebrates were combined. However, it stands out that
508 belowground invertebrates are almost exclusively combined with aboveground invertebrates, while
509 aboveground invertebrates showed higher proportions of different combinations. The opposite pattern
510 was observed for bacteria and fungi, as aboveground bacteria and fungi were most often combined with
511 their belowground counterpart, while belowground bacteria and fungi were most often combined with
512 aboveground invertebrates. These patterns were consistent, irrespective of stressor category.
513 Aboveground vertebrates were combined with different belowground groups in equal shares. No patterns
514 were observable for belowground vertebrates, as only one study including this group was recorded. Out
515 of 64 possible combinations of stressor categories, aboveground, and belowground groups ($n = 64$) a
516 total of 43 different combinations were recorded, resulting in 33% of possible combinations remaining
517 unstudied in our dataset.

518

519 The observed patterns of organism group and stressor combinations suggest that the observed
520 proportional coverage of land-use, biotic stressors, and climate change is consistent across almost all
521 organism groups. This coverage seems to correspond with the estimated impact of these stressors on

522 biodiversity, presented by Jaureguiberry et al (2022) and the IPBES Report (2019). However, considering
523 the coverage of all possible stressor and organism combinations in our dataset, we assume that the
524 available data on many of these combinations will not be sufficient to draw reliable conclusions on the
525 effect of specific global change stressors on certain groups. For example, belowground invertebrates have
526 only been studied once together with aboveground fungi in response to biotic stressors. In particular,
527 pollution and belowground vertebrates were only investigated in very few different stressor-organism
528 group combinations. The observed combinations indicate that certain groups are often investigated in the
529 same ecological contexts. Such common organism groups and contexts include, for example,
530 belowground bacteria and fungi as soil-microbiome addition to aboveground invertebrates, above-
531 belowground bacteria and fungi as plant symbionts or above-belowground invertebrates, specifically
532 earthworms, as indicators for pollution. These combinations will be driven by common ecological
533 hypotheses or relevance in the literature. However, this does not diminish the importance of investigating
534 rarely-studied combinations, as little knowledge carries the risk of unreliable predictions of future
535 responses.

536



537

538 **Figure 4.** Alluvial diagram of co-occurrences of above- and belowground organism groups and stressors
 539 within studies investigating simultaneous above- and belowground organism responses to global change
 540 (total studies $n = 178$). Box length and line width represent the number of co-occurrences, while colors
 541 indicate the type of investigated stressor. Organism groups and stressors are sorted by decreasing
 542 number of co-occurrences (left to right).

Comparison of observational versus experimental approaches

543
544 In our dataset 108 (61 %) of total studies were designed as observational studies without experimental
545 manipulations, while 66 (37 %) included experimental setups to manipulate or simulate global change
546 stressors (Figure 5a). Assignment to either observational or experimental design was not possible for
547 four (2 %) synthesis studies. Both study designs play important roles in evaluating global change impacts
548 on organisms. Observational studies investigate real-world ecosystems under actually occurring
549 stressors, which means that comparisons of various factors, such as habitats, organisms or stressors,
550 examine processes that are currently or have previously affected those ecosystems (Sagarin & Pauchard,
551 2010). Thereby, long term trends can be observed, which can allow predictions on future trends. At the
552 same time, it can be difficult to disentangle the role of single stressors from that of others and stressor
553 combinations that are not currently occurring but that might occur in the future cannot be studied
554 observationally. Here, experimental setups offer the possibility to investigate the effect of single or few
555 stressors in isolation or interaction to mechanistically test which stressors drive organism responses and
556 how certain stressors interact. Additionally, predicted future scenarios can be simulated to make
557 assumptions on how organisms will be affected by global change in the future. This will be especially
558 important in the case of rare events, like extreme weather events, as their frequency is predicted to
559 increase in future climate scenarios (IPCC, 2023). Given that global change is accelerating through
560 amplification effects, like climate change benefitting invasive species, previously-observed trends might
561 not be representative of future trends. However, experimental setups always require a certain amount of
562 control on the observed system, which reduces realism compared to observational studies. Both study
563 setups represent essential parts in ecological global change research to uncover the processes that affected
564 our ecosystems in the past but also to predict how they might affect them in the future. The observed
565 imbalance towards more observational studies could be an indication that there is a lack of knowledge

566 on the impact of global change in future scenarios. Predictions on the future will be particularly important
567 to design and enforce effective conservation measurements. However, observational studies also provide
568 fundamental knowledge, particularly regarding ecological context, and they will continue to be required
569 to ground-truth predictions and effects of conservation measurements.

570

571 *Biodiversity metrics*

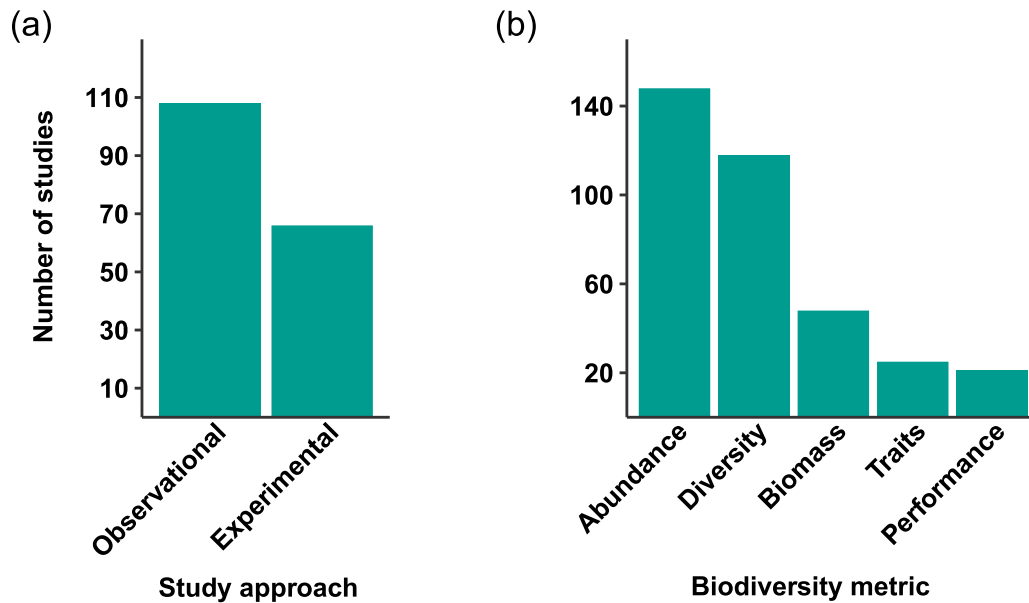
572 Different biodiversity metrics of organism assemblages can provide very different types of information.
573 The abundance or biomass of an organism group carries information fundamentally different from their
574 functional traits, diversity metrics, or performance indicators. Thus, we assessed which properties of such
575 assemblages were most-commonly covered when studying global change impacts on above- and
576 belowground organisms (Figure 5b). The most commonly investigated metric in our dataset was
577 organism abundance, which was considered by 83 % of total studies, followed by taxonomic diversity
578 (66 %). Biomass was investigated in 27 % of total studies, while organism traits, such as wing length,
579 and performance indicators, such as growth rates or thermal tolerance, were only considered by 14 and
580 12 % of the studies, respectively.

581 That abundance was the most often investigated metric is not surprising, as abundance is easily assessable
582 and required for calculation of other metrics such as e.g. diversity indices. Taxonomic diversity was also
583 expected to be often used, as there are various different types of diversity indices covering different
584 taxonomic levels, spatial scales or analyses. Additionally, biodiversity received increased attention in the
585 past decades as awareness for the topic of biodiversity-loss rose (Cardinale et al., 2012; Hald-Mortensen,
586 2023; Jaureguiberry et al., 2022; Newbold et al., 2015), which was accompanied by the linkage of
587 ecosystem functions and services to biodiversity (Balvanera et al., 2014; Soliveres et al., 2016). Biomass,

588 traits and organism performance might be less often investigated because they require additional or more
589 elaborate measurements like weight, length or physical responses. Some of these measurements, like
590 organism growth rates, can be difficult to assess in the field, leading to 33 % studies from our dataset
591 investigating organism performance being carried out in common garden or laboratory setups (Kutyniok
592 & Müller, 2013; Wei et al., 2016). Another reason might be different study approaches, as abundance
593 and diversity primarily provide information on which and how many organisms were recorded, while
594 biomass, traits and performance more often provide a deeper insight in ecosystem processes. In our
595 dataset, traits are often either used for comparison between individuals within a taxonomic group e.g.
596 bees (Forrest et al., 2015; Uemori et al., 2022) or for assignment to functional groups like trophic guilds
597 (Birkhofer et al., 2017; Susanti et al., 2021). Traits in general have shown to be closely linked with
598 ecosystem functions (de Bello et al., 2010) making them a valuable metric to investigate the impact of
599 global change on ecosystem functioning (Gagic et al., 2015; Vandewalle et al., 2010). Biomass is also
600 often used to evaluate ecosystem functions of specific groups like earthworms (Nachtergale et al., 2002;
601 Tresch et al., 2019) or microbes (Birkhofer et al., 2008; Leidinger et al., 2017), but it can also be used to
602 investigate long term trends, like insect decline (Hallmann et al., 2017; Müller et al., 2024), which
603 received increased attention in recent years. Organism performance can be used to assess processes like
604 thermal adaptation (Kaspari et al., 2015) or herbivory (Gutbrodt et al., 2011) on individual level. In
605 particular, organism performance can provide important information on the direct physical or behavioural
606 responses of organisms to global change (Ashe-Jepson et al., 2023; Awmack et al., 2004). Assessment
607 of abundance, taxonomic diversity and biomass provide essential information on the presence and
608 absence of organisms. However, they are often not directly offering information on how organisms
609 interact with each other and how they impact certain ecosystem functions. For this, biodiversity metrics
610 like individual traits or performance will be required. Combining these different types of metrics will be

611 essential to draw comprehensive conclusions on how global change affects ecosystems and their
612 functions and services. Considering the low representation of biomass, individual traits and performance
613 in our dataset, we suggest that further studies should more often include these metrics and especially
614 focus on linking organism occurrences to their respective role in ecosystem functioning.

615



616

617 **Figure 5.** Study design, including approach and investigated biodiversity metrics, of studies on
 618 simultaneous above- and belowground organism responses to global change (total studies $n = 178$). **(a)**
 619 Number of total studies divided into either observational approaches without any experimental
 620 manipulation or experimental approaches with any kind of experimental modifications. For four
 621 synthesis studies, assignment was unfeasible and they are not displayed here. **(b)** Number of studies per
 622 investigated metric. Records of multiple different metrics per study were possible.

623 *Limitations*

624 We identified methodological limitations that could have impacted our results, such as only focusing on
625 digitally available and English literature and different interpretations of certain terms addressing
626 organism groups or stressors. A detailed evaluation of these limitations can be found in the supporting
627 information. Despite these caveats, we are convinced that our identification of knowledge gaps in
628 simultaneous above-belowground organism responses to global change is the most comprehensive to
629 date and our results are relevant for future research.

630

631 Conclusion

632 When assessing published research on global-change impacts on combined above- and belowground
633 organisms, we found an increasing trend of studies per year which shows that the importance of
634 simultaneously studying above- and belowground organism responses to global change is being
635 understood and this realization seems to reach both scientists and funding organizations. Still, the total
636 number of studies that we retrieved from our search was low compared to the number of studies on single
637 taxonomic and ecological groups or stressors (Ashe-Jepson et al., 2024; Beaumelle et al., 2021; de
638 Souza Stockmann et al., 2024; Phillips et al., 2024). For all investigated study elements, we identified
639 possible knowledge gaps with the most prominent ones being shown in BOX 1. We conclude that there
640 is a need for further research with stronger focus on connecting and combining multiple stressors and
641 organism groups to retrieve comprehensive information on realistic global change effects on combined
642 above-belowground organisms. A special focus should lie on the described gaps as data might not be
643 sufficient there to draw conclusions for future predictions. One approach to close these knowledge gaps
644 could be to specifically focus on above-belowground interactions under global change in future studies.
645 Another approach could be to carry out studies on single or few organisms and stressors but within the
646 framework of large-scale projects so that data of multiple studies can be combined and analysed in
647 syntheses. Either way, combining aboveground and belowground organisms and multiple stressors will
648 be the key to obtain in-depth knowledge on how terrestrial ecosystems are affected by global change and
649 how this corresponds to changes in the functions they maintain and the services they provide. This
650 knowledge will not only improve conservation measures but might also offer relevant economic and
651 societal benefits for example via agricultural advancements and the stable provision of ecosystem
652 services under future global change.

653

654 **BOX 1.** Main findings concerning knowledge gaps in studies investigating simultaneous responses of
655 above- and belowground organisms to global change, retrieved from our systematic map.

- 656 ● Geographical distribution
 - 657 ○ Low number of studies conducted in the tropics
 - 658 ○ Underrepresentation of non-agricultural ecosystems, like wetlands, urban areas or deserts
- 659 ● Global-change stressors
 - 660 ○ Underrepresentation of certain aspects of global-change stressors, like non-agricultural
661 pollutants, extreme weather events, or direct exploitation
 - 662 ○ Low number of studies focusing on more than two different global-change stressors
- 663 ● Organism groups
 - 664 ○ Strong focus on invertebrates while studies on other organism groups lag behind
 - 665 ○ Low number of studies focusing on more than two different organism groups
- 666 ● Combination of global-change stressors and organism groups
 - 667 ○ Many poorly studied above-belowground organism and stressor combinations, 33 % of
668 possible combinations remained unstudied
 - 669 ○ Especially aboveground bacteria and fungi and pollution show a lack of diversity in
670 combinations
- 671 ● Study approach and investigated biodiversity metrics
 - 672 ○ Underrepresentation of studies with experimental approaches to simulate future scenarios
 - 673 ○ Low number of studies investigating organism traits or performance, which directly link
674 organism occurrence to ecosystem functions

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678 Würzburg, the whole team gave extensive feedback regarding the visual illustration of results.

679

680

681 **Author contributions**

682 HM, EAJ, and MJ conceived the study idea. HM and EAJ adjusted the Systematic Map approach to our
683 study system with contributions of MJ. HM led the writing and all authors contributed to writing and
684 editing the manuscript.

685

686

687 **Data accessibility**

688 The data that support the findings of this study are openly available in the supporting information. The
689 code used for analyses and creating figures is openly available on zenodo: [10.5281/zenodo.20038279](https://zenodo.org/doi/10.5281/zenodo.20038279).

690

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- 1379

1380 **Supporting information**

1381 **Data extraction and coding**

1382 For all included studies, the following information have been extracted: studied countries, ecosystems,
1383 organism groups, stressor aspects, biodiversity metrics, and study approach (Table S4). Study countries
1384 were defined as sovereign states where the empirical work took place. Sovereign state level implies that
1385 for example overseas territories like French Guiana were considered as “France”. In the case of study
1386 setups, like greenhouse experiments, without connection to real-world ecosystems, study country was
1387 referred to as “laboratory setup”. For consistency, studied ecosystems were assigned to one or several of
1388 six levels defined by us (cropland, forest, grassland, shrubland, urban, wetland). Assignments to multiple
1389 levels were made in the case of studies that covered more than one ecosystem or took place in
1390 heterogeneous environments like savannas with mixes of shrub- and grasslands. Level assignment was
1391 based on the given ecosystem description in the respective studies. Studied organisms were assigned to
1392 multiple levels consisting of eight groups; vertebrates, invertebrates, bacteria, or fungi, each either from
1393 above- or belowground compartments. The assignment to either above- or belowground compartments
1394 was made based on the authors’ own description in the study, which led, for example in the case of litter
1395 fauna, to assignments for one taxon to different compartments based on the study context. Global change
1396 stressor aspects whose effects on study organisms have been investigated were recorded and used as
1397 levels for data coding. Afterwards we grouped them into four categories: biotic stressors, climate change,
1398 land use, and pollution (Table S4). Biotic stressor aspects (here biodiversity loss, invasions and pests)
1399 were grouped into one category, since they may be of different origins. Biotic stressor aspects were only
1400 counted as such, if the author described them as stressors, for example when the effect of plant diversity
1401 on above- and belowground organisms was investigated e.g. Scherber et al. (2010). Climate change

1402 included weather events and stressors related to climatic variables, like temperature and moisture. The
1403 land-use category included all aspects that have their origin in different forms of land use (e.g.,
1404 agriculture, forestry, urbanization). Forms of pollution that are not clearly attributable to land use, like
1405 microplastic or industrial heavy metal pollution, were summarized as “pollution” and treated separately
1406 from agricultural pollutants (Rodríguez-Eugenio et al., 2018) like fertilization or pesticides, which were
1407 included in the land-use category. We chose this form of categorization based on the context these
1408 stressor aspects have been discussed in the investigated studies. We recorded all biodiversity metrics that
1409 were assessed for at least one of the investigated taxa, which resulted in the following levels: abundance,
1410 taxonomic diversity (which can be any kind of diversity index like species richness, shannon index or
1411 community composition based on e.g., Non-metric Multidimensional Scaling (NMDS)), biomass,
1412 individual traits, and performance (thermal tolerance, number of offspring, etc.). Study setup
1413 distinguished between two levels, observational studies which collected data or samples without any
1414 experimental manipulation, and experimental studies where some kind of environmental manipulation
1415 was part of the study design.

1416

Limitations

1417
1418 We identified the following methodological limitations that could have impacted our results. As we
1419 conducted a digital online literature search, all literature that has not been digitalized and is only available
1420 physically will be missed. This will most likely affect mostly older literature. However, we estimate that
1421 only a small percentage of literature will be missed because of this, as the topic of linking above- and
1422 belowground compartments started to gain attention in the 1990s (Bardgett, 2018) and most scientific
1423 literature of this time will be digitally available. More significant might be the exclusion of studies that
1424 are not published in the English language. Considering the findings of Amano et al. (2021), we expect
1425 that some studies in non-English languages were missed, but given that the majority of scientific studies
1426 are published in the English language we assume that the knowledge gaps we identified represent a
1427 comprehensive overview at the global scale. Another limitation is the choice and interpretation of certain
1428 terms, due to complex definition and terminology of above- and belowground organisms in the literature.
1429 Earthworms, for example, are often divided into three ecological groups: epigeic, endogeic, and anecic
1430 (Capowiez et al., 2024). Thereby, epigeic earthworms are, by definition, aboveground fauna, while often
1431 being considered as soil or belowground fauna at the same time. Often these differences seem to be a
1432 result of the diverse research disciplines that occur in our dataset, as the same terms in bird ecology might
1433 carry different meanings in microbial ecology. The challenges that arise from this also translate to search
1434 term creation, as including all different terms used in the literature is challenging. Nevertheless, we are
1435 confident that we included the most important terms for a wide range of research areas, by using a diverse
1436 selection of benchmarks, which were all extracted by our search term. Despite these challenges, we are
1437 convinced that our approach to identify knowledge gaps in simultaneous above-belowground organism
1438 responses to global change is the most comprehensive to date and our results are relevant for future
1439 research.

1440 **Table S1:** List of our 15 benchmark publications, which were used to create and test our search term to extract publications investigating
 1441 simultaneous above- and belowground organism responses to global change, alphabetically ordered by first author.

Authors	Title	Year	DOI
Delgado-Baquerizo, M; Eldridge, DJ; Travers, SK; Val, J; Oliver, I; Bissett, A	Effects of climate legacies on above- and belowground community assembly	2018	http://dx.doi.org/10.1111/gcb.14306
Fukami, T; Wardle, DA; Bellingham, PJ; Mulder, CPH; Towns, DR; Yeates, GW; Bonner, KI; Durrett, MS; Grant-Hoffman, MN; Williamson, WM	Above- and below-ground impacts of introduced predators in seabird-dominated island ecosystems	2006	http://dx.doi.org/10.1111/j.1461-0248.2006.00983.x
Gao, EL; Ma, H; Yang, T; Kaiser-Bunbury, CN; Zhao, ZG	Meadow transformations alter above- and below-ground ecological networks and ecosystem multifunctionality	2023	http://dx.doi.org/10.1111/1365-2435.14333
Heinen, J; Smith, ME; Taylor, A; Bommarco, R	Combining organic fertilisation and perennial crops in the rotation enhances arthropod communities	2023	http://dx.doi.org/10.1016/j.agee.2023.108461
Hilpold, A; Seeber, J; Fontana, V; Niedrist, G; Rief, A; Steinwandter, M; Tasser, E; Tappeiner, U	Decline of rare and specialist species across multiple taxonomic groups after grassland intensification and abandonment	2018	http://dx.doi.org/10.1007/s10531-018-1623-x
Kumar, A; O'Donnell, S	Elevation and forest clearing effects on foraging differ between surface - and subterranean - foraging army ants (Formicidae: Ecitoninae)	2009	http://dx.doi.org/10.1111/j.1365-2656.2008.01483.x
Le Provost, G; Thiele, J; Westphal, C; Penone, C; Allan, E; Neyret, M; van der Plas, F; Ayasse, M; Bardgett, RD; Birkhofer, K; Boch, S; Bonkowski, M; Buscot, F; Feldhaar, H; Gaulton, R; Goldmann, K; Gossner, MM;	Contrasting responses of above- and belowground diversity to multiple components of land-use intensity	2021	http://dx.doi.org/10.1038/s41467-021-23931-1

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Tanner, RA; Varia, S; Eschen, R; Wood, S; Murphy, ST; Gange, AC	Impacts of an Invasive Non-Native Annual Weed, <i>Impatiens glandulifera</i> , on Above- and Below-Ground Invertebrate Communities in the United Kingdom	2013	http://dx.doi.org/10.1371/journal.pone.0067271
Vanolli, BS; Pereira, APA; Franco, ALC; Cherubin, MR	Edaphic and epigeic macrofauna responses to land use change in Brazil	2023	http://dx.doi.org/10.1016/j.ejsobi.2023.103514

1443 **Table S2:** Search string used to extract studies on simultaneous above- and belowground organism
 1444 responses to global change from Web of Science core collection database.

Subject	Search term
Above and belowground simultaneously	(((above-ground* OR "above- and*" OR aboveground* OR "above ground" OR epigeic*) AND (below-ground* OR "below- and*" OR belowground* OR "below ground" OR edaphic* OR soil* OR underground* OR subterr*)) OR (green AND brown) OR "above-below*" OR "above below*" OR "above and below*")
AND	
Global change stressors	(stress* OR driver* OR "driving force*" OR threat* OR "global change*" OR "global change*" OR "environment* NEAR/3 change*" OR urbaniz* OR urbanis* OR *management* OR "land use*" OR "land-use*" OR landuse* OR agricult* OR *farming* OR mowing* OR *mower* OR fertiliz* OR fertilis* OR eutrophicat* OR "N enrichm*" OR grazing* OR graze* OR fungicid* OR bacteriocid* OR herbicid* OR pesticid* OR "habitat loss" OR "habitat-loss" OR fragmentation* OR isolation OR transformation OR homogenization OR homogenisation OR heterogeneity OR climat* OR "weather NEAR/3 change" OR warming* OR cooling* OR temperature* OR precipitat* OR rainfall* OR "water availab*" OR "rain OR flood* OR water NEAR/3 short*" OR drought* OR desertificat* OR *pollut* OR "heavy metal*" OR "heavy-metal*" OR microplastic* OR "*diversity* NEAR/3 *loss*" OR "*diversity* NEAR/3 *decline*" OR invasive* OR invad* OR alien OR introduce* OR "non*native" OR pest OR pests OR exploit* OR deforest* OR logging*)
AND	
Organism groups	(arthropod* OR insect* OR *fauna* OR animal* OR invertebrate OR arachnid* OR araneae* OR spider* OR coleopt* OR beetle* OR hemipt* OR "true bug*" OR heteropt* OR "typical bug*" OR bug OR bugs OR auchenorrhya* OR cicada* OR leafhopp* OR sternorrhya* OR "plant lice*" OR aphid* OR diptera* OR fly OR flies OR hymenop* OR bee OR bees OR wasp OR wasps OR formicid* OR ant OR ants OR orthopt* OR grasshopp* OR cricket* OR phasmid* OR phasma* OR "stick insect*" OR lepidop* OR butterfly OR butterflies OR moth* OR odonat* OR dragonfl* OR damselfl* OR thysanop* OR thrips* OR dermapt* OR earwig* OR blattode* OR cockroach* OR termite* OR isopter* OR gastropod* OR heterobranch* OR slug OR slugs OR snail* OR myriapod* OR chilopod* OR centiped* OR diplopod* OR milliped* OR isopod* OR woodlice* OR acari* OR mite OR mites OR collembola* OR springtail* OR lumbricid* OR earthworm* OR worm* OR enchytraeid* OR nematod* OR rotifer* OR tardigrad* OR pauropod* OR symphyla* OR protura* OR diplura* OR mammal* OR rodent* OR carnivor* OR *ungula* OR primate* OR ape OR apes OR chiropt* OR bat OR bats OR aves OR bird OR birds OR reptil* OR testudine* OR turtle* OR squamata* OR lizard* OR serpente* OR snake* OR crocod* OR amphibia* OR anura* OR frog* OR toad* OR caudata* OR *salamander* OR newt* OR

gymnophiona* OR caecilia* OR microb* OR fungi* OR fungal* OR protist* OR protozoa* OR *bacteri* OR “micro*org*” OR archae* OR *biota OR organism* OR consumer* OR “trophic group*” OR “trophic level*” OR herbivore* OR fungivore* OR myceto* OR bacterivore* OR predator* OR detrivor* OR omnivor* OR pollinator*)

1445

1446 **Table S3:** Selection of inclusion and exclusion criteria used for screening extracted studies. Based on
 1447 the PICOS (**P**opulation, **I**ntervention, **C**omparator, **O**utcome, **S**tudy design) framework.

	Inclusion	Exclusion
Population /Investigated organisms	<ul style="list-style-type: none"> • Above- and belowground organisms 	<ul style="list-style-type: none"> • Only above- or belowground organisms • Only one single species investigated • Plants • Pure aquatic organisms
Intervention /Global change stressors	<ul style="list-style-type: none"> • At least one stressor or driver in the context of global change (land use, climate change, pollution, etc) is observed or manipulated 	<ul style="list-style-type: none"> • No global change stressor
Comparator	<ul style="list-style-type: none"> • Any 	
Outcome	<ul style="list-style-type: none"> • Any 	
Study design	<ul style="list-style-type: none"> • Observational or experimental studies based on empirical data • Language: English 	<ul style="list-style-type: none"> • Studies in non-terrestrial ecosystems • Theoretical studies • Reviews • Meta-analyses • Any other language than English

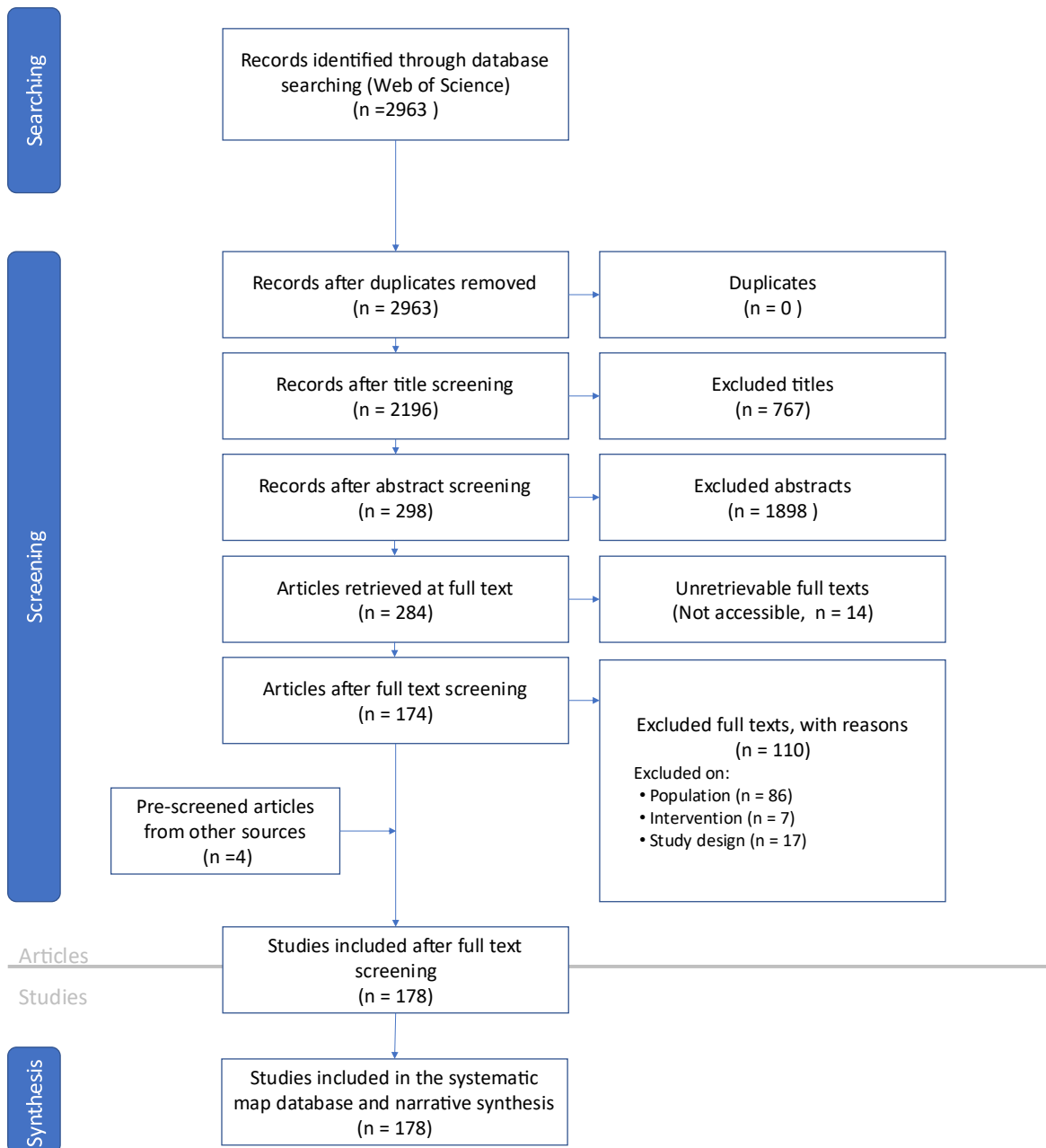
1448

1449 **Table S4:** Coding of different information extracted from all 178 accepted studies.

Information	Levels	Assignment to multiple levels possible (y/n)	Description
Publishing year	Years until 2025	no	Year study was published for the first time in a peer-reviewed journal
Study countries	All sovereign states	yes	Countries where the study took place (sampling, data collection). In the case of study setups, like greenhouse experiments, without connection to real-world ecosystems, study country was referred to as “laboratory setup”.
Studied ecosystems	Cropland; forest; grassland; shrubland; urban; wetland	yes	Ecosystems where the study took place (sampling, data collection); levels were defined by us for consistency
Studied global change stressors	<u>Biotic stressors</u> : biodiversity loss, invasions, pests; <u>climate change</u> : storms, temperature change, water availability; <u>land-use</u> : burning, crop type, eutrophication, forest management, grazing, habitat transformation, mowing, mulching, pesticides, tilling, urbanization; <u>pollution</u> : pollution	yes	Global change stressors whose effects on study organisms were investigated. Collected during screening and based on author descriptions. Afterwards they were grouped by us into the following categories: Biotic stressors; climate change; land-use; pollution
Studied organism groups	AG bacteria; AG fungi; AG invertebrates; AG vertebrates; BG bacteria; BG fungi; BG invertebrates; BG vertebrates;	yes	Above(AG)- and belowground(BG) organism groups that were investigated. Levels were defined by us for consistency. Assignment to levels was based on author descriptions

Studied biodiversity metrics	Abundance; biomass; performance; taxonomic diversity; traits	yes	Organism metrics, which were used to investigate the effect of global change. Collected during screening
Study approach	Experimental; observational	no	Distinguishes between observational studies, which collected data or samples without any experimental manipulation and experimental studies where some kind of environmental manipulation was part of the study design

ROSES Flow Diagram for Systematic Maps. Version 1.0 (modified)



1451

1452 **Figure S1:** Flow diagram of single steps of the systematic map, including counts of accepted and rejected
 1453 studies at each step, adapted from ROSES (Haddaway et al., 2018).

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