Global change and their environmental stressors have a significant impact on soil biodiversity – a meta-analysis

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Abstract

Anthropogenic global changes are impacting biodiversity, however, many previous meta-analyses investigating the impact of different global changes on biodiversity have omitted soil fauna, or are limited in the scope of the global changes studied. Threats to soil biodiversity by global changes need to be understood to mitigate effects on ecosystem services provided by soils. We conducted a meta-analysis using 3,173 effect sizes from 627 publications focused on six global changes (climate change, land-use intensification, pollution, nutrient enrichment, invasive species, and habitat fragmentation) and their associated environmental stressors on soil fauna. We classified stressors as either pulse (short-term, acute) or press (long-term, chronic) stressors, and expected pulse stressors to have less impact on soil biodiversity due to buffering effects of the soil. Unexpectedly, pollution caused the largest loss in soil fauna communities, which is worrying due to continually increasing levels of pollution, as well as the poor mechanistic understanding of pollution impacts. There was no clear pattern of pulse stressors having a smaller impact on soil biodiversity than press stressors. Overall, this work shows the importance of including soil biodiversity in large-scale global change analyses, as soil organisms often do not show the same responses as organisms above-ground.

Global change and their environmental stressors have a significant impact on soil biodiversity – a meta-analysis

Running Title: GC and stressor impacts on soil biodiversity

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Abstract

Anthropogenic global changes are impacting biodiversity, however, many previous meta-analyses investigating the impact of different global changes on biodiversity have omitted soil fauna, or are limited in the scope of the global changes studied. Threats to soil biodiversity by global changes need to be understood to mitigate effects on ecosystem services provided by soils. We conducted a meta-analysis using 3,173 effect sizes from 627 publications focused on six global changes (climate change, land-use intensification, pollution, nutrient enrichment, invasive species, and habitat fragmentation) and their associated environmental stressors on soil fauna. We classified stressors as either pulse (short-term, acute) or press (long-term, chronic) stressors, and expected pulse stressors to have less impact on soil biodiversity due to buffering effects of the soil. Unexpectedly, pollution caused the largest loss in soil fauna communities, which is worrying due to continually increasing levels of pollution, as well as the poor mechanistic understanding of pollution impacts. There was no clear pattern of pulse stressors having a smaller impact on soil biodiversity than press stressors.

Overall, this work shows the importance of including soil biodiversity in large-scale global change analyses, as soil organisms often do not show the same responses as organisms above-ground.

Introduction :

Human impacts are causing unprecedented changes in biodiversity, at local scales and global scales . Climate change, land use intensification, invasive species, and nutrient enrichment are among the human impacts that are often studied, hereafter referred to as Global Changes (GCs) . Understanding the impact of such GCs on biodiversity in a generalisable way is important to be able to predict potential biodiversity changes . Thus, meta-analyses and synthesis studies have become a popular way to investigate GC effects .

Meta-analyses and synthesis studies often find that land-use change and climate change are the biggest threats to biodiversity , and invasive species also are significantly reducing biodiversity . However, other global changes, such as pollution, are often understudied in aboveground terrestrial biomes , despite their potential damaging effects , and their ever-growing rates of use . Moreover, we still lack a general understanding of how the variety of GCs are impacting soil biodiversity. Meta-analyses and synthesis studies have generally overlooked soil organisms, and those focused solely on soil biodiversity tend to address only specific GCs. This could be due to lack a of harmonised terminology resulting in inappropriate search terms , or selection criteria of the analysis (e.g., the focus on species richness;) that can preclude soil biodiversity studies.

Soil can be regarded as the most biologically diverse habitat providing a variety of ecosystem functions and services . This high diversity is mostly due to the highly complex habitat that spans multiple scales, from between soil pores to across landscapes . Thus, there is a disparity between the scale of GCs and soil biodiversity. Some GCs, such as climate change, are global (although not uniform across the entire world), whereas others act at more regional scales, such as land-use intensification or pollution, although are often widespread .

GCs can impact local biodiversity through a range of different environmental stressors, for example, climate change resulting in decreased precipitation or increased temperature . Despite the term 'stressor' implying a negative effect, global change can result in both decreases and increases in biodiversity). As a result, here, we follow definition, where stressors are causing any detectable biological change, no matter the direction. Although the environmental stressors are a result of a wide variety of different GCs, they may result in similar impacts on biodiversity due to similar mechanisms . Thus, classifying global changes based on the similarities of the characteristics and traits of the environmental stressors may allow better predictions across a wider range of global changes . Moreover, this approach may also provide a framework for exploring potential mechanisms that explain biodiversity responses to certain stressors .

In particular, we consider whether the stress has a 'pulse' or a 'press' trait . 'Pulse' stressors are discrete disturbances that may be extreme in nature and occur less often, such as droughts. Alternatively, pulse stressors may be less severe but occur more regularly; for example, tillage, which can have negative effects on soil fauna . There is some expectation that soil fauna would be less negatively impacted by pulse stressors given that soil can provide a buffer to protect against fluctuations in climate or adverse conditions , as well as a physical buffer for organisms not directly dwelling at the surface . A buffering effect of soil against the pulse stress is especially likely if the stressor does not directly impact the soil environment (e.g., harvesting of aboveground biomass;).

'Press' stressors are more continuous in nature than pulse stressors . Therefore, after a certain timeframe, press stressors result in gradual species loss . For example, pollutants can generally be considered as press stressors in soils. Pollutants, such as heavy metals resulting from industrial or urban activities or persistent pesticides can remain in the soil for centuries because they are not degraded . And although several pesticides are degraded in shorter time-frames, their regular applications over the crop season may represent a press stressor for soil communities. Over longer time frames, it is likely that press stressors would change soil physico-chemical properties, resource availability and habitat structure , as is seen with invasions of new species that directly affect the soil environment or with additions of organic amendments (such as manure, compost and sludge). This eventually can change the soil environment strongly enough to cause compositional changes in soil fauna communities.

This expectation of stress effects on soil biodiversity is not necessarily in line with effects seen in aboveground communities, where organisms may be more directly impacted by pulse stressors due to having a limited number of habitats that can provide a buffer . For example, droughts can have immediate consequences for the physiology of an aboveground organism, resulting in mortality . Alternatively, harvesting aboveground biomass removes or degrades either a part or all the habitats required for aboveground organisms, thereby also reducing populations . Therefore, using the framework of pulse *versus*press events, and determining the differences in impact mechanisms in the GCs and environmental stressors, we can start to see the importance of ensuring the explicit inclusion of soil biodiversity into global change research.

The impacts of the environmental stressors are likely to be context dependent , for example, depending on the habitat type . Impacts may also depend on the soil taxa being studied . Due to the huge diversity within the soil, soil organisms are often classified into three body size categories from micro-fauna (< 100µm), to meso-fauna (>100µm to 2mm) up to macro-fauna (> 2mm) . Within these groups, it has been assumed that traits, such as microhabitat requirements, dispersal capabilities, and reproductive rates, are sufficiently similar to influence invertebrates' responses to external pressures . Larger organisms may be more sensitive to the impacts of stressors than micro- and meso-fauna , because they have longer generation times and require larger microhabitats . As most soil micro-fauna is considered aquatic, their responses may also differ from those seen in meso- and macro-fauna .

We conducted a meta-analysis to compare the effects of six GCs (climate change, land-use intensification, pollution, nutrient enrichment, invasive species and habitat fragmentation) and their associated environmental stressors on micro, meso, and macro soil-fauna. We hypothesize that pulse stressors will have less impact on soil biodiversity than press GCs and stressors. Given that different contexts are likely to affect the impact of GCs and their environmental stressors, we hypothesize that impact of GCs and stressors will vary across the different body size categories, with macro-fauna showing the largest responses.

Methods :

Six global changes (GCs) were considered for the meta-analysis: climate change, land-use intensification, pollution, nutrient enrichment, invasive species, and habitat fragmentation. These were chosen based on the main drivers of biodiversity loss presented in other large-scale works .

Literature search

A Web of Science search was performed on 15th October 2018 searching all available literature in the Core Collection using a combination of search terms that captured groups of soil organisms 'AND' metrics of biodiversity 'AND' global change (see supplementary materials Appendix 1 for full list of search terms). This resulted in 24,979 records considered for screening (see Supplementary Figure 2 for PRISMA diagram).

Screening of titles, abstracts, and main text

Titles and abstracts were screened for suitability. Suitable abstracts mentioned at least one group of soil fauna measured in at least one reference, undisturbed, or control site, and one site impacted by a GC. To aid in screening of titles and abstracts, we used a machine-learning algorithm in the program Abstrackr alongside human-screening. Whilst the abstracts and titles were being manually screened, all papers were being dynamically assigned confidence scores by Abstrackr. After the manual screening of 9,535 abstracts (of which 6,143 were irrelevant and 3,389 were included), the Abstrackr confidence score was 0.58 or under for the remaining 15,444 articles, a low enough value to indicate the remaining articles were not relevant for the meta-analysis. This cut-off value of 0.58 was chosen based on a quality control procedure in which we randomly sampled 5% of the records within each 0.1 band of confidence scores, and screened their titles to check that they 'may be' suitable or were "definitely not" suitable. The cut-off confidence score was then based on the point where the number of 'definitely not' suitable papers was the majority of the titles within a 0.01 band. Thus, the 15,444 articles were not considered further.

The full texts of the 3,389 papers with relevant abstracts and titles were then manually screened. In order to be suitable for the analysis the article needed to have (1) measured at least one soil fauna group (e.g., earthworms, macro-fauna, oribatid mites), (2) captured the impact of one or several GCs according to our GC-specific inclusion criteria (see supplementary materials), and (3) presented the necessary data (mean values, variance, n's) to allow us to calculate an effect size for the meta-analysis.

As no definition, catalogue, or list exists of organisms considered 'soil biodiversity' , soil fauna was determined based on sampling protocol. Suitable sampling methods included soil cores, hand-sorting excavated soil blocks, or mustard extraction. Pitfall traps on their own were not considered suitable, as these data are more representative of activity densities of ground-dwelling invertebrates . However, if the pitfall traps were associated with another method targeting the soil, they were considered suitable .

Data extraction

Data, such as the control and treatment means, variances, and sampling effort were extracted either from the text, tables, or figures using Web Plot Digitizer (https://apps.automeris.io/wpd/). When data were presented as a time-series, the last time point in the series was used for the control and treatment means to maximise independence . When a gradient of impacts was presented, e.g., different fertilizer levels, the most extreme level was used as the treatment. Data were extracted at the highest level of taxonomic resolution possible but above family level (except enchytraeids, which are an important group commonly reported only at family level). When presented as functional groups (as is often seen in nematode and earthworm studies), the data were pooled together into the taxonomic group.

Each study could provide more than one comparison between a control and treatment, henceforth referred to as a 'case'. Most commonly, primary papers presented data for multiple biodiversity metrics (for example, abundance, biomass and species richness), different taxonomic groups, different GCs or environmental stressors, or from different habitat types. Each was extracted as an individual case. Where a paper presented multiple GCs/environmental stressors, each was extracted independently from any other.

Global change variables

Each case was assigned to one of six main GCs (land-use intensification, habitat fragmentation, climate change, invasive species, pollution, and nutrient enrichment). We considered nutrients and pollution separately, given that we had different hypotheses for their effects, and following . Here, pollution refers to a change in concentration of substances such as metals, pesticides, and other chemicals, although we acknowledge that pollution due to excess nutrients occurs as well.

In addition, depending on the main GC, each case was also categorised with one environmental stressor (Table 1). The stressor depended on the main GC, and the full list of stressors for all GCs, including those not used in the modelling, is provided in Supplementary Table 1. Each environmental stressor was then categorized as either a 'pulse' or 'press' stressor (Table 1). This was based on the ecological understanding of the stressor in relation to the majority of the data in the stressor (e.g., most temperature change was longer term, so was assigned as a press stressor, as opposed to shorter term 'heat wave' events which would have resulted in being assigned as a pulse stressor).

Predictor variables

For each case, data for model moderators, such as the taxonomic group, body size, and habitat type were collected. Taxonomic names were harmonised to those used by the Global Soil Biodiversity Atlas (GSBA; (Table S2). From the GSBA harmonisation, each taxonomic group was assigned to a body-size category (micro-, meso-, macro-fauna) if that had not already been done by the original author. Body-size categories were also based on . Microarthropods were assigned to meso-fauna, macro-arthropods and macro-invertebrates were assigned to macro-fauna. Any cases where authors did not classify the data to a taxonomic or size unit (e.g., described as 'All soil fauna'), were classed into one category, "All Sizes". The type of habitat the samples were from was also classified into one of six predefined classifications; agriculture, grassland, woody, cold/dry, wetlands, or artificial.

To help ensure consistency in data extraction, all project members followed a data extraction protocol created at the start of the project. In addition, data extracted from nearly all articles were checked by a second individual.

Effect Sizes

Prior to calculating the effect size for each case, variances that were not already expressed as a standard deviation, were transformed. For cases where means were zero, variances were assumed to also be zero when missing. In two publications, non-zero (< 0.1) standard deviations had been rounded to zero, these were set to 0.01 (in one publication the abundances were < 0.1 individuals m^2x10^3, and in the other publication abundances were between 0 and 50 individuals). Cases that were missing non-zero variances in either the control or treatment were removed from the analysis, as standard deviations are needed to calculate the effect size used.

For each case in the dataset, Hedges' g , a standardised mean difference, was calculated using the metafor package . A standardised mean difference is required when different cases are on different scales , and this is a common effect size calculated in ecological meta-analyses . In addition, Hedges' g is appropriate when zeros are present within either the control or treatment means (n = 127 zeros in control mean, and n = 159 zeros in treatment mean) .

Cases that measured anything other than taxonomic (species, genus) richness, biomass, abundance, or Shannon diversity, were removed, to ensure adequate data across the four metrics. Richness, biomass, abundance, and Shannon diversity accounted for 95.78% of the cases.

Four effect sizes were removed from the database due to being extreme outliers of the dataset. The median effect size of the full dataset was -0.11 and the median variance was 0.42. Three of the removed data points had effect sizes smaller than -50 (ranging from -95 to -233), with variances > 400 (ranging from 455 to 4538). The fourth datapoint that we removed had an effect size of 184, and variance of 568. Removal of the four data points had no impact on results. All four outliers were caused by relatively extreme changes in abundances and richness between the control and treatment.

Model structure

Multi-level random effects models were used for all models , using the metafor package . All models had a study-level ID (a unique ID to each primary literature source), with a unique case ID nested within it (each case, regardless of study or GC, was given a unique ID) as random effects. In addition, as the biodiversity metric used in each case resulted in significantly different impacts on the effect size (although, all resulted in a negative impact, Figure S1), the biodiversity metric was used as a crossed-effect within the random effects .

For most of the models, the fixed effects were all structured similarly. For each model, the variable of interest was interacted with body size. The interaction was then tested with a Wald-Type test ('anova' function in metafor), and removed if $p > 0.01$. If the interaction was removed the singular effects were then tested, and removed if $p > 0.01$. Main effects were retained if the interaction was retained. All models used a compound symmetry variance structure, and were fitted with restricted maximum-likelihood.

Four broad groups of models were created. Firstly, a model was created with the six main GCs (hereafter, 'main model'), where the six main GCs were the variable of interest, and the entire dataset was used. Secondly, using only the data for one GC at time (i.e., just data relating to climate change), a model was created where the variable of interest was the environmental stressor (Table 1; 'environmental stressor models'). Not all data for each GC was used in the environmental stressor models, as some environmental stressors had too little to provide robust coefficients. Thirdly, to determine how responses vary across taxonomic groups, the dataset was subset to the four most represented taxonomic groups: Acari, Collembola, earthworms, and nematodes. These were not only well represented across the six GCs, but well distributed across all environmental stressors within the GCs. These four groups were then used as the variable of interest in one model ('taxonomic model'); however, body size was not included in this model. Finally, to determine if the habitat type influenced the biodiversity response, a model was created using the main six-level GC classification, habitat type, and the interaction between the two ('habitat model'). Model simplification occurred as previously described.

Publication bias

Funnel plots were produced from the final main model and all the environmental stressor models, and therefore account for any covariates that were retained in the model. Funnel plots were produced using the 'funnel' function in the metafor package . In addition, the impact of small-study effects and decline effects/time-lag bias were tested (see Supplementary Materials, Appendix 2).

All analyses were performed in R . The dataset used in the analysis is available: https://doi.org/10.5281/zenodo.6903152. The R code for data preparation and analysis, as well as the protocol for paper screening and data extraction can also be accessed: https://github.com/helenphillips/GCimpactsSB.

Results :

In total, 3,173 cases were available for modelling, from 627 published articles (see Supplementary Figure 2 for PRISMA diagram). The cases were distributed across the globe, however, large numbers of cases were from the USA and China (Figure 1). Land-use intensification (n = 876), pollution (n = 769), and nutrient enrichment (n = 789) were the most represented GCs, with habitat fragmentation (n = 104) having the least number of cases. Most cases were in relation to meso-fauna, which included micro-arthropods (n = 1,293). However, macro-fauna and micro-fauna were also well represented (n = 1,001 and n = 731, respectively; Figure S3).

For the main model with the six main GCs, body size was removed from the model, as both the interactive and the main effect. Thus, the effect of the different GCs was the only remaining term in the model (Figure 2). The I^2 of the model was 86.31% (total variance due to heterogeneity). 48.34% of the total variance was estimated to be due to between-cluster heterogeneity, 35.89% due to within-cluster heterogeneity, and only 1.06% due to the crossed effects of measurement type. The remaining 13.69% was sampling variance.

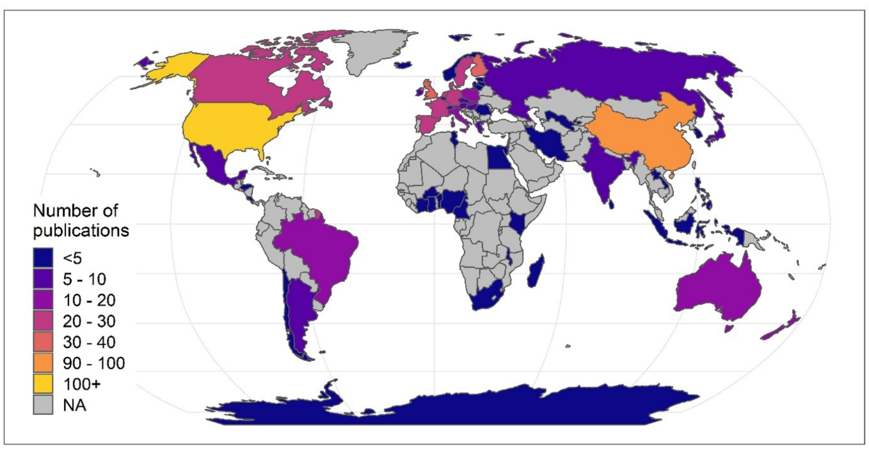

Figure 1: Global distribution of studies included in the meta-analysis**.** Colours show the number of studies from each country that were included in the analysis. Grey areas indicate countries where no studies had been conducted that were included in this analysis. Map lines do not necessarily depict accepted national boundaries.

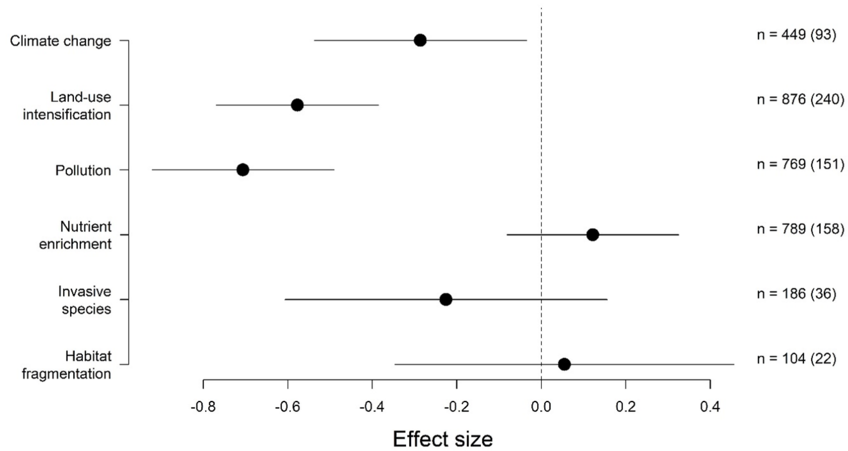

Figure 2: Change in soil biodiversity in response to global changes (GCs). Hedges' g was used as the effect size. Negative effect sizes indicate that the GC causes a reduction in biodiversity, and a positive effect size indicates an increase in biodiversity. Error bars indicate 95% confidence intervals. Effect sizes where error bars do not cross the dashed vertical zero line, are significantly different from zero. The values of n indicate the number of cases of each GC in the model, with values in parentheses indicating the number of publications.

Pollution had a significant negative impact on biodiversity (estimate = -0.71; ±95% CIs = -0.92, -0.49; p-value < 0.0001), the largest effect of all the GCs. Land-use intensification (estimate = -0.58; ±95% CIs = -0.77, -0.39; p-value = < 0.0001) and climate change (estimate = -0.28; ±95% CIs = -0.54, -0.04; p-value = 0.01) also had a significant negative effect on biodiversity, whilst habitat fragmentation, invasive species, and nutrient enrichment did not have a significant effect.

When focusing on the environmental stressors model relating to climate change, body size was removed as an effect from the model (both as an interactive effect, and a main effect). The only climate change environmental stressor that had a significant effect on biodiversity was the detrimental impact of drought (estimate = -0.52; ±95% CIs = -0.76, -0.28; p-value <0.0001; Figure 3a). The effects of gas (CO_2 and O_3) and temperature change, although trending towards a negative impact of biodiversity, were not significant. The impact of increased water (absolute amount, rates, or number of events) through floods trended towards a positive impact on biodiversity but, again, was not significant (although also had the least amount of data, n = 41 cases).

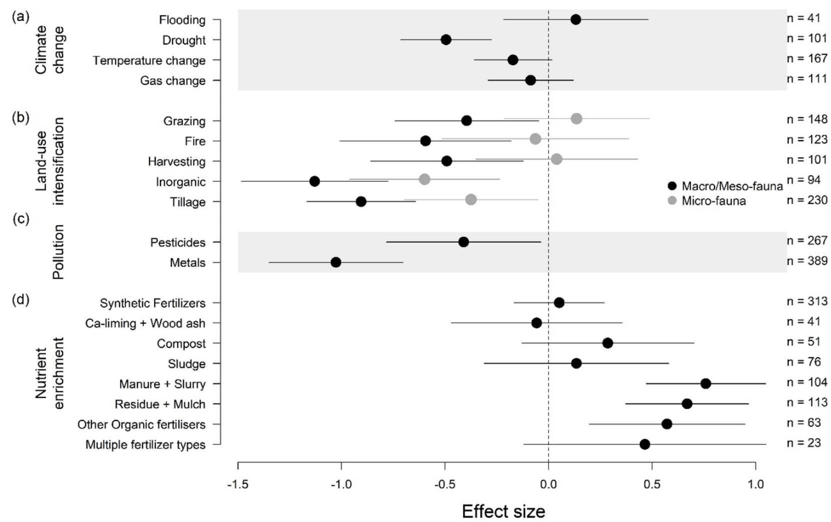

Figure 3: Change in soil biodiversity in response to environmental stressors associated with (a) climate change, (b) land-use intensification, (c) pollution, and (d) nutrient enrichment. In panel (b), the estimate for macro- and meso-fauna is shown in black, and micro-fauna in grey as body size remained as an additive term in the model. Hedges' g was used as the effect size in all models. Negative effect sizes indicate that the environmental stressor causes a reduction in biodiversity, and a positive effect size indicates an increase in biodiversity. Error bars indicate 95% confidence intervals. Effect sizes where error bars do not cross the dashed vertical zero line, are significantly different from zero. The values of n indicate the number of cases of each environmental stressor in the model. Grey shading is for enhancing readability only.

For the environmental stressors model investigating different stressors related to land-use intensification, the effect of body size remained in the model, although as an additive effect only. Overall, macro-fauna was more negatively impacted by each of the land-use intensification stressors, while micro-fauna were impacted less (estimate = 0.53; ±95% CIs = 0.22, 0.84; p-value < 0.001). Meso-fauna was not significantly different from macro-fauna, and thus was not presented separately (Figure 3b).

For both macro-/meso- and micro-fauna, the change from an organic system to an inorganic system had the biggest negative impact on biodiversity (estimate = -1.12; ±95% CIs = -1.48, -0.78; p-value <0.0001, for macro-fauna), with the increase in tillage (i.e., comparing reduced tillage practices to conventional tillage) having the second biggest negative impact (estimate = -0.91; ±95% CIs = 1.17, -0.64; p-value < 0.0001, for macro-fauna). The impact of increased fire (intensity or frequency), harvesting, and grazing also had significant negative impacts on biodiversity, although to a lesser extent (and not a significant effect when adjusting environmental stressor estimates for micro-fauna).

Within the model focussed on pollution stressors, the main and interactive effect of body size was removed from the model. The effect of pollutant type was significant, with both pesticides (estimate = -0.41; ±95% CIs = -0.78, -0.04; p-value = 0.03) and metals (estimate = -1.03; ±95% CIs = -1.35, -0.70; p-value < 0.0001) having a significantly negative effect on soil fauna communities (Figure 3c). Further inspection of the raw effect sizes, when accounting for different sources of metals and pesticides (using FAO 2018 categories;) show that there was variation of the effect sizes within each category (Figure S4). Notably, effect sizes of metals from mining/smelting demonstrate the greatest variation, often being more negative.

For the nutrient enrichment model, as with most of the models, the body size variable was removed as both an interactive and main effect, leaving just the impact of different nutrient enrichment stressors (Figure 3d).

Of the 8 different stressors, five did not have any significant impact on biodiversity (synthetic fertilizers, Ca-liming + Wood ash, compost, sludge and multiple fertilizer types) but all trended towards a positive impact, except Ca-liming + Wood ash. The impacts of manure + slurry, other organic fertilizers, and residue + mulch, were all similar, and all significantly positive (estimate = 0.76; ±95% CIs = 0.47, 1.05; p-value < 0.001, estimate = 0.57; ±95% CIs = 0.20, 0.95; p-value = 0.003, estimate = 0.67; ±95% CIs = 0.37; 0.97, p-value < 0.001, respectively).

For the invasive species environmental stressors model, as with the pollution model, both the terms for the body size and the different types of invasive species were removed from the model completely. However, in line with the main model, the overall intercept of the models was not significantly different from zero (estimate = -0.15; ±95% CIs = -0.55, 0.25; p-value = 0.47).

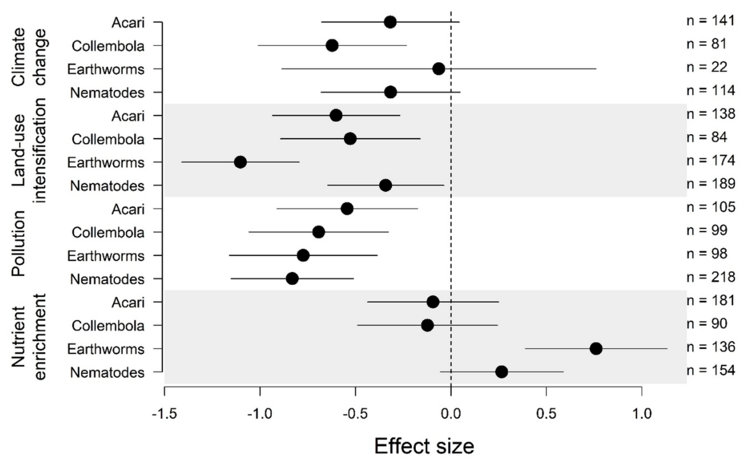

Figure 4: Change in the biodiversity of four soil taxa groups (Acari, Collembola, earthworms, and nematodes) in response to four global changes (GCs). Hedges' g was used as the effect size. Negative effect sizes indicate that the GC causes a reduction in biodiversity, and a positive effect size indicates an increase in biodiversity. Error bars indicate 95% confidence intervals. Effect sizes where error bars do not cross the dashed vertical zero line, are significantly different from zero. The values of n indicate the number of cases of each taxa group within GC in the model. Grey shading is for enhancing readability only.

The final taxonomic model (containing Acari, Collembola, earthworms, and nematodes data) retained the interaction between the taxonomic group and the GC. Just over half of the groups showed a significant negative decline in biodiversity with the GCs (9 coefficients out of 16; see Table S3 for coefficients, 95% CIs and p-values). Only earthworms showed a significant increase in biodiversity with the impact of nutrient enrichment, which contrasted with the other three taxonomic groups that showed no significant impact from nutrient enrichment.

Finally, for the habitat model containing habitat types, the six-level GCs variable, and the interaction between the two, habitat type was removed from the model as both from the interaction and the main effect.

Publication bias

The funnel plots show the asymmetry in the data (discussed further below), particularly in the case of land-use intensification (Figure S5). In addition, in the data for the main model, as well as the data for the models focused on the stressors of land-use intensification, nutrient enrichment, and to a lesser extent climate change, there is a lack of small effect sizes that have high precision (i.e., the tip of the funnel) (Figure S5).

Discussion :

We examined a wide array of GCs across all soil fauna, and in doing so, we identified that pollution and land-use intensification had the greatest negative impacts on soil fauna communities. Climate change also had a negative, albeit smaller, impact, although after adjusting for biases within the publications, this significant effect was lost. For GCs where environmental stressor was a significant predictor, there was no strong indication that press stressors had greater impact on biodiversity, except in the case of land-use intensification. Overall, the effect of the GCs did not vary with context, as there was no effect of habitat type on the estimate, and rarely was there an effect of the different body size classes. Studying the impact of pollutants may not be possible with aboveground organisms, due to the lack of primary studies focussed on pollutant impacts , but by focusing on soil biodiversity, we are able to understand how detrimental environmental pollution is relative to all other GCs. The only GC that comes close is land use intensification.

Climate change

Climate change is often referred to as one of the biggest threats to biodiversity . In this meta-analysis, despite the general decline in soil fauna biodiversity, climate change was not the greatest threat. However, a more nuanced view may be needed. Based on aboveground organisms, it might be expected that temperature changes would result in a decline in biodiversity . However, our results further reinforce the hypothesis that soils can buffer the impacts of temperature change (also found in). Indeed, the observed decline was due to clear negative effects of reduced water availability, which has previously been shown in other meta-analyses to be a strong driver of soil biodiversity . This is cause for concern, as areas of climate change-induced drought are increasing . Thus, it is likely that the detrimental impact of drought, as well as depleted soil fauna community will result in reduced ecosystem function and services in those areas , thus human populations in those areas may experience two-fold impacts.

Although we categorised drought as a pulse stressor and expected less impact on soil biodiversity than changes in temperature and gas, it was impossible to determine and quantitatively compare the strength or duration of the drought manipulations (relative to the normal levels) across the different studies with the information available. If the drought manipulations were too severe (too extreme or too long), there is the potential for the buffering capacity of the soil to be significantly reduced , resulting in biodiversity loss. In a similar vein, the temperature manipulations may also not be an appropriate length to be considered a press stressor. found that longer climate-change treatments resulted in more significant effects, although in their study, the effect was positive.

Considering the length of the treatment application using an alternative modelling structure, may provide further insights. However, often temperature changes occur simultaneously with water-regime changes, and previous studies have demonstrated that if soil water is available for soil organisms, the effects of other stressors, such as temperature increases, can be buffered against . Thus, it would be prudent to consider the synergistic effects of many of the stressors simultaneously (discussed further below), to fully understand the most detrimental components of climate change for soil biodiversity.

Land-use intensification

Land-use intensification was the second strongest GC impacting soil fauna communities. When looking at the different environmental stressors of land-use intensification, all were significantly negatively impacting soil fauna, although the shift from an organic system to an inorganic system, a press stressor, and the intensification of tillage practices, a pulse stressor, resulted in the greatest decrease. Previous meta-analyses have also found intensification of tillage practices to be detrimental to soil fauna . Tillage causes direct mortality and destruction of habitat, which exposes soil organisms to predators . However, effects can also be indirect and longer term, through a reduction of soil structure (limiting access to nutrient resources, especially for smaller organisms, and increasing exposure to an environment that may result in desiccation), changes in plant community composition altering resource quality, and reduction in soil organic matter at the surface . This highlights the weakness of using just a single trait of an environmental stressor, and shows the need to consider more than one characteristic in future studies .

It is difficult to pin-point the exact agricultural practices that promote soil biodiversity in organic systems, because organic farming specifications depend on countries, crops, and other factors . Based on previous meta-analyses the decline in biodiversity may be the result of the shift in nutrient addition regimes, as it is probable that the strong decline was most associated with the change from organic fertilisers and reduction in mulch. The addition/retention of mulch (plus other soil amendments) and organic fertilisers were particularly beneficial in this analysis, as well as others . Individually, these components promote soil biodiversity (see below), and in concert could provide even greater benefits to the soil community. However, as the addition of pesticides (singularly within the pollutants category) also significantly negatively impacted soil communities, the shift away from high pesticide use cannot be ruled out as a contributor to the positivity of organic agricultural systems. What is interesting to note is the effect of the different land-use intensification types interacted with the body size of the organisms, with macro-fauna (predominantly comprised of earthworms) being most negatively impacted. Given that earthworms mostly benefitted from the addition of nutrient enrichment there is some indication that, at least for earthworms, the nutrient enrichment aspect of organic agriculture may be the most important (Figure 4).

Pollution

Of critical concern is the strong impact of pollution on soil biodiversity. We found that both metals and pesticides had a strong impact on soil biodiversity. The fact that metals did have such strong impacts on biodiversity is not necessarily surprising. Typically, studies focused on metal pollutants were conducted in landscapes with a long history of pollution associated with mining and smelting activities . The sustained toxicity of the soil may not only result in direct mortality but may also prevent recovery of the soil fauna populations , thus resulting in large soil biodiversity loss. Additionally, authors often investigated gradients of metal pollution across a large range of concentrations , and given that our meta-analysis cases were based on the most intense comparison, this may also result in the larger effect size for metal pollutants. Indeed, pesticide studies mostly applied pesticides at the recommended application rates, that may represent much less intense levels than metal pollution gradients. In addition, although metals in soil are 'press' stressors, many pesticides can be degraded over time so their classification as a 'press' stressor may not be correct for all the studies included here. However, as long-term studies of pesticide degradation times are lacking for all the types of pesticides covered by this meta-analysis , a dichotomy in the response of press/pulse stressors may have held true if we were able to classify pesticides into their most appropriate press/pulse categories.

Additional insight would also be likely if we were able to further determine or classify the concentration of pollutants or, alternatively, compare different types of pollutants at equivalent levels. In traditional dose-effect theory in ecotoxicology, the dose of the pollutant is typically one of the strongest drivers of biological response. For instance, focussed their meta-analysis solely on nematodes and heavy metal pollutants and were able to determine that increasing concentrations of heavy metals resulted in more pronounced declines in biodiversity. However, found that across terrestrial and aquatic systems, decomposers' community responses to pollutants did not change with pollutant levels but were generally negative. The community-level response may be affected by combined direct toxic and indirect effects mediated by changes in species interactions, yielding not so straightforward dose-response curves at this ecological scale. Moreover, primary studies often addressed the combined effects of multiple pollutants that may have interactive effects causing even further deviation from classical dose-effect theory .

In general, the impact of pollutants on terrestrial biodiversity is particularly understudied , and although there are several studies on the impact of pollutants on soil biodiversity, there are still large gaps in our knowledge . As there was a limited number of pollutant stressors that could be analysed in this meta-analysis, we hope that future studies will address other types of pollutants (such as microplastics, hydrocarbons, emerging pollutants;) in order to understand the role they may play in biodiversity change. Given the clear negative effects reported here, our results thus call for more research focusing on the mechanisms that lead to community-level responses, on the impacts of a broader range of pollutant types, and more consistent ways of standardising pollutant levels in primary studies. Our results also reinforce recent calls for coordinated global monitoring and policy-actions based on scientific evidence and call for a proper integration of soil biodiversity in such initiatives .

Nutrient enrichment

Nutrient enrichment did not have an overall significant effect on soil fauna communities. However, the effects on soil fauna did vary depending on the nutrient-based environmental stressors. Given that all nutrient stressors were considered to be press stressors, this once again highlights that the use of just a single trait does not capture the complexity of the stressors, especially when it is unclear how long each nutrient type remained in the soil before degrading. Organic-based amendments and fertilisers increased soil biodiversity, and several mechanisms may explain this pattern. It may be due to the increased carbon in the soil . found that inorganic nitrogen fertilisers simplified nematode communities but organic fertilisers (for example, crop residue) increased carbon in the soil and had positive impacts on the nematode community. However, it may also be because the organic-based fertilizers provide the nutrient resources at a slower rate , as well as create micro-habitats for a variety of soil organisms . The fact that we did not find a significant decline in biodiversity with synthetic fertilizers was somewhat surprising, although this result has been found in another meta-analyses .

, in their meta-analysis, found that nutrient addition had positive effects on soil biodiversity at low doses, and effects became negative at higher concentrations. Thus, if concentration amount was not taken into consideration, the overall mean effect size was neutral. Additionally, found that synthetic fertilisers had a significant negative effect on soil fauna but were no longer significant when the duration of the application was increased (>5 years). Similar results were found in , where long-term application of synthetic fertilizers did not negatively impact earthworms. Both hypothesised that any effect on soil biodiversity was indirect, as the increased nitrogen in the soil benefited the crops, and thus in the longer term the increased plant biomass in the soil resulted in increased carbon, ultimately benefiting the soil community . Without looking into the concentration and application rates, or the temporal aspects of the treatment, all of which are hard to standardise across such a wide variety of studies, we would not be able to test these mechanisms, but these may explain the lack of a significant decline with synthetic fertilizers.

Context-dependency of the impacts

The effect of the global changes did not vary across different habitat types or organism body size classes for most of our analyses. The lack of significance for body size was also highlighted when we analysed only the four most abundant taxonomic groups (Acari, Collembola, nematodes, and earthworms), which represent all three body size classes. The patterns for nutrient enrichment were the most surprising, where earthworms responded differently from the other three taxa. For the other GCs, there were limited differences. However, looking at community composition or functional and trophic groups instead of taxa or body size groupings may tease apart other context-dependencies . For example, previous work has shown various responses to environmental stressors and GCs depending on the different functional types of earthworms .

In other analyses, community composition of soil microbial communities were more affected than metrics of alpha- and beta-diversity to different GCs. Incorporating such metrics of soil fauna communities may be possible, especially in the case of nematodes and earthworms, as communities are often reported at the level of functional types. In addition, the biodiversity metrics used in this meta-analysis may not have captured all the changes that occur to soil communities in invaded ecosystems, resulting in the non-significant changes. For example, established that soil communities responded more similarly within trophic groups, and accounting for trophic group (and habitat type) within the meta-analytic framework was needed to see the impact of invasive species on soil fauna abundance.

Publication bias

Across the entirety of the dataset, as well as within each GC, there was a distinct lack of positive large effect sizes, resulting in asymmetry. Yet, it is difficult to fully understand the type(s) of bias that has caused the asymmetry . It is most likely that the bias is a result of certain experiments never being published , through selective reporting from either authors or journals . However, it is possible that the GCs rarely have a positive effect on soil biodiversity. Thus, in that instance the ‘bias’ is not a true bias, and in theory the results should not be adjusted, as done here. Although we are unable to establish the underlying cause of the bias, adjusting for the bias had minimal significant impact on the outcomes of the meta-analysis (Supplementary Materials, Appendix 2). The results that did significantly change, either by no longer being a significant impact or becoming significant, were those with the least amount of data, and therefore least robust coefficients.

Limitations and future directions

Using the ‘pulse’ and ‘press’ traits to describe the environmental stressors helped to introduce the mechanisms, and highlight the similarities, that may result in biodiversity change, regardless of the GC they are associated with. However, the lack of consistency in results may be due to the simplistic nature of using just a single trait for each stressor. Indeed, proposed 30 different traits to characterize environmental stressors, a classification scheme that they found worked well when applied to a soil microbial experiment. further stated that stressors should not only be classified based on their traits but also sources, temporal overlap, mode of action, and co-tolerance to determine their similarities and aid predictions. Unfortunately, there is currently no classification scheme that assigns environmental stressors to such a wide range of different traits, which would be needed to fully realise the benefits of this approach.

As not all GCs and environmental stressors had enough data to enable in depth investigation, further questions remain as to the specific impacts of habitat fragmentation and invasive species on soil fauna. It would be expected that both habitat fragmentation and invasive species alter the soil enough to impact many soil organisms . Alternatively, more moderators may be needed to capture the heterogeneity (e.g., habitat type;), and/or more complex interactions between the moderators .

The breadth of this meta-analysis provides us with insight and comparisons that have previously not been possible. However, it also reduces our ability to ‘zoom’ into specific effects, such as different doses of GCs (stressor concentrations, amounts), temporal aspects or community composition shifts. Therefore, further experimental work is needed to elucidate variations in exposure to different GCs and their influences on soil biodiversity, as well as more specific meta-analyses. Although this meta-analysis contained a large number of data points, there still was a lack of data for specific questions, for example, habitat fragmentation and invasive species as discussed above, different pollutant types, and better representation of taxonomic groups. An additional focus on additional diversity indices, such as community composition and beta diversity metrics, may also be insightful. We hope that by highlighting the relative lack of data, these gaps may be overcome in the future with additional studies.

One aspect of the study of global change that is being highlighted in the scientific literature as an important avenue of research is the potential impact of two or more GCs simultaneously . Many meta-analyses that looked at the additive and interactive effects of GCs on biodiversity have found that the interactions between GCs are important . Although it might be anticipated that the interaction between GCs may result in greater negative impacts than expected based on the singular GCs , there is the potential for the presence of two GCs to result in less of a negative impact than expected . Given the changing world that we are in, and that GCs rarely act singularly on biodiversity , this would be the most important avenue to study further, and is indeed possible within a meta-analysis framework when factorial data are present .

Conclusion

Overall, many of the GCs and environmental stressors studied here reduced soil biodiversity, irrespective of the body size of the organisms or habitat type. However, there are notable exceptions where a biodiversity increase occurred, namely with addition of more organic-based nutrient enrichments. Given the profound decline of soil biodiversity due to pollution, a GC that is understudied in aboveground literature, we emphasize the need to increase research on its impact across all realms. By classifying GCs and environmental stressors in terms of pulse or press traits we were able to link the similarities between the different stressors in terms of their mechanisms with the ways they may impact soil fauna communities. As the responses of soil organisms to GCs and environmental stressors differed from published responses of aboveground organisms, soil biodiversity needs to be explicitly included into large-scale analyses of global change impacts.

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References

Table 1: The environmental stressors associated with the five GCs that were analysed (Habitat fragmentation lacked sufficient data to investigate the associated environmental stressors). All environmental stressors were classified as either a 'press' stressor or a 'pulse' stressor.

Global Change	**Environmental stressor**	**Stressor trait**
Climate change	Gas change (CO_2, O_3)	PRESS
	Temperature change	
	Water availability - Drought	PULSE
	Water availability - Flood	
Land-use intensification	Grazing Organic versus inorganic	PRESS
	Harvesting Fire Tillage	PULSE
Pollution	Metals Pesticides	PRESS
Nutrient enrichment	Synthetic fertilizers Ca-liming + Wood ash Compost Manure + Slurry Mixture Other Organic fertilisers Residue + Mulch Sludge (including Biosolids)	PRESS
Invasive species	Aboveground animal Belowground animal Plants-non-woody Plants-woody	PRESS
Habitat fragmentation	NA	NA

Table 2 : Adjusted and unadjusted effect sizes (Hedges' g) and CIs for all models (GCs and environmental stressors). Effect sizes were adjusted using methods in to account for small-study effects, see Supplementary Materials Appendix 2. Bolded effect sizes indicate statistically significant from zero.

	GC/Environmental Stressor	**Adjusted effect size**	**Adjusted CIs**	**Unadjusted effect size**	**Unadjusted CIs**
GC main model	Climate change	-0.13	[-0.37,0.12]	**-0.29**	[-0.54,-0.04]
	Land-use intensification	**-0.41**	[-0.60,-0.21]	**-0.58**	[-0.77,-0.39]
	Pollution	**-0.50**	[-0.72,-0.29]	**-0.71**	[-0.92,-0.49]
	Nutrient enrichment	**0.31**	[0.10,0.51]	0.12	[-0.08,0.33]

	GC/Environmental Stressor	Adjusted effect size	Adjusted CIs	Unadjusted effect size	Unadjusted CIs
	Invasive species	-0.11	[-0.48,0.26]	-0.23	[-0.61,0.16]
	Habitat fragmentation	0.18	[-0.21,0.57]	0.05	[-0.35,0.46]
Climate change	Flooding	0.30	[-0.07,0.66]	0.11	[-0.25,0.48]
	Drought	**-0.32**	[-0.56,-0.08]	**-0.52**	[-0.76,-0.28]
	Temperature change	-0.02	[-0.23,0.20]	-0.20	[-0.41,0.01]
	Gas change	0.06	[-0.17,0.29]	-0.11	[-0.34,0.12]
Land-use intensification	Grazing	0.02	[-0.32,0.35]	**-0.40**	[-0.74,-0.05]
	Fire	-0.11	[-0.51,0.29]	**-0.59**	[-1.01,-0.18]
	Harvesting	-0.02	[-0.38,0.34]	**-0.49**	[-0.86,-0.12]
	Organic vs. Inorganic	**-0.68**	[-1.03,-0.33]	**-1.13**	[-1.48,-0.78]
	Tillage	**-0.40**	[-0.67,-0.14]	**-0.91**	[-1.17,-0.64]
Pollution	Pesticides Metals	**-0.37 -0.91**	**[-0.73,-0.002] [-1.23,-0.59]**	**-0.41 -1.03**	**[-0.78,-0.04] [-1.35,-0.70]**
Nutrient enrichment	Synthetic fertilizers	-0.18	[-0.43,0.06]	0.05	[-0.17,0.27]
	Ca-liming + wood ash	-0.28	[-0.70,0.15]	-0.06	[-0.47,0.35]
	Compost	0.01	[-0.43,0.44]	0.29	[-0.13,0.70]
	Sludge (including biosolids)	-0.08	[-0.53,0.38]	0.13	[-0.31,0.58]
	Manure + slurry	**0.48**	[0.16,0.80]	**0.76**	[0.47,1.05]
	Residue + mulch	**0.43**	[0.11,0.75]	**0.67**	[0.37,0.97]
	Other organic fertilisers	0.34	[-0.05,0.73]	**0.57**	[0.20,0.95]
	Multiple fertilizer types	0.21	[-0.39,0.81]	0.47	[-0.12,1.05]
	Invasive species (all stressors mean)	**0.52**	[0.05, 0.98]	-0.15	[-0.55, 0.25]