Dear Dr Kees Jan van Groenigen,

Thank you for the opportunity to revise our manuscript and for your thoughtful comments. We appreciate the careful review and constructive suggestions by the referees that helped us improve our manuscript considerably. We hereby submit our revised manuscript entitled “Soil responses to manipulated precipitation changes: An assessment of meta-analyses.” As indicated in the responses that follow, we have addressed all the comments made by you and the referees in the revised manuscript.

Editor’s comments

- **Comment 1**: Your manuscript has now been seen by two reviewers. Both of them provided some excellent suggestions to improve your manuscript. While I fully agree with both reviewers that a quantitative synthesis of the various meta-analyses would be a worthwhile effort, this would amount to an enormous amount of extra work. It would require access to the raw data of all meta-analyses (to remove overlap between datasets; calculating an average across meta-analyses without removing such overlap would amount to pseudo-replication). About 10 years ago I was involved in such a "meta-meta-analysis" for just one variable (soil C stocks under elevated CO_2), synthesising results for only 4 meta-analyses (see Hungate et al. 2009, GCB). That analysis alone resulted in an enormous amount of work; doing the same thing for 16 meta-analyses and 42 variables is not realistic.
  However, I agree with both reviewers that "synthesis" in the title implies that this is exactly the kind of work you would be doing. A proper synthesis would also address points like the one brought up in comment 4 by Dr. Dijkstra. Perhaps the authors could choose a phrase that more accurately describes their approach? "Comparison" or "assessment" could both work.

  Response to Comment 1: Thank you for your understanding regarding the difficulty of conducting a meta-analysis of meta-analyses. We also thought of conducting a meta-analysis at the very initial stage of this project. However, we realized that many meta-analyses have been already conducted on the same variables of interest, but in some cases, yielded contradicting results. This is how we came up with this idea of comparing multiple meta-analyses, and we believe that it is beneficial information to show to the community. We agree that “synthesis” could be misleading in the title and in the text, and therefore, we changed the title to “Soil responses to manipulated precipitation changes: An assessment of meta-analyses”. We also replaced “synthesis” or “summary” with “comparison” or “assessment” in the text.

- **Comment 2**: Both reviewers provide good suggestions to add depth to your discussion, and you indicated you would be willing to incorporate these. In the absence of a true quantitative synthesis of the meta-analysis, addressing comment 2 by Dr. Dijkstra and comment 21 by Dr. Baker seem especially important.

  Response to Comment 2: Thank you for your specific advice. Please find our responses to each comment below.

Referee #1: Feike Dijkstra

- **Comment 1**: Unlike what the title suggests, this is not a synthesis, but merely a summary, which is unfortunate.

  Response to Comment 1: We see how the word "synthesis" in the title could give the wrong impression. We have now changed the title to "Soil responses to manipulated precipitation changes: An assessment of meta-analyses", and replaced "synthesis" in the text with "comparison" or "assessment". In this way, the audience should expect to read about what we actually did in this paper - not a meta-analysis of meta-analyses or a giant combined analysis but rather a comparative study. We would like to kindly note that conducting a combined synthesis that incorporated all original data from all studies was not realistic for us considering the time and effort required. Although our original idea was to conduct a true synthesis, we immediately realized that it was infeasible for us (also the recent large-scale meta-analysis by Song et al. (2019) took a similar role, if with a somewhat different focus), and chose instead to compare the existing meta-analyses. We found that a good number of meta-analyses had been already conducted on many of the same variables, but they sometimes yielded contradictory results. We believe that our comparative study, providing an overview across many studies, has value and is worth presenting to the scientific community.

- **Comment 2**: It provides some research gaps (e.g., lack of data on nitrification, denitrification and fixation), but even there, the authors do not really provide a rationale for WHY more information on this is needed.

  Response to Comment 2: We believe that these "process" variables need further examination because they have a greater potential of informing model design and helping to evaluate model responses. For example, Salazar et al. (2019) has shown that incorporating microbial metabolic state (active vs. dormant) could improve R_h models compared to the models based solely on physical predictors. Meta-analytical treatments of processes such as nitrification and denitrification could reduce uncertainty related to the representation of these processes in models; accurate representation is important for projecting societally relevant changes in variables such as nitrate leaching and soil emissions of N_2O and NO_x. We included this discussion in Sect. 4.1 (*l*. 349-356).

- **Comment 3**: I also disagree about the statement in the abstract that "rates of processes underlying these variables are less frequently covered" than pools. Indeed, respiration rates (Figure 1) have some of the largest observations compared to some of the pools.

  Response to Comment 3: Yes, this is a good point. Respiration is the most obvious exception; it is one of the most frequently covered variables. We mentioned "rates of processes" generally in the abstract, and specifically listed rates of mineralization, fixation, and de/nitrification as examples. We clarified that there are some processes that are frequently studied, such as respiration (*l*. 25-26), so there should no longer be confusion.

- **Comment 4**: I was further disappointed that no distinctions were made that go beyond effects of decreased and increased precipitation. It is well known that a large number of the 42 soil response variables listed here are quite dynamic in time and depend not only on the overall relative decrease or increase in precipitation, but also on timing, duration and frequency. I believe different soil responses to changes in precipitation among studies could for a large degree be described to differences in intensity and frequency, and I think this is a missed opportunity for discussing these issues in greater detail.

Response to Comment 4: This is a great point, and we did initially attempt to cover in detail differences related to treatment timing, duration, intensity, and frequency, as well as other methodological and environmental factors. However, even covering the general responses to so many variables for both decreased and increased precipitation led to a lengthy manuscript, and we decided that the text should only discuss the effects of treatment timing and other factors briefly. Therefore, in each section, we concisely highlighted cases in which these factors affected each meta-analysis result. In the supplemental information, we discuss the importance of these factors in further detail, as well as how frequently they are taken into account in meta-analyses. We clarified this point in Sect. 4.2 (l. 378-381). We believe that another project could more fully examine methodological and environmental differences.

- **Comment 5**: It was further unclear if only field studies were included when extracting the data from the 16 meta-analyses. I know some of the meta-analyses did include soil laboratory incubation studies,but I am not sure about all 16 meta-analyses. I can imagine that some of the soil variables would respond quite differently depending if they were measured in the field, greenhouse, or lab (and with or without plants).

  Response to Comment 5: In section 2.1 we specify that "we collected meta-analyses that included only field studies where the magnitude of precipitation was manipulated." We have now added "Some meta-analyses included both field and lab/greenhouse experiments, but we only analyzed field data in our comparisons." to clarify this point (*l*. 84-85).

- **Comment 6**: I was unclear what the difference was between "root biomass" and "belowground biomass" (Table 2). How are they different?

  Response to Comment 6: Belowground biomass was measured by drying soil cores (Wu et al., 2011), and thus includes roots and other plant and animal materials. Root biomass includes biomass that derives from roots only. We clarified this with new text in Sect. 3.1 (l. 123-125) and a footnote in Table 2.

- **Comment 7**: l. 110: I guess strong agreement is not surprising if the same data are used for different meta-analyses. How much overlap in data used does there exist among the meta-analyses?

  Response to Comment 7: This is a great question, and we have to note that we did not set out to do our own meta-analysis, nor to specifically analyze the overlap in data across the meta-analyses we found. We now mention this clearly in Sect. 4.2 (*l*. 398-401). However, one can guess an approximate extent of overlap from the sample size and study year, which we present. The publication years of the meta-analyses range from 2011 to 2018, and newer studies likely include data that earlier studies could not have included. We think it is important to show that, while every meta-analysis has a unique sample size and time range, there is typically strong agreement among them for any given variable.

- **Comment 8**: l. 234: "humidity affects P deposition". How? I thought most atmospheric deposition of P was in the form of dry deposition.

  Response to Comment 8: While some P is dissolved and deposited in rain, mist, and snow, these are not the same as humidity, and the amounts are typically quite small. This phenomenon is not critical for this manuscript, and the statement was somewhat misleading, so we deleted it (Sect. 3.4).

- **Comment 9**: l. 268-272: I don't believe microbial community responses to precipitation changes are as clear as suggested here, and probably strongly depend on timing, intensity and frequency of the precipitation manipulation.

  Response to Comment 9: Thank you. We agree that these caveats are important. We added remarks at the conclusion of this section to highlight these dependencies (*l*. 307-311).

Referee #2: Nameer Baker

- **Comment 1**: The authors present a useful meta-analysis of meta-analyses on the response of a wide variety of soil factors to increased or decreased precipitation. I believe that the authors have collated published data in a manner that merits publication, but I believe that the results of the study could be significantly improved if a consistent manner to combine and interpret data across meta-analyses could be employed, rather than the method of treating each meta-analysis as an individual unit for comparison. I appreciate that the authors do bring up the sample sizes of each meta-analysis when discussing them and weight the inferences drawn from larger studies more heavily, but I wonder if there is a more effective way to combine the results from the various studies to draw conclusions. Could meta-analyses that presented the same variables have the effect sizes for that variable combined to produce one effect size for the response of the variable to changes in precipitation more generally across studies? This would require knowing the standard deviation of each variable within each meta-analysis, but would make for a much simpler presentation and interpretation of the data, as well as a more valid weighting of the results.

  Response to Comment 1: We appreciate this suggestion, and we agree that having one effect size for each variable would greatly simplify the presentation and interpretation. However, we find it challenging to implement because a few 95% CIs are missing, and there are some overlaps of empirical data used among meta-analyses. Therefore, deriving one effect size would not be an accurate calculation. The fact that there are some overlaps of empirical data has been pointed out by the first referee, and for this reason, we included sample size and publication year of each meta-analysis (please see our complete response to the first referee's Comment 7 above; we included discussion in Sect. 4.2, *l*. 398-401). Furthermore, there are some merits of showing individual meta-analyses; this approach displays the (in)consistency among the meta-analyses' results, and also displays which variables have been more frequently covered (and with greater or lesser sample sizes) compared to other variables.

- **Comment 2**: That is my main request that would require significant alterations to the text and the figures, but I do have some more easily implemented concerns, as well. I wonder if would it be possible to change the abbreviations "IP" and "DP" to something like "up arrow P" and "down arrow P," respectively. This would be easier for the reader to follow in the text, though you might then also want to think about using "W" instead of "P" to refer to precipitation/water to avoid then making it look as though phosphorus content is what is being discussed.

  Response to Comment 2: We understand that P could be confusing shorthand for precipitation, but "W" can also cause confusion in the global change community as "W" often refers to warming. We also see IP and DP used in other literature (such as Zhou et al., 2018), and we believe that IP and DP would not cause significant confusion, especially because we clearly define IP and DP in the text and each figure's caption. We very much appreciate this suggestion, but we prefer to keep IP and DP.

- **Comment 3**: Is there also a consistent way to talk about results that had a trend with precipitation, i.e. where something was reduced when precipitation was reduced and increased when precipitation was increased? For instance, saying a variable is positively correlated with precipitation across treatments or negatively correlated with precipitation across treatments? This might also be easier for readers to follow.

  Response to Comment 3: While we agree that showing a trend with precipitation could be useful information, it is difficult to make, for example, a graph of x = precipitation change (%) and y = effect size and show the relationship (= trend) because a meta-analytic result could incorporate multiple precipitation change levels. Although we could not quantitatively describe trends across the meta-analyses, qualitative trends are evident for some variables. When qualitative trends can be summarized across treatments, we now describe them (*l*. 179-183, 227-228).

- **Comment 4**: Finally, I wonder if it also might make more sense to group enzyme results with microbial biomass, as they are a microbial response and that way you don't have to spread their discussion out over multiple sections. This is just a suggestion, however.

  Response to Comment 4: We initially considered including enzymes in the microbial biomass section. However, as there are respective enzymes for carbon, nitrogen, and phosphorus cycles, we decided to break them into each section. In this way, we were able to summarize enzyme responses in each cycle and relate their responses to other components of the cycle.

- **Comment 5**: 94 – Did you also use Hedge's d for just these variables, or did you then use it for all variables?

Response to Comment 5: We used Hedge's d for only these variables.

- **Comment 6**: 122 – This is a place where it would help to be more explicit with your results given that you are saying they are in-line with an expectation, and you can use whatever way you decide to to talk about consistent trends with precipitation (for instance, the response of belowground NPP to both decreasing and increasing precip).

  Response to Comment 6: Thank you for your suggestion. We changed the text to be more explicit about our findings, and also included the trend for changes in belowground NPP with precipitation changes (*l*. 133-134).

- **Comment 7**: 127 – If these are general trends across meta-analyses, then how do differences in soil type explain these results more than the differences in nature of the C pool being measured?

  Response to Comment 7: Upon reflection, we felt that this section of our manuscript was confusing, and have rewritten it (see lines 139-143). Among other changes, we have removed the reference to soil type here.

- **Comment 8**: 149 – Are there any hypotheses as to why Rh is affected by decreased precip in boreal forest and wetlands, but not in tropical or temperate forests? How about for the effect of increased precipitation in forests and grasslands, but not in wetlands?

  Response to Comment 8: We added the following sentences to address this point (*l*. 170-174): "We hesitate to draw strong conclusions from these differences because of the relatively small sample sizes. Zhou et al. (2016), for example, have a sample size of four and five for the tropical and temperate forests, respectively, for DP, and the effects are highly uncertain. The biomes with significant effects – wetlands under DP and grasslands under IP – have higher sample sizes, of 10 and 15, respectively. Biological mechanisms behind these differences can also be hypothesized, such as differences in microbial sensitivity to moisture across systems."

- **Comment 9**: 151 – It is unclear what the conclusion to be drawn from this sentence is.

  Responses to Comment 9: This paragraph introduces variability in effect size depending on biomes, methods, and other factors. We added more synthetic paragraph following this sentence that clarifies that these general effects can depend on a variety of factors (*l*. 174-177).

- **Comment 10**: 185 – This is an example of where your presentation and discussion of results would benefit greatly from being able to combine effect sizes across meta-analyses for like variables.

  Response to Comment 10: As we described earlier, it is challenging for us to combine effect sizes. Nevertheless, we appreciate this suggestion and leave it for the next project to achieve.

- **Comment 11**: 192 – This is a difficult sentence to parse, I'm not sure how best to remedy it but perhaps something like "However, the product of mineralization and N2 fixation is NH4+, and it increases under DP according to one of three meta-analyses even though fixation could be suppressed."

  Response to Comment 11: We modified the sentence accordingly (*l*. 223-225).

- **Comment 12**: 225 – This brings up something that is a bit lacking in discussion of these metaanalyses – are any of them biased or targeted in some fashion, or are they all global? And would a geographic analysis of where all the study sites employed in all of the meta-analyses reveal some obvious blind spots or areas that have been overrepresented in the literature? These would be valuable conclusions to be able to make as a result of your study.

  Response to Comment 12: None of the meta-analyses has targeted region/country/biome to conduct their meta-analysis except for Brzostek et al. (2012), meaning that they all include empirical observations from around the world. Yet, the observations are concentrated in the US, Europe, and China, and are sparse in other regions. Brzostek et al. (2012) is US-only, but they include a wide range of ecosystems and biomes. We included this description in the Methods (*l*. 92-95). Since this is a great point to discuss, we added discussion in the Knowledge Gap section as well (*l*. 358-366).

- **Comment 13**: 237 – It may be worth bringing up timescale of studies here for reference relative to P-weathering rates.

  Response to Comment 13: We modified the section as suggested (*l*. 258-261).

- **Comment 14**: 255 – It seems that you may be able to draw the conclusion that moisture appears to be generally limiting for microbes in soil.

  Response to Comment 14: We added a sentence at the end of the paragraph (*l*. 292-293).

- **Comment 15**: 260 – What direction was this response?

  Response to Comment 15: The sentences you pointed to are showing a non-significant effect, so there is no direction. If you meant "Although Blankinship et al. (2011) and Yan et al. (2018) estimated significant effects on the abundance of fungi and F:B ratio (n = 4), ...", both negative and positive effects of IP on the abundance of fungi, and negative effect of DP on F:B ratio. We modified the sentence to clarify the direction (*l*. 297).

- **Comment 16**: 271 – I am not sure that this is the best way to phrase this result, as it appears more that changes in precip don't favor one over the other.

Response to Comment 16: We had a similar comment from the first referee as well, and we changed the concluding sentence to emphasize the variability of effects based on the magnitude, duration, and timing of the precipitation treatment (*l*. 307-311).

- **Comment 17**: 281 – In what direction could the ratio be altered?

  Response to Comment 17: As MBC:MBN increased with IP, soil microbial biomass C:N:P could also be increased to have more weight on carbon. We modified the sentence to clarify this point (*l*. 323-324).

- **Comment 18**: 283 – How would the mycorrhizal symbiosis change the dynamics? A bit more detail would be useful to the reader.

  Response to Comment 18: Strong mycorrhizal symbiosis might be able to help a plant with nutrient uptake under DP and help maintain the soil N:P ratio. We added a sentence to explain this (*l*. 326-327).

- **Comment 19**: 287-292 – This section feels sparse, and would be well-served to also bring up ecosystems or geographic regions that have been under- or over-sampled, as mentioned in a previous comment. Also, what about the paucity of studies that have measured bacterial:fungal biomass responses to increased precipitation?

  Response to Comment 19: It is a great point to include the geographic differences in observations, as well as the paucity of studies in bacterial:fungal biomass responses. We improved the entire section to reflect this suggestion (Sect. 4.1).

- **Comment 20**: 301 – Some more discussion of what this blind spot in terms of N-process rates means for inferring conclusions about the N-cycle in soil would be useful to the reader to understand why this is valuable fruit to pursue.

  Response to Comment 20: We had a similar comment from the first referee as well, and we agree that we needed to elaborate on the importance of these nitrogen process rates variables. We improved the section to reflect your suggestion (Sect. 4.1, *l*. 349-356).

- **Comment 21**: 317 – Do you have any suggestions as to what types of data formatting / archiving you ran into that was helpful or a hindrance? You have an opportunity to say some things from this pulpit, take advantage!

  Response to Comment 21: Great suggestion. We added discussion in Sect. 4.2.

- **Comment 22**: 322 – I'm not sure this statement is quite true given the response of microbial biomass and the crude measures of microbial community assayed – it is fair to say that the ratio of fungi to bacterial biomass is insensitive, but that is not the same as the community being resistant.

Response to Comment 22: We agree with this point, and modified the section based on your comment (Sect. 5).

- **Comment 23**: Figures – Could you bold the symbols used to indicate the direction of the effect to make them stand out more? Also, if you are not going to use the raindrops to denote precip effects on each flow-figure then don't use it on any of them.

  Response to Comment 23: We bolded the symbols used in Figures 1 and 3, and removed the raindrops in Figure 1.

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Soil responses to manipulated precipitation changes: An ~~synthesis~~assessment of meta-analyses

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Abstract. In the face of ongoing and projected ~~precipitation~~climatic changes, precipitation manipulation experiments (PMEs) have produced a wealth of data about the effects of precipitation changes on soils. In response, researchers have undertaken a number of synthetic efforts. Several meta-analyses have been conducted, each revealing new aspects of soil responses to precipitation changes. Here, ~~W~~we ~~synthesize~~conducted a comparative analysis of ~~-~~ the findings of 16 meta-analyses focused on the effects of ~~decreased and increased~~ precipitation changes on 42 soil response variables, covering a wide range of soil processes.~~, and examining~~ We examine responses of individual variables as well as more integrative responses of carbon and nitrogen cycles. We find ~~found a~~ strong agreement among meta-analyses that belowground carbon and nitrogen cycling accelerate under ~~decreased and~~ increased precipitation and slow under decreased precipitation ~~inhibits and promotes belowground carbon and nitrogen cycling, respectively,~~ while bacterial and fungal ~~microbial~~ communities are relatively resistant to ~~precipitation changes~~decreased precipitation. Much attention has been paid to fluxes and pools in carbon, nitrogen, and phosphorus cycles, such as gas emissions, soil carbon, soil phosphorus, extractable nitrogen ions, and biomass.~~, but t~~The rates of processes underlying these variables (e.g., mineralization, fixation, and de/nitrification) are less frequently covered in meta-analytic studies~~, (e.g., rates of mineralization, fixation, and de/nitrification~~ with the major exception of respiration rates~~)~~. Shifting scientific attention to these less broadly evaluated "processes" would~~, therefore,~~ deepen the current understanding of the effects of precipitation changes on soil and provide new insights. By ~~comparing~~ jointly evaluating meta-analyses focused on a wide range of ~~different~~ variables, we provide here a ~~quantitative and~~ holistic view of soil responses to changes in precipitation.

1 Introduction

Soil is an important component of terrestrial ecosystems through which carbon, nitrogen, phosphorus, and other elements cycle. Biological processes in soils, such as those driven by plant roots, microbes, and enzymes, regulate nutrient cycling, with direct impacts on aboveground plant and animal communities (Bardgett et al., 2008). Rates of biological activity in soils are largely determined by physical parameters, one of the most influential being soil moisture (Stark and Firestone, 1995; Brockett et al., 2012; Schimel, 2018). Historical observations have shown that annual precipitation has either increased or decreased significantly in many regions, and the intensity and frequency of precipitation extremes (heavy rainfalls and droughts) have likewise increased in many regions (Frei et al., 2006; Lenderink and van Meijgaard, 2008). These changes in precipitation patterns are projected to continue in the future, possibly at a faster rate (Bao et al., 2017).

The activity of plant roots, microorganisms and enzymes is maximized at optimal soil water content, which is unique to each group of organisms, soil type and ecosystem (Bouwman, 1998; Schimel, 2018). Water in soil functions as (1) a resource to promote metabolism of microbes and plants, (2) a solvent of nutrients, and (3) a transport medium to provide pathways to solutes and microorganisms (Schimel, 2018; Tecon and Or, 2017). In a water-limited environment, reduced belowground activities are common (Borken et al., 2006; Sardans and Peñuelas, 2005). The negative responses of soil processes to decreased precipitation are attributed to reduced metabolism of the organisms (Salazar-Villegas et al., 2016; Schimel et al., 2007), limited substrate availability/diffusivity (Manzoni et al., 2016), restricted mobility of the organisms (Manzoni et al., 2016), or a combination of these (Schimel, 2018). Increased precipitation, on the other hand, generally promotes processes by shifting the soil moisture level closer to the optimum (Zhang et al., 2013; Zhou et al., 2013). However, excess water in soil often results in lower biological activity due to the limitation of oxygen flow (Bouwman, 1998; Reinsch et al., 2017), while anaerobic processes such as methane production are greatly promoted (Le Mer and Roger, 2001).

Natural variation in precipitation provides opportunities to observe responses of belowground activities (e.g., Goldstein et al., 2000; Granier et al., 2007), but targeted studies of belowground responses are difficult. Controlled precipitation manipulation experiments offer the opportunity to specifically study ecosystem responses to changes in precipitation compared to naturally occurring fluctuations and have become common in recent decades (Beier et al., 2012; Borken et al., 2006; Knapp et al., 2017). Precipitation manipulation experiments (PMEs) involve constructing an experimental structure in the field, such as rainout shelters, curtains, and/or sprinklers, to simulate alternative precipitation patterns (Beier et al., 2012). These setups enable direct comparisons between a manipulated precipitation treatment and a control (ambient precipitation) in the same study system, while keeping other environmental conditions nearly identical. PMEs have been established across ecosystem types and characteristics (biome, ecosystem, soil type, and land type), and often use different methodological approaches (e.g., in terms of the magnitude and duration of the precipitation manipulation, size of the experiment, method of rain exclusion, and/or variables measured) (Vicca et al., 2014).

A number of meta-analyses have assembled and synthesized large and diverse PME datasets (Blankinship et al., 2011; Canarini et al., 2017; Wu et al., 2011). The first to examine soil responses to precipitation changes was conducted by Wu et al. (2011), compiling 85 manipulation studies and presenting the changes in aboveground and belowground carbon dynamics. Since then, several additional meta-analyses have considered belowground responses to precipitation changes. As of April 2019, according to our search criteria (details below), a total of 16 meta-analyses in this area were published. These meta-analyses focused on different but complementary soil properties [e.g., soil C (Zhou et al., 2016) or N (Yue et al., 2019)]. A combined analysis of these meta-analyses would provide a holistic view of the potential effects of projected precipitation changes on soil processes.

In this paper, we ~~synthesize~~ conduct a comparative analysis of 16 meta-analyses that have examined soil responses to manipulated (increased and decreased) precipitation *in-situ*, encompassing 42 response variables including greenhouse gas exchanges, carbon and nitrogen dynamics, phosphorus content, microbial community, and enzyme activities. By collating the results of the published meta-analyses, we aimed to (1) provide a more holistic view of the effects of precipitation changes on soil composition and functioning, (2) discuss the potential underlying mechanisms of each response, and (3) identify knowledge gaps and propose future research directions. This study covers an unusually wide range of soil processes and examines the responses of individual variables as well as nutrient cycles.

2 Review of meta-analyses

2.1 Meta-analysis collection

We collected peer-reviewed meta-analyses focused on the effects of decreased and/or increased precipitation on soil variables. We collected meta-analyses that included only field studies where the magnitude of precipitation was manipulated. Some meta-analyses included both field and lab/greenhouse experiments, but we only analyzed field data in our comparisons. We used Google Scholar and Web of Science with the search terms "meta-analysis" AND "soil" AND ("respiration" OR "CO_2" OR "carbon" OR "nutrient" OR "nitro" OR "phosph" OR "N_2O" OR "CH_4" OR "microb" OR "enzyme" OR "bacteria" OR "fungi") AND ("altered precipitation" OR "drought" OR "decreased precipitation" OR "increased precipitation" OR "water addition" OR "water reduction"). We identified 16 meta-analyses (Table 1); four of them focused on decreased precipitation (DP), one of them on increased precipitation (IP), and 11 on both DP and IP. A total of 42 soil variables were covered, encompassing a wide range of soil characteristics such as soil greenhouse gas exchanges, soil carbon, nitrogen, phosphorous, microbial and bacterial communities, enzymes, and physical characteristics of soil (Table 2). Only meta-analyses written in English and published before April 2019 were included in our analysis. All of the meta-analyses except for Brzostek et al. (2012) collected observations globally, with a greater concentration of data in the United

States (US), Europe, and China than other parts of the world. The dataset of Brzostek et al. (2012) is US-only, yet their data covers a wide range of ecosystem types and biomes.

2.2 Effect sizes

From each meta-analysis, we obtained the mean effect size of each soil variable. In this review, effect sizes are the natural log of response ratios (lnRR) defined as:

$$lnRR = \ln(\frac{X_t}{X_c}) , \quad (1)$$

where X_t and X_c are the mean values of the treatment (DP or IP) and control, respectively, for each observation. Homyak et al. (2017) used Hedge's *d* instead of Eq. 1 for N_2O emissions and N supply due to the negativity of RR. Hedge's *d* is defined as $J(X_t-X_c)/S$ where S is the pooled standard deviation, and J is the correction of small sample bias (Homyak et al., 2017). Both lnRR and Hedge's *d* are negative for inhibitory effects, and positive for stimulatory effects (Brzostek et al., 2012; Homyak et al., 2017). All meta-analyses calculated mean effect sizes and 95% confidence intervals (CI) with sample size or the inverse of the variance as the weighting function. The effect is considered significant when 95% CI does not overlap zero. Some meta-analyses applied additional weighting functions or normalized the measurements under different manipulation levels (Liu et al., 2016; Wu et al., 2011). We used these sample size- or variance-weighted effect sizes when available. We obtained the values from the main texts or supplementary materials of the articles. If necessary, we used the digitizing software Plot Digitizer (Huwaldt, 2015), to extract values from graphs. When only percent changes were reported, we converted to lnRR as in Ren et al. (2017, 2018):

$$lnRR = \ln\left(\frac{\%\,change}{100} + 1\right) . \quad (2)$$

Some 95% CI were unavailable because points were not visible on graphs or because values of percent change below -100% were not convertible using Eq. 2 (e.g. He and Dijkstra, 2014). We also obtained the sample size, defined as the number of studies or observations included in the meta-analyses. The collected information is available in Abbasi et al. (2020).

3 Soil responses to precipitation changes

3.1 Responses of soil respiration and belowground biomass

Meta-analyses on autotrophic (R_a), heterotrophic (R_h), and total soil ($R_s = R_a + R_h$) respiration provide strong agreement that DP decreases, and IP increases, R_s, R_a, and R_h (Fig. 1a). Litter biomass (B) follows the same pattern (Fig. 1b). Although the response of R_a reaches significance in only one of two meta-analyses, the direction of the response is consistent. Responses of soil carbon variables [total carbon (C), soil organic C (SOC), and dissolved organic C (DOC)] to precipitation differ among meta-analyses, both in direction and significance (Fig. 1b). Interestingly, root B is strongly suppressed by both DP and IP. In contrast, IP stimulates belowground B and belowground net primary productivity (NPP), and DP increases root C (Fig. 1b). It is difficult to reconcile that IP suppresses root B but increases belowground B; the difference between the two measures is that belowground B includes not just roots, but also any other plant or animal-derived materials found in a soil core. We note that these two contrasting results come from different, single, meta-analyses with small sample sizes.

To understand the effects of precipitation on R_s, we need to understand the responses of roots, microbes, and substrates to DP and IP.~~ Commonly~~ When soil moisture is below field capacity and plants are active, R_a and R_h, and belowground NPP are typically positively correlated with soil water availability. R_a decreases under limited water supply due to (1) reduced plant growth and nutrient demand, (2) reduced root tissue activity due to limited soil water, and (3) reduced respiratory substrate production from photosynthetic activity (Hasibeder et al., 2015). In contrast, increased water supply increases R_a by enhancinge~~s~~ plant growth and photosynthetic rates (Heisler-White et al., 2008; Maire et al., 2015)~~, which results in increased R_a~~. In concordance with these plant physiological responses, belowground NPP decreases with DP and increases with IP (Figure 1; Zhou et al., 2016). Belowground B also increases with IP. ~~The responses of belowground B to IP and belowground NPP to DP and IP (Fig. 1b) are also likely to result from these changes in plant and root growth.~~ However, not all belowground responses follow this pattern;~~ are consistent with this storyline.~~ ~~Root C and~~ total C (which is also affected by microbial activity) increases with DP, and root B – with a very small sample size - decreases with IP (Fig. 1b).

~~This contradictory evidence could be due to variability~~ Some responses vary by biome~~ and soil type~~. For example, the effects of DP on total C is negative in temperate forests, and positive in tropical forests and grassland (Yuan et al., 2017; Zhou et al., 2016). Total C reflects a balance of plant inputs and microbial outputs, so differences in responses among systems may reflect differences in the strength of PME effects on plants vs. microbes across those systems. Responses of this metric also depend on the size of the initial pool relative to fluxes, and so may be differentially dampened across systems.

~~Also, in our study, both~~ Responses of R_a to DP and IP were either significant ~~effects~~ (Zhou et al., 2016) or non-significant ~~and no effects~~ (Liu et al., 2016), depending on the study (although the mean responses were consistent in direction across studies)~~ of DP and IP on R_a were found~~. ~~This~~ The difference in significance ~~effects~~ could be attributed to small samples sizes and high variability in the case of DP.~~, for example,~~ ~~The~~the samples sizes are somewhat larger for IP effects on R_a, and these responses depend~~ing~~ on biome and R_a separation method. For instance,~~ Specifically,~~ significant IP effects were found ~~can be significant~~ in temperate forest and grassland, but not in boreal forest (Zhou et al., 2016), and R_a separated from R_h by clipping methods responded more positively than when trenching methods were used (Liu et al., 2016). ~~Sample~~ Nonetheless, sample sizes remain relatively small~~ for R_a responses to changes in precipitation~~, suggesting that additional research could help to identify how this process response varies with biomes and methods.

R_h is the consequence of soil microbial activity decomposing soil organic matter (SOM) under aerobic conditions. SOM is frequently estimated by measuring its carbon component, SOC. R_h is mainly regulated by microbial access to substrate and the physiological condition of microbes (Schimel, 2018). In dry soil, substrate tends to be isolated from microbes as solute

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mobility is low (Manzoni et al., 2012; Schimel, 2018). Furthermore, a great number of empirical observations and synthetic studies have shown that microbial activity is lower during droughts (Hueso et al., 2012; Jensen et al., 2003; Manzoni et al., 2012). This is because dry conditions force microbes into dormancy or shift their efforts from growth to survival (Salazar et al., 2018; Schimel et al., 2007). ~~Excess water~~Wetting of dry soil, on the other hand, ~~not only~~ increases substrate availability to microbes (Skopp et al., 1990),~~ it also~~ makes microbes dispose of osmolytes from their body cells to regulate~~ the~~ osmotic pressure (Schimel et al., 2007), and can activate dormant microbes (Salazar et al., 2018). These responses ~~are~~can be particularly rapid and~~ drastic~~ strong~~ when dry soils rewet~~, yielding ~~a large~~ pulses of respiration~~, which could significantly~~ that are large enough to affect the net carbon exchanges in terrestrial ecosystems (Placella et al., 2012).

As with R_a, R_h typically decreases under DP and increases under IP, with variations among biomes and R_h separation methods. DP effects on R_h are significant in boreal forest and wetland, but not in tropical and temperate forests (Zhou et al., 2016). Likewise, IP effects on R_h are significant in forest and grassland, but not in wetland (Liu et al., 2016; Zhou et al., 2016). We hesitate to draw strong conclusions from these differences because of the relatively small sample sizes. Zhou et al. (2016), for example, have a sample size of four and five for the tropical and temperate forests, respectively, for DP, and the effects are highly uncertain. The biomes with significant effects – wetlands under DP and grasslands under IP – have higher sample sizes, of 10 and 15, respectively. Biological mechanisms behind these differences can also be hypothesized, such as differences in microbial sensitivity to moisture across systems. Furthermore, the effects of DP and IP~~ effects~~ on soil respiration can depend on methodological factors of the field experiments not explicitly considered in all meta-analyses. For example, the effects of IP on R_a can be significant when field work included clipping~~are significant if the clipping method was used~~, but not when it included~~with~~ trenching~~ and root extraction~~ (Liu et al., 2016).

Overall, responses of R_s, R_a, and R_h are positively correlated with precipitation changes and soil moisture (Liu et al., 2016; Ren et al., 2017; Zhou et al., 2016). Responses of SOC, DOC, and belowground NPP also tend to be positively correlated with precipitation changes (Ren et al., 2017; Zhou et al., 2016). Despite the broad agreement among meta-analyses, the responses of respiration and soil carbon vary across studies, and can depend on biome, measurement method, treatment intensity, and other factors.

Microbial activity in soils is strongly controlled by the actions of enzymes (Ren et al., 2017). Many of these enzymes, which are produced and released by microbes, depolymerize complex carbon compounds (Ren et al., 2017). While enzyme activity is relatively unresponsive to IP (Fig. 2), DP increases hydrolytic enzyme activity (breakdown of labile carbon) and inhibits oxidative activity (de-polymerization of recalcitrant carbon) (Fig. 2). This indicates that under dry conditions, the relative contributions of substrates from labile carbon sources increase, while the respective relative contributions from recalcitrant sources decrease.

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The summary diagrams (Fig. 1c, 1d) illustrates how DP generally slows the belowground carbon cycle, while IP promotes it. Nearly all steps of the carbon cycle - carbon stock, substrates, microbial activity, and respiration – are altered by both types of precipitation changes. However, enzyme activity tends to be relatively unresponsive, particularly to IP, and the observations of biomass and carbon variables vary both in direction and significance among meta-analyses. These variables also tend to vary across biomes, ecosystems, and soil types.

3.2 Responses of methane uptake

We found only one meta-analysis that addressed the effects of precipitation on soil CH_4 (Yan et al., 2018). The results show a significant increase and decrease of soil CH_4 uptake in response to DP and IP, respectively (Fig. 1a). Soil CH_4 fluxes involve two groups of microbes: methanogens and methanotrophs. Methanogens produce CH_4 and are predominantly active in anaerobic conditions, while methanotrophs oxidize CH_4 and are active in aerobic environments (Conrad, 2007). CH_4 oxidation seems to peak at 10-15% volumetric water content because these conditions favor methanotroph activity as well as CH_4 and O_2 diffusion (Adamsen and King, 1993; Del Grosso et al., 2000).

The results of Yan et al. (2018) were significant across a wide range of ecosystem types, treatment durations, and magnitudes of precipitation manipulation. The effects of DP were greater in farmlands than other land types, in shorter-term (< 1 year) experiments than longer-term ones, and in more extreme experiments (> 50% rain reduction). The effects of IP were greatest in boreal forest and in longer-term experiments (1-5 years) with greater rain addition (> 50%). However, a few empirical studies have shown opposite responses to this meta-analysis (Billings et al., 2000; Christiansen et al., 2015); for instance, a precipitation removal experiment in a floodplain decreased CH_4 uptake, possibly due to the acclimation of methanotrophs to high soil moisture conditions (Billings et al., 2000), or differences in the types of methanotrophs in floodplain (low-affinity methanotrophs) versus upland soil, where most CH_4 uptake occurs (Christiansen et al., 2015).

3.3 Responses of soil nitrogen dynamics

Several soil nitrogen variables, including root nitrogen (N), N_2O emissions, total N, dissolved organic nitrogen (DON), and extractable $NH_4^+ + NO_3^-$ are significantly affected by precipitation changes (Fig. 3a). Specifically, DP decreases root N and N_2O emissions and increases total N, DON, and extractable $NH_4^+ + NO_3^-$. We also found that two meta-analyses (sample sizes < 20) suggest no change in total N, while one (sample size = 156) suggests an increase with DP. Similarly, one meta-analysis suggests an increase of extractable NH_4^+ with DP while other two meta-analyses suggest no effects. In contrast, IP increases root N, N_2O emissions, and extractable NH_4^+ (Fig. 3a). Two meta-analyses suggest that total N decreases with IP, while one meta-analysis suggests no effects.

Mineralization rate, defined as N supply by Homyak et al. (2017), does not change under DP despite the increase in substrate (i.e., DON) (Fig. 3). However, the product of mineralization and N_2 fixation is NH_4^+, whichand it increases under DP

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according to one of three meta-analyses (Homyak et al., 2017) even though another source of NH_4^+, N_2 fixation, could be suppressed (Hume et al., 1976; Streeter, 2003). This is reasonable considering that the consumption of NH_4^+ is likely to decrease with DP, mainly because of reduced plant nitrogen uptake (He and Dijkstra, 2014; Matías et al., 2011; Yuan et al., 2017) and microbial nitrogen assimilation (Homyak et al., 2017; Månsson et al., 2014). Homyak et al. (2017) found the increase in extractable NH_4^+ is greater under more intense DP. Nitrification and denitrification are expected to slow down with DP (Bouwman, 1998; Lennon et al., 2012; Stark and Firestone, 1995), also reducing N_2O emission (Fig. 3b). This suggests that soil moisture could be a stronger regulator of nitrification and denitrification processes than the availability of NH_4^+ and NO_3^- (Weier et al., 1993). The input (nitrification) and outputs (denitrification, plant uptake and microbial assimilation) of NO_3^- both decline under DP, leaving extractable NO_3^- unchanged (Fig. 3b).

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Extracellular enzyme activity, here shown both as total proteolytic activity (pro-enzyme) and three particular N-acquisition enzyme activities (β-1,4-N-acetyl-glucosaminidase, leucine amino peptidase, and urease), does not change with DP or IP (Fig. 2). This indicates that the production of N-enzymes is not sensitive to water stress. Important outputs of the soil nitrogen cycle (denitrification and plant uptake) decrease while inputs remain constant or decline (Fig. 3b). As a result, total soil N increases or remains unchanged.

In contrast to DP, soil nitrogen cycling is accelerated by IP (Fig. 3c). Although no mineralization indicator was included in the meta-analyses, ample evidence shows that nitrogen mineralization is likely to increase with IP (Hu et al., 2014; Sierra, 1997; Pilbeam et al., 1993; Mazzarino et al., 1998). Along with greater N_2 fixation (Hume et al., 1976), which contributes to increasing NH_4^+ (Fig. 3c), positive responses are also expected in nitrification and denitrification rates (Bouwman, 1998; Niboyet et al., 2011; Stark and Firestone, 1995), plant nitrogen uptake (Schaeffer et al., 2013; Liu et al., 2016; Ma et al., 2013), and microbial nitrogen assimilation (Månsson et al., 2014), which result in increased N_2O emissions, and lead to unchanged NO_3^- as well as total N.

Soil nitrogen undergoes a wide range of chemical and biological transformations, some of which are difficult to quantify. Despite the large number of empirical studies included in meta-analyses, some nitrogen variables, such as rates of mineralization (for IP), nitrification, denitrification, and N_2 fixation, have not yet been examined in meta-analyses focused on PMEs.

3.4 Responses of soil phosphorus

We found four meta-analyses that examined how precipitation changes affect the soil phosphorus (P) cycle (He and Dijkstra, 2014; Yan et al., 2018; Yuan et al., 2017; Yue et al., 2018). The results differ among meta-analyses; for instance, according to these meta-analyses, IP can have a negative, positive, or non-significant effects on total P (Fig. 4). Yuan et al. (2017) assembled the largest dataset and found that IP decreases total P, while DP increases total P. As phosphorus is commonly a limiting nutrient for vegetation, plant P uptake and concentration are frequently studied, but studies of soil phosphorus ~~storage~~stocks are rarer (He and Dijkstra, 2014; Yue et al., 2018). The timescale of precipitation experiments can be as short as one growing season (or less), and the effect of such short-term precipitation manipulations on slow processes such as chemical weathering is negligible. However, phosphorus cycling through faster processes such as decomposition of organic matter, plant uptake, and consumption by microbes can respond

~~Phosphorus in soil originates from weathering rocks, deposition from the atmosphere, and decomposition of organic matter (Wang et al., 2010). Outputs from soil involve plant uptake and consumption by microbes. As is the case with carbon and nitrogen, microbial decomposition and consumption activities of P can be affected by precipitation changes~~ (Van Meeteren et al., 2007). Plant P uptake tracks in the same direction as changes in precipitation (He and Dijkstra, 2014). ~~However, challenges lie in generalizing the effects of precipitation changes on weathering and deposition, as these processes involve complex chemical and physical reactions. For example, soil water content determines the rate of chemical weathering, and humidity affects P deposition from the atmosphere (Newman, 1995).~~ The effects on total P are strongly linked to soil type (Yuan et al. 2017). Although Yuan et al. (2017) found significant effects of DP and IP on total P, the effects were small (-0.1 < effect sizes < 0.1), and other meta-analyses show that soil P, as well as P-acquisition enzyme activity, are relatively unresponsive to precipitation changes (Fig. 2, 4). Other global changes such as warming, elevated CO_2, and anthropogenic P and N deposition tend to have ~~higher~~stronger impacts on the terrestrial P cycle than precipitation changes (Yue et al., 2018).

3.5 Responses of microbial biomass and community structure

Microbial biomass (MB) in soil either decreases or does not respond to DP (Fig. 5a)~~. MB responses to DP vary with~~, and these responses depend on the amount of precipitation ~~that is~~ removed (Zhou et al., 2016; Ren et al., 2017, 2018), the length of droughts (Ren et al., 2018), vegetation type (Zhou et al., 2016; Ren et al., 2017, 2018) and mean annual precipitation (MAP; Ren et al., 2017). MB is affected by DP only when ~~reduced~~ precipitation is reduced by more ~~larger~~ than ~33% (Ren et al., 2017, 2018), the drought period is ≤ 2 years (Ren et al., 2018), and in wet (MAP > 600mm) regions (Ren et al., 2017). Additionally, vegetation type affects MB responses to DP; DP consistently decreases MB in forests (tropical and temperate but not in boreal; Zhou et al., 2016; Ren et al., 2017, 2018) and heathlands (Blankinship et al., 2011), but not in shrublands (Ren et al., 2017, 2018). A meta-analysis conducted by Zhou et al. (2016) found that DP decreases MB in grassland soils. However, more recent meta-analyses that included more studies (Ren et al., 2017, 2018) suggest that MB in grasslands does not respond to DP.

In contrast, ~~except when added precipitation is very high (> 70%; Ren et al., 2017),~~ IP stimulates microbial growth and thus increases MB unless the proportion added is very high (> +70%; Ren et al., 2017). ~~Contrary to~~ Unlike DP, IP affects MB in dry (MAP < 600 mm) but not in wet (MAP > 600 mm) sites (Ren et al., 2017). This is consistent with IP increasing MB in soils from ecosystems that are generally water-stressed, such as deserts, shrublands, and grasslands (Zhou et al., 2016; Ren et al., 2017). Zhou et al. (2016) found that IP increases MB in soils in temperate forests. Other meta-analyses that included more studies (also including tropical forests) suggest that MB in forest soils is generally not affected by IP (Blankinship et al., 2011; Canarini et al., 2017; Ren et al., 2017). Overall, increased precipitation typically increases MB in the direct systems, where it makes conditions less extreme.

In contrast to the responsiveness of MB to altered precipitation, the composition of bacterial and fungal communities is rather unresponsive (Fig. 5b). Although Blankinship et al. (2011) and Yan et al. (2018) estimated significant effects on the abundance of fungi (both positive and negative effects of IP) and F:B ratio (negative effect of DP; n = 4), other studies with sample sizes an~~one~~ order of magnitude larger (e.g., Ren et al. 2018) estimated non-significant effects. The high resistance of bacteria and fungi to soil moisture changes has been frequently highlighted (Evans and Wallenstein, 2012; Schimel et al., 2007; Yuste et al., 2011). Fungi in particular, due to their filamentous structure, are capable of accessing substrates even in very dry soils (Manzoni et al., 2012). Bacteria and fungi also have a wide breadth of soil moisture niches; diverse types of bacteria and fungi tolerate water stress (Lennon et al., 2012). Differences in resistance between bacteria, fungi, and other functional types can alter microbial structure under precipitation changes; DP could promote a more fungi-dominated community (Yuste et al., 2011). Although gram-positive bacteria are more resistant to soil moisture changes than gram-negative bacteria due to their thicker and stronger cell walls (Schimel et al., 2007; Salazar et al., 2019), both gram-positive and negative bacteria have been unresponsive to DP (Fig. 5b). The sample sizes for bacteria and fungi in meta-analyses are small compared to MB meta-analyses (Fig. 5). Although the currently available data cover a substantial range of locations and conditions, microbial responses within each site are likely to vary by treatment timing, intensity, frequency, and other environmental/climatic factors. Future studies of bacterial and fungal community responses can improve our understanding of the microbial responses to precipitation in terms of the composition and structure of the microbial community by more comprehensively exploring these factors.~~Although an increase in the number of bacterial and fungal studies would improve our understanding of community responses to precipitation changes in terms of significance and magnitude of effects, current available data already covers a significant range of locations and conditions, and highlights the clear trend of low responsiveness of bacterial and fungal communities to DP and IP manipulations.~~

3.6 Responses of belowground C:N:P stoichiometry

Belowground stoichiometric relationships of carbon, nitrogen, and phosphorus can help researchers interpret and infer nutrient movements in soil organisms and their environments. Yet, few meta-analyses have synthesized belowground stoichiometric responses to precipitation treatments; greater attention has been paid to stoichiometry of aquatic systems and plants (Cleveland and Liptzin, 2007; Redfield, 1958; Yuan and Chen, 2015). He and Dijkstra (2014) and Yan et al. (2018) found no changes in soil C:N and N:P with DP (Fig. 3), but MBC:MBN responded to both precipitation changes (Fig. 5). Increased MBC:MBN with IP indicates that wetter conditions stimulated greater metabolic activity of microbes, which accumulated more carbon in their bodies. This suggests that the soil microbial biomass C:N:P ratio, which is wellconstrained globally (60:7:1) (Cleveland and Liptzin, 2007), could be altered by IP to have more weight on carbonprecipitation changes. Soil N:P ratios can be heavily dependent on plant nutrient uptake; as discussed in Sect. 3.3, DP reduces plant nitrogen uptake, which could increase soil N:P. However, this effect depends on site aridity (Sardans et al., 2012), and could be mitigated by robust strong mycorrhizal symbioses (Mariotte et al., 2017), which could help maintain soil N:P ratios by sustaining plant nutrient uptake under DP. and depend on site aridity (Sardans et al., 2012).

4 Implications for future research

4.1 Knowledge gaps

Meta-analyses have substantially advanced our understanding of the impacts of precipitation changes on soil processes and properties. Specifically, a great number of Responses of several variables have been investigated by three or more meta-analyses, and with robust datasets; have investigated these include soil respiration, nitrogen stocksions, total phosphorus, and microbial biomass. Nevertheless However, there are still many other variables have receiveding less attention.; fFor example, the sample sizes for analyses of autotrophic respiration areis smaller than heterotrophic respiration, and substrate availability has not been analyzed while soil C, N and P content have, and analyses of bacterial and fungal responses to IP are sparser than DP. CH_4 fluxes have received less attention than CO_2 and N_2O, and no meta-analyses have examined the processes of nitrification, denitrification, and nitrogen fixation.

Filling these knowledge gaps could help to reveal the underlying mechanisms underlyingof soil responses to precipitation changes. For example, there is robust agreement across studies that soil and heterotrophic respiration slows under DP and accelerates under IP, and so does heterotrophic respiration. However, the relative importance of different mechanisms in the response of heterotrophic respiration is still unknown – in other words, how much of this response comes from changes in the level of microbial activity (e.g., entering and exiting dormancy) vs. substrate availability? Similarly, what are the most important mechanisms behind changes in N_2O emissions, and how quickly will total soil nitrogen respond? Interestingly, the variables receiving the greatest attention are largely the easier to measure “fluxes” (i.e., greenhouse gas emissions) and “pools” (i.e., soil carbon, biomass, and bacterial abundance).

Measuring process rates (i.e., rates of nitrification, denitrification and fixation) that cannot be simply measured from gas fluxes requires more resources (time and money).Studies of processes that have received less attention (e.g., microbial metabolic state, nitrification, denitrification and N fixation) have the potential to inform models and improve predictions of the effects of precipitation changes on important fluxes and pools. This benefit can be seen in ecosystem models that explicitly represent active and dormant microbial biomass, which can outperform those representing microbial biomass as a single pool (He et al., 2015; Salazar et al., 2019; Wang et al., 2015). A more synthetic understanding of nitrification and denitrification responses across ecosystems could improve projections of societally relevant nitrate leaching and soil emissions of N_2O and NO_x, and inform carbon-associated modeling, as the availability of N in ecosystems has a close connection with C sequestration (Barnard et al., 2005).

The meta-analyses we examined had strong geographical imbalances, as has been identified elsewhere. While all but one meta-analyses collected global empirical data, the data are concentrated in the US, Europe, and China. Almost 90% of the existing PMEs are located at mid-latitudes (30-60°), and there is an obvious sparsity at lower and higher latitudes (Beier et al., 2012). As a result, sample sizes for tropical and boreal ecosystems are substantially smaller than for temperate ecosystems in many of the meta-analyses. Studies of the effect of IP on R_s provide good examples: Zhou et al. (2016) has a sample size of 13 for temperate forest, but only two for tropical forest and zero for boreal forest. Yan et al. (2018) features a larger sample size of 66 for temperate forest, but still has only four subtropical forest samples and two in boreal forest. The comprehensive meta-analysis recently conducted by Song et al. (2019) has similar geographical gaps. Expanding PMEs to the under-represented regions is critical in order to obtain a truly planetary synthesis.

4.2 Challenges in meta-analyses and synthetic studies

PMEs are quite diverse, adopting a variety of approaches, treatment levels, and treatment types (Beier et al., 2012; Kreyling and Beier, 2013), and so are the data derived from them. Many PMEs use long-term rainout shelters, which unavoidably modify the ambient environment in other ways (Kreyling et al., 2017). While synthesizing the results of PMEs around the globe in the context of these experimental issues could be challenging, meta-analyses provide one somewhat simplistic approach, through an exhaustive statistical summary of empirical studies (Hedges et al., 1999). ~~One of the limitations of m~~Meta-analysis~~, however, is that it~~ can obscure the substantial influence of environmental characteristics and methodological differences on effect sizes. Categorization by environmental characteristics, such as climate, geography, ecosystem, soil, and soil biota, can provide a local- to regional- view of soil responses that is specific to the given environmental characteristic. Categorization by methodology, such as experimental duration, intensity of treatment, measurement method, and fertilizer use, can clarify the human-derived impacts on effect sizes. These categorization efforts ~~can~~help to identify when and how soil responses depend on their environmental context. While an exhaustive analysis of these categories is beyond the scope of this paper, we have highlighted the cases in which these factors affected each meta-analysis result in the text above. A further breakdown of these categories by environmental characteristics and methodology can be found in the Supplement (S1). As more and more PMEs are implemented, sample sizes available for meta-analysis are increasing (Song et al., 2019). In this regard, the recent deployment of broad networks of PMEs with standardized methodology and sampling procedures (Fraser et al., 2013; Halbritter et al., 2020) could ultimately contribute to more powerful meta-analyses with more easily interpreted outcomes (Hilton et al., 2019; Knapp et al., 2012, 2017). ~~Details of categorization by environmental characteristics and methodology can be found in the Supplement (S1).~~

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We identified some technical challenges during this comparative study, including data collection and the definition of samples. Data collection is perhaps the most time-consuming process of searching literature and contacting researchers. Most meta-analyses extract effect size, standard deviation, and sample size from publication when possible, commonly with the use of digitizing software (Canarini et al., 2017; Liu et al., 2016; Ren et al., 2017; Xiao et al., 2018; Yan et al., 2018; and others). While digitizing software is helpful, the accuracy of the digitized values depends on the resolution of the figures. In some cases, digitizing is not feasible when points are too large, or error bars are too close to the points. Thus, we emphasize the importance of comprehensively presenting and publishing data, both in original studies and meta-analyses, to minimize errors associated with digitizing. Secondly, we found that the definition of a sample used in meta-analyses differs by studies. Specifically, some meta-analyses treat observations over multiple years from the same experiment as distinct individual samples, which could potentially violate the assumption of sample independence. We recommend, therefore, that a meta-analysis accounts for within-study dependency (Canarini et al., 2017) or selects a single year or season to include in the analysis. Lastly, we note that we aimed a comparison of existing meta-analyses to visualize the (in)consistency among the meta-analyses and identify the variables receiving more (or less) attention. We did not account for overlapping empirical data between meta-analyses, and thus, do not provide a unified dataset for new analyses. Instead, we clarified the sample sizes and publication year of each meta-analysis to help interpret the results.

5 Conclusions

This ~~synthesis~~ assessment of meta-analyses provides a broad perspective on how precipitation changes affect soils and belowground processes. Belowground carbon and nitrogen cycles speed up with increased precipitation and slow down with decreased precipitation, while ~~microbial~~bacterial and fungal communities are relatively ~~resistant~~ insensitive to decreased precipitation~~precipitation changes~~. While the responses of the fluxes and pools of each cycle – gas emissions, soil carbon, nitrogen ions, and biomass – have been studied extensively, responses of the associated process rates remain less studied or unexamined by meta-analyses. There are also gaps in the study of soil elements such as phosphorus and nitrogen ions, as well as stoichiometric relationships, and bacterial/fungal biomass under increased precipitation. We suggest that additional scientific attention to these ~~"processes"~~ gaps is warranted, and would help to deepen and consolidate ~~strengthen the~~ current knowledge of soil responses to precipitation changes.

Data Availability

The ~~collected~~ data collected from meta-analyses and used in this paper are~~is~~ available through the Purdue University Research Repository (https://doi.org/10.4231/16NT-CW47).

Author contribution

AOA, AS, YO, MRU, IR, and JSD designed the research. AOA, AS, YO, SR, MRU, JL, and IR conducted the ~~synthetic analysis~~ comparative analysis and contributed to writing the original draft. AOA prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1: List of meta-analyses used in this study.

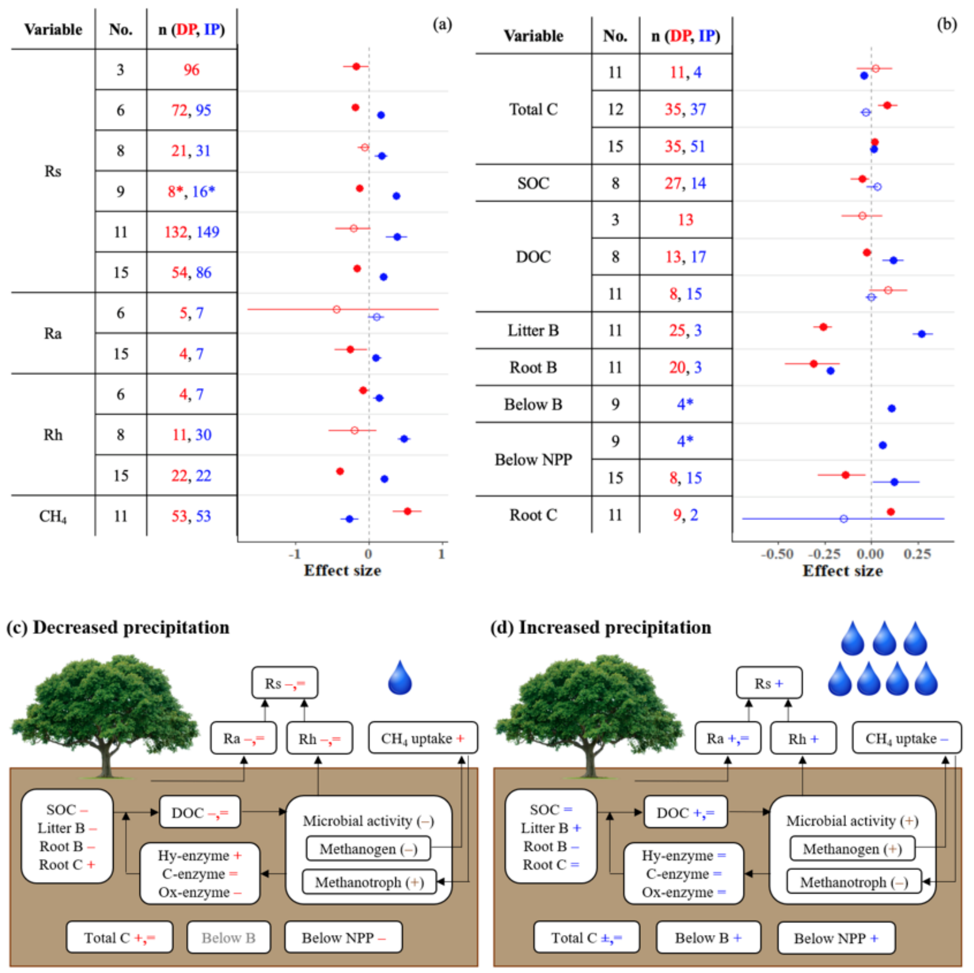
No.	Meta-analysis
1	Blankinship et al. 2011
2	Brzostek et al. 2012
3	Canarini et al. 2017
4	He & Dijkstra 2014
5	Homyak et al. 2017
6	Liu et al. 2016
7	Ren et al. 2018
8	Ren et al. 2017
9	Wu et al. 2011
10	Xiao et al. 2018
11	Yan et al. 2018
12	Yuan et al. 2017
13	Yue et al. 2019
14	Yue et al. 2018
15	Zhou et al. 2016
16	Zhou et al. 2018

Table 2. List of soil variables and their definitions as analyzed in the meta-analyses. The numbers indicate meta-analysis number corresponding to Table 1, examining the effects of decreased precipitation (DP) and increased precipitation (IP) on each soil variable.

Variable	Definition	DP	IP	Variable	Definition	DP	IP
Rs	Soil respiration	3,6,8,9,11,15	6,8,9,11,15	NH_4^+	Extractable NH_4^+	5,11,13	11
Ra	Autotrophic respiration	6,15	6,15	NO_3^-	Extractable NO_3^-	5,11,13	11
Rh	Heterotrophic respiration	6,8,15	6,8,15	N:P	Extractable N:P	4	None
CH_4	CH_4 uptake	11	11	Ext P	Extractable soil P	4,14	14
Total C	Total soil C	11,12,15	11,12,15	Total P	Total soil P	11,12,14	11,12,14
SOC	Soil organic C	8	8	MB	Microbial biomass	3,5,7,8,16	1,8,16
DOC	Dissolved organic C	3,8,11	8,11	MBC	Microbial biomass C	11,15	10,11,15
Litter B	Litter biomass	11	11	MBN	Microbial biomass N	11,13	11,13
Root B	Root biomass	11	11	MBC:MBN	Microbial biomass C: Microbial biomass N	11	11
Below B	Belowground biomass[a]	None	9	Bacteria	Abundance of bacteria	7,11	1,11
Below NPP	Belowground NPP	15	9,15	Fungi	Abundance of fungi	7,11	1,11
Root C	Fine root C concentration	11	11	Gram+	Gram positive bacteria	7	None
Root N	Fine root N concentration	11	11	Gram-	Gram negative bacteria	7	None
Root C:N	Fine root C concentration: Fine root N concentration	11	11	F:B	Fungi:Bacteria ratio	3,7,11	11
C:N	Total soil C:N	11	None	Hy-enzyme	Hydrolytic enzyme activity[b]	8	8
				C-enzyme	C-acquisition enzymes	10	10
N_2O	N_2O emissions	5,11	11	N-enzyme	N-acquisition enzymes	10	10
Total N	Total soil N	11,12,13	11,12,13	P-enzyme	P-acquisition enzymes	10	10
Inorganic N	Inorganic N	13	13	Ox-enzyme	Oxidase activity	8,10	8,10
N supply	N mineralization	5	None	Pro-enzyme	Potential proteolytic enzyme activity	2	2
DON	Dissolved organic N	11	None	Soil temperature	Soil temperature	None	11
$NH_4^+ + NO_3^-$	Extractable $NH_4^+ + NO_3^-$	4	None	pH	Soil pH	11	None

a. Belowground biomass was measured by drying soil cores (Wu et al., 2011), and thus includes roots and other plant- and animal-derived materials. Root biomass includes biomass that derives from roots only.

b. C-acquisition enzymes are β-1,4-glucosidase and β-D-cellobiohydrolase, N-acquisition enzymes are β-1,4-N-acetyl-glucosaminnidase, leucine amino peptidase, and urease, and the P-acquisition enzyme is acid phosphatase (Xiao et al., 2018).



Variable
No.
n (DP, IP)
(a)
Rs
3
96
6
72, 95
8
21, 31
9
8*, 16*
11
132, 149
15
54, 86
Ra
6
5, 7
15
4, 7
Rh
6
4, 7
8
11, 30
15
22, 22
CH_4
11
53, 53
-1
0
1
Effect size
(b)
Total C
11
11, 4
12
35, 37
15
35, 51
SOC
8
27, 14
DOC
3
13
8
13, 17
11
8, 15
Litter B
11
25, 3
Root B
11
20, 3
Below B
9
4*
Below NPP
9
4*
15
8, 15
Root C
11
9, 2
-0.50
-0.25
0.00
0.25
Effect size
(c) Decreased precipitation
Rs –,=
Ra –,=
Rh –,=
CH_4 uptake +
SOC –
Litter B –
Root B –
Root C +
DOC –,=
Microbial activity (–)
Methanogen (–)
Methanotroph (+)
Hy-enzyme +
C-enzyme =
Ox-enzyme –
Total C +,=
Below B
Below NPP –
(d) Increased precipitation
Rs +
Ra +,=
Rh +
CH_4 uptake –
SOC =
Litter B +
Root B –
Root C =
DOC +,=
Microbial activity (+)
Methanogen (+)
Methanotroph (–)
Hy-enzyme =
C-enzyme =
Ox-enzyme =
Total C ±,=
Below B +
Below NPP +

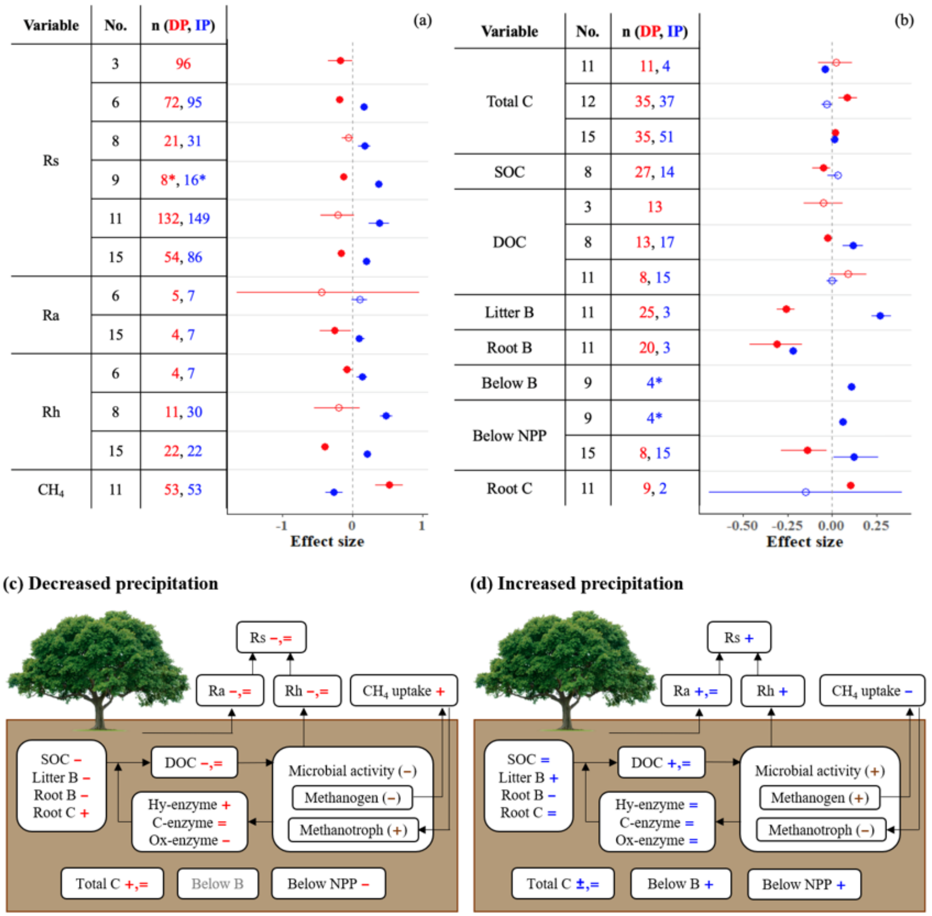


Figure 1: (a, b) ~~The e~~Effect sizes for~~of~~ (a) soil respiration and methane uptake, and (b) carbon and belowground biomass variables with respect to decreased (red) and increased (blue) precipitation. Filled points represent ~~a~~ significant effect sizes (95% CI not overlapping 0), and open points represent ~~a~~ non-significant effect sizes. Variable names correspond to Table 2. No. is meta-analysis number ~~and it corresponds to~~ as listed in Tables 1 and ~~Table~~ 2. The sample size is indicated by n. Asterisks indicate missing 95% CIs. (c, d) The effects of (c~~b~~) decreased precipitation and (d~~e~~) increased precipitation on the soil carbon cycle. Negative, positive, and non-significant effects are represented by −, +, and =, respectively. Red and blue represent ~~are the~~ variables found in one or more meta-analyses. Brown symbols in parentheses represent the variables that no meta-analyses quantified; in these cases, we estimated the effects based on our review of empirical studies in Sect. 3.1.

Variable	No.	n (DP, IP)
Hy-enzyme	8	33, 52
C-enzyme	10	16, 14
N-enzyme	10	10, 10
P-enzyme	10	9, 13
Ox-enzyme	8	12, 13
	10	5, 5
Pro-enzyme	2	4, 4
Soil temperature	11	13
pH	11	10, 43

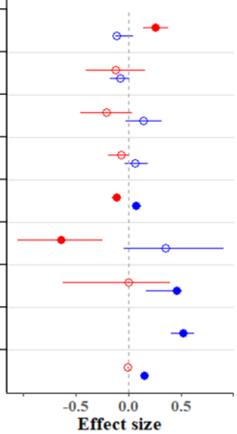
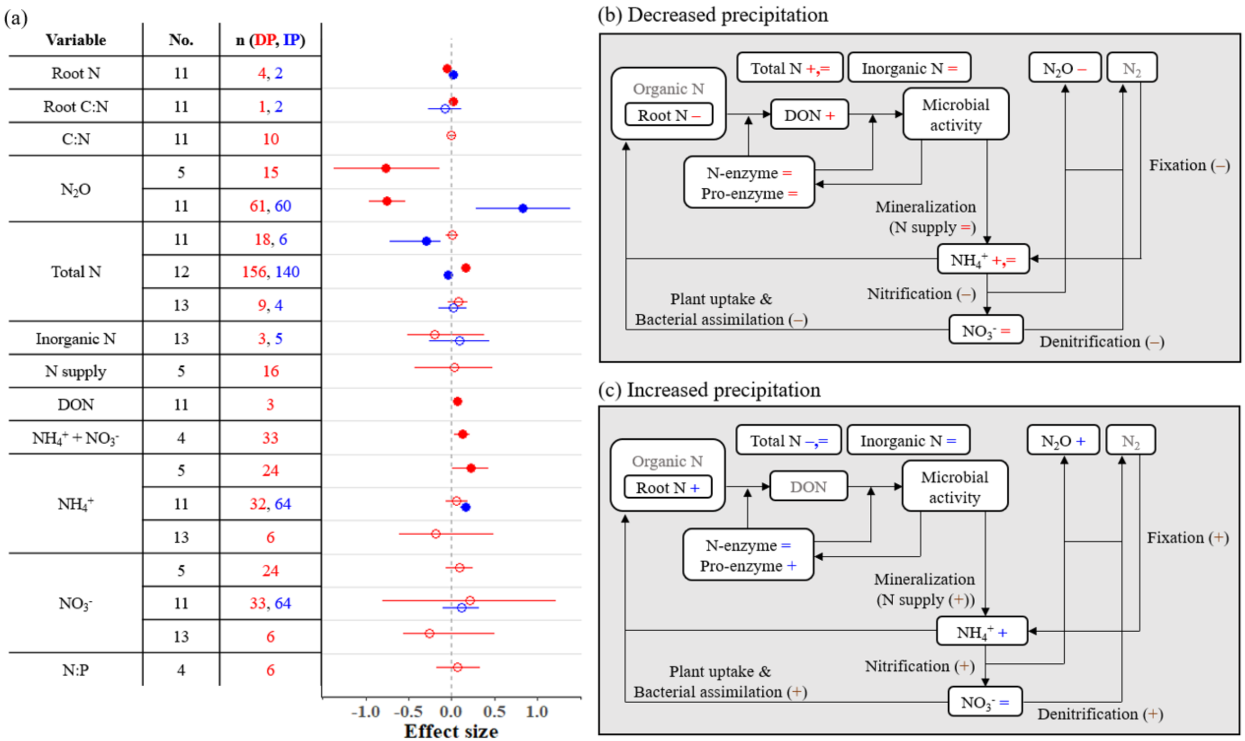


Figure 2: ~~The e~~Effect sizes~~ of~~ for soil enzyme and physical variables with respect to decreased (red) and increased (blue) precipitation. Filled points represent a significant effect size (95% CI not overlapping 0), and open points represent a non-significant effect size. Variable names correspond to Table 2. No. is meta-analysis number as~~nd it corresponds to~~ listed in Tables 1 and ~~Table~~ 2. The sample size is indicated by n.


(a)
Variable
No.
n (DP, IP)
Root N 11 4, 2
Root C:N 11 1, 2
C:N 11 10
N2O 5 15
11 61, 60
Total N 11 18, 6
12 156, 140
13 9, 4
Inorganic N 13 3, 5
N supply 5 16
DON 11 3
NH4+ + NO3- 4 33
NH4+ 5 24
11 32, 64
13 6
NO3- 5 24
11 33, 64
13 6
N:P 4 6
-1.0 -0.5 0.0 0.5 1.0
Effect size
(b) Decreased precipitation
Organic N
Root N –
DON +
Total N +,=
Inorganic N =
Microbial activity
N2O –
N2
N-enzyme =
Pro-enzyme =
Fixation (–)
Mineralization (N supply =)
NH4+ +,=
Plant uptake & Bacterial assimilation (–)
Nitrification (–)
NO3- =
Denitrification (–)
(c) Increased precipitation
Organic N
Root N +
DON
Total N –,=
Inorganic N =
Microbial activity
N2O +
N2
N-enzyme =
Pro-enzyme +
Fixation (+)
Mineralization (N supply (+))
NH4+ +
Plant uptake & Bacterial assimilation (+)
Nitrification (+)
NO3- =
Denitrification (+)

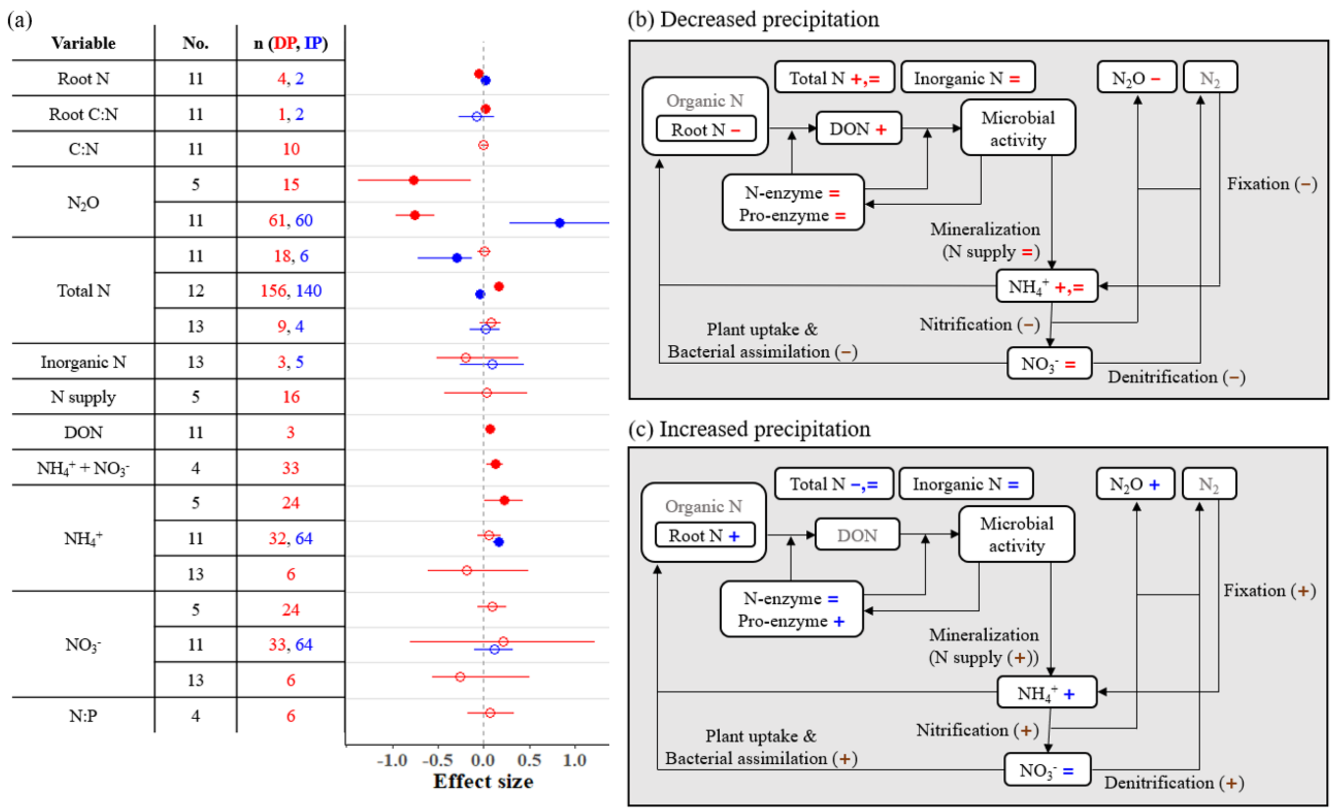


Figure 3: (a) ~~The e~~Effect sizes ~~of~~ for soil nitrogen variables ~~with respect to~~ responding to decreased (red) and increased (blue) precipitation. Filled points represent a significant effect size (95% CI not overlapping 0), and open points represent a non-significant effect size. Variable names correspond to Table 2. No. is meta-analysis number ~~and it corresponds to~~ as listed in Tables 1 and ~~Table~~ 2. The sample size is indicated by n. (b, c) The effects of (b) decreased precipitation and (c) increased precipitation on a simplified schematic of the soil nitrogen cycle. Negative, positive, and non-significant effects are represented by −, +, and =, respectively. ~~Red~~ These symbols are colored in red and blue if ~~are the~~ variables are found in one or more meta-analyses. Brown symbols in parentheses represent ~~the~~ variables that no meta-analyses have quantified; in these cases, we estimated the effects based on our review of empirical studies in Sect. 3.3.

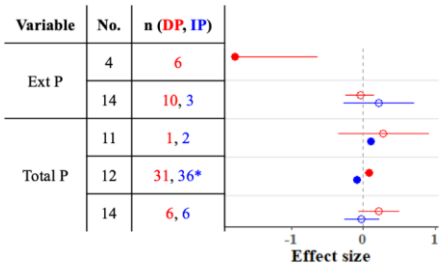


Figure 4: ~~The e~~Effect sizes ~~of~~for soil phosphorus variables ~~with respect to~~ responding to decreased (red) and increased (blue) precipitation. Filled points represent a significant effect size (95% CI not overlapping 0), and open points represent a non-significant effect size. Variable names correspond to Table 2. No. is meta-analysis number as listed in ~~and it corresponds to~~ Tables 1 and ~~Table~~ 2. The sample size is indicated by n. Asterisks indicate missing 95% CIs.

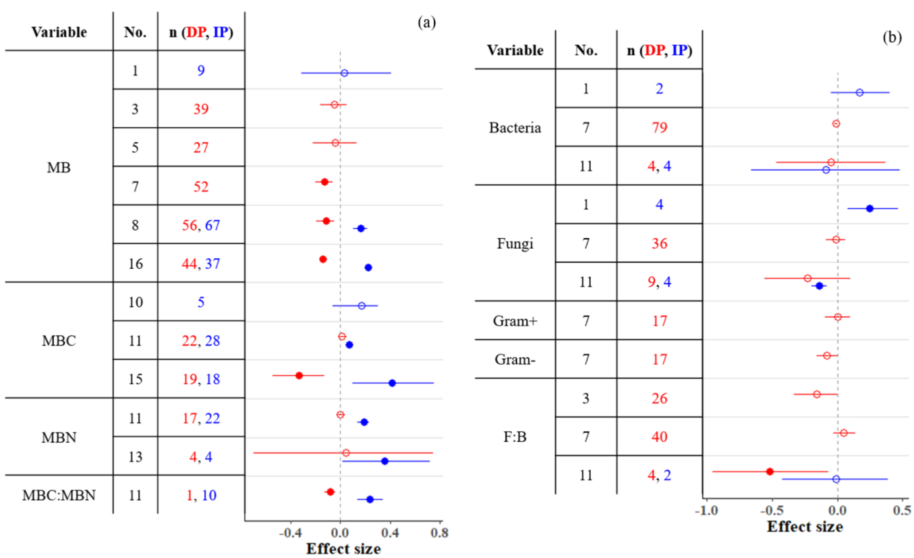


Figure 5: ~~The e~~Effect sizes ~~of~~for (a) microbial biomass, carbon, and nitrogen, and (b) bacterial and fungal variables responding to ~~with respect to~~ decreased (red) and increased (blue) precipitation. Filled points represent ~~a~~ significant effect sizes (95% CI not overlapping 0), and open points represent ~~a~~ non-significant effect sizes. Variable names correspond to Table 2. No. is meta-analysis number as listed in ~~and it corresponds to~~ Tables 1 and ~~Table~~ 2. The sample size is indicated by n.

Supplement of

Soil responses to manipulated precipitation changes: An ~~synthesis~~assessment of meta-analyses

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1. Categorization of meta-analyses by environmental characteristics and methodology

While it is important to understand general responses of soil properties and processes to precipitation changes, differences in site characteristics and experimental methodology cause a large amount of variability in the results of meta-analyses, and this variability is also important. By reviewing 42 soil variables studied in 16 meta-analyses, we found that environmental and methodological characteristics commonly influence effect sizes. Almost all meta-analyses, therefore, divide their dataset into smaller categories, or test the relationships between these factors and effect sizes. We identified that these factors can be categorized into six groups (Table S1): climate (temperature, precipitation and aridity), methodology (duration and intensity of treatment, measurement method, and fertilizer use), geography (latitude, longitude, and elevation), ecosystem (biome, forest type, and plant characteristics), soil (soil type, texture, depth, and carbon), and soil biota (taxonomic group, size, and trophic role).

Temperature, precipitation, and latitude are the most common abiotic factors to account for differences in ecosystem characteristics. This information is usually reported in scientific articles, and thus is a convenient means by which to group studies. Similarly, many studies use biomes (or ecosystem types) for grouping. Alternatively, aridity index is suitable for precipitation manipulation experiments as dry regions could be more sensitive to IP than wet regions, and wet regions more sensitive to DP than dry regions (Ren et al., 2018). The aridity index can be calculated with mean annual temperature (MAT) and precipitation (MAP) (Liu et al., 2016), or with MAP and potential evapotranspiration (Yuan et al., 2017; Zhou et al., 2016).

Methodological differences are also critical to take into consideration. Duration and intensity of manipulative treatments, especially, have a significant impact on soil responses (Smith et al., 2009). For R_s, R_a, R_h, and MB, measurement methods could be a significant factor; Liu et al. (2016) show that the effect size of R_s did not differ among R_s measurement methods (dynamic chamber with IRGA or other instruments, static chamber with GC, and static chamber with alkali absorption), but R_a/R_h partitioning methods (trenching, clipping, root extraction) had a significant influence on R_a and R_h effect sizes.

Moreover, synthetic fertilizer application could alter responses of nitrogen and phosphorus cycles (Xiao et al., 2018; Yue et al., 2018).

Finally, it is a common practice among meta-analyses of microbial communities to consider soil characteristics (Canarini et al., 2017; Ren et al., 2017; Zhou et al., 2018). Soil type, texture, SOC, and soil C are commonly considered in studies. Because of the association between phosphorus and soil parent materials, it is also common for studies focused on this element to consider soil characteristics such as soil type and soil depth (Yuan et al., 2017; Yue et al., 2018). We recommend that future meta-analyses categorize their dataset based on ecosystem characteristics, methodology, and other groupings that are relevant to the target soil variables.

Table S1. List of environmental and methodological factors affecting effect sizes, and count of meta-analyses taking each factor into account.

Climate	Count
Mean annual temperature	10
Mean annual precipitation	12
Mean GS temperature	1
Mean GS precipitation	1
GS potential evapotranspiration	1
GS soil moisture deficit	1
Aridity	5

Methodology	Count
Duration of treatment	11
Intensity of treatment	9
GS only or whole year	1
Rs measurement method	1
Ra/Rh partitioning method	1
MB extraction method	1
Fertilizer use	2

Geography	Count
Latitude	7
Longitude	4
Elevation	2

Ecosystem	Count
Biome	10
Forest type (natural or plantation)	1
Plant functional type	2

Soil	Count
Soil type	2
Texture	2
Soil carbon	1
Soil organic carbon	2
Soil depth	1

Soil biota	Count
Taxon	1
Body width class	1
Trophic group	1

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