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A meta-analysis of the response of soil moisture to experimental warming

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Abstract
Soil moisture is an important variable for regulating carbon, water and energy cycles of terrestrial ecosystems. However, numerous inconsistent conclusions have been reported regarding the responses of soil moisture to warming. In this study, we conducted a meta-analysis for examination of the response of soil moisture to experimental warming across global warming sites including several ecosystem types. The results showed that soil moisture decreased in response to warming treatments when compared with control treatments in most ecosystem types. The largest reduction of soil moisture was observed in forests, while intermediate reductions were observed in grassland and cropland, and they were both larger than the reductions observed in shrubland and tundra ecosystems. Increases (or no change) in soil moisture also occurred in some ecosystems. Taken together, these results showed a trend of soil drying in most ecosystems, which may have exerted profound impacts on a variety of terrestrial ecosystem processes as well as feedbacks to the climate system.

Keywords: soil moisture, global warming, meta-analysis

S Online supplementary data available from stacks.iop.org/ERL/8/044027/mmedia

1. Introduction

Soil moisture plays an important role in determining a variety of terrestrial ecosystem structures and functions, and modulating regional climate by impacting both biophysical and biogeochemical processes, including the carbon cycle, water cycle, nitrogen cycle, plant phenology, forest growth, vegetation distribution and microbial activity in decomposition (Rustad *et al* 2001, Koster *et al* 2004, Walker *et al* 2006, Fan *et al* 2008, Sherry *et al* 2008, Jung *et al* 2010, Elmendorf *et al* 2012, Escolar *et al* 2012, Schwalm *et al* 2012). Soil moisture has been found to change substantially with rising global temperatures, and has therefore received increasing interest in recent years (Dai *et al* 2004, Emmett *et al* 2004, Dermody *et al* 2007, Wan *et al* 2007, Subin *et al* 2012, Dai 2013, Seager *et al* 2013).

Numerous studies have shown inconsistent conclusions regarding the effects of experimental warming on soil moisture, with positive (Zavaleta *et al* 2003, Wang *et al* 2011), negative (Harte *et al* 1995, Luo *et al* 2001, Verburg *et al* 2005, Xia *et al* 2010) or neutral effects being observed in various ecosystems (Luo *et al* 2009a, Li *et al* 2011). For example, Harte *et al* (1995) reported that 15 W m^{-2} downward infrared flux increased summer soil temperature by up to 3 °C and reduced soil moisture by up to 25% in a montane meadow in Colorado, USA. However, other studies showed opposite conclusions regarding the responses of soil moisture to increased soil temperature. Wang *et al* (2011) reported that soil water content below 10 cm increased with heating in a desert steppe in Siziwang Banner, Inner Mongolia, China. Similarly, simulated warming in California grassland increased spring soil water content by 5–10%

(Zavaleta *et al* 2003). In addition, when considering factors including precipitation, vegetation, slope and temperature, which could all influence soil water balance, the responses of soil moisture to warming trends are complex and highly variable temporally and spatially (Liancourt *et al* 2012).

Over the last two decades, as predictions of global warming have become more widely recognized and accepted, the need for information regarding the response of soil moisture to changing temperature has been addressed by a growing number of temperature-manipulation experiments initiated in various ecosystems around the world. Warming experiments have been used to extrapolate future climate conditions on a global scale for many years (Rustad 2008, Aronson and McNulty 2009). Some of the warming experimental sites have long time series and duration (Luo *et al* 2009b, Xue *et al* 2011, Xu *et al* 2012), and it is convenient to study and compare the effects of simulating warming on variations in soil moisture.

In this study, global experimental warming measurements were synthesized to examine responses of soil moisture to experimental warming on a global scale. Specifically, meta-analysis was used to investigate (1) the responses of soil moisture to experimental warming; (2) the extent to which soil moisture is altered by simulating warming; (3) the differences in the response of soil moisture to experimental warming among ecosystem types.

2. Data and methods

2.1. Data collection

In this meta-analysis, we reviewed more than 200 published papers on experimental warming studies recovered from the Web of Science (1980–2013). We selected data according to the following criteria: (1) the studies reported changes in soil moisture in both warming and control groups; (2) the measurements were conducted at least over an entire year; (3) the means, standard deviations of soil moisture and sample sizes were reported or could be calculated. In cases in which no standard errors were reported, we assigned standard deviations that were 1/10 of means (Luo *et al* 2006). (4) Relevant experimental information was reported, including the mean annual precipitation (MAP), mean annual temperature (MAT), warming methods, increased soil temperature, soil properties, and ecosystem types.

Overall, this study included 41 study sites with 139 paired experimental records for investigation of the response of soil moisture to warming (supplemental table S1, supplemental figure S2, supplemental information S3 available at stacks.iop.org/ERL/8/044027/mmedia). The measurements under different ecosystem managements (i.e., clipping, grazing, etc) or plant communities were considered as independent treatment data. Therefore, the same environmental conditions were maintained for all selected experiments (including rainfall conditions), except for temperature. Moreover, we did another literature research and collected 76 paired records at 31 sites to examine the changes in net primary production (NPP), above-ground net primary production (ANPP), below-ground net primary production (BNPP), leaf area index (LAI) or ecosystem evapotranspiration (ET) in response to warming. Only a few experimental records were collected from the same articles as for soil moisture.

2.2. Statistical analysis

The response ratio (RR, the ratio of the mean value of a concerned variable in warming treatment to that of a control treatment) is used here as an index of the magnitude of experimental warming effects (Hedges *et al* 1999). An RR value larger than 0, indicates a positive impact of experimental warming on soil moisture with increased soil moisture. The response ratio (RR) was calculated as:

$$\mathrm{RR} = \ln(\overline{X_\mathrm{t}}/\overline{X_\mathrm{c}}) = \ln(\overline{X_\mathrm{t}}) - \ln(\overline{X_\mathrm{c}}) \quad (1)$$

where $\overline{X_\mathrm{t}}$ and $\overline{X_\mathrm{c}}$ are the mean values of the warming and control groups, respectively.

The variance (ν) was estimated by:

$$\nu = \frac{S_\mathrm{t}^2}{n_\mathrm{t} X_\mathrm{t}^2} + \frac{S_\mathrm{c}^2}{n_\mathrm{c} X_\mathrm{c}^2} \quad (2)$$

where n_t and n_c are the sample sizes for the warming and control treatments, respectively, and S_t and S_c are the standard deviations for the warming and control groups, respectively.

The weighted response ratio (RR_{++}) of each ecosystem type is calculated from the RR of individual pair comparisons between warming and control groups, and the standard errors (S) and weighting factor (w_{ij}) are calculated by:

$$\mathrm{RR}_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{ki} w_{ij}\mathrm{RR}_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{ki} w_{ij}} \quad (3)$$

$$S(\mathrm{RR}_{++}) = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{ki} w_{ij}}} \quad (4)$$

$$w_{ij} = \frac{1}{\nu}. \quad (5)$$

If the 95% confidence interval (95% CI $= \mathrm{RR}_{++} \pm 1.96S(\mathrm{RR}_{++})$) value of RR_{++} for a variable does not cover zero, the responses of soil moisture to experimental warming differ significantly between the warming and control treatments at a given ecosystem type (Lu *et al* 2011a, 2011b, Lu *et al* 2013).

We plotted frequency distributions of RR to display variability among individual studies. The frequency distributions were assumed to follow normal distributions and fitted by a Gaussian function (i.e., normal distribution).

$$y = a\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \quad (6)$$

where x is RR, y is the frequency (i.e., number of RR values), a is a coefficient showing the expected number of RR values at $x = \mu$, and μ and σ are the mean and variance of the frequency distributions of RR, respectively. We used a t-test to examine whether the response ratio in the warming treatment was significantly different from that in control. The percentage change of a variable was calculated by the formula: $(e^{\mathrm{RR}_{++}} - 1) \times 100\%$ (Lu *et al* 2013).

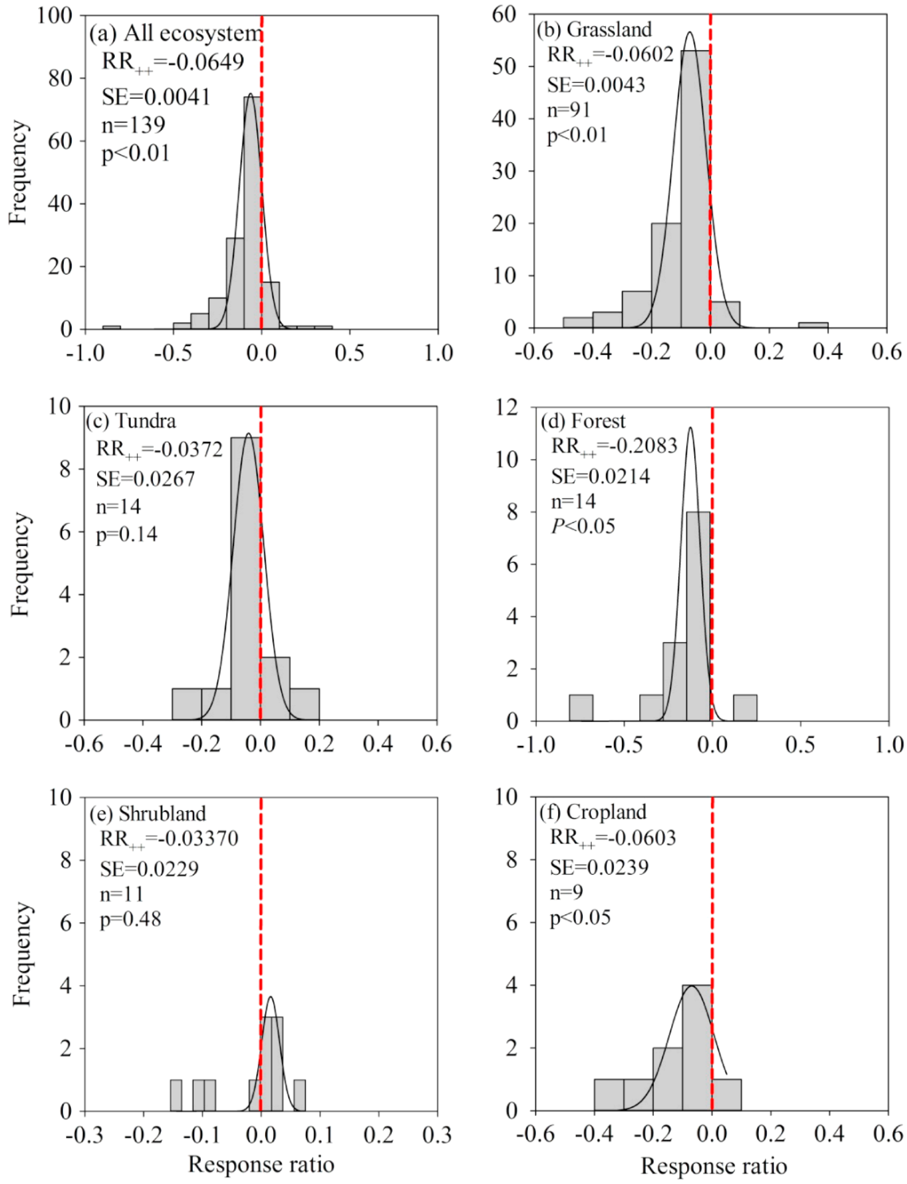

Figure 1. Frequency distributions of response ratios (RR) of soil moisture for all ecosystem (a), grassland (b), tundra (c), forest (d), shrubland (e), and cropland (f). The '*n*' is sample size and the solid line is the fitted Gaussian (normal) distribution of frequency data. The *x* axis is RR and *y* axis is frequency. The vertical lines are drawn at RR = 0.

3. Results

Across all studies, soil surface temperature increased by 1.62 °C with a range of 0.17–5.52 °C in response to warming when compared to the control. Warming induced changes in soil moisture showed large variability across studies, ranging from a minimum RR of −0.8109 to a maximum of 0.3276 in all ecosystems (figure 1). On average, experimental warming significantly decreased soil moisture in most ecosystem types, with a decrease of 7.78% being observed in all ecosystems ($p < 0.01$), 8.50% in grassland ($p < 0.01$), 11.73% in forest ($p < 0.05$) and 9.25% in cropland ($p < 0.05$) (figures 1 and 2; table 1). However, in tundra and shrubland ecosystem types, the effects of warming on soil moisture were insignificant, with a 3.38% decrease occurring in tundra ($p = 0.14$) and a 1.25% decrease occurring in shrubland ($p = 0.48$) (figures 1 and 2; table 1).

We also found a larger decrease of magnitude of soil moisture with elevated soil temperature across all measurements (figure 3(a)). For grassland ecosystems, a majority of the changes in soil volumetric water were negative with increasing soil temperature after removing interference of data (i.e., clipping, grazing; figure 3(b)). Similarly, the response ratios were significantly correlated with elevating soil temperature in all studies ($R^2 = 0.14, p < 0.01$) and grassland without grazing/or clipping ($R^2 = 0.12, p < 0.01$) (figures 3(c) and (d)).

Moreover, we analyzed the responses of vegetation production (NPP: net primary production; ANPP: above-ground NPP; BNPP: below-ground NPP), leaf are a index (LAI) and ecosystem evapotranspiration (ET) to experimental

Table 1. Percentage changes of soil moisture, net primary production (NPP), above-ground NPP (ANPP), below-ground NPP (BNPP), leaf area index (LAI), and ecosystem evapotranspiration (ET) in response to experimental warming. (Note: percentage change was calculated as $(e^{RR_{++}} - 1) \times 100\%$; values are means ± SE.)

Variable	Percentage change (%)	Sample size (n)
Soil moisture		
All ecosystem	−7.78 ± 0.91	139
Grassland	−8.50 ± 0.99	91
Tundra	−3.38 ± 2.37	14
Forest	−11.73 ± 4.82	14
Shrubland	−1.25 ± 1.62	11
Cropland	−9.25 ± 3.79	9
Net primary production (NPP)	3.54 ± 7.59	8
Above-ground NPP (ANPP)	9.80 ± 4.41	35
Below-ground NPP (BNPP)	3.39 ± 8.12	12
Leaf area index (LAI)	20.15 ± 0.06	13
Ecosystem evapotranspiration (ET)	1.67 ± 1.74	8

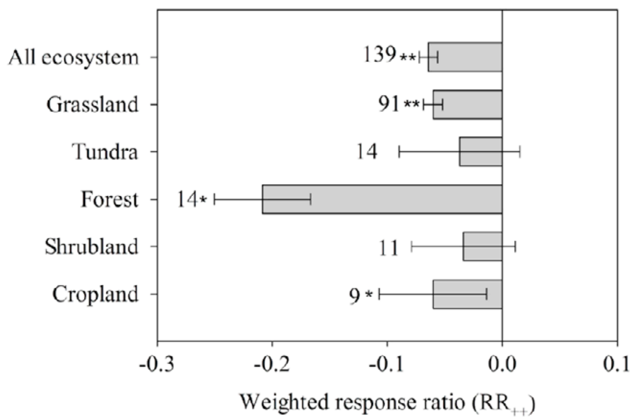

Figure 2. The weighted response ratio (RR_{++}) of those ecosystems responds to simulating warming. The sample size for each ecosystem type is shown next to the bar (*$p < 0.05$; **$p < 0.01$).

warming. Our results showed that warming stimulated NPP by 3.54%, ANPP by 9.80% and BNPP by 3.39% (figures 4(a)–(c); table 1). Due to the limited dataset of leaf area index (LAI) and ecosystem evapotranspiration (ET) data, we only obtained 13 and 8 paired measurements of LAI and ET, respectively, which covers a few ecosystem types (figures 4(d) and (e)). LAI increased in tundra ($p < 0.05$), but showed insignificant changes in shrubland under warming conditions (figure 4(d); $p = 0.21$). Warming stimulated ET by 1.67% in grasslands (figure 4(e), $p < 0.05$).

4. Discussion

4.1. Responses of soil moisture to warming

Our results showed significant negative effects of experimental warming on soil moisture in most study sites. The overall responses of soil moisture to warming decreased significantly from 8.50% to 11.73% in forest, grassland and cropland (figure 1, table 1). The negative responses of soil moisture to warming conditions could be attributed to the enhanced plant growth and transpiration processes (Wan *et al* 2002, Xia *et al* 2010). Evaporation from the soil surface and transpiration by plants are major avenues of water loss from the soil reservoir (Chapin *et al* 2002). Previous studies have showed that warming can alter plant phenology, leading to changes such as earlier flowering and leafing (Wolkovich *et al* 2012), increased height and cover of plants (Walker *et al* 2006), and prolonged growing season (Sherry *et al* 2007), which may enhance plant growth and eventually increase losses of water from plant transpiration (Xia *et al* 2010).

Experimental warming stimulated plant growth from both above- and below-ground NPP, leading to increased NPP (figures 4(a)–(c); table 1). Our synthesized results are consistent with those from other meta-analyses that focused on the response of above-ground plant growth to warming (Rustad *et al* 2001, Lin *et al* 2010, Wu *et al* 2011). For example, the latest study indicated that plant growth (NPP, ANPP and BNPP) was enhanced under warming conditions in 16 experimental samples (Lu *et al* 2013).

The warming induced significant increase LAI in tundra, while shows insignificant changes in shrubland (figures 4(d) and (e)). Previous studies supported our conclusion over various regions. A meta-analysis showed that warming increased plant height and cover at 11 sites across the tundra biome (Walker *et al* 2006). Another study showed that warming treatment increased the effective green leaf area index (green LAI) at most sites from six European shrublands located along a north–south climatic gradient (Mänd *et al* 2010). An increased LAI will strengthen plant transpiration and eventually exacerbate the losses of soil moisture with warming.

4.2. Different responses across ecosystem types

The responses of soil moisture to warming may differ considerably among ecosystem types. The results obtained in this synthesis show that experimental warming significantly decreased soil moisture in forests, grasslands and croplands ($p < 0.05$; figures 1(b), (d), (f) and 2), while the warming induced soil moisture was insignificant in tundra and shrubland ($p > 0.05$; figures 1(c), (e) and figure 2). Although the weighted response ratio (RR_{++}) of tundra was negative,

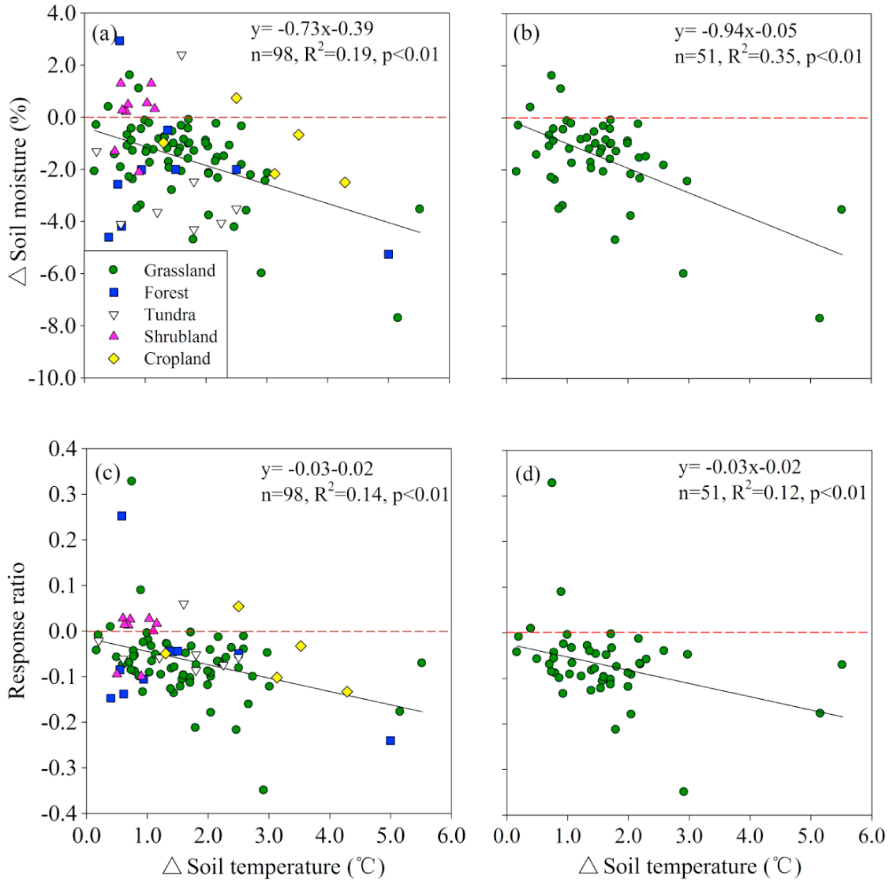

Figure 3. The changes of soil moisture with elevating temperature in different ecosystem (a) and grassland ecosystem without grazing and clipping (b), the changes of response ratio (RR) with elevating temperature in different ecosystem (c) and grassland ecosystem without grazing and clipping (d) in this meta-analysis study.

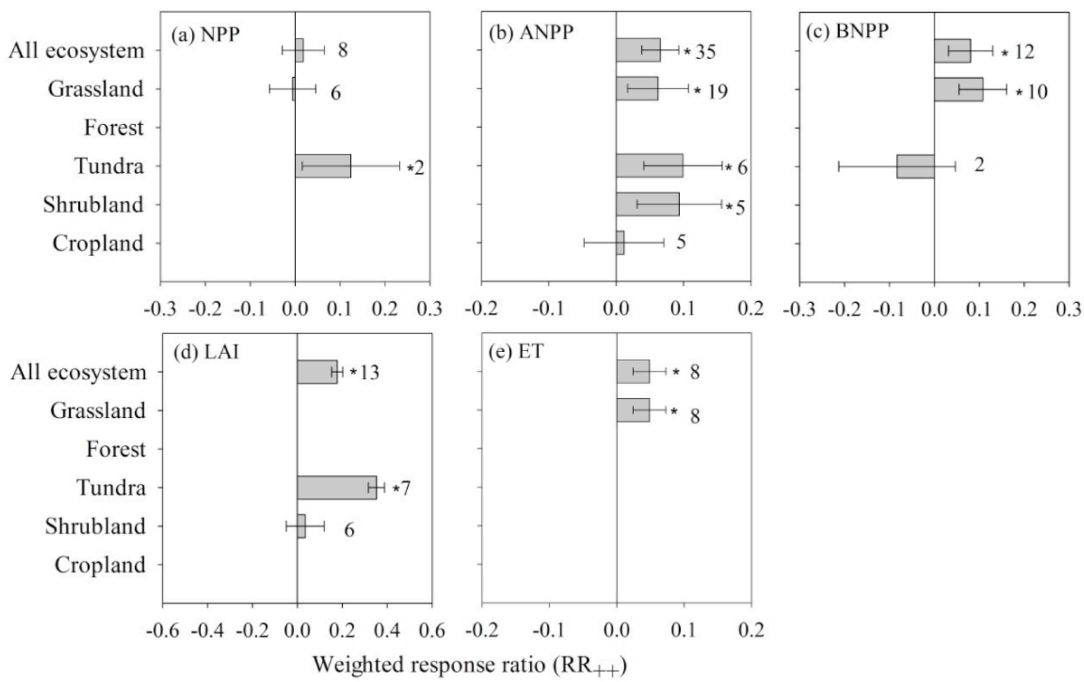

Figure 4. The weighted response ratio (RR_{++}) for the response to experimental warming of five variables related to the soil moisture: (a) net primary production (NPP); (b) above-ground NPP (ANPP); (c) below-ground NPP (BNPP); (d) leaf area index (LAI); (e) ecosystem evapotranspiration (ET). Bars represent RR_{++} and 95% confidence intervals. The sample size for each variable is shown next to the bar. The vertical lines are drawn at RR = 0 (*$p < 0.05$).

decreases of soil moisture were not significant (figure 1(c)), owing to changes in surface hydrology induced by warming. In general, tundra ecosystems are located at high latitude regions, where permafrost thaw is an important source of soil moisture in addition to precipitation. Experimental warming may accelerate permafrost melting, leading to increases in soil moisture (Natali *et al* 2011).

An insignificant decrease in soil moisture was also found in shrublands. More than half of shrubland sites showed increased soil moisture under warming treatments; however, it should be noted that the increase was very low (figure 1(e)). According to previous studies, increases in soil moisture in response to experimental warming were not significant when compared with control treatments (Beier *et al* 2004). Several studies have reported that warming decreased soil moisture via enhanced plant growth, as indicated by increasing shrub growth and biomass with experimental warming (Klein *et al* 2007, Peñuelas *et al* 2007, Mänd *et al* 2010). Due to the limited experimental data available for shrubland ecosystems, the current meta-analysis can not reflect comprehensive responses of soil moisture. Accordingly, this analysis should be repeated when more experimental data are available.

4.3. Factors influencing the response of soil moisture to warming

Environmental (e.g., mean annual temperature and mean annual precipitation) and ecosystem management (e.g., clipping, grazing) may potentially influence the responses of soil moisture to experimental warming since we extracted data from diverse manipulative experiments at a global scale. Ecosystem management (e.g., clipping or grazing) may indirectly accentuate soil water evaporation by reducing shading of the soil surface, which may in turn lead to large decreases in soil moisture (Xue *et al* 2011). When compared with the results of a ten years warming study, decreases in soil moisture were larger in clipped than unclipped plots with warming in a grassland in Oklahoma, USA (Luo *et al* 2009b, Xu *et al* 2012). The topography (e.g., slope) also indirectly impacts soil water evaporation through different plant cover and species composition (Liancourt *et al* 2012). Analyses revealed that the soil drying rate was faster on the drier upper slope or with vegetation and faster overall in drier years under warming conditions (Liancourt *et al* 2012). Moreover, vegetation can not only increase soil drying through plant transpiration, but also by bringing water up from deeper soil layers (Horton and Hart 1998), which may further desiccate deeper soil layers.

Moreover, warming induced phenology changes will strongly influence soil moisture response. In a previously conducted 2-year field experiment, simulated warming increased soil moisture by 5–10% during the end of the growing season (Zavaleta *et al* 2003). Analyses found that warming accelerated the decline of canopy greenness (normalized difference vegetation index) each spring by 11–16% by inducing earlier plant senescence. Lower transpiration losses resulting from the earlier senescence provide a possible mechanism for the unexpected increases in soil moisture.

4.4. Impacts of soil moisture changes

As an important variable for terrestrial ecosystem structure and function, soil moisture will undergo substantial changes in response to warming, significantly influencing biogeochemical and biogeography processes as well as climate systems (Dai *et al* 2004, Asharaf *et al* 2012). Our results showed significantly decreased trends of soil moisture in most ecosystem types (i.e., forest, grassland and cropland), which will result in profound impacts of the vegetation production. Numerous studies showed that soil drying will restrict the plant growth in water-limited ecosystem (Austin and Sala 2002, Schenk and Jackson 2002, Yuan *et al* 2007). A global analysis employing monthly data records from 238 micrometeorological tower sites distributed globally across 11 biomes revealed that vegetation production was 50% more sensitive to drought than ecosystem respiration (Schwalm *et al* 2012). Moreover, with decreasing soil moisture, plants will alter their carbon allocation strategy, promoting allocation of photosynthetic product to the root and decreasing its allocation to the stems and leaves (Schenk and Jackson 2002, Mokany *et al* 2006). More roots may bring water up from deeper soil layers (Horton and Hart 1998), leading to soil drying at deeper soil layers (Shaver *et al* 2000).

The impacts of soil drying on soil carbon showed large uncertainty (Falloon *et al* 2011). Laboratory studies and field observations suggest that soil respiration is low under dry conditions, reaches the maximal rate in intermediate soil moisture levels, and decreases at high soil moisture content when anaerobic conditions prevail to depress aerobic microbial activity (Luo and Zhou 2010). Therefore, in humid regions, soil drying alone appears to increase soil respiration and result in soil carbon losses (Smith *et al* 2005). On contrary, in arid and semi-arid regions, soil moisture changes alone appear to have acted to increase soil carbon storage. This was presumably because drying generally acts to increase soil carbon storage by reducing the respiration rate (Falloon *et al* 2011).

Soil moisture modulates the land surface energy balances by changing the land surface characteristics and energy components (Chapin *et al* 2002). Changes in soil moisture can alter land surface albedo and soil thermal capacity (Wang *et al* 2005). In general, both albedo and emissivity of dry soil are larger, which decreases absorbed shortwave radiation and increases emitted long wave radiation, respectively, leading to local energy reduction (Chapin *et al* 2002). Therefore, the present study highlights the importance of the responses of soil moisture to warming; however, further investigations simulating soil moisture coupling with the responses of other climate variables to climate change are necessary.

5. Summary

Our findings illustrate the strong impacts of global warming on soil moisture in several terrestrial ecosystems. In forests, grasslands and croplands, experimental warming increased ecosystem evapotranspiration. Moreover, positive responses of soil moisture to experimental warming were observed at several study sites, especially tundras and shrublands. Specifically, permafrost thaw resulting from warming of tundra areas was found to be major resources increasing soil moisture. Overall, our results demonstrate that understanding the response of warming is critical to predicting the dynamics of ecosystem structure and function, which are directly linked to regional climate systems.

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