Dear Dr. De Kauwe:

Thank you for your letter and the reviewers' comments concerning our manuscript entitled "Soil carbon release responses to long-term versus short-term climatic warming in an arid ecosystem". These valuable suggestions and comments help us greatly to improve our manuscript so that we have studied them carefully and made corrections point by point according to the constructive comments. The main changes in the revised manuscript have been highlighted using red font. Please see our point-by-point responses to your and the reviewers' comments in detail as following.

C**:** the original comments; ***R*****:** the responses to the comments.

Response to Dr. De Kauwe:

C**:** I have read through the three reviews you've received as well as your manuscript and I have decided that major revisions are necessary. All of the reviewers were positive about your manuscript but they also suggested some important revisions.

R**:** Thank you for the positive comments.

C**:** I suspect there has been a bit of a misunderstanding about the Biogeosciences process. The process involves the authors responding with how they plan to revise the manuscript, awaiting the editor's decision and then submitting a revised manuscript alongside detailed point by point changes. In practice, you often have to revise the manuscript to do this and I can see that you've already attempted to upload a revised manuscript. As a result, I have looked through this and my sense is that the current changes are not yet sufficient.

R**:** Sorry for the misunderstanding about the Biogeosciences process. Yes, in the new revision, we have again revised and corrected the manuscript as kindly suggested. Please see details below.

C**:** The reviewers made some very specific suggestions about improvements about the clarity of experimental protocol and implications of results. I think more effort could be made in revising the text to accommodate these changes. In particular, I would like to see further discussion of the mechanisms and wider implications. I look forward to seeing these changes in the future.

R**:** More information on the experimental protocol was added (e.g., lines 130-137, 144-149, and line 244 as kindly suggested by the reviewers, red words). Particularly, more information on the mechanisms and implications were added in Discussion section. For the mechanisms, please see the lines 343-360, and 377-390. For the implications, please see lines 340-342, 364-366, 388-390; 421-425, and 465-467. This can strengthen our results. Many thanks for the kind suggestions.

C**:** In addition, one reviewer asked about data sharing. I refer the authors to the journals data availability statement https://www.biogeosciences.net/about/data_policy.html. I feel very strongly that all data should be shared in an open repository, I didn't find the existing statement sufficient. The journal specifically states: "If the data are not publicly accessible, a detailed explanation of why this is the case is required." I hope the authors will reconsider freely sharing their data.

R**:** Yes, we have shared the data in an open repository, the zenodo; and the statements has been added in the new version: “Data availability. The final derived data presented in this study are available at https://doi.org/10.5281/zenodo.3546062 (Yu et al., 2019)”.

C**:** Finally, I see a comment directed at Dr. Bahn? This was confusing as they didn't review the manuscript, was this a mistake?

R**:** Sorry, this is a mistake. We should contact directly with you. Many thanks.

Response to RC1:

General Comments:

C**:** This paper specifically addresses our lack of knowledge on climate change within desert grassland ecosystems. While there have been many studies within boreal and temperate ecosystems, warming experiments focused on soil microbial community function and C stock assessments in arid systems are rare. Therefore, this study fills an important gap. The sampling design appears robust and is accompanied with a clear presentation of data. The methods for analyses are valid and informative enough for readers that might not be familiar with these techniques to understand, or where to read more, if desired. The authors further supported their hypotheses succinctly that warming reduced microbial respiration while wetting events enhanced respiration. However, my one concern is that 0.5 – 1.0 degree (Line 244) warming is not enough of a difference to define two treatments of warming (long-term, moderate and short-term, acute). Although, when moisture became limiting in August, there was a greater separation of the warming treatments which does highlight seemingly subtle differences. Perhaps a more direct addressing of the miniscule differences in the warming treatments until SWC becomes the greatest inhibitor to respiratory rates. Overall, I find this study well conducted and clearly presented. I would recommend for publication.

R: Thank for the positive comments. The larger differences occur between the two warming treatments and the control (i.e., ambient condition). Yes, acute warming treatments may not reach a higher level. However, it gradually induced a decline in soil moisture, finally limiting soil respiration. The major revision hade made carefully as kindly suggested (see detail below).

Specific Comments:

C: Line 12: Can examples of severe impacts be included here?

R: We have listed examples of severe impacts: the changes in litter decomposition and soil respiration in line 12-13 in the new revised version (red font). Thank you.

C: Lines 16-17: Since many readers do not get past an abstract, it would be useful to list treatment pressures in parantheses following long-term (ex.), short-term, etc.
R: Thanks. We have added the relevant information concerning the warming treatments in lines 16-17.

C: Line 19: Give the percentage of substantial water input treatment?
R: We fully irrigated the soil to field capacity and we have added it to this sentence lines 20-21. Many thanks.

C: Line 55: Use a more updated IPCC statistics (this one is 2014)
R: Thank you very much. But we are sorry about that because this information is from the last version (AR5 report of IPCC) that we can just find from IPCC. The future AR6 report has not been published (www.ipcc.ch/). However, we found a recent IPCC special report that highlights the warming-induced ecosystem degradation in relation to the study, and cited (IPCC 2019) (Line 59).

C: Warming treatment pressures were only applied during the growing season (June-Aug) of each year. In many temperate ecosystems, there has been evidence of seasonal extensions. Has there been any evidence that the growing season is becoming extended (earlier springs, later falls) at this site? If so, should this warrant extending warming treatments beyond June – August?
R: Thank you for your helpful advice. The growing season was not extended in our experimental site, an arid area, during our experiment. The warming-induced drought may limit the seasonal extensions, which may be outside our scope of the study. This may need to be explored in the future study in the arid ecosystem.

C: Line 774: If outlier point does not change equations, why not remove it completely?

R: Because it is the actual values that we measured; and the data have been included when the equations and their parameters were analyzed. Thus, it could be better that the points were shown. Additionally, we also presented the results excluded outlier points in Supplementary Figure S2.

Technical Comments:

C: Figure 2 line 769: Linear line is blue and not black as stated

R: Many thanks, we have corrected it accordingly.

C: Line 773: Typo? What does "soil animal" refer to?

R: Thanks for the kind comments. This is an improper phrase, and we have deleted it accordingly.

Thank you again for the valuable suggestions.

Response to RC2:

General Comments:

***C*:** This study addresses an important research topical at climate change impacts on dryland soil carbon dynamics. This article presents valuable data from a field manipulation study in which the authors examined how warming and watering regimes of varying intensity and duration impact soil respiration in a desert steppe. While the study methods appear sound and the results provide strong evidence for warming-driven reductions in soil respiration, many sections in the text are unclear and need to be improved to strengthen and clarify the manuscript. The authors could modify hypothesis two into a statement that could be tested in this study and contribute to new insight on the dynamics of soil respiration in water-limited ecosystems.

R: Thank you for the positive comments. In the newest version, we have carefully revised and checked again the manuscript to strengthen and clarify the results as kindly suggested (please see the details below). The two hypotheses have been modified accordingly (Lines 106-110 of the newest version, highlighted by red words).

C**:** There are key findings that are not clearly reported and challenge my interpretation as a reader. Specifically, the authors should address an apparent conflict: warming decreased R_s despite the positive relationship between R_s and soil temperature. The authors should explicitly highlight the important role of soil moisture as the dominant control on R_s rates and temperature sensitivity.

R: Thank you for helpful comments. Actually, that is, the persistent warming treatments decreased average R_s. The positive relationship between R_s and soil temperature occurs in each plot or each treatment. The two data sets are different, the former is continued warming treatment effect (comparison among the treatments: long-term warming, short-term warming, and ambient as a control), and the latter is the relationship between R_s and soil temperature. Yes, the important roles of soil moisture as the dominant control on R_s rates and temperature sensitivity were highlighted in many appropriate places of the newly revised version (e.g., lines, 22-23, 100-101, 377-390).

C**:** Lastly, the data availability statement does not appear to meet the journal’s data policy requirements, and I suggest uploading data to a public repository, if possible.

R: Many thanks. In the newest version, we have shared the data in an open repository, the zenodo; and the statements has been added in the new version: “Data availability. The final derived data presented in this study are available at https://doi.org/10.5281/zenodo.3546062 (Yu et al., 2019)”.

Specific comments: Parts of this manuscript would benefit from additional explanation. Below I provide some specific examples.

***C*:** L 24-27. “This indicates that soil carbon release responses strongly depend on the duration and magnitude of climatic warming, which may be driven by SWC and soil temperature.” This is unclear. Please explain how SWC and soil temperature influence soil respiration, and then perhaps infer how those relationships have implications for climatic warming impacts on soil carbon dynamics.

R: Thank you, we have revised it to “This indicates that climatic warming constrains soil carbon release, which is controlled mainly by decreased soil moisture, consequently influencing soil carbon dynamics” to be clearer and more concise (Lines 21-23 of the newly revised version). The relevant mechanism has been added as kindly suggested (Lines 343-360).

***C*:** L 55-59: An explanation of why low precipitation and biomass enhances vulnerability would strengthen the authors’ claim that deserts are sensitive to climate change.

R: Many thanks. We have made it to be clearer and concise accordingly, and the explanation was also added accordingly: “For instance, water deficit and heat waves during growing season can markedly decrease plant cover and productivity in this arid ecosystem” (Lines 59-63).

***C*:** L 60-66: This section shows that temperature and moisture are well-known controls on R_s. However, this conflicts with the previous claim (L43-47) that Rs responses to biotic and abiotic factors are poorly understood. Can this apparent contradiction be addressed in a way that makes a stronger case for this study? E.g. whereas soil moisture and temperature are well-known controls on R_s, it is not well known how soil moisture modulates the response of R_s to changes in the duration and intensity of warming.

R: we have changed the expressions in both sections to be clearer and more logical

(Lines 44-48; 66-68). Many thanks.

C**:** L 84: Please elaborate on “undefined” since many studies have reported *R*$_s$ pulses after water inputs (Huxman et al., 2004; Sponseller, 2007). Huxman, Travis E., et al. "Precipitation pulses and carbon fluxes in semiarid and arid ecosystems." Oecologia 141.2 (2004): 254-268. Sponseller, Ryan A. "Precipitation pulses and soil CO_2 flux in a Sonoran Desert ecosystem." Global Change Biology 13.2 (2007): 426-436.

R: Thank you for the useful advice, this part has been revised accordingly: the inappropriate word “ undefined” has been removed. And we cited the two references (Lines 90-93).

C**:** L 86-88. This argument would be stronger if the authors explained why a long-term study (4 years) might yield insights undetected in previous two-year studies. Why do the authors expect to find something new?

R: Thank you. Yes, we have important findings in previous two-year which have been published (Liu et al. Plant Soil, 2016, 400:15–27). In the current study, however, we expect that the long-term (four-year) warming have different effects on *R*$_s$ (i.e., more profound, even reverse effects relative to previous two-year short term); and the underlying mechanism under longer term warming condition, and the role of soil water status to *R*$_s$ responses to climatic warming, are also uncertain (added this explanation in the new version, lines 97-101).

C**:** L 88-89: Unclear. Please elaborate.

R: Thanks very much, we have re-edited it to “and the underlying mechanism under longer term warming condition, and the role of soil water status to *R*$_s$ responses to climatic warming, are also uncertain” (also see above).

***C*:** L 97-98: The introduction section already provides evidence in support of H2. In its current form, it is not clear why it is worth testing H2 in this study. How could H2 be modified into a hypothesis that could be tested in this study and contribute to new insight on the dynamics of soil respiration in water-limited ecosystems?

R: This H2 has been modified to "the dynamics of R_s in the water-limited ecosystem can be driven mainly by the combination of soil temperature and soil moisture, and soil moisture can modulate the response of R_s to warming". Many thanks.

***C*:** Results 3.1. Warming effects on soil features L 251-254: According to the Supplementary Table S1, belowground biomass is 11.5 units for the Acutely Warmed treatment. Is this a typo? It is considerably higher than the BB reported for other treatments.

R: Thanks for your comments. This is a mistake, it should be 1.15, and we have corrected it (Supplementary Table S1).

***C*:** 3.2: It is unclear why this is section is titled "Watering pulse effects on R_s." Does this section refer to data collected only after watering? Or does the section report findings from all measurement dates?

R: We have two experiments: one is the warming experiment which included three treatments: control, long-term moderate warming, and short-term acute warming. The other is the watering pulse treatments which included control and watering treatment to further highlight the important role of water status. Yes, this section referred to data collected in the plots of watering treatments.

***C*:** Figure 2: Please explain the data source – do the data represent the control or warmed treatments? Also, is it necessary to show the linear and quadratic fits? Are these pieces of information reported or used to make inferences?

R: This section mainly focused on the relationship between R_s and soil water content. The data were collected in the plots of watering treatments (added in the figure 2 legend of the new version), and were used to determine the relationship between R_s and soil water content in dessert steppe. Here, we focused on the comparisons between the linear, quadratic, and Gompertz functional models. Thus, the information used could be useful. Many thanks for the kind comments.

C: Figure 3A. This figure presents information that is critical for the authors' conclusion. It provides evidence for why R_s was lower in warmed treatments, despite having a positive relationship with soil temperature. I suggest leading Section 3.2 or 3.3 with a strong statement describing the relationship between R_s, temperature, and moisture. For example, soil respiration increased exponentially with temperature in watered plots but was lower and insensitive to temperature in the control plots.

R: Thanks for your useful advice, it has been revised accordingly in lines 294-298.

C**:** L 771: Unclear. What is the initial R_s response to SWC? What do the other points represent?

R: It should be linear R_s response to SWC at low levels. This is Gompertz functional model features: for the all points, with SWC increasing, R_s linearly increased sharply, then reaching a maximum value, and levelling off at a stable level. The relevant explanations have been added accordingly (Lines 377-390). Many thanks.

C**:** Section 3.3 Suggest leading with conclusive evidence. For example, "Warming regimes resulted in marked declines in R_s. Whereas no difference in Rs was observed in July, during August average R_s values were x, y, z for the control, moderately warmed, and acutely warmed treatments, respectively.”

R: Thanks, it has been done in lines 285-288.

C**:** Section 3.4 needs a figure reference.

R: The reference figure is figure 5, and was added (Line 303).

C**:** This section should explain why R_s decreased in warmed plots despite having a positive relationship with soil temperature.

R: They are different two terms: R_s in warmed plots were the values averaged in the warming treatments, whereas R_s values used for the relationship with soil temperature are the data in each plots or each treatments; and particularly, the soil temperature data used for the relationship R_s and soil moisture are the values when the R_s were measured simultaneously. They two are matching values each other. Thus, long-term warming rather than temporary high temperature reduced R_s, despite having a positive relationship with soil temperature (also added, lines 294-298).

C**:** L 319-322: Unclear how R_s can acclimate to warming but also decrease. Please explain the mechanism. Is the acclimation referring to changes in microbial respiration? Are net reductions in R_s driven by temperature-stress impacts on plant and root activity?

R: R_s can acclimate to warming but also decrease. The acclimation refers to changes in both root and microbial respiration. A net reduction in R_s may be partly driven by temperature-stress impacts on root activity (e.g., the continual warming can limit the root activity, thus reducing R_s). The “plant” has been removed because this study mainly focused on the belowground parts. This section has been substantially revised, the relevant mechanism has been added as kindly suggested (Lines 343-360, red parts): “Actually, the R_s [the sum of root (autotrophic, R_a) and

R_h respiration–the former accounting for *c.* 22 % of the total R_s in the ecosystem, Liu et al. 2016] may acclimatize to warming within an appropriate range of temperature change at an ample soil moisture; however, it decreases with increasing temperatures above an optimum level. The mechanisms may include: within an appropriate range of temperature change at an ample soil moisture, climatic warming can enhance both plant root (Luo et al., 2001; Liu et al. 2016) and microbial activities (Tuker et al. 2014), leading to increases in both R_a and R_h , consequently the R_s (Luo et al., 2001; Tuker et al. 2014; Xu et al., 2019). However, when warming continues or with increasing temperatures above an optimum level, the root growth can be constrained, directly reducing R_a (Carey et al., 2017; Liu et al., 2016; Luo et al., 2001; Wan et al., 2007); and the limitation to microbial activities may also occur (Tucker et al.. 2013; Yu et al., 2018), decreasing the R_h (Bérard et al., 2011; Tucker et al., 2013; Bérard et al., 2015; Romero-Olivares et al., 2017). In addition, decreases in soil enzyme pools and its activity under warming may also contribute to a reduction in R_a (e.g., Alvarez et al. 2018). Further, R_s decreases with warming under water deficit (Moyano et al., 2013; Wang et al., 2014; and see below). Together, the declines in both root and microbial respirations finally reduce the R_s". Many thanks for the valuable comments.

C**:** L358-362: Consider citing previous studies documenting that the temperature response of R_s is conditional on moisture (Roby et al., 2019; Conant et al., 2000).
Roby, M. C., Scott, R. L., Barron-Gafford, G. A., Hamerlynck, E. P., & Moore, D. J. (2019). Environmental and Vegetative Controls on Soil CO2 Efflux in Three Semiarid Ecosystems. Soil Systems, 3(1), 6.
Conant, Richard T., Jeffrey M. Klopatek, and Carole C. Klopatek. "Environmental factors controlling soil respiration in three semiarid ecosystems." Soil Science Society of America Journal 64.1 (2000): 383-390.
R: Thank you, we have cited them already in lines 416-417, and added in the

reference list (red parts).

TECHNICAL COMMENTS

***C*:** L22: Features is unclear.

R: This has been changed it to “The belowground biomass, soil nutrition, and microbial biomass” to detail these soil variables in line 26 of the new revision.

***C*:** L 143: What are the units of soil moisture?

R: It has been added (a ratio: v/v) (Line 160).

***C*:** L 227: Please provide depth of soil temperature measurements.

R: We have provided it in line 244.

***C*:** L 199: First mention of SWC; please define or introduce this acronym in section 2.3

R: the SWC whole name has been added in line 180 in the new version. Thanks.

***C*:** L 126. Unclear. Is 1 m the wavelength of radiation or dimension of the heater?

R: This indicates the dimension of the heater (1.0 m long); and we have revised it accordingly in line 141.

***C*:** L117-119: Suggest using concise and consistent treatment names. E.g. control, long term moderate warming, short-term acute warming.

R: It has been done in line 130-131, and throughout the entire text.

***C*:** L 283: “Mode” typo.

R: Sorry for this mistake, it should be “model”, and was corrected.

***C*:** L 283: Please provide equation number.

R: the equation number is 4, and was added (Line 303).

***C*:** L 238: Suggest different word for features

R: We have changed to “belowground characteristics” in line 255.

***C*:** L 241-243: Suggest reporting an error estimate instead of range.

R: This has been done in lines 259.

***C*:** L 246: Define v/v

R: it is defined as ratios of water volume and soil volume (added in the new revision, lines 262-263)

***C*:** Throughout: Be consistent with significant figures (L264 : $R^2 = 0.31$ vs. L284: $R^2 = 0.404$

R: Thank you, we have revised R^2 values with two 2 digits throughout the text. Many thanks for the constructive comments and suggestions.

Response to RC3:

General Comments:

***C*:** The paper describes a four year warming and wetting experiment in a desert steppe in Northern China. The introduction gives a good overview of the latest and more established scientific insights and the authors did a thorough measurement campaign. I particularly appreciate how much work went into the various additional belowground measurements. Given the limited number of such experiments for this ecosystem type, this work is certainly of interest to readers of Biogeosciences. Overall, the paper is well structured and written clearly, but I feel there are some elements in the text that require clarification or some more in-depth information. If the authors manage to improve these elements I would recommend the paper for publication.

R: Thank for the positive comments. The manuscript has been revised as kindly suggested.

Major comments:

C**:** My first major comment is directly about the abstract. There is a seemingly counterintuitive message there that confused me when reading it: Long-term warming reduced R_s by 32.5 percent (line 18). Yet, long term climatic warming decreased SOC (line 24)? While this is certainly possible, it is not directly what one would expect. Was this reduction in SOC caused by an initial spike in R_s at the beginning of the experiment? The lower SOC content could then also contribute to decreasing respiration due to reduced availability of substrate to microbes to decompose. Yet, the authors mainly talk about the moisture effect and how low soil moisture decreased R_s. The mentioned decline in SOC from the abstract is not presented in the results and discussion. Actually, the authors state that "in the present study, SOC concentrations were not significantly affected by climatic warming" and then later write "although SOC might be expected to decrease with long-term climatic warming" (conclusion iv). I do not understand how such a strong statement can be made in the abstract when the results and discussion show otherwise and even contradict one another. Given the high number of people that generally do not read beyond the abstract, my suggestion is to 1) rewrite this part of the abstract more clearly and 2) to present the evidence to support this claim more clearly in the results and discussion.

R: This suggestion is very valuable for us. To be clearer and more logical throughout the text, we have rewritten the relevant expressions: e.g., we deleted the "soil organic carbon content tended to decrease with long-term climatic warming" because of the results: "SOC concentrations were not significantly affected by climatic warming (Supplementary Table S1). Yes, based on the present results, we mainly focused on the new significant findings' aspects: the long-term warming effects on soil preparation, watering effects, and the its relationships with soil moisture and soil temperature. Thank you for the kind suggestions.

***C*:** My second major comment is about the authors' choice for the various model fittings in the statistical analysis and in particular for the Gompertz function. The authors provide limited explanation for choosing the Gompertz equation in section 4.2, line 334-337 and mention the parabolic curve function as another viable option. Indeed, in section 3.2 there is another model with a better fit: the quadratic functional model. The authors do not argue further why they still continued parameter fitting with the Gompertz curve, despite the quadratic model having a seemingly better fit (figure 2 and section 3.2). I would like to know 1) why the Gompertz function was selected and 2) how picking that curve to fit the parameters for the non-linear regression model (eq 4) affected the results compared to taking the parameters from a quadratic model fitting (sensitivity analysis)?

R: We conducted the Gompertz relationship to clarify the relationship because the data most likely support a Gompertz (i.e., saturating, sigmoidal) relationship rather than a linear relationship. The parabolic curve mentioned (in section 4.2) is inappropriate, was deleted. 1) the Gompertz relationship can well fit with the relationships between R_s and soil water content ($R^2 = 0.87$; RMSE = 4.88; also refer to e.g., Gompertz, 1825; Yin et al., 2003), which also can obtain some key thresholds (e.g., the asymptote value, the optimal SWC) that can not obtain from both linear and quadratic functional models. 2) A non-linear regression model (eq 4) is used to fit the relationship of R_s with both soil temperature and soil moisture. The optimal SWC of 0.229 (v/v) was estimated by the Gompertz functional curve. This optimal SWC (means that a SWC value when R_s reach a maximum) is a necessary parameter of equation 4, which is just obtained the Gompertz functional model. Thanks for the valuable comments.

Minor comments:

C**:** The Gompertz function (line 22): This function (and its shape) might not be a given knowledge for all readers. My suggestion is to rephrase in the abstract to "whereas the relationship between R_s and soil moisture was better fitted to a sigmoid function" and explain the Gompertz curve further in Section 2.6 (see major comment #2).

R: Thank you, this has been done in line 25 the abstract and line 229 in Section 2.6. From the sigmoid function curve, the thresholds of the changes in Rs with increasing SWC can be obtained (236-237).

C: Line 48: The desert steppe is c. 8.8 million square hm. Do the authors mean total global desert steppe area or the area in China?

R: It means the area in China, and has been revised to "The desert steppe of China" (Line 51). It should be *c.* 8.8 million square hm, and was corrected. Many thanks.

C**:** Line 74/75: I would suggest adding the more recent reference to Yan et al. 2018 here as well.

R: Thanks, we have added it already in line 82, and in the reference list.

C**:** Reference:

Yan, Z., B. Bond-Lamberty, K. E. Todd-Brown, V. L. Bailey, S. Li, C. Liu, and C. Liu (2018), A moisture function of soil heterotrophic respiration that incorporates microscale processes, Nature Communications, 9(1), 2562, doi: 10.1038/s41467-018-
04971-6.

R: It has been cited and added in the reference list.

Many thanks for the constructive comments and suggestions.

Anonymous Referee #4:

C**:** I forgot to add one minor textual edit to my review:

Line 195: Replace were with was. The analysis (of variation) is singular and therefore requires a singular verb.

R: Thanks for the kind correction, it has been done.

We greatly appreciate your constructive comments and kind suggestions which help us very much to improve our study, and hope our revisions and corrections would meet with your approval.

Soil carbon release responses to long-term versus short-term climatic warming in an arid ecosystem

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Abstract Climate change severely impacts grassland carbon cycling such as the changes in litter decomposition and soil respiration (R_s), especially in desert steppes. However, little is known about the R_s responses to different warming magnitudes and watering pulses *in situ* in desert steppes. To examine their effects on R_s, we conducted long-term moderate warming (four-year, around 3°C), and short-term acute warming (one-year, around 4°C), and watering field experiments in a desert grassland of Northern China. While experimental warming significantly reduced average R_s by 32.5% and 40.8% under long-term moderate and short-term acute warming regimes, respectively, watering pulses (fully irrigated the soil to field capacity) stimulated it substantially. This indicates that climatic warming constrains soil carbon release, which is controlled mainly by decreased soil moisture, consequently influencing soil carbon dynamics. Warming did not change the exponential relationship between R_s and soil temperature, whereas the relationship between R_s and soil moisture was better fitted to a sigmoid function. The belowground biomass, soil nutrition, and microbial biomass were not significantly affected by either long-term or short-term warming regimes, respectively. The results of this study highlight the great dependence of soil carbon emission on warming regimes of different durations and the important role of precipitation pulse during growing season in assessing the terrestrial ecosystem carbon balance and cycle.

Key words: Long-term warming; Precipitation pulse; Soil carbon release; Response sensitivity; Belowground characteristics; Desert grassland.

1 Introduction

The global carbon (C) cycle is a critical component in the earth's biogeochemical processes and plays a major role in global warming, which is mainly exacerbated by the elevated carbon dioxide (CO_2) concentration in the atmosphere (e.g., Falkowski et al. 2000; Carey et al. 2016; Ballantyne et al. 2017; Meyer et al. 2018). Soil respiration (R_s), mainly including the respiration of live roots and microorganisms, is a key component of the ecosystem C cycle as it releases *c*. 80 Pg of C from the pedosphere to the atmosphere annually (Boone et al., 1998; Karhu et al., 2014; Liu et al., 2016; Ma et al., 2014; Schlesinger, 1977). The effects of both soil moisture and temperature on R_s processes and the eco-physiological mechanism are reported extensively; however, it is not well known how soil moisture modulates the response of R_s to changes in the duration and intensity of warming, particularly in arid and semiarid areas, where water and nutrients are both severely limited (e.g., Dacal et al., 2019; Fa et al., 2018; Reynolds et al., 2015; Ru et al., 2018).

The desert steppe of China is *c*. 88 million hm^2, accounting for 22.6% of all grasslands in China, and is located in both arid and semiarid areas. More than 50% of the total area of the steppe is facing severe degradation in terms of the decline of community productivity and soil nutrient depletion, primarily due to improper land use, such as over-grazing and adverse climatic changes, including heat waves and drought stresses (Bao et al., 2010; Kang et al., 2007). Global surface temperature—mainly caused by the anthropogenic CO_2 increase—is expected to increase from 2.6 to 4.8°C by the end of this century, accelerating land degradation (IPCC 2014; 2019). Moreover, the desert steppe ecosystem with low vegetation productivity is vulnerable to its harsh environmental conditions, such as scarce precipitation and barren soil nutrition. For instance, water deficit and heat waves during growing season can markedly decrease plant cover and productivity in this arid ecosystem (Hou et al., 2013; Luo et al., 2018; Maestre et al., 2012; Yu et al., 2018).

Numerous studies have shown that soil temperature and moisture are the two crucial factors that mainly control R_s; however, it is not well known how soil moisture status mediates the response of R_s to the changes in the duration and intensity of climatic warming. Soil temperature is the primary factor driving temporal R_s variations (e.g., Carey et al., 2016; Gaumont-Guay et al., 2006; Li et al., 2008; Wan et al. 2005). Generally, R_s is significantly and positively correlated with soil temperature when soil moisture is ample (Curiel et al., 2003; Jia et al., 2006; Lin et al., 2011; Reynolds et al., 2015; Yan et al., 2013). In general, the seasonal variations of R_s coincide with the seasonal patterns of soil temperature (Keith et al., 1997; Lin et al., 2011; Wan et al., 2007). For instance, Lin et al. (2011) reported that 63 to 83% of seasonal variations of R_s are dominantly controlled by soil temperature. Diurnal R_s variations are highly associated with variations in soil temperature (Drewitt et al., 2002; Jia et al., 2006; Song et al., 2015). Soil respiration, according to previous studies, is expected to increase with soil water content (SWC) (e.g., Chen et al., 2008; Song et al., 2015; Wan et al., 2007; Yan et al., 2013). However, when the SWC exceeds the optimal point to reach saturated levels, R_s decreases (Huxman et al., 2004; Kwon et al., 2019; Moyano et al., 2012; Moyano et al., 2013; Wang et al., 2014; Yan et al., 2018). In a study conducted in a tall grass prairie, water addition dramatically increased soil CO_2 efflux (Liu et al., 2002). Liu et al. (2009) showed a significant R_s increase after a precipitation pulse in a typical temperate steppe. Therefore, in arid and semiarid regions, where soil water is limited, the SWC may control R_s, and regulate the warming effect (Chen et al., 2008; Curiel et al., 2003; Shen et al., 2015). Furthermore, the effect of watering pulses depends on the pulse size, antecedent soil moisture conditions, soil texture and plant cover (Cable et al., 2008; Chen et al., 2008; Shen et al., 2015; Hoover et al., 2016). For instance, the results by Huxman et al. (2004) showed that different precipitation pulses have different effects on carbon fluxes in these arid and semiarid regions; and Sponseller (2007) indicated that CO_2 efflux increases with storm size in a Sonoran Desert ecosystem.

A previous study reported the effects of relatively short-term (two-year) warming (2°C) on soil respiration (Liu et al., 2016). However, there is limited information about the long-term (four-year) warming effects on R_s and the underlying mechanism. In this current study, we expect that the long-term (four-year) warming have different effects on R_s (i.e., more profound, even reverse effects relative to previous two-year short term); and the underlying mechanism under longer term warming condition, and the role of soil water status to R_s responses to climatic warming are also uncertain. Thus, in the present study, we used a randomized block design with three treatments: control (no warming, no watering), long-term moderate warming (four years extending from 2011 to 2014, about 3°C), and short-term acute warming (one year in 2014, about 4°C). Moreover, a watering pulse treatment (a full irrigation to reach field capacity) was also established. We present the following hypotheses: (i) both long- and short-term climatic warming can reduce soil CO_2 efflux, in which soil moisture plays a key factor controlling R_s in the arid ecosystem; and (ii) the dynamics of R_s in the water-limited ecosystem can be driven mainly by the combination of soil temperature and soil moisture, and soil moisture can modulate the response of R_s to warming.

2 Methods and Materials

2.1 Experimental site

The experiment was conducted in a desert steppe about 13.5 km from Bailingmiao in Damao County (110°19′53.3″E, 41°38′38.3″N; 1409 m above sea level), situated in Nei Mongol, Northern China. This area is characterized by a typical continental climate. The mean annual temperature of this area was 4.3°C with a minimum of –39.4°C and a maximum of 38.1°C from 1955 to 2014. The mean annual precipitation is 256.4 mm and approximately 70% of the annual precipitation is distributed in the growth season period occurring from June to August (Supplementary Figure S1). According to Chinese classification, the soil type is called “chestnut” (Calcic Kastanozems in the FAO soil classification) with a bulk density of $1.23\ \mathrm{g{\cdot}cm^{-3}}$ and a pH of 7.4. The area has not been grazed since

1980; the dominant species is *Stipa tianschanica* var. klemenzii, accompanied by *Cleistogenes squarrosa*, *Neopallasia pectinata*, *Erodium stephanianum* and *Artemisia capillaris* (e.g., Hou et al., 2013; Ma et al. 2018).

2.2 Experimental design

The warming experiment used a randomized block design that included three treatments: control (i.e., ambient temperature), long-term moderate warming, short-term acute warming. The long-term moderate warming plots were exposed to long-term warming from early June to late August (the growing season) for four years (2011–2014), while short-term acute warming was manipulated only during the growing season (June to August) in 2014.The targeted increases in temperatures relative to ambient temperature (control) are around 3°C and 4°C under the long-term moderate warming (four-year), and short-term acute warming regimes(one-year), respectively. Watering pulse treatments were conducted in August in 2014 and 2017. The control plots received no additional treatments of either temperature or water (they were recognized as warming or watering control treatments). All of the warmed plots were heated 24 h/day by infrared (IR) lamps (1.0 m long) (GHT220-800; Sanyuan Huahui Electric Light Source Co. Ltd., Beijing, China) at 800 W during growing seasons in the experimental years (2011–2014). The IR lamp heights above the ground were 1.5 m and 1.0 m in moderately and acutely warmed plots, respectively. This facility can effectively mimic different climatic warming regimes in field *in situ*, as previously reported (e.g., Hou et al., 2013; Ma et al., 2018; Yu et al., 2018). The watering pulse plots were fully irrigated to field capacity to simulate a watering pulse on August 19, 2014, and August 14, 2017. The neither watering nor warming plots were made as the control plots. For the field warming facility, to simulate the shading effects, the control plots were designed to install a “dummy” heater similar to those used for the warmed plots. There were a total of 15 experimental plots (2 m × 2 m) arranged in a 3 × 5 matrix with each treatment randomly replicated once in each block across three experimental blocks; a 1 m buffer for each adjacent plot was made.

2.3 Soil temperature and moisture

At the center of each plot, a thermocouple (HOBO S-TMB-M006; Onset Computer Corporation, Bourne, MA, USA) was installed at a depth of 5 cm to measure the soil temperature, and a humidity transducer (HOBO S-SMA-M005; Onset Computer Corporation, Bourne, MA, USA) was installed at a depth of 0 to 20 cm to monitor the soil moisture (v/v). Continuous half-hour measurements were recorded by an automatic data logger (HOBO H21-002; Onset Computer Corporation, Bourne, MA, USA).

2.4 Soil respiration

The soil respiration was measured with a Li-8100 soil CO_2 Flux System (LI-COR Inc., Lincoln, NE, USA) with the R_s chamber mounted on polyvinyl chloride (PVC) collars. Fifteen PVC collars (10 cm inside diameter, 5 cm in height) were inserted into the soil 2 to 3 cm below the surface. They were randomly placed into the soil in each plot after clipping all plants growing in the collar placement areas. The collars were initially placed a day before measurements were begun to minimize the influence of soil surface disturbance and root injury on R_s (Bao et al., 2010; Wan et al., 2005). Respirations for the control and all of the warmed plots were measured from 6:00 a.m. to 6:00 p.m. on July 7 and 8 and August 18, 19, 20 and 21, 2014. The R_s for watering pulse treatment was measured after the water additions on August 19, 2014, and August 14, 15, 16 and 17, 2017. To stabilize the measurement, R_s was measured only on the selected typical days (i.e., mildly windy, sunny days). The R_s in all plots was measured once every 2 h on that day and each measurement cycle was finished within 30 min to minimize the effects of environmental variables, such as temperature and light. Thus, a total of six measurement cycles was completed each day. The soil water content (SWC, (0–20 cm soil depth) in watering plots was measured using the Field Scout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL, USA).

2.5 Belowground biomass and related soil characteristics

Soil samples of 0 to 10 cm in depth were taken from each collar after the R_s measurements and then passed through a 1 mm sieve to separate the roots. The roots were washed and oven-dried at 70°C for 48 h to a constant weight and then weighed. Subsamples of each soil sample were separated to determine the gravimetrical water content and soil chemical properties. Briefly, to determine the soil organic C (SOC) content, we mixed a 0.5 g soil sample, 5 ml of concentrated sulfuric acid (18.4 mol L^{-1}), and 5.0 ml of aqueous potassium dichromate ($K_2Cr_2O_7$) (0.8 mol L^{-1}) in a 100 ml test tube, then heated them in a paraffin oil pan at 190°C, keeping them boiling for 5 minutes. After cooling, the 3 drops of phenanthroline indicator were added and then the sample was titrated with ferrous ammonium sulphate (0.2 mol L^{-1}) until the color of the solution changed from brown to purple to dark green (Nelson and Sommers, 1982; Chen et al. 2008; Edwards et al. 2013). The soil ammonium-nitrogen (N) (NH_4^+-N) concentration and the nitrate-N (NO_3^--N) concentration were extracted with a potassium chloride (KCl) solution and measured using a flow injection analyzer (SEAL Auto Analyzer 3; SEAL Analytical, Inc., Mequon, WI, USA) (Liu et al. 2014). Soil samples (0–10 cm in depth) from each collar were oven-dried at 105°C for at least 48 h and weighed to determine the SWC. The soil microbial biomass C (MBC) and microbial biomass N (MBN) were measured using the chloroform-fumigation extraction method and calculated by subtracting extractable C and N contents in the unfumigated samples from those in the fumigated samples (Liu et al., 2014; Rinnan et al., 2009). All extracts were stored at 4°C until further testing commenced.

2.6 Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics 21.0 (IBM, Armonk, NY, USA). All the data were normal as tested by the Shapiro-Wilk method. A one-way analysis of variation (ANOVA) with LSD multiple range tests was conducted to test the statistical significance of the differences in the mean values of the soil temperature, soil moisture, R_s, belowground biomass, SOC, NH_4^+-N and NO_3^--N concentrations, and MBC and MBN concentrations at depths of 0 to 10 cm among the different treatments. A linear regression analysis was also used to test the relationship between the SWC and R_s. The relationship between R_s and the soil temperature in each treatment was tested with an exponential function.

We used Q_{10} to express the temperature sensitivity of R_s and calculated it according to the following equations:

$$R_s = ae^{b\mathrm{Ts}} \qquad (1)$$

$$Q_{10} = \mathrm{e}^{10b} \qquad (2)$$

Here, T_s is the soil temperature, a refers to the intercept of R_s when the soil temperature is 0°C, and b is the temperature coefficient reflecting the temperature sensitivity of R_s and is used to calculate Q_{10} (Lloyd and Taylor, 1994; Luo et al., 2001; Shen et al., 2015).

The relationship between R_s and the SWC was further conducted to fit the Gompertz function, a sigmoid function (Gompertz, 1825; Yin et al., 2003), which could express that the linear increase is rapid followed by a leveling off:

$$R_s = \mathrm{a}*\mathrm{e}^{-\mathrm{b}*(\exp(-\mathrm{k}*\mathrm{SWC}))} \qquad (3)$$

Here, a is an asymptote; the SWC halfway point of a/2 equals -ln(ln(2)/b)/c. The turning point of the maximum rate of R_s increase equals ak/e when the SWC equals ln(b)/k. Thus, from the sigmoid function curve, the thresholds of the changes in R_s with increasing SWC can be obtained from the Gompertz function (Gompertz, 1825; Yin et al., 2003).

A non-linear regression model was used to fit the relationship of R_s with both soil temperature and soil moisture (Savage et al., 2009):

$$R_s = (R_{\mathrm{ref}} * Q_{10}^{(\mathrm{Ts}-10)/10}) * \beta^{(\mathrm{SWC_{OPT}} - \mathrm{SWC})^2} \qquad (4)$$

where T_s is the soil temperature at a soil depth of 5 cm, R_{ref} is R_s at 10°C and Q_{10} is a unitless expression in R_s for each increase in 10°C. SWC is water content in 0 to 20 cm soil depth, SWC_{OPT} is the optimal water content and β is a parameter modifying the shape of the quadratic fit.

Following the key factors selected by the stepwise regression method, a path analysis was used to examine the primary components directly and indirectly affecting R_s by integrating both the stepwise linear regression module and Pearson correlation analyses (Gefen et al., 2000). The statistical significances were set at $P < 0.05$ for all tests, unless otherwise indicated.

3 Results

3.1 Warming effects on belowground characteristics

The soil temperatures at a soil depth of 5 cm in the warmed plots were much higher than those in the control plots (Figure 1). During growing season, the mean soil temperatures in the control, the moderately and acutely warmed plots were 21.9°C (±0.13 SE), 24.5°C (±0.15), and 25.0°C (±0.18), respectively. The moderately and acutely warmed plots were respectively increased by 2.6°C ($P < 0.001$) and 3.1°C ($P < 0.001$) compared to those in the control plots. The SWC in the moderately and acutely warmed plots (0–20 cm soil profile, defined as ratios of water volume and soil volume) were significantly reduced ($P < 0.001$) compared to those in the control plots (Figure 1), indicating that warming led to marked declines in the SWC, consequently enhancing drought stress. On August 18, 19, 20 and 21, which were the dates that we measured R_s, the daily soil temperatures in the moderately and acutely warmed plots were around 3°C and 4°C higher than those in the control plots, respectively. All belowground variables (belowground biomass, soil N and microbial characteristics) were not significantly altered by warming regimes at the site of this experiment (Supplementary Table S1; $P > 0.05$). However, the organic soil carbon content tended to decrease with long-term climatic warming.

3.2 Watering pulse effects on R_s

The R_s significant increased with SWC both linearly ($R^2 = 0.83$; $P < 0.01$) and quadratically ($R^2 = 0.88$; $P < 0.01$, Figure 2A). Moreover, the Gompertz function was well fitted to their relationship ($R^2 = 0.87$; RMSE = 4.88) (Figure 2B). From the Gompertz functional curve, the R_s asymptote value, as an estimated maximum, was 3.76 $\mu\cdot mol\cdot m^{-2}\cdot s^{-1}$ when the optimal SWC was 22.85%. In the watering plots, an exponential function was well fitted to the relationship between soil respiration and the soil temperatures ($R^2 = 0.31$; $P < 0.01$), with a temperature sensitivity (Q_{10}) of 1.69. However, the exponential function was not well fitted in the control plots (Figure 3A).

3.3 Effects of warming regimes on R_s

Warming regimes resulted in marked declines in R_s. Whereas no difference in R_s was observed in July, during August average R_s values were 1.57, 1.06, and 0.93

$\mu\cdot\mathrm{mol}\cdot\mathrm{m}^{-2}\cdot\mathrm{s}^{-1}$ in the control, moderately warmed and acutely warmed plots, respectively, indicating that warming regimes resulted in marked declines (Figure 4). Changes in R_s differed significantly between the control and both warmed plots ($P < 0.01$), while the R_s in the two warmed plots did not significantly differ ($P = 0.45$). The relationships between the R_s and soil temperature of each treatment were well fitted by the exponential equations ($P < 0.05$) (Figure 3B). The Q_{10} values were 1.88, 2.12 and 1.58 in the temperature controlled, moderate and acute warming treatments, respectively (Figure 3B). It indicated that R_s increases exponentially with temperature in watered plots but was lower and insensitive to temperature in the control plots (Figure 3A); and that long-term warming rather than temporary high temperature reduced R_s, despite having a positive relationship with soil temperature (Figure 3B, 4).

3.4 Interactive effects on R_s from soil temperature and soil water content

Across all watering and warming treatments, generally, a high temperature led to an increase in R_s under ample soil moisture, whereas R_s was limited under a soil water deficit. As shown in Figure 5, A non-linear regression model (equation 4) was well fitted to the relationship of R_s with both soil temperature and soil moisture in the control plots ($R^2 = 0.40$, RMSE = 0.60). Based on the function $R_s = (0.733*1.796^{(Ts-10)/10})*\beta^{(0.229-SWC)^2}$, the key parameters were obtained: R_{ref}, a R_s at 10°C, was 0.73 $\mu\cdot\mathrm{mol}\cdot\mathrm{m}^{-2}\cdot\mathrm{s}^{-1}$; Q_{10}, a unitless expression in R_s for each increase in 10°C, was 1.80; and β, a parameter modifying the shape of the quadratic fit, was 0.001 (Figure 5).

3.5 Effects of multiple factors on R_s: a path analysis

Based on a stepwise regression analysis of the relationships between the R_s and multiple factors, four key factors were screened: soil temperature, soil moisture, belowground biomass and SOC. Their effects on R_s were further determined by a path analysis. The results showed that soil moisture and soil temperature were two major direct factors controlling R_s (the two direct path coefficients were 0.72 and 0.55, respectively). SOC had the highest indirect effect on R_s (the indirect path coefficient was 0.57). Soil moisture highly correlated with R_s ($R = 0.78$, $P < 0.01$; Supplementary Table S2, Figure 6), indicating again that the soil water status may impose the greatest effect on the carbon release from soil in the desert grassland.

4. Discussion

4.1 Warming effects on R_s

Previous studies have shown positive R_s responses to increased soil temperatures below a critical high temperature (e.g., Carey et al., 2016; Drewitt et al., 2002; Gaumont-Guay et al., 2006; Meyer et al., 2018). However, in the current study site, the climatic warming finally reduced the average R_s by 32.5% and 40.8% under long-term versus short-term climatic warming conditions in the desert dryland, respectively, which chiefly confirmed our first hypothesis. In a semiarid grassland on the Loess Plateau of China, the total R_s was also constrained substantially by a field manipulative experiment (Fang et al., 2018). This result may have been caused by the following factors. First, high temperatures may cause thermal stress on microbes and subsequently reduce microbial respiration (i.e., heterotrophic, R_h, Chang et al., 2012; Dacal et al., 2019). For instance, in an alpine steppe on the Tibetan Plateau, microbial respiration was significantly reduced when the temperature rose to 30°C (Chang et al., 2012). Second, in the desert grassland, where water is often limited, the SWC becomes the primary factor affecting R_s (Supplementary Table S2; Figure 6), while warming can cause greater evapotranspiration, consequently lessening soil moisture (Figure 1), and finally reducing R_s (Munson et al., 2009; Wan et al., 2007; Yan et al., 2013). The decreases in average R_s with warming implicate that positive feedback on climatic change may be weaken with warming time or under an acute warming condition.

Actually, the R_s [the sum of root (autotrophic, R_a) and R_h respiration–the former accounting for *c.* 22 % of the total R_s in the ecosystem, Liu et al. 2016] may acclimatize to warming within an appropriate range of temperature change at an ample soil moisture; however, it decreases with increasing temperatures above an optimum level. The mechanisms may include: within an appropriate range of temperature change at an ample soil moisture, climatic warming can enhance both plant root (Luo et al., 2001; Liu et al. 2016) and microbial activities (Tuker et al. 2014), leading to increases in both R_a and R_h , consequently the R_s (Luo et al., 2001; Tuker et al. 2014; Xu et al., 2019). However, when warming continues or with increasing temperatures above an optimum level, the root growth can be constrained, directly reducing R_a (Carey et al., 2017; Liu et al., 2016; Luo et al., 2001; Wan et al., 2007); and the limitation to microbial activities may also occur (Tucker et al.. 2013; Yu et al., 2018), decreasing the R_h (Bérard et al., 2011; Tucker et al., 2013; Bérard et al., 2015; Romero-Olivares et al., 2017). In addition, decreases in soil enzyme pools and its activity under warming may also contribute to a reduction in R_a (e.g., Alvarez et al. 2018). Further, R_s decreases with warming under water deficit (Moyano et al., 2013; Wang et al., 2014; and see below). Together, the declines in both root and microbial respirations finally reduce the R_s. Nevertheless, the drastic declines in R_s under both long-term and short-term climatic warming regimes in the desert dryland ecosystem may be driven by multiple factors, including the ecosystem type, time and soil features (Liu et al., 2016; Wan et al., 2007; Meyer et al., 2018; Thakur et al., 2019). It implies that the effects of multiple factors should be considered in assessing the carbon balance between ecosystem and atmosphere.

4.2 Interactive effect of soil water status and temperature

As stated above, in an arid ecosystem, soil water deficit is a primary factor inhibiting soil carbon release (Supplementary Table S2; Figure 6; Liu et al., 2016; Munson et al., 2009; Yan et al., 2013). Thus, R_s linearly increases with increasing soil moisture. However, it could be leveled off or decreased when soil moisture exceeds an optimal level for the soil carbon release (Huxman et al., 2004; Moyano et al., 2013; Wang et al., 2014). Thus, the relationship between R_s and SWC may be well fitted to the Gompertz functional curve model, a sigmoid function (Gompertz, 1825; Yin et al., 2003), which can be confirmed by the present results in the native arid desert ecosystem (Figure 2). The mechanisms mainly are: an increase in SWC may increase rapidly microbial activities (Cable et al., 2008; Meisner et al., 2015; Wu & Lee, 2011), and enhance root growth (Xu et al., 2014), leading to a linear increase in R_s. However, when soil moisture reaches an ample level, microbial activities may also reach a maximum where the limiting effects of substrate occur (Skopp et al., 1990), finally maintaining a stable change in R_h at a higher level. Similar response to watering appears for root growth (Xu et al., 2014), and also similarly leading to a stable change in R_h at a higher level. Thus, R_s can be leveled off at a high and stable level. Moreover, the decrease in R_s at a saturated SWC level may be ascribed to inhibitions of both root systems and microbial activities under the anaerobic environment (Drew 1997; Huxman et al., 2004; Kwon et al., 2019; Sánchez-Rodríguez et al. 2019; Yan et al., 2018). The model concerning the relationship R_s with a broad range of SWC is helpful to assess and predict the dynamics in soil carbon release in natural arid ecosystems.

As indicated by Tucker and Reed (2016), soil water deficit can shrink the R_s itself and its response to temperature, suggesting the changes in R_s may be determined simultaneously by both soil temperature and water status (Janssens et al., 2001; Yan et al., 2013; Sierra et al., 2015). Moreover, in the present experiment, the interactive effects of both factors were tested based on the relationship of R_s with both soil temperature and soil moisture in a non-linear regression model (Savage et al., 2009). The model utilized was well fitted but marginally so ($R^2 = 0.40$, RMSE = 0.596; Figure 5), indicating that both the soil temperature and soil water content coordinated the changes in R_s. However, this interaction may also be affected simultaneously by other abiotic and biotic factors, such as soil nutrition availability and soil microbe activity (e.g., Camenzind et al., 2018; Karhu et al., 2014; Thakur et al., 2019; Zhang et al., 2014).

4.3 Key factors and the influence path

As noted above, R_s is affected by several abiotic and biotic factors. The current results showed that soil moisture and soil temperature were two major direct factors, and SOC only was an indirect factor controlling R_s (Supplementary Table S2, Figure 6). Importantly, soil moisture, with both the highest direct path coefficients (0.7) and correlation coefficient (0.8) for R_s, may become the most important factor affecting *R*$_s$ in this desert steppe. These findings agree with the previous results: Improved soil water status had a significantly positive effect on *R*$_s$ (e.g., Chen et al., 2008; Liu et al., 2016; Xu et al., 2016). Furthermore, the soil moisture condition can mediate the relationship between soil temperature and *R*$_s$, thus affecting the its temperature sensitivity; it becomes the main key factor controlling *R*$_s$, especially in arid ecosystems, such as desert steppes, where the available soil water is limited (Conant et al., 2000; Curiel et al., 2003; Fa et al., 2018; Jassal et al., 2008; Roby et al., 2019). Thus, under both the long-term and short-term climatic warming regimes, soil moisture could modulate the response of *R*$_s$ to warming; and the changes in *R*$_s$ might be driven by both soil temperature and soil moisture as two key factors, and SOC as an indirect factor, thus mostly confirming our second hypothesis. The findings again implicate that the multiple factors may together coordinate *R*$_s$, and provide new insight into how to control soil carbon release in arid ecosystems. The models on the *R*$_s$ changes should consider multiple-factor effects of soil carbon dynamics when assessing and predicting carbon cycle, and its climate feedback.

4.4 Warming effects on the variables belowground

Elevated temperature has been shown to increase or decrease root productivity and biomass, depending on experimental sites and vegetation types (Bai et al., 2010; Fan et al., 2009; Litton and Giardina, 2008; Wan et al., 2004). The decreased availability of soil nutrients apparently limits root growth, finally inducing root mortality and weakening responses to the elevated temperature (Eissenstat et al., 2000; Johnson et al., 2006; Wan et al., 2004; Zhang et al., 2014). In our experiment, no significantly different changes occurred in either soil NH_4^+-N or NO_3^--N concentrations among the three treatments (Supplementary Table S1), and these might be linked to the non-significant response of belowground biomass to increasing temperature. Microbial biomass and its activities in soil depend on the root biomass, SWC and soil N conditions (Liu et al., 2014; Rinnan et al., 2007; Zhang et al., 2008; Zhang et al., 2014). Warming regimes had no significant effects on either MBC or MBN in the current study (Supplementary Table S1), which might be due to the lack of any difference in the changes in basic soil nutrition status, such as the N conditions, among the three warming treatments. This result is consistent with that of Zhang et al. (2005) and Liu et al. (2015). Moreover, in the present study, SOC concentrations were not significantly affected by climatic warming (Supplementary Table S1), which is inconsistent with the findings of previous studies (Jobbágy and Jackson, 2000; Prietzel et al., 2016). However, there might be a decreasing trend evident with long-term warming. For instance, Crowther et al. (2016) reported a loss of approximately 30 ± 30 Pg of C in the upper soil horizons at 1°C warming in global soil C stocks and projected a loss of 203 ± 161 Pg of C under 1°C of warming over 35 years. The C losses from soil moving into the atmosphere may result in positive feedback regarding global warming (Bradford et al., 2016; Dacal et al., 2019; Jenkinson et al., 1991; Liu et al., 2016). However, SOC exerted an indirect effect via a path analysis (Figure 6). For this difference, therefore, more evidence needs to be provided to address the issue (Xu et al., 2019).

In conclusion, we determined the responses of R_s to field experimental long-term versus short-term climatic warming and watering pulses in a desert steppe ecosystem. We found the following: i) both long- and short-term warming significantly reduced R_s during the peak growth season; ii) soil moisture was the main factor controlling R_s in desert grassland; iii) R_s was significantly and exponentially increased with soil temperature, meanwhile soil moisture condition can mediate the relationship between soil temperature and R_s, thus affecting its temperature sensitivity; and iv) belowground biomass, soil nutrition variables and soil microbial characteristics showed no significant changes after either long-term or short-term climatic warming. These findings may be useful to assess and predict dynamics of soil CO_2 fluxes, particularly the feedback of warming to climatic change, and finally optimize C management work in arid and semiarid regions under the changing climate. However, the patterns of the changes in soil C fluxes and the underlying mechanism in response to climatic change are markedly complicated at various spatial-temporal scales during growing season—from site and regional to global scales, and from daily, seasonal and yearly to decade scales––and still need to be investigated further (e.g., Ballantyne et al., 2017; Dacal et al., 2019; ; Meyer et al., 2018; Romero-Olivares et al., 2017).

Data availability. The final derived data presented in this study are available at https://doi.org/10.5281/zenodo.3546062 (Yu et al., 2019).

Supplement. The supplement related to this article is available online at:

Author contributions. ZX and GZ conceived and designed this study. HY, ZX and YS conducted this experiment and analysed the data. All authors wrote and proofread this manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Figure legends

Figure 1. Effects of warming on the soil temperature and soil moisture during the growth peak in 2014 (Mean ± SE). Mean daily values were presented (n = 120). The mean values with the same lowercase letters on the SE bars are not different at $P < 0.05$ according to LSD multiple range tests (P values and F ratios are shown inside).

Figure 2. Relationship between R_s and soil water content based on a linear (blue line) and a quadratic (black line) functional model (A), and Gompertz functional model (B). Close and open circles denote the data in 2014 and 2017, respectively. The close red circles indicate data used for the linear R_s response to SWC at low levels. The one open triangle may be an outlier point due to some errors, but it does not notably affect the functional fitting when removing it (ref. Figure S2). Based on Gompertz functional curve, the R_s asymptote value, as an estimated maximum, is 3.76 $\mu \cdot mol \cdot m^{-2} \cdot s^{-1}$ when the optimal SWC is 22.85% [The red line denotes the initial R_s response to SWC; the blue line denotes R_s = constant value of the maximum estimated by the asymptote value; and the intersection of the two lines represents a point (the blue arrow) at which R_s levelled off]. Note, we measured the R_s during 9:00-10:00 in these cloudless days with calm/gentle wind in order to maintain other environmental factors such as soil temperature and radiation to relatively stable and constant. The data were collected in the plots of watering treatments (n = 92)..

Figure 3. The relationships between soil respiration and soil temperature under both watering (n = 23-25, A), and warming treatments (n=28-33, B) (Mean ± SE).

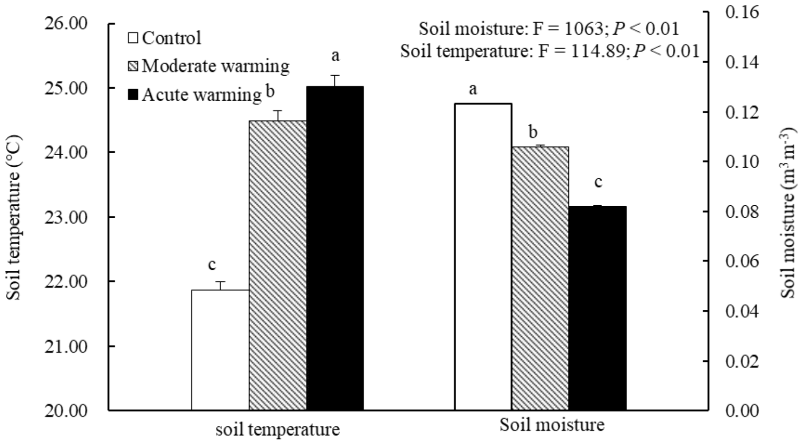
Figure 4. Effects of warming regimes on average soil respiration in 2014 (mean ± SE), the mean values with the same lowercase letters on the SE bars are not different at $P < 0.05$ according to LSD multiple range tests (P values and F ratios are shown inside).

Figure 5. An interactive relationship of soil respiration with both soil temperature (Ts) and soil water content (SWC) based on a nonlinear mixed model ($R_s = (0.733*1.796^{(Ts-10)/10})*\beta^{(0.229-SWC)^2}$). The data were used in control plots in the warming experiment. The optimal SWC of 0.229 was estimated by the Gompertz functional curve (see Figure 2B).

Figure 6. A diagram of the effects of key environmental factors on soil respiration and their relationships. Blue double-headed arrows represent the relationships between the key environmental factors, data on the arrows are correlation coefficients. Black arrows represent the relationships between soil respiration and the key environmental factors, data on the arrows are correlation coefficients (bold) and direct path coefficients (italic), respectively. *, $P < 0.05$; **, $P < 0.01$, n = 12. For other details, see Supplementary Table S2.

Supplementary Figure S1. Long-term air temperature (A) and total annual precipitation (B) records from 1955 to 2014 in the experiment site in the desert steppe ecosystem, Damao Banner, Nei Mongol, China.

Supplementary Figure S2. Relationship between R_s and soil water content based on a linear (black line) and a quadratic (dotted line) functional model (A), and Gompertz functional model (B). Close and open circles denote the data in 2014 and 2017, respectively. The close red circles indicate data used for the initial R_s response to SWC. The functional fitting does not substantially affect despite a slight improvement with greater R^2 values when the outlier point was removed (ref. Figure 2). Note, we measured the R_s during 9:00-10:00 in the cloudless days with calm/gentle wind in order to maintain other environmental factors such as soil temperature and radiation to relatively stable and constant (n = 91).



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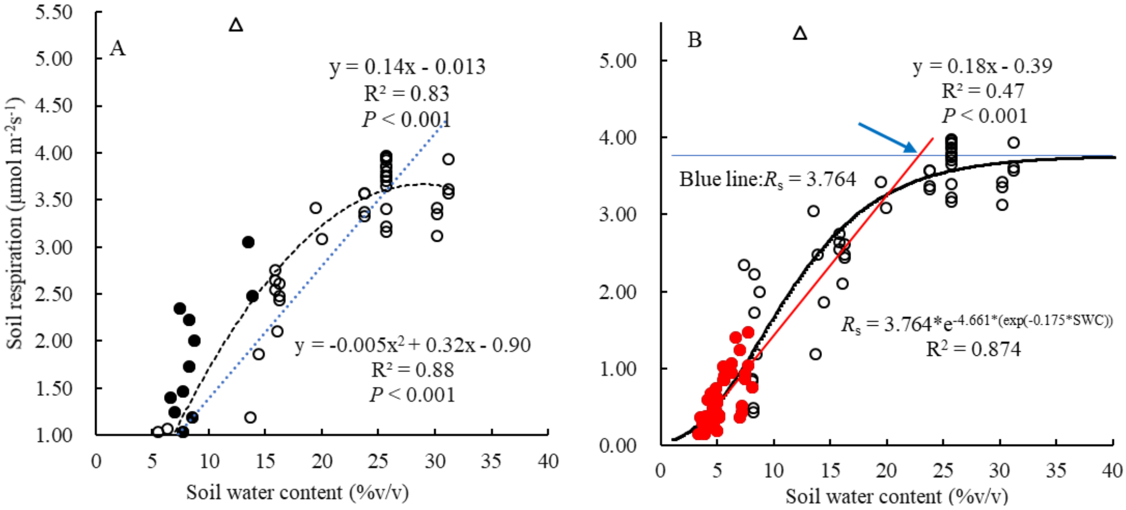

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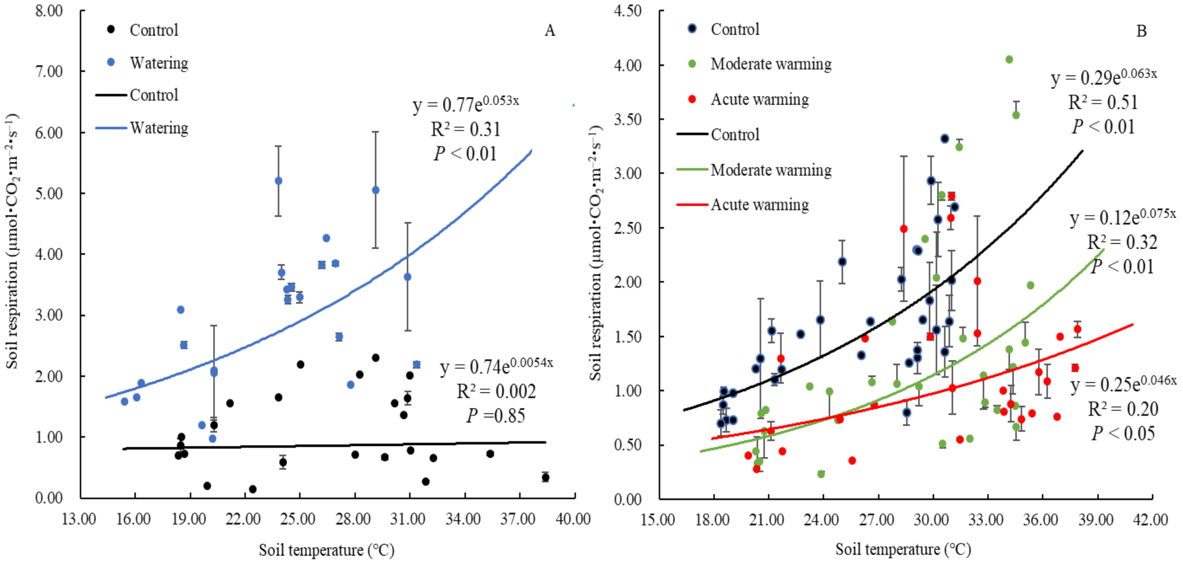

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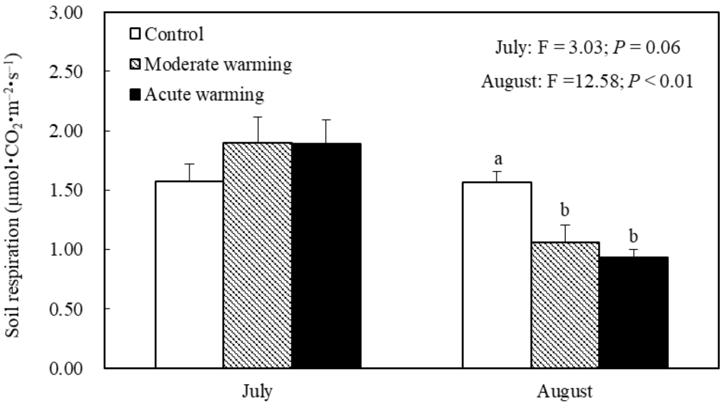

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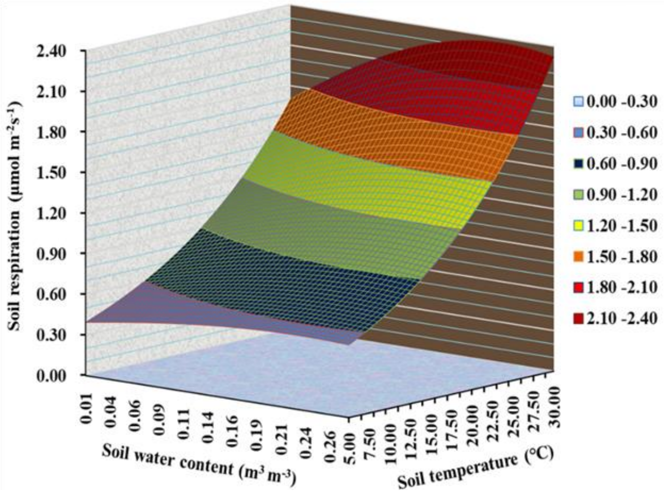

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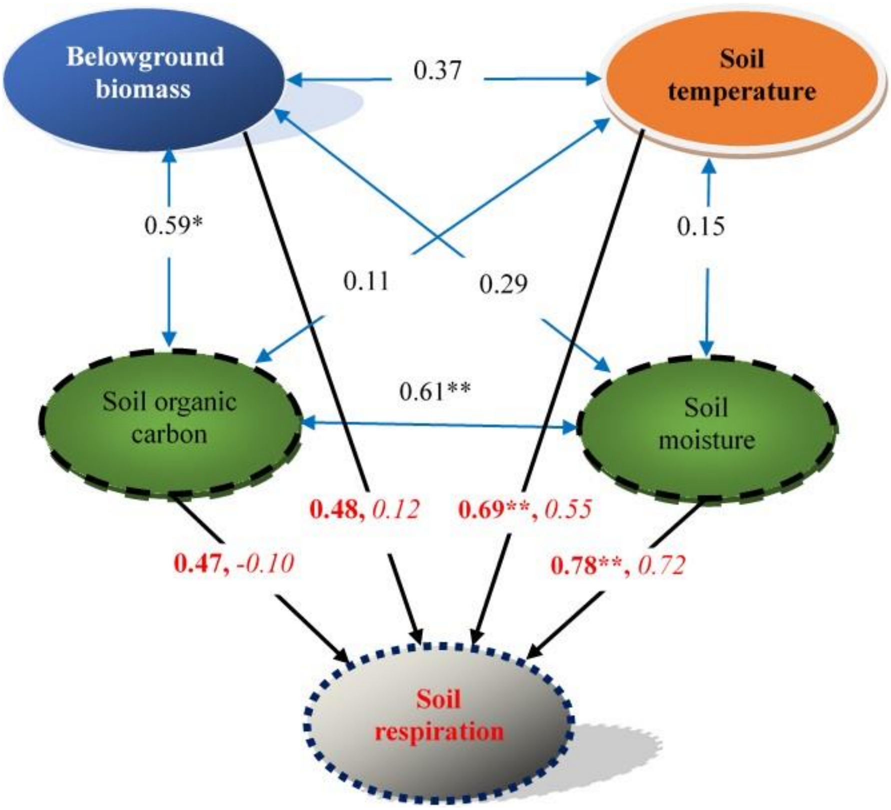

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