

## **Reply to the Associate Editor, Dr. Christopher Williams**

**Editor's Comment #1:** Your responses to reviews appear to be broadly satisfactory and the corresponding changes to the manuscript that you describe are likely to make it acceptable for publication. Accordingly, you are encouraged to submit a revised paper, in particular with additional revision or discussion to address the following continued issues:

**Response:** We are grateful to the editor, Dr. Williams, for the constructive comments, and for the opportunity to further revise our manuscript. During this revision, we carefully studied the editor's comments, considered the previous reviewers comments, and incorporated them into the revision accordingly. We listed the responses to the editor's comments one by one below and the corresponding revisions (line numbers) in the marked-up revised manuscript. Hopefully these responses and revisions would make the work being acceptable for publication in your journal.

**Editor's Comment #2:** -the method of model calibration was challenged and could have been improved beyond manual parameter tuning.

**Response:** Both the editor and reviewer #1 suggest a more rigorous way of model calibration (i.e. cross-validation and bootstrapping). However, the PALS model is only available in the STELLA platform, which hinders us from making the automated model runs necessary to complete automated model calibration. We have requested funding to recode PALS into an open source language. Nevertheless, our goal is not to obtain the best parameterization, but parameters that are plausible. These parameters are provided in the Supplementary Table S1. We use the parameterization with the expectation of reduced specificity to the site but increased generality to the region. The model was therefore calibrated within the platform through expert knowledge and experience with adjusting some of the key parameters such as photosynthate allocation ratios, death rates of plant organs, and decomposition coefficients of litter and soil organic matter to reach the best fit between the simulated and observed fluxes. We added discussion on the calibration in the revised manuscript (see lines 280-282 in the highlighted copy).

**Editor's Comment #3:** -the use of calendar year is unfortunate given the strong presence of seasonal dynamics at the study sites as well as the focus on legacy effects.

**Response:** We agree with the editor that using calendar year may have influences on the calculation of legacy effects. Following the reviewer #1's comment, we re-define our annual scale from the start of the main/warm growing season (i.e. July) to the end of the warm dry season (i.e. June of the next year). This revision is described in detail in lines 243-250. The re-definition of the 'annual' period does not affect the inter-decadal legacy calculations since it is quantified based on the cumulative C fluxes over 14 years of the current period (i.e. 1995-2010, see Fig.1a). We have however recalculated the inter-annual legacies, replotted the new data in

Fig. 6, and re-conducted the correlation analysis between interannual legacy and PPT characteristics. Correspondingly, the revised descriptions on these new results, which are very similar to the previous results, are presented in lines 407-431. In addition, we replotted Fig. 1 to better show the precipitation characteristics in the past 30 years at the study site by adding the frequency distribution of rainfall sizes (Fig. 1b) and the drought duration (or between event interval) in the four seasons (see page 54).

**Editor's Comment #4:** -a figure or table show the magnitude of carryover effects in comparison to the magnitude of current-year controlling factors (weather) would add value as noted by R1

**Response:** Following the suggestion by the editor and Reviewer #1, we reanalyzed the correlation between legacy effects and current-year PPT characteristics. The new results are presented in Table 1 (see page 48). This new table also contains the correlation analysis results for the previous-year PPT characteristics, and the PPT difference (i.e.  $\Delta$ PPT) between current- and previous-year. The descriptions for the new table are given in lines 419-431. Because the correlation analysis results between legacy effect and  $\Delta$ PPT are now presented in the new Table 1, the original Fig. 7 has been deleted (see page 62).

**Editor's Comment #5:** -additional critical discussion is needed to clarify the model's assumption regarding nitrogen buildup during dry periods that then stimulates productivity when rewetting occurs. observational support for this behavior must be presented, or if evidence is lacking, this should be called out openly. some good questions are raised in R1's comments 22 and 30.

**Response:** The accumulation of soil inorganic N (i.e.  $N_{\text{soil}}$  in this simulation analysis) during dry episodes or under drought experimental treatments has been reported in many dryland studies (e.g., Reynolds et al., 1999; Yahdjian et al., 2006; Yahdjian and Sala, 2010; de Vries et al., 2012; Evans and Burke, 2013; Reichmann et al., 2013b). What has been controversial is the fate of the accumulated  $N_{\text{soil}}$  during dry periods. On one hand, the accumulated  $N_{\text{soil}}$  may be conserved to a later period and thereby can stimulate primary production (or GEP) - the mechanism we think is responsible for the positive impacts of dry legacy on GEP with respect to our simulation results. Alternatively, the accumulated  $N_{\text{soil}}$  may have a higher risk of leaching loss or soil to atmosphere gas emissions in drier, rather than in wetter, conditions (e.g. McCulley et al., 2009; Evans et al., 2013; Reichmann et al., 2013b; Homyak et al. 2014), which is contrary to our model assumption that  $N_{\text{soil}}$  leaching loss is a linear function of PPT amount (i.e. more PPT results in greater N leaching loss or N leaching loss is greater in wet than in dry conditions/years). If the recent field study results are also true for our semi-desert savanna ecosystem, the model assumption could potentially cause an overestimation of  $N_{\text{soil}}$  carryover effects because more  $N_{\text{soil}}$  should be lost through leaching during the dry period. However we don't have observational support for such behavior at our study site to justify the model assumption. We have added two paragraphs ( lines 584-628) to discuss

more critically about the N accumulation mechanism explaining the simulated PPT legacy effects on GEP.

**Editor's Comment #6:** -improved discussion of mechanisms is warranted and responses suggest that this will already be part of a revised version.

**Response:** During this and the previous revision, the whole subsection (4.2 Potential mechanisms of the modeled PPT legacies) has been largely revised (see lines 542-673). We discussed the mechanisms first by explaining why a process-based model like PALS can generate the legacy behaviors from a systems perspective (see lines 543-569), and then by explaining the specific response patterns of different C fluxes to dry and wet legacies from a biogeochemical perspective (see lines 570-652). We think that these explanations account for the major response behaviors observed in this simulation analysis and would be helpful in identifying future research needs.

## 1 Abstract

2 The precipitation legacy effect, defined as the impact of historical precipitation (PPT) on  
3 extant ecosystem dynamics, has been recognized as an important driver in shaping the temporal  
4 variability of dryland aboveground primary production (ANPP) and soil respiration. How the  
5 PPT legacy influences whole ecosystem-level carbon (C) fluxes has rarely been quantitatively  
6 assessed, particularly at longer temporal scales. We parameterized a process-based ecosystem  
7 model to a semiarid savanna ecosystem in southwestern US, calibrated and evaluated the model  
8 performance based on 7 years of eddy covariance measurements, and conducted two sets of  
9 simulation experiments to assess interdecadal and interannual ~~scale~~ PPT legacy effects over a  
10 30-yr simulation period. The results showed that decreasing the previous period/year PPT (dry  
11 legacy) always ~~imposed positive impacts~~ ~~increased~~ ~~subsequent~~ ~~on~~ net ecosystem production (NEP)  
12 whereas increasing the previous period/year PPT (wet legacy) ~~had negative impacts on~~ ~~decreased~~  
13 NEP ~~— a negative PPT legacy effect~~. The simulated dry legacy impacts ~~were~~ mostly ~~positive~~  
14 ~~on~~ ~~increased~~ ~~subsequent~~ gross ecosystem production (GEP) and ~~negative~~ ~~reduced~~ ~~on~~ ecosystem  
15 respiration ( $R_e$ ) but the wet legacy ~~impacts were~~ mostly ~~negative on~~ ~~reduced~~ GEP and ~~positive~~  
16 ~~on~~ ~~increased~~  $R_e$ . Although the direction and magnitude of GEP and  $R_e$  responses to the  
17 simulated dry and wet legacies were influenced by both the previous and current PPT conditions,  
18 the NEP responses were predominantly determined by the previous PPT characteristics including  
19 rainfall amount, seasonality and event size distribution. Larger PPT difference between  
20 periods/years resulted in larger legacy impacts, with dry legacies fostering more C sequestration  
21 and wet legacies more C release. ~~By analyzing the resource pool (C, N, and H<sub>2</sub>O) responses to~~

22 ~~the simulated dry and wet legacies, we found that the~~The carryover of soil N between  
23 periods/years was mainly responsible for the GEP responses while the carryovers of plant  
24 biomass, litter and soil organic matter were mainly responsible for the  $R_e$  responses. These  
25 simulation results suggest that previous PPT conditions can exert substantial legacy impacts on  
26 current ecosystem C balance, which should be taken into account while assessing the response of  
27 dryland ecosystem C dynamics to future PPT regime changes.—

28 **Keywords:** [AmeriFluxLegacy](#), [eCarbon flux](#), lagged effect, biogeochemical carryover,  
29 ecosystem modeling, [legacy](#), semiarid.

30

31

## 32 1 Introduction

33 Drylands play an important role in global carbon (C) cycle and future C sequestration  
34 (Houghton et al., 1999; Asner et al., 2003), as they cover 30-45% of the earth's land surface  
35 (Asner et al., 2003; Reynolds et al., 2007), store about 15% of the global soil organic carbon  
36 (Schlesinger, 1991), and represent 30-35% of ~~the~~ terrestrial net primary production (Field et al.,  
37 1998). Driven by sporadic precipitation (PPT) and nonlinear biological responses, dryland C  
38 fluxes are especially variable across time and space (Maestre et al., 2012; Collins et al., 2014),  
39 making the prediction of dryland C budgets a challenging task (Jenerette et al., 2012).  
40 Moreover, climate models predict that the intra- and inter-annual PPT variability may be further  
41 intensified in dryland regions with longer drought durations and more large-sized events  
42 (Solomon et al., 2007; Diffenbaugh et al., 2008; Cook and Seager, 2013). Further, sequences of  
43 wet years followed by sequences of dry years and *vice versa* are also increasingly likely (Peters  
44 et al., 2012; Sala et al., 2012). Understanding the response of dryland ecosystem C fluxes to  
45 PPT variation is, therefore, important to characterizing the global C cycle and predicting how  
46 future PPT regime changes will affect dryland C balance.

47 As a measure of ecosystem C balance, net ecosystem production (NEP) has a value that is  
48 positive when an ecosystem accumulates C and negative when an ecosystem loses C. Dryland  
49 NEP ~~has been thought to be~~ is closely tied to current-year PPT amount, with wetter than average  
50 years being a C sink, drier than average years being a C source, and years with average rainfall  
51 being C neutral (Flanagan et al., 2002; Hastings et al., 2005). Importantly Additionally, at  
52 seasonal within annual scales, the distribution of precipitation PPT in addition to the total

53 amount can have large influences on ecosystem production (Porporato et al., 2004; Katul et al.,  
54 2007). ~~At interannual scales In addition, the a precipitation-PPT~~ legacy effect, defined as the  
55 impact of past PPT conditions on the current structure and functioning of ecosystems (Lauenroth  
56 and Sala, 1992; Sala et al., 2012; Monger et al., 2015), has also been found to play an important  
57 role in shaping the temporal variability of dryland ecosystem C fluxes (Knapp et al., 2002;  
58 Huxman et al., 2004a, b; Heisler and Weltzin, 2006; Sala et al., 2012; Ogle et al., 2014). For  
59 example, Hasting et al. (2005) attributed the C sink status of a desert shrub ecosystem in the  
60 early spring of 2002 to the above-average rainfall in the late fall of 2001. Scott et al. (2009)  
61 and Hamerlynck et al. (2013) found that ~~the a~~ cool season (Dec -- Apr) drought was followed by  
62 an unusually large net C loss during the following warm monsoon season (Jul - Sep) in a  
63 semiarid savanna and a semidesert grassland ~~ecosystems in southwestern US~~. Moreover, the  
64 savanna ecosystem has recently been a net C source and one hypothesized but untested  
65 explanation is due to an increase in current respiration of organic C that accumulated in the  
66 preceding wetter decade (Scott et al., 2009), ~~but has yet been tested~~. While these studies reveal  
67 the existence of PPT legacy effects on NEP at the seasonal scale, only a few studies have  
68 quantitatively assessed the contribution of PPT legacy to the temporal variability of dryland NEP  
69 at interannual and interdecadal time scales ~~has not been quantitatively assessed (Williams and~~  
70 Albertson, 2006), mainly because it is methodologically difficult to separate the past and current  
71 PPT impacts on C fluxes with the limited existing observational data (Sala et al., 2012), and  
72 there is a general lack of field manipulative experiments to address the PPT legacies at these  
73 scales (Reichmann et al., 2013a).

74 Much of our current understanding of the PPT legacy effects on dryland C fluxes is based on  
75 ~~the~~ aboveground net primary production (ANPP). A number of studies have documented that  
76 dryland ANPP is not only linearly related to current-year PPT, but also closely related to the PPT  
77 amount and seasonality several months to years before (Lauenroth and Sala, 1992; Oesterheld et  
78 al., 2001; [Huxman et al., 2004c](#)). For example, field studies have found a positive ~~wet~~ legacy  
79 ~~effect~~impact where ANPP is higher than expected if preceded by a wetter year, or ~~a negative dry~~  
80 ~~legacy effect where ANPP is~~ lower than expected if preceded by a drier year (Jobbagy and Sala,  
81 2000; Oesterheld et al., 2001; Wiegand et al., 2004; Sherry et al., 2008; Sala et al., 2012).

82 Proposed mechanisms explaining such observed positive PPT legacy effects on ANPP mainly  
83 involve the structural carryovers ~~of structural attributes~~ between years. ~~The structural~~  
84 ~~attributes, which~~ can ~~include be~~ leaf and root biomass (Oesterheld et al., 2001), the composition  
85 of species differing in rooting depth and phenology (Paruelo et al., 1999; Jobbagy and Sala, 2000;  
86 ~~Jenerette et al., 2010~~), or the density of seeds, tillers and plant individuals (Oesterheld et al.,  
87 2001; Yahdjian and Sala, 2006; Reichmann et al., 2013a). Alternatively, a negative legacy  
88 effect occurs when production ~~may be is~~ lower than expected if ~~preceeded~~ preceded by a wet  
89 period (~~a negative wet legacy effect~~) or higher than expected if preceded by a dry period (~~a~~  
90 ~~positive dry legacy effect~~) (Jenerette et al., 2010). ~~A negative~~ Such PPT legacy effects may be  
91 influenced more by biogeochemical effects carryovers that influence the resource availability to  
92 respond to current PPT (Evans and Burke, 2013; Reichmann et al., 2013b), whereby increased  
93 growth in response to a higher PPT can reduce the available nutrients (e.g., nitrogen (N)) for the  
94 following period and *vice versa*. Although various mechanisms have been proposed for the



95 PPT legacy impacts on ANPP, few of them have been rigorously tested, and the key underlying  
96 mechanisms still remain poorly understood (Sherry et al., 2008; [Williams et al., 2009](#); Sala et al.,  
97 2012; Monger et al., 2015).

98 Soil respiration ( $R_s$ ), as a major component of ecosystem C efflux, has also been found to have  
99 lagged responses to PPT variations ([Huxman et al., 2004b](#); Sponseller, 2007; Ma et al., 2012;  
100 Cable et al., 2013). This is particularly true at the event scale; after a period of drought, a  
101 rainfall event can result in a pulse of  $CO_2$  efflux that may be orders of magnitude larger than that  
102 before the event and then decline exponentially for a few days to weeks (Xu et al., 2004;  
103 Jenerette et al., 2008; Borken and Matzner, 2009; Cable et al., 2013; [Oikawa et al., 2014](#)). At a  
104 seasonal scale, Vargas et al. (2010) found no lags between  $R_s$  and soil moisture across 13  
105 vegetation types including four grasslands; but Hamerlynck et al. (2013) presented longer-term  
106 ecosystem flux data that suggest seasonal drought ~~legacy-legacies~~ affects ecosystem respiration  
107 ( $R_e$ ) in a semi-desert grassland in southeastern AZ, US. They posited that the increased C  
108 substrate availability resulting from the previous cool-season drought induced plant mortality  
109 was responsible for the higher  $R_e$  in the following monsoon season. However, very few studies  
110 have been devoted to understanding the PPT legacy impacts on dryland respiration at greater  
111 than seasonal timescales.

112 In this study, we conducted simulation experiments with a widely-used dryland ecosystem  
113 model, Patch Arid Land Simulator (PALS; Kemp et al. 1997, 2003; Reynolds et al. 2004; Shen et  
114 al. 2009), to analyze the PPT legacy effects on ecosystem-level C fluxes including NEP, gross  
115 ecosystem production (GEP), and  $R_e$ . The PALS model was built on the pulse-reserve concept

116 (Noy-Meir, 1973) and had been used to analyze the impacts of antecedent moisture conditions  
117 and the lagged responses of different plant functional types in three North American deserts at  
118 the rainfall event scale (Reynolds et al., 2004). We parameterized, calibrated, and evaluated the  
119 model based on the long-term eddy covariance measured fluxes at a semidesert savanna  
120 ecosystem in southwestern US (Scott et al., 2009) to analyze the PPT legacy effects at  
121 interannual and interdecadal scales. Specifically, we ~~aimed to address~~ the following ~~three~~  
122 two questions. First, what are the direction and magnitude of ecosystem C flux responses to dry  
123 and wet legacies? We expected that the PPT legacy impacts would occur over annual and  
124 decadal scales in correspondence to PPT fluctuations at these scales, and the dry and wet legacy  
125 impacts would differ in direction and magnitude. Second, how are the direction and magnitude  
126 of PPT legacy effects related to the PPT characteristics of both the previous and the current year /  
127 period? For PPT characteristics, we were not only interested in the annual and seasonal PPT  
128 amount but also between-event interval and event size distribution, since ~~all~~ these variables are  
129 widely-recognized key PPT features to dryland ecosystems (Porporato et al., 2004; Katul et al.,  
130 2007; Shen et al., 2008). We expected that ~~\*\*\*~~greater variability in precipitationPPT would lead  
131 to corresponding increases in legacy effects.... ~~Third, what are the mechanisms responsible for~~  
132 ~~the PPT legacy effects?—We assumed that changes in the structural and biogeochemical~~  
133 ~~pools/reserves (C, N, and H<sub>2</sub>O) resulting from changes in previous year / period PPT would~~  
134 ~~influence current ecosystem C fluxes as conceptualized in the pulse-reserve framework and~~  
135 ~~implemented in the PALS model.—~~

136

## 137 2 Methods

### 138 2.1 Model description

139 PALS is a process-based ecosystem model that consists of four modules: atmospheric forcing,  
140 a water cycling and energy budget, plant production and respiration, and soil organic matter  
141 (SOM) decomposition and heterotrophic respiration ( $R_h$ ). The four modules are interactively  
142 linked by the cycling of C, N, and  $H_2O$  through the atmosphere-plant-soil continuum. The  
143 PALS model explicitly considers seven plant functional types (FTs) commonly found in the  
144 North American warm deserts: evergreen shrub, deciduous shrub, perennial forb, perennial  $C_3$   
145 and  $C_4$  grasses, and native and exotic  $C_3$  annual grasses (Reynolds et al., 1997; Shen et al., 2009).  
146 Since the detailed model structure and mechanistic relationships have been presented in several  
147 publications (Kemp et al., 1997, 2003; Reynolds et al., 1997, 2000, 2004; Gao & Reynolds, 2003;  
148 Shen et al., 2005, 2008a, 2008b, 2009), here we briefly describe the four modules and refer  
149 ~~interested audience~~ to the specific literature [for detailed description](#).

150 The atmospheric driving force module reads in data for atmospheric driving variables (e.g.  
151 atmospheric  $[CO_2]$ , N deposition rate, daily maximum and minimum air temperatures,  
152 ~~precipitation~~ $PPT$ , relative humidity, and solar radiation), and based on these driving variables,  
153 calculates other important variables such as vapor pressure deficit (VPD) that determines  
154 stomatal conductance and soil temperature that influences SOM decomposition and soil  
155 respiration. Calculations of VPD and soil temperature can be found in Equations (2) - (7) in  
156 Shen et al. (2005).

157 The water cycling and energy budget module mainly calculates soil water contents at six

158 layers, the rates of water infiltration into and percolation out of a layer, and water losses via  
159 evaporation and transpiration from different layers. Water infiltration and percolation rates of a  
160 layer are determined by the effective PPT reaching the soil surface, previous water content, and  
161 the water holding capacity as a function of soil texture (Shen et al., 2005). Soil evaporation is  
162 determined by soil water availability and energy available in the two top soil layers (10 cm in  
163 depth). Water uptake by plants is partitioned among the soil layers according to the proportion  
164 of roots in each layer for all plant FTs (Kemp et al., 1997; Shen et al., 2008b). Canopy  
165 transpiration is calculated by using the energy budget and the canopy stomatal resistance  
166 (Reynolds et al., 2000; Gao and Reynolds, 2003).

167 The plant production and respiration module mainly simulates phenology, primary production,  
168 growth and maintenance respiration, photosynthate allocation, and litterfall of each plant FT.

169 Three major phenophases (i.e. dates of germination, leafing, and dormancy) are determined in  
170 PALS based on the observed dates, air temperature, and ~~precipitation~~PPT (Shen et al., 2009).

171 Primary production for each FT is calculated based on the leaf area, potential net photosynthetic  
172 rate, stomatal conductance, leaf N content modifier, and the difference between intercellular and

173 atmospheric [CO<sub>2</sub>]. The plant photosynthesis rate is estimated as a product of stomatal

174 conductance and the partial pressure gradient between atmospheric and intercellular [CO<sub>2</sub>].

175 The stomatal conductance is calculated as an exponential function of leaf water potential that

176 decreases linearly with atmospheric vapor deficit (see Equations (10) - (14) in Shen et al., 2005).

177 Photosynthate is allocated to different plant organs (leaf, stem, and root) using fixed allocation

178 ratios after subtracting the maintenance respiration, which is estimated as a function of live

179 biomass, basal respiration rate, and modifiers of temperature and plant water potential (Shen et  
180 al., 2008a). Growth respiration is calculated based on the growth yield coefficient and the net  
181 photosynthate used for growth (Shen et al., 2008a). Litterfall amount is mainly determined as a  
182 function of observed dormancy dates, maximum air temperature and drought conditions (Shen et  
183 al., 2008a; Shen et al., 2009).

184 The SOM decomposition and heterotrophic respiration module simulates the decomposition of  
185 metabolic and structural litter material, SOM in active, slow and passive pools, and CO<sub>2</sub>  
186 emissions associated with these decomposition processes (Kemp et al., 2003 and Shen et al.,  
187 2009). The SOM decomposition rate or heterotrophic rate is calculated as a first-order kinetics  
188 rate with a decomposition coefficient multiplied by the pool size and the temperature and  
189 moisture scalars (see Equations (A4)-(A11) in Shen et al., 2009). In addition, this module also  
190 simulates the dynamics of soil mineral N pool by using N mineralization and atmospheric  
191 deposition as the major inputs, and plant N uptake and leaching loss as the major outputs.  
192 Among these the N mineralization and plant uptake processes are modeled in more detail while  
193 the rates of the other processes are basically assigned with empirical constant values. The N  
194 mineralization processes are directly coupled to litter and SOM decomposition processes and are  
195 calculated as a product of the C flow rates and the C/N ratio of the corresponding litter or SOM  
196 pools (Parton et al., 1993; Kemp et al., 2003). The plant N uptake is a product of water  
197 transpiration and N concentration in soil solution (see Equation (8) in Shen et al., 2008b).

198

## 199 **2.2 Model parameterization**

200 For this study, we modified and parameterized PALS to represent an upland mesquite savanna  
201 ecosystem in the Santa Rita Experimental Range (SRER; 31.8214° N, 110.8661° W, elevation  
202 1116 m), about 45 km south of Tucson, AZ, USA. Soils at this site are a deep sandy loam  
203 (Scott et al., 2009), and the mean groundwater depth likely exceeds 100 m (Barron-Gafford et al.,  
204 2013). ~~Precipitation~~PPT was therefore considered as the only source of water input into the  
205 system. Based on the vegetation composition (Scott et al., 2009), there were five major plant  
206 FTs included in PALS: shrub (e.g. *Prosopis velutina*), subshrub (e.g. *Isocoma tenuisecta*), C<sub>4</sub>  
207 perennial grass (e.g. *Digitaria californica*), perennial forb (e.g. *Ambrosia psilostachya*), and C<sub>3</sub>  
208 annual grass, among which the velvet mesquite shrub with average height of ca. 2.5 m accounted  
209 for ~35% of the total canopy cover and other FTs (mainly perennial grasses) accounted for ~22%  
210 (Scott et al., 2009). Therefore, we derived the site-characteristic parameters for the two major  
211 FTs (shrub and perennial grass) from previous studies carried out in SRER, with those for the  
212 other FTs being adopted from a generic parameter dataset for the PALS model to be used in the  
213 North American warm deserts (Reynolds et al., 2004; Shen et al., 2005). These site-specific  
214 parameters mainly included plant-related parameters (e.g. canopy cover, C allocation ratio,  
215 rooting distribution ratio, and the initial values of living and dead plant biomass pools) and  
216 soil-related parameters (e.g. soil chemical and physical properties, C/N ratios, decomposition  
217 rates, and initial values of the litter and SOM pools). The values of these parameters are  
218 provided in Supplementary Table S1, with cited literature also being listed below the table.

219 For the climatic variables used to drive the PALS model, we compiled a 30-year  
220 meteorological dataset that included daily ~~precipitation~~ (PPT), maximum and minimum air

221 temperatures ( $T_{\max}$  and  $T_{\min}$ ), relative humidity (RH), and total solar radiation ( $S_{\text{rad}}$ ) from 1981 to  
222 2010. The  $T_{\max}$ ,  $T_{\min}$ , RH, and  $S_{\text{rad}}$  data from 1981-1990 were observations from the Tucson  
223 ~~Weather-weather~~ [Station-station](#) (about 50 km north of the mesquite savanna site and lower  
224 elevation) and obtained through the Arizona Meteorological Network online data access  
225 (AZMET: <http://ag.arizona.edu/azmet>). The remaining 20 years (1991-2010) of  $T_{\max}$ ,  $T_{\min}$ , RH  
226 and  $S_{\text{rad}}$  data were observations from the Kendall ~~Weather-Station~~ [Grassland met site](#) (about 85  
227 km east of the mesquite savanna site and slightly higher elevation) and obtained through the  
228 Southwest Watershed Research Center (SWRC) online data access  
229 (<http://www.tucson.ars.ag.gov/dap/>). The 30-year PPT data were observations from the Santa  
230 Rita Watershed rain gage #5 (1.5 km from the site) and obtained also from the SWRC online  
231 data access. These different sources of meteorological data were adjusted based on the 7 years  
232 (2004-2010) of the meteorological data obtained from the AmeriFlux eddy-covariance flux tower  
233 at the mesquite savanna site (US-SRM, see Supplementary [Figure Fig\\_S1](#)). At last, we used the  
234 AZMET and SWRC data from 1981 to 2003 plus the flux tower data from 2004 to 2010 to drive  
235 the model.

236 Since our simulation experiment was based on the manipulations of the 30-year (1981-2010)  
237 PPT data, we report the PPT characteristics here in more detail. In the past 30 years, the mean  
238 annual PPT ([MAP](#)) amount was 401 mm at the site, slightly greater than the long-term  
239 (1937-2007) mean of 377 mm (Scott et al., 2009). ~~Based on the computed SPI, t~~ [These 30 years](#)  
240 [were divided into two periods: a wet period from 1981-1994 with mean annual rainfall](#) ~~the a~~  
241 [MAP of 465](#) ~~49~~ mm and a dry period from 1995 to 2010 with ~~mean annual rainfall~~ [the a MAP of](#)

242 3457 mm (Fig. 1a). For the analysis of PPT legacy effects at interdecadal scale, the wet period  
243 was treated as the previous period and the dry period as the current period. For the analysis of  
244 PPT legacy effects at interannual scale, the annual scale was defined as from July through June  
245 of the next year. To analyze the relationship between PPT legacy effects and seasonal rainfall  
246 characteristics, each year was further divided into four seasons (with their mean rainfall in  
247 parentheses): the main-~~or the~~ warm growing season from July to September (warm-GS, 224  
248 mm), the cool dry season from October to November (cool-DS, 48 mm), the minor cool growing  
249 season from December to March (cool-GS, 104 mm), and the warm ~~dominant/dormant~~ dry season  
250 from April to June (warm-DS, 26 mm). Based on the seasonal PPT amount, we distinguished  
251 ~~four seasons with their mean PPT being listed in parenthesis: the cool growing season from Dec-~~  
252 ~~to Mar (cool-GS, 104 mm), the warm dry season from Apr to Jun (warm-DS, 27 mm), the warm-~~  
253 ~~growing season from Jul to Sep (warm-GS, 223 mm), and the cool dry season from Oct to Nov-~~  
254 ~~(cool-DS, 47 mm).~~—At the site, as in many other dryland regions (Sala et al., 1992;  
255 Heisler-White et al., 2008), most rainy days have only light ~~amounts~~ rainfall events. About 80 %  
256 of daily rainfall was < 10 mm, with medium- to large-sized events (10 - 50 mm) accounting for  
257 about 20% and only 10 events larger than 50 mm in the 30 years (Fig. 1b). The no-rain-day  
258 duration between events (hereafter between-event interval or BEI) was ~5 days on average in the  
259 warm-GS and ~10 days in the cool-GS (Fig. 1c). The average BEI was ~17 days in the cool-DS  
260 and 24 days in the warm-DS; but there could be no rain for three months in these dry seasons  
261 (Fig. 1c).

262 ~~To further assess the degree of dryness/wetness of a particular year or growing season relative-~~



263 ~~to the normal annual or seasonal rainfall, we computed the Standard Precipitation Index (SPI) for~~  
264 ~~the 30 years and the 2 growing seasons of each year using the software SPI\_SL\_6 (available at~~  
265 ~~<http://drought.unl.edu/MonitoringTools>), with  $SPI \approx 0$  indicating a normal year/season,  $SPI < 0$  a~~  
266 ~~dry year/season, and  $SPI > 0$  a wet year/season. Based on the computed SPI, the 30 years were~~  
267 ~~divided into two periods: a wet period from 1981–1994 with mean annual rainfall of 465 mm and~~  
268 ~~a dry period from 1995 to 2010 with mean annual rainfall of 345 mm (Fig. 1a). The 1995–2010~~  
269 ~~dry period was dominated by cool GS drought (Fig. 1b), whereas the warm GS seemed to be~~  
270 ~~wetter in the 1981–1994 wet period (Fig. 1c). These SPI values were used to analyze the~~  
271 ~~relationships between PPT legacy effect and PPT amount.~~

272

### 273 **2.3 Model calibration and evaluation**

274 After model parameterization, we calibrated the model based on four years (2004–2007) of  
275 CO<sub>2</sub> and H<sub>2</sub>O flux data monitored using the eddy covariance technique at the savanna site.  
276 Detailed descriptions of instrumentation, sensor heights and orientations, and data processing  
277 procedures for the eddy covariance data can be found in Scott et al. (2009). During model  
278 calibration, we mainly adjusted the parameter values of photosynthate allocation ratios, live  
279 biomass death rates, and SOM decomposition rates to achieve a best fit between modeled and  
280 observed GEP and R<sub>e</sub>. since these parameters have been identified as the most sensitive and  
281 uncertain ones (e.g. photosynthate allocation ratios) in influencing the modeled ecosystem  
282 carbon fluxes (Shen et al., 2005). The model performed well in capturing the seasonal variation  
283 patterns of actual evapotranspiration (AET), GEP, R<sub>e</sub>, and NEP in the four calibration years

284 (Supplementary ~~Figure Fig. S2~~), with ~~faster-larger C exchanges-fluxes~~ during the warm-GS. At  
285 ~~seasonal and the~~ annual scales, simulated AET, GEP, and  $R_e$  ~~could-explained~~ over ~~690%~~ of the  
286 variations in ~~the observed-oneations~~ (Fig. 2, left panels). ~~Compared to AET, GEP, and  $R_e$ , but~~  
287 the correlation between ~~the~~ simulated and observed NEP was ~~very weakerweak~~ (Fig. 2d). This  
288 was mainly ~~due to the poor match in 2006; because~~ the model substantially overestimated GEP  
289 ~~(120 g C m<sup>-2</sup> simulated versus 52 g C m<sup>-2</sup> observed) during in the warmcool-GS of 2006 but~~  
290 ~~underestimated  $R_e$  during the cool-GS~~ (Supplementary ~~Figure Fig. S32~~). ~~Further explanations~~  
291 ~~on the possible causes of the GEP overestimation in 2006 shall be provided latter in discussions.~~  
292 If the data of this year were excluded, the ~~explanative-explanatory~~ power for annual ~~and seasonal~~  
293 NEP ~~was-could reach 5274%~~. ~~Since our goal was to use an empirically plausible model to~~  
294 ~~understand the long-term temporal variations in ecosystem fluxes, we consider the calibration~~  
295 ~~results acceptable. Year 2006 had extreme cool-GS drought with the SPI = -2.09 (Fig. 1b) and~~  
296 ~~rainfall of 35 mm — less than half of those in the other three years. — This cool-GS drought may~~  
297 ~~have caused increased plant mortality similar to that reported for a semi-desert grassland nearby~~  
298 ~~our study site (Scott et al., 2010; Hamerlynck et al., 2013). — We suspect that the model failed to~~  
299 ~~capture such extreme drought impacts and resulted in the poor performance in 2006, since the~~  
300 ~~empirical relations describing plant mortality and climate conditions in PALS account for more-~~  
301 ~~normal, rather than extreme, conditions. This is appropriate for our study as we are examining~~  
302 ~~non-extreme influences of legacies.~~

303 The model performance was further evaluated by assessing the degree of correlation between  
304 the PALS-simulated and flux-tower-measured C and H<sub>2</sub>O fluxes from 2008 through 2010, which

305 were not used for model calibration. The coefficients of determination ( $R^2$ ), which describe the  
306 proportion of the variance in measured data explained by the model, were all larger than 0.98 at  
307 ~~the seasonal and annual scales in the three validation years (2008-2010; Fig. 2, right-left panels).~~  
308 ~~Model performance is typically considered to be acceptable with  $R^2$  value  $> 0.5$  (Moriassi et al.,~~  
309 ~~2007).~~—These evaluation results indicate that the model was capable of capturing the temporal  
310 variability of observed fluxes at ~~seasonal and the~~ annual scales. ~~Furthermore, we also analyzed~~  
311 ~~the relationships between the observed and simulated fluxes with the corresponding current-year~~  
312 ~~PPT to see how the flux variations were explained by current-year PPT under baseline conditions~~  
313 ~~(i.e. the PPT variations shown in Fig. 1). The explanatory power ( $R^2$ ) for both the observed and~~  
314 ~~simulated fluxes were mostly over 70% (Fig. 2, right panels), which further indicates that the~~  
315 ~~model is capable of capturing the impacts of PPT variability on ecosystem fluxes. The following~~  
316 ~~simulation experiments were therefore designed to discriminate the contributions by previous-~~  
317 ~~and current-year PPT impacts. Since our goal was to use an empirically plausible model to~~  
318 ~~understand long-term temporal variations of ecosystem fluxes, we therefore consider the overall~~  
319 ~~model performance acceptable.~~—

320

## 321 2.4 Simulation experiments

322 We designed two sets of simulation experiments to examine the interdecadal and interannual  
323 PPT legacy effects. To analyze the interdecadal legacy effects, we first changed the PPT of the  
324 14-year previous period (1981-1994) by 0%,  $\pm 10\%$ ,  $\pm 30\%$ ,  $\pm 50\%$  and  $\pm 80\%$  (multipliers  
325 of existing daily PPT amounts in the record) while keeping the 16-year current-period

326 (1995-2010) PPT unchanged. After these manipulations, the average PPT of the previous  
327 period ranged from 93 mm corresponding to the 80% of decrease to 837 mm corresponding to  
328 the 80% of increase. This design detects how changes in previous-period PPT influence the  
329 current-period C fluxes and the associated C pool dynamics. On top of each previous period  
330 PPT manipulation level, we further changed the current-period PPT by 0%,  $\pm 10\%$ ,  $\pm 30\%$ ,  $\pm$   
331  $50\%$ , and  $\pm 80\%$ , which resulted in the average current-period PPT varying from 69 mm to 621  
332 mm. This design detects how changes in the current-period PPT influence the legacies resulting  
333 from changes in the previous-period PPT. As a result, we ~~made~~conducted 73 simulation runs  
334 corresponding to the 73 combinations of the above previous- and current-period PPT  
335 manipulations (9 previous PPT levels times 8 current PPT levels plus 1 baseline run).

336 To analyze the interannual legacy, we changed the PPT of each individual year by  $\pm 30\%$   
337 while keeping the PPT of the subsequent years unchanged. This design resulted in 54  
338 simulation runs (27 years from 1981-2007 times 2 PPT manipulation levels) and illustrates the  
339 effects of changes in the PPT of the previous one year on the C fluxes and resource pools of the  
340 current year(s). After a 30% of PPT change, annual PPT ranged from 162 mm to 925 mm in  
341 the 27 years, which was large enough to cover the PPT interannual variation at the study site.  
342 Another consideration of using 30% as the PPT manipulation level was that future projected  
343 annual PPT variation in dryland regions will be -30% to +25% (Bates et al., 2008; Maestre et al.,  
344 2012).

345

## 346 **2.5 Data analysis**

347 Legacy effect was quantified as the C flux (or resource pool size) of the current-period/year  
348 after PPT changes in the previous-period/year minus that without PPT changes in the  
349 previous-period/year. As an example, the following equation calculates the legacy effect of  
350 increasing the previous-period PPT by 30% on the current-period NEP:

$$351 \quad \text{Legacy}_{NEP} = \Delta NEP = NEP_{PPT+30\%}^{CP} - NEP_{PPT+0\%}^{CP}$$

352 where  $NEP_{PPT+30\%}^{CP}$  is the cumulative NEP throughout the current period (1995-2010) under a  
353 30% of previous-period (1981-1994) PPT increase;  $NEP_{PPT+0\%}^{CP}$  is the cumulative NEP  
354 throughout the current period with no previous-period PPT change (i.e. the baseline PPT  
355 conditions shown in Fig. 1). This method directly quantifies whether changes in PPT of the  
356 previous period will impose a positive, negative, or no legacy effect on the C fluxes (or resource  
357 pools) of the current period. For simplicity, hereafter we refer to the legacy effect resulting  
358 from the decreased previous-period/year PPT as the dry legacy and that resulting from the  
359 increased previous-period/year PPT as the wet legacy. Spearman correlation analysis was used  
360 to detect the relationships between legacy effects and PPT characteristics, including PPT  
361 amount, SPI, BEI, and the number of large ( $\geq 10$  mm) *versus* small ( $< 10$  mm) events at yearly and  
362 seasonal scales. The correlation analysis was performed in SPSS 16.0 (Chicago, IL, USA).

363

## 364 3 Results

### 365 3.1 Interdecadal legacy

366 Changes in ~~the~~ PPT of the previous period (1981-1994) imposed obvious legacy impacts on  
367 the C fluxes of the current period (1995-2010). The direction of the simulated interdecadal dry  
368 and wet legacies on GEP and  $R_e$  was dependent upon the direction of both the previous- and  
369 current-period PPT changes. When the current-period PPT was reduced (Fig. 3, left panels),  
370 the simulated dry legacies ~~imposed~~ mostly ~~positive impacts on~~ increased the current-period GEP  
371 (Fig. 3a) but ~~negative impacts on~~ decreased  $R_e$  (Fig. 3c); whereas wet legacies imposed ~~mostly~~  
372 ~~negative~~ little impacts on the current-period GEP (Fig. 3a) but ~~mostly positive impacts~~  
373 ~~on~~ increased  $R_e$  (Fig. 3c). When the current-period PPT was enhanced (Fig. 3, right panels),  
374 both the dry and wet legacies imposed mostly positive impacts on GEP and  $R_e$  (Fig. 3b, d).  
375 Regardless of current-period PPT changes, NEP always ~~responded positively to the~~ increased  
376 with dry legacies ~~but and negatively to~~ decreased with the wet legacies (Fig. 3e, f), indicating a  
377 consistent that the direction of ~~negative~~ NEP responses to ~~the~~ PPT legacies ~~was predominantly~~  
378 ~~determined by the direction of the previous period PPT changes.~~

379 The simulated absolute magnitude of the PPT ~~legacies~~ legacy influence on ecosystem C fluxes  
380 (i.e. GEP,  $R_e$ , and NEP) generally increased with the absolute magnitude of changes in the  
381 previous-period PPT (Fig. 3, Fig. 4). Increasing the current-period PPT generally amplified the  
382 legacy effects compared to decreasing the current-period PPT (comparing the left to the right  
383 panels of Fig. 3). The magnitude of the PPT legacies was also significantly correlated with the

384 PPT difference between the ~~previous-current~~ and ~~previouscurrent~~ period ( $\Delta$ PPT, equals to the  
385 current-period PPT minus the previous-period PPT; Fig. 4). If the previous period was wetter  
386 than the current period (i.e.  $\Delta$ PPT < 0 or a wet-to-dry period transition), the legacy effect on  $R_e$   
387 was negatively related with  $\Delta$ PPT (Fig. 4c) but that on NEP was positively related with  $\Delta$ PPT  
388 (Fig. 4e), indicating more current-period C release after a wetter previous period. In contrast, if  
389 the previous period was drier than the current period (i.e.  $\Delta$ PPT > 0 or a dry-to-wet period  
390 transition), the correlations were all positive for GEP,  $R_e$  and NEP (Fig. 4, right panels),  
391 indicating more current period C sequestration after a drier previous period.

392 The resource pool dynamics were also shaped by the alterations in the previous- and  
393 current-period PPTs. We only showed the 30% decrease and increase in the previous- and  
394 current-period PPT (i.e. 4 out of 72 pairs of PPT change combinations) as representative  
395 examples in Fig. 5, because the major response patterns for the other paired combinations were  
396 similar. The duration of the PPT legacy impacts generally lasted for about 6-8 years for plant  
397 biomass, litter mass and soil water content (SWC), but much longer for soil organic matter  
398 (SOM) and soil mineral N ( $N_{soil}$ ) (Fig. 5). Based on the resource pool responses in the early 1-2  
399 years (i.e. 1995 and 1996) of the current period, the dry legacies ~~imposed negative impacts~~  
400 ~~and decreased~~ biomass, litter and SOM (Fig. 5a-f), but ~~positively~~ impacted ~~eds on~~  $N_{soil}$  (Fig. 5g-h).  
401 Contrastingly, the wet legacies ~~imposed positive impacts on~~ ~~increased~~ biomass, litter and SOM  
402 (Fig. 5a-f), but ~~negatively~~ impacted ~~eds on~~  $N_{soil}$  (Fig. 5g-h). Similar to the influences on C fluxes,  
403 increasing the current-period PPT (Fig. 5, right panels) amplified the PPT legacy impacts on  
404 biomass and litter (Fig. 5a-d), and hastened the recovery rates of SOM and  $N_{soil}$  to their baseline

405 levels (Fig. 5e-h).

406

### 407 3.2 Interannual legacy

408 At the interannual scale, a 30% decrease or increase in ~~the PPT of one previous year~~ could  
409 ~~cause~~ have ~~the~~ legacy impacts on ecosystem C cycling lasting for 2-12 ~~following~~ years (Fig.  
410 6a-b). Notably, ~~the~~ direction of GEP and  $R_e$  responses to decreasing or increasing  
411 previous-year PPT could be positive or negative (Fig. 6c-f). The dry or wet legacy effects on  
412 these two fluxes were ~~very variable and~~ idiosyncratic, and, ~~although~~ in some cases, large at  
413 this timescale. However, ~~the~~ simulated dry legacies ~~had~~ mostly positive impacts on increased  
414 GEP (Fig. 6e) and NEP (Fig. 6g) ~~but negative impacts on  $R_e$  (Fig. 6e).~~ Conversely, ~~whereas~~ the  
415 simulated wet legacies ~~imposed~~ mostly negative impacts on decreased GEP (Fig. 6d) and NEP  
416 (Fig. 6h), which was similar as what had been found at to legacy responses at the interdecadal  
417 scale (Fig. 3e-f), ~~but positive impacts on  $R_e$  (Fig. 6f).~~ However, both the direction and  
418 magnitude of the simulated dry and wet legacies were very variable and idiosyncratic at this  
419 timescale, depending on the C fluxes of interest and the PPT conditions of specific years.

420 The correlation analysis showed that not only rainfall amount but also BEI and event size  
421 distribution could ~~influence~~ be related to the magnitude of the simulated dry and wet legacies  
422 (Table 1). The warm-GS precipitation PPT of a previous year was ~~detected to have significantly~~  
423 correlated ~~ions~~ with the dry legacies for NEP and the wet legacies for GEP and NEP (Table 1).  
424 Contrastingly On the other hand, the cool-GS precipitation PPT of a current year ~~had~~ was found to  
425 have important influences ~~on~~ the dry and wet legacies for C fluxes, but not all of them were



426 ~~statistically significant (Table 1). These results indicate that the legacies were mainly generated~~  
427 ~~in the warm-GS of a previous year, but the current-year cool-GS precipitationPPT conditions~~  
428 ~~could influence the C flux responses to the previous-year generated legacies. Unlike at the~~  
429 ~~interdecadal scale (Fig. 4), our correlation analysis showed that only the dry legacies for NEP~~  
430 ~~had significantly correlations with the PPT difference ( $\Delta$ PPT) between two consecutive years or~~  
431 ~~cool-GSs (Table 1), indicating that the larger the PPT difference between a previous dry year and~~  
432 ~~a current wet year, the greater the legacy impacts on NEP imposed by the previous dry year. the~~  
433 ~~simulated dry and wet legacies on NEP were only significantly related with the previous-year~~  
434 ~~PPT conditions including annual and warm-GS SPI, BEI, and number of large events ( $NE > 10$~~   
435 ~~mm;  $P < 0.05$ ; Table 1), but not the current-year PPT conditions (Table 1). With respect to GEP~~  
436 ~~and  $R_e$  responses, only the wet legacies were found to be significantly correlated with some of~~  
437 ~~these PPT variables ( $P < 0.05$ ; Table 1). Further examining the correlation between the PPT~~  
438 ~~legacy effects and the PPT difference between two consecutive years (i.e.  $\Delta$ PPT = current year~~  
439 ~~PPT minus previous year PPT), we found that only  $R_e$  and NEP responses were significantly~~  
440 ~~correlated with  $\Delta$ PPT if  $\Delta$ PPT  $< 0$  (i.e. under a wet to dry year transition; Fig. 7c, e).~~

441 To analyze the interannual PPT legacy impacts on the dynamics of resource pools (i.e.  
442 biomass, litter, SOM,  $N_{soil}$ , and SWC), two wet years (1983 and 1994) with positive SPI and two  
443 dry years (1986 and 1995) with negative SPI (see Fig. 1a) were chosen as examples (see Fig. 1a).  
444 The simulated dry legacies had negative impacts on reduced biomass, litter and SOM, but  
445 positive impacts on increased  $N_{soil}$  and SWC in the first current year (Fig. 87). In contrast, the  
446 simulated wet legacies imposed just the opposite direction of impacts on the five resource pools.

447 (Fig. 7). The simulated PPT legacy impacts on the resource pools could also last for several  
448 years, and the direction and magnitude of the legacy impacts in the following years could differ  
449 from those in the first year as described above. For example, increasing the PPT of 1995 by 30%  
450 caused a positive legacy impact on the biomass of the first following year (i.e. 1996; Fig. 7b) but  
451 it became negative in the latter following years (e.g. in 1998; Fig. 8b7b), further indicating that  
452 current-year PPT conditions ~~can~~ influence the direction and magnitude of ~~the~~ previous-year  
453 PPT legacies.

454

## 455 4 Discussion

### 456 4.1 Direction and magnitude of the simulated PPT legacies

457 Through this simulation analysis, we demonstrated that previous PPT could impose substantial  
458 legacy impacts on current ecosystem C fluxes at interannual and interdecadal timescales.  
459 Notably, our simulation results support the hypothesis proposed for our study site (Scott et al.  
460 2009) that the accumulated SOM during the previous-wet period contributed to the net C release  
461 from the ecosystem during the current dry period. This specific test illustrates aA major finding  
462 from our simulation study of ~~was that a negative PPT legacy effect on NEP~~the direction and  
463 magnitude of the simulated PPT legacies on NEP were ~~was~~ predominantly determined by the  
464 direction of the previous PPT changes, i.e. decreasing previous PPT resulted in positive legacy  
465 impacts ~~increased on current NEP (Fig. 3e-f, Fig. 6g) whereas increasing previous PPT resulted in~~  
466 negative legacy impacts ~~on decreased current NEP (Fig. 3e-f, Fig. 6h).~~ - Thi Increasing prior  
467 PPT (wet legacy) led to limited changes in GEP but consistently increased  $R_e$ . Decreasing prior

468 PPT (dry legacy) led to more variable effects for both GEP and  $R_e$  that were strongly conditioned  
469 on current period PPT such that increasing current PPT was associated with increases in the dry  
470 legacy effect. Overall, the effects on GEP were larger than  $R_e$  for reduced prior PPT and  
471 smaller for increased prior PPT, which resulted in a consistent negative PPT legacy on NEP  
472 regardless of current PPT. The complexity in the legacy effects on ecosystem C cycling we  
473 show here are in part influenced by the contrasting PPT legacy responses of C uptake and  
474 emission and their distinct interactions with current PPT distributions. ~~s is \*\*\*\* despite the fact~~  
475 that However, the dry and wet legacy impacts on the two processes (GEP and  $R_e$ ) determining  
476 NEP ( $NEP = GEP - R_e$ ) were largely influenced by both the previous and current PPT changes  
477 (Fig. 3a-d, Fig. 6c-f). The main reason was that alterations in current PPT influenced GEP and  
478  $R_e$  in the same direction (e.g. increasing current PPT stimulated both GEP and  $R_e$ ; see Fig. 3 and  
479 Fig. 6), which canceled out the current PPT impacts on the previous PPT legacies for NEP (again  
480  $NEP = GEP - R_e$ ). But Nevertheless, the reason of that why the ~~dry~~ overall legacies for NEP were  
481 positiveneegative whereas the wet legacies for NEP were negative was that ? mainly because the  
482 dry legacies were mostly positiveincreased for GEP (Fig. 3a-b, Fig. 6c), the wet legacies were  
483 mostly negative fordecreased GEP (Fig. 3a-b, Fig. 6d), and the absolute magnitude of the dry and  
484 wet legacies for GEP was generally larger than those for  $R_e$  (Fig. 3a-d, Fig. 6c-f). . while  
485 alterations in previous PPT influenced GEP and  $R_e$  in the opposite direction (Fig. 3a-d, Fig. 6c-f).  
486 These simulation results imply that the direction of the PPT legacy impacts on NEP can be  
487 inferred from previous PPT conditions: a previous drier condition may foster more C  
488 sequestration in a current wet period/year and a previous wetter condition may cause more C

489 ~~release in a current dry period/year.~~

490 In projecting future dryland C dynamics, the effects of PPT legacies increase the complexity  
491 of ecosystem responses to PPT variability. One consistent interaction between legacy and  
492 current PPT effects was that ~~Based on the eddy covariance measured NEP, Scott et al. (2009)~~  
493 ~~found that the mesquite savanna ecosystem was a net CO<sub>2</sub> source during the four~~  
494 ~~below-average-rainfall years from 2004 through 2007. They ascribed the net release of C by~~  
495 ~~the system to the cool GS drought, but also suspected that the system was likely “burning off”~~  
496 ~~much of the C sequestered during the previous wet period (~1975-1995) (Scott et al., 2009).~~  
497 ~~Our simulation results of the positive wet legacy effects on SOM and negative effects on NEP~~  
498 ~~(Fig. 4c, e) support this hypothesis that the accumulated SOM during the previous wet period~~  
499 ~~(Fig. 5e, f) contributed to the C released during the current dry period. We also found that~~  
500 ~~larger between-period/year PPT differences~~ could result in larger legacy effects (Fig. 4 ~~and Fig.~~  
501 ~~7~~), which is in agreement with what have been found in some field studies. For example, the  
502 magnitude of drought legacy on ANPP is proportional to the severity of the drought (Yahdjian  
503 and Sala, 2006; Swemmer et al., 2007), and dry- or wet-year legacies on ANPP are linearly  
504 related to the PPT difference between years (Sala et al., 2012; Reichmann et al., 2013a). Our  
505 simulation analysis detected that not only annual PPT amount but also finer scale PPT  
506 characteristics such as GS-rainfall, BEI, and event size could be important in determining the  
507 interannual-scale PPT legacy effects (Table 1). These simulation results suggest that PPT  
508 legacy effects may play ~~an~~ more important role in shaping the temporal variability of dryland  
509 ecosystem C fluxes under the projected increase in future PPT variability (Solomon et al., 2007;

510 Cook and Seager, 2013) but that their characterization remains a challenge.

511 The influence of PPT legacies to dryland ecosystem C balance may strongly interact with  
512 other sources of variability in dryland C balance including current year PPT. ~~Evidences~~  
513 ~~suggests that Ddryland ecosystems are commonly thought to be a C sinks in wet years, a C~~  
514 ~~sources in dry years, and C neutral in normal years (Flanagan et al., 2002; Hastings et al., 2005).~~  
515 ~~While recent studies have shown the importance of other factors including~~ growing season  
516 length (Xu and Baldocchi, 2004; Ma et al., 2007), seasonal drought (Scott et al., 2009; Scott et  
517 al., 2010; Hamerlynck et al., 2013), and other factors such as temperature and vegetation  
518 composition (Hui et al., 2003; Hamerlynck et al., 2010; Barron-Gafford et al., 2012; Scott et al.,  
519 2014). ~~Our simulation results indicate that PPT legacies may also have important~~  
520 ~~consequences to dryland ecosystem C dynamics balance.~~ These interactions are shown by  
521 several examples from our simulations. ~~For example,~~ While PPT was wetter than normal in  
522 1987 ~~-(537 mm) with the SPI of 1.21, but with the NEP of was -85 g C m<sup>-2</sup> yr<sup>-1</sup> (a C source),~~  
523 due to the negative wet legacy impacts on NEP from several previous wet years before  
524 ~~(1982-1985; see Fig. 6h).~~ PPT was nearly normal in 2008 ~~(402 mm) with the SPI of 0.09,~~ but  
525 ~~with the simulated NEP of was 79.680 g C m<sup>-2</sup> yr<sup>-1</sup> and the observed NEP of 69.2 g C m<sup>-2</sup> yr<sup>-1</sup> (a~~  
526 ~~C sink), again~~ due to the positive dry legacy impacts on NEP from several previous dry years  
527 ~~(2002-2007; see Fig. 6g).~~ Our findings of substantial PPT legacy effects are consistent with ~~in~~  
528 a recent analysis ~~on~~ of 14 years (1997-2011) of eddy covariance measurements, where Zielis et  
529 al. (2014) reported that inclusion of previous year's weather (PPT and temperature) into the  
530 linear predicting models for NEP increased the explained variance to 53% compared to 20%

531 without accounting for previous year's weather, indicating that previous year's weather also  
532 played an important role in determining the C balance of the Switzerland subalpine spruce forest.  
533 Although ~~we compared some~~ response patterns generated from this simulation study compared  
534 well with those derived from previous field observations, there exists no field study that, to our  
535 knowledge, ~~is comparable to our simulation experiment to allow us conducting a direct~~  
536 ~~comparison between the simulated and observed responses~~ provides a similarly comprehensive  
537 analysis of PPT legacies. The simulation experimental design of this study ~~may~~ provides  
538 helpful insights into designing field manipulative experiments to further test the modeled  
539 patterns by focusing on contrasting wet and dry legacies, separating ecosystem production and  
540 decomposition, and exploring the difference in prior and current PPT on the magnitude of the  
541 PPT legacy effect.

542

#### 543 **4.2 Potential mechanisms of the modeled PPT legacies**

544 There are three basic mechanisms explaining why PPT legacy impacts can occur in ~~the a~~  
545 model system like PALS. First, the rate of C fluxes is a function of not only various ~~influential~~  
546 ~~environmental~~ factors (e.g. PPT and temperature) but also the pool size itself. For example, soil  
547 heterotrophic CO<sub>2</sub> efflux ( $R_h$ ) rate is a product of the decomposition coefficient, ~~the size of the~~  
548 ~~SOM pool, and~~ two scalar functions accounting for temperature and moisture influences, and  
549 also the size of the SOM pool (Kemp et al., 2003; Shen et al., 2009). ~~Therefore, the~~ Changes in  
550 altered the SOM pool size from previous PPT ~~changes can thereby~~ affects current  $R_h$ . Second,  
551 different C pools have different turnover rates that determine whether biogeochemical materials

552 (e.g. biomass or SOM) can be carried over. If the ~~resources-material~~ (e.g. water, biomass and  
553 ~~SOM) produced in a previous legacy-year has a turnover rate less than one year, then it would~~  
554 ~~not be carried over to the next year to form a legacy impact~~~~were not completely lost from the~~  
555 ~~pool/reserve due to slower turnover rate, the resources may be carried over to the current year~~  
556 ~~and influence the C fluxes~~ as explained in the first mechanism. In addition, the turnover rates  
557 of different C pools also determine legacy duration. For example, SOM pools in the model  
558 have relatively slower turnover rates than biomass pools (Shen et al., 2005; Shen et al., 2008b),  
559 thus resulting in the longer-lasting legacy impacts on SOM than on biomass or litter pools (Fig. 5  
560 and Fig. 78). Third, the interactions between Carbon fluxes and resource (e.g., N or and water)  
561 availability also determine the direction and magnitude of legacy effects. For example, N  
562 carryover as a legacy of a prior dry period (Fig. 5g, h) can impose impacts on the current-period  
563 GEP only when the current-period PPT is not so limiting (Fig. 3b). ~~It would have impose little~~  
564 ~~or no legacy impacts on GEP when the current-period PPT is limiting (Fig. 3a).~~ C, N and H<sub>2</sub>O  
565 eycling processes are closely coupled in the PALS model. ~~Carried-over resources (e.g. C and N)~~  
566 ~~can therefore interact with current PPT conditions to influence the responses of current fluxes.~~  
567 ~~Based on~~ These are the general model-mechanisms explaining the occurrence of the modeled  
568 PPT legacies from a systems perspective. ~~Below we discuss more specifically on the major~~  
569 ~~responsive patterns of response~~ and the responsible biogeochemical carryovers found in this  
570 study.

571 An intuitive first explanation for the simulated wet legacies would be the carryover of water.  
572 However, in most cases soil water carryover did not occur because the wet ~~and dry~~ legacies on

573 SWC were mostly negative or close to zero at the beginning of the current period/year (Fig. 5i-j;  
574 Fig. 7&i-j). Soil water carryover was therefore not the major contributor to the modeled PPT  
575 legacy effects at interdecadal and interannual scales. This simulation result corroborates with  
576 ~~those of~~ field studies that have shown that carryover of water across long temporal scales is rare  
577 in dryland ecosystems, because the rainy growing seasons or wet years are often separated by dry  
578 dormant seasons or dry years resulting in short residence times ~~of water in the system~~  
579 (Oosterheld et al., 2001; Reichmann et al., 2013a; Scott et al., 2014). ~~However, it is noted here~~  
580 ~~that the carryover of soil water might be possible at finer temporal scales. For example,~~  
581 ~~Raz-Yaseef et al. (2012) reported that water from large storms could infiltrate into deep soil~~  
582 ~~layers, be stored there for longer periods of time and carried over across seasons/months (also~~  
583 ~~see Wiegand et al., 2004). Thus, carryover of stored soil water should be considered as one of~~  
584 ~~the potential mechanisms while addressing the PPT legacy effects at seasonal or event scales.~~

585 The carryover of soil N ( $N_{\text{soil}}$ ) is mainly responsible for the modeled GEP responses. In the  
586 PALS model, the photosynthetic rate is linearly related to N availability if plant N demand is not  
587 fulfilled (Reynolds et al., 2004; Shen et al., 2005). ~~The~~ refore, the enhanced  $N_{\text{soil}}$  as from dry  
588 legacies (Fig. 5g, h and Fig. 7&g, h) ~~therefore generated resulted in the~~ mostly positive responses  
589 of GEP (Fig. 3a, b and Fig. 6c). ~~Conversely, the reduced  $N_{\text{soil}}$  by wet legacies (Fig. 5g, h and~~  
590 ~~Fig. 8g, h) resulted in the mostly negative responses of GEP (Fig. 3a, b and Fig. 6d).~~ The  
591 simulated dry legacies increased  $N_{\text{soil}}$  mainly by through decreasing PPT suppressed plant growth  
592 (e.g., the reduced biomass and litter production shown in Fig. 5 and Fig. 7) and therefore that  
593 limited N uptake. ~~This, which~~ is consistent with many field measurements that  $N_{\text{soil}}$



594 accumulates under drought conditions (Reynolds et al., 1999; Yahdjian et al., 2006; [Yahdjian and](#)  
595 [Sala, 2010](#); de Vries et al., 2012; Evans and Burke, 2013; Reichmann et al., 2013b). [Although](#)  
596 [diverse mechanisms of inorganic N accumulation during dry periods have been proposed in field](#)  
597 [studies, such as including the diffusion restriction of N ions in thin water films of dry soil, the](#)  
598 [reduced N immobilization by microbial growth and plant uptake, and the reduced N loss from](#)  
599 [the soil via leaching \(Yahdjian et al., 2006\), our simulation results suggest that reduced plant](#)  
600 [uptake might be the main contributor to the  \$N\_{soil}\$  accumulation during dry periods. Given the](#)  
601 [accumulated  \$N\_{soil}\$  as a dry legacy, how ecosystem C fluxes such as GEP respond to this dry](#)  
602 [legacy may be influenced by current PPT conditions. If current PPT conditions were favorable](#)  
603 [\(e.g., the increasing current-period PPT treatment shown in Fig. 3b and the relatively wet years](#)  
604 [shown in Fig. 6c\), GEP ~~responded mostly positively~~ increased with to the a dry legacy \(or the](#)  
605 [accumulated N\) because both N and H<sub>2</sub>O availabilities ~~y~~ were favorable for plant growth \(or](#)  
606 [GEP\). Contrastingly, if current PPT conditions were unfavorable \(e.g., the decreasing](#)  
607 [current-period PPT treatment shown in Fig 3a and the relatively dry years shown in Fig. 6c\), the](#)  
608 [GEP responses could ~~become negative~~ be reduced because of the constrained plant growth and](#)  
609 [the reduced biomass in previous dry years \(see Fig. 5c and Fig. 7b\).](#)

610 [Similarly, the mostly negative responses of GEP to wet legacies \(~~or increasing previous PPT,~~](#)  
611 [see Fig. 3a, b and Fig. 6d\) can be explained by the reduced  \$N\_{soil}\$  ~~from wet legacies~~ \(Fig. 5g, h and](#)  
612 [Fig. 7g, h\). The decrease of  \$N\_{soil}\$  with increasing PPT in the PALS model is mainly attributed to](#)  
613 [the increases in plant N uptake and the N leaching loss that is calculated as a linear function of](#)  
614 [PPT amount \(Shen et al., 2005\). ~~Also~~ Similar to our simulation results, \[several\]\(#\) field studies](#)

615 found that N uptake increases and  $N_{\text{soil}}$  decreases under wet conditions in dryland ecosystems  
616 (McCulley et al., 2009; [McCalley and Sparks, 2009](#); [Yahdjian and Sala, 2010](#); Reichmann et al.,  
617 2013b). However, contrary to our model assumption that N leaching loss is greater in wet than  
618 in dry years, some recent field studies reported that the N leaching loss actually is higher in dry  
619 than in wet years or at wet sites (McCulley et al., 2009; Evans et al., 2013; Reichmann et al.,  
620 2013b; (Homyak et al., 2014), resulting in a more “open” N cycle under drier conditions.  
621 Given that these recent field study results are also true for our semidesert savanna ecosystem,  
622 the model assumption could potentially cause an overestimation of  $N_{\text{soil}}$  carryover effects as  
623 shown in Fig. 3 and Fig. 6. But we do not have no observational supports at our study site to  
624 specifically justify the model assumption.—Further studies are needed to discriminate the  
625 relative contributions of different N processes (e.g., plant uptake, microbial immobilization and  
626 mineralization, denitrification, ammonia volatilization, and leaching) to the dynamics of soil  
627 inorganic N pools. Nevertheless, this simulation analysis highlights the importance of  
628 interactions between N and  $H_2O$  availabilities in creating the legacy impacts of  
629 precipitation PPT and in shaping the temporal variability of dryland ecosystem C fluxes.  
630 The N-enhancement as dry legacies also explains why the simulated dry legacy impacts on  
631 NEP were positive (Fig. 3e, f and Fig. 6g), particularly under the circumstance of the dry to wet  
632 period/year transition (Fig. 4e, Fig. 7e).—The  $N_{\text{soil}}$  carried over from the previous dry  
633 period/year and the current wetter conditions ameliorated both the N and  $H_2O$  limitations on GEP,  
634 therefore resulted in more C sequestration in the current period/year.—

635 The carryover of organic matter-material (biomass, litter and SOM) is mainly responsible for

636 the modeled  $R_e$  responses. In the PALS model, the autotrophic ( $R_a$ ) and heterotrophic ( $R_h$ )  
637 respiration rates are linearly related to the size of biomass, litter and SOM pools (Kemp et al.,  
638 2003; Shen et al., 2008a; Shen et al., 2009). The previous wet condition stimulated-benefited  
639 biomass, litter and SOM accumulation (Fig. 5 and Fig. 78) ~~therefore-which~~ resulted in the mostly  
640 positive wet legacy impacts on  $R_e$  (Fig. 3c, d and Fig. 6f). Conversely, the dry legacy decreased  
641 these pools (Fig. 5 and Fig. 78) and therefore resulted in the mostly negative dry legacy impacts  
642 on  $R_e$  (Fig. 3c, d and Fig. 6e). Contrary to our simulation results that dry legacies are mostly  
643 negative on SOM and  $R_h$ . Some field studies suggest that the labile C resulting from litter  
644 decomposition in a dry season may stimulate  $R_h$  in the following wet season (Jenerette et al.,  
645 2008; Scott et al., 2009; Ma et al., 2012), ~~i.e. the dry season had a positive legacy impact on the~~  
646 ~~labile C pool and  $R_h$ , which is contrary to our simulation result that dry legacies are mostly~~  
647 ~~negative on SOM and  $R_h$ .~~ This is mainly-likely because the labile soil C pool in the PALS  
648 model only accounts for ~3% of the total SOM and has a very short residence time (1.7 year; see  
649 Supplementary Table S1); small amount of seasonal labile C carryover therefore may not exert  
650 obvious legacy impacts on the total SOM pool size and  $R_h$  across interannual and interdecadal  
651 scales. These results imply that the PPT legacy effects differs in direction and magnitude,  
652 depending on the type of C fluxes under consideration, the type of legacies (i.e. dry vs wet), and  
653 the temporal scale of analysis.

654 While this Several lines of future research will likely be needed to continue improving  
655 understanding of ecosystem legacy dynamics. ~~simulation analysis mainly addressed the PPT~~  
656 ~~legacy impacts on dryland ecosystem C fluxes from a biogeochemical perspective.~~ ~~Structural~~

657 shifts in vegetation composition such as woody plant encroachment (Potts et al., 2008; Scott et  
658 al., 2014), exotic species invasion (Hamerlynck et al., 2010; Scott et al., 2010), and changes in  
659 microbial communities (de Vries et al., 2012; Evans and Wallenstein, 2012; Collins et al., 2014),  
660 may also interact with the biogeochemical processes to shape the PPT legacy effects on the  
661 temporal variability of dryland C fluxes. Furthermore, we need to better understand the legacy  
662 effects of extreme events such as the cool-GS drought in 2006 (see Fig. 1a) so that these  
663 important events can be adequately simulated. This cool-GS drought may have caused  
664 increased plant mortality as reported for a semid-desert grassland nearby our study site (Scott et  
665 al., 2010; Hamerlynck et al., 2013), but that is poorly represented in the model and may have  
666 caused the overestimation of the modeled NEP in comparison with the observation (see Fig. 2c).  
667 Finally, our approach that uses a highly resolved process model provides information  
668 complementary to contrasting analytical approaches that evaluate ecosystem responses to  
669 statistical rainfall regimes (Rodrigo-Iturbe et al., 2006; Katul et al., 2007; Porporato et al., 2013).  
670 Improvement of these alternative modeling approaches is needed to both understand general and  
671 specific ecosystem responses to changing precipitation PPT regimes at temporal time-scales from  
672 of events to interdecades. al. Future studies incorporating both the structural and biogeochemical  
673 aspects and involving multiple temporal scales are needed in order to achieve a more  
674 comprehensive understanding of the PPT legacy effects on dryland ecosystem C dynamics.

## 675 **5 Conclusions**

676 ~~W~~Through this simulation analysis, we learned through this simulation analysis that: i1)

677 previous PPT conditions can impose substantial legacy impacts on the C balance of dryland

678 ecosystems, with dry legacies fostering more current C sequestration and wet legacies causing  
679 more current C release; [#2](#)) the responses of ecosystem C fluxes to the simulated dry and wet  
680 legacies are mostly opposite in direction and asymmetrical in magnitude, with dry legacies being  
681 greater for GEP than for  $R_e$  and wet legacies being greater for  $R_e$  than for GEP; [#3](#)) the  
682 carryover of  $N_{soil}$  is mainly responsible for the GEP responses, and the carryovers of biomass,  
683 litter and SOM are mainly responsible for the  $R_e$  responses; and [iv4](#)) the simulated PPT legacy  
684 effects can last for several years even with [a](#) one-year PPT change and therefore the direction and  
685 magnitude of [interannual](#) PPT legacy effects are less predictable ~~at interannual~~ than ~~at~~  
686 interdecadal ~~scale~~ones. These ~~Our~~ simulation results ~~imply suggest~~ that [dryland ecosystems](#)  
687 [such as these in southwestern US and likely other dryland regions may emit more C that was](#)  
688 [sequestered in the past into the atmosphere](#) with the predicted ~~decreasing~~ [drying](#) trends in  
689 ~~future PPT amount~~[the region](#) (Seager et al., 2007; Solomon et al., 2007), ~~dryland ecosystems in~~  
690 ~~southwestern US may emit more C that was sequestered in the past into the atmosphere. With~~  
691 ~~the projected more extreme and variable PPT regime (Seager et al., 2007; Solomon et al., 2007;~~  
692 ~~Diffenbaugh et al., 2008), t; T~~ the temporal variability of ecosystem C fluxes may be further  
693 intensified in the region due to the increasing PPT variability and the associated legacy impacts.  
694 ~~While this simulation analysis mainly addressed the PPT legacy impacts on dryland ecosystem C~~  
695 ~~fluxes from a biogeochemical perspective, structural shifts in vegetation composition such as~~  
696 ~~woody plant encroachment (Potts et al., 2008; Scott et al., 2014) exotic species invasion~~  
697 ~~(Hamerlynek et al., 2010; Scott et al., 2010), and changes in microbial communities (de Vries et~~  
698 ~~al., 2012; Evans and Wallenstein, 2012; Collins et al., 2014), may also interact with the~~

699 ~~biogeochemical processes to shape the PPT legacy effects on the temporal variability of dryland~~  
700 ~~C fluxes. Future studies incorporating both the structural and biogeochemical aspects and~~  
701 ~~involving multiple temporal scales are needed in order to achieve a more comprehensive~~  
702 ~~understanding of the PPT legacy effects on dryland ecosystem C dynamics.~~

703

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714 **References**

- 715 Asner, G. P., Archer, S., Hughes, R. F., Ansley, R. J., and Wessman, C. A.: Net changes in  
716 regional woody vegetation cover and carbon storage in Texas Drylands, 1937-1999, *Global*  
717 *Change Biol.*, 9, 316-335, 2003.
- 718 Barron-Gafford, G. A., Scott, R. L., Jenerette, G. D., Hamerlynck, E. P., and Huxman, T. E.:  
719 Landscape and environmental controls over leaf and ecosystem carbon dioxide fluxes under  
720 woody plant expansion, *J. Ecol.*, 101, 1471-1483, 2013.
- 721 Barron-Gafford, G. A., Scott, R. L., Jenerette, G. D., Hamerlynck, E. P., and Huxman, T. E.:  
722 Temperature and precipitation controls over leaf- and ecosystem-level CO<sub>2</sub> flux along a  
723 woody plant encroachment gradient, *Global Change Biol.*, 18, 1389-1400, 2012.
- 724 Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. (Eds.): *Climate Change and Water.*  
725 *Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat,*  
726 *Genenva, 2008.*
- 727 Boroken, W. and Matzner, E.: Reappraisal of drying and wetting effects on C and N  
728 mineralization and fluxes in soils, *Global Change Biol.*, 15, 808-824, 2009.
- 729 Cable, J. M., Ogle, K., Barron-Gafford, G. A., Bentley, L. P., Cable, W. L., Scott, R. L., Williams,  
730 D. G., and Huxman, T. E.: Antecedent conditions influence soil respiration differences in  
731 shrub and grass patches, *Ecosystems*, 16, 1230-1247, 2013.
- 732 Collins, S. L., Belnap, J., Grimm, N. B., Rudgers, J. A., Dahm, C. N., D'Odorico, P., Litvak, M.,  
733 Natvig, D. O., Peters, D. C., Pockman, W. T., Sinsabaugh, R. L., and Wolf, B. O.: A  
734 multiscale, hierarchical model of pulse dynamics in arid-land ecosystems, *Annu. Rev. Ecol.*

735 Evol. S., 45, 397-419, 2014.

736 Cook, B. I. and Seager, R.: The response of the North American Monsoon to increased  
737 greenhouse gas forcing, *J. Geophys. Res. Atmos.*, 118, 1690-1699, 2013.

738 de Vries, F. T., Liiri, M. E., Bjornlund, L., Setala, H. M., Christensen, S., and Bardgett, R. D.:  
739 Legacy effects of drought on plant growth and the soil food web, *Oecologia*, 170, 821-833,  
740 2012.

741 Diffenbaugh, N. S., Giorgi, F., and Pal, J. S.: Climate change hotspots in the United States,  
742 *Geophys. Res. Lett.*, 35, 116709, doi: 16710.11029/12008GL035075, 2008.

743 Evans, S. E. and Burke, I. C.: Carbon and nitrogen decoupling under an 11-year drought in the  
744 shortgrass steppe, *Ecosystems*, 16, 20-33, 2013.

745 Evans, S. E. and Wallenstein, M. D.: Soil microbial community response to drying and rewetting  
746 stress: does historical precipitation regime matter?, *Biogeochemistry*, 109, 101-116, 2012.

747 Field, C. B., Behrenfeld, M. J., Randerson, J. T., and Falkowski, P.: Primary production of the  
748 biosphere: Integrating terrestrial and oceanic components, *Science*, 281, 237-240, 1998.

749 Flanagan, L. B., Wever, L. A., and Carlson, P. J.: Seasonal and interannual variation in carbon  
750 dioxide exchange and carbon balance in a northern temperate grassland, *Global Change*  
751 *Biol.*, 8, 599-615, 2002.

752 Gao, Q. and Reynolds, J. F.: Historical shrub-grass transitions in the northern Chihuahuan Desert:  
753 modeling the effects of shifting rainfall seasonality and event size over a landscape gradient,  
754 *Global Change Biol.*, 9, 1475-1493, 2003.

755 Hamerlynck, E. P., Scott, R. L., and Barron-Gafford, G. A.: Consequences of cool-season



756 drought-induced plant mortality to Chihuahuan Desert grassland ecosystem and soil  
757 respiration dynamics, *Ecosystems*, 16, 1178-1191, 2013.

758 Hamerlynck, E. P., Scott, R. L., Moran, M. S., Keefer, T. O., and Huxman, T. E.: Growing season  
759 ecosystem and leaf-level gas exchange of an exotic and native semiarid bunchgrass,  
760 *Oecologia*, 163, 561-570, 2010.

761 Hastings, S. J., Oechel, W. C., and Muhlia-Melo, A.: Diurnal, seasonal and annual variation in  
762 the net ecosystem CO<sub>2</sub> exchange of a desert shrub community (*Sarcocauloscent*) in Baja  
763 California, Mexico, *Global Change Biol.*, 11, 927-939, 2005.

764 Heisler-White, J. L., Knapp, A. K., and Kelly, E. F.: Increasing precipitation event size increases  
765 aboveground net primary productivity in a semi-arid grassland, *Oecologia*, 158, 129-140,  
766 2008.

767 Heisler, J. L. and Weltzin, J. F.: Variability matters: towards a perspective on the influence of  
768 precipitation on terrestrial ecosystems, *New Phytol.*, 172, 189-192, 2006.

769 [Homyak, P. M., Sickman, J. O., Miller, A. E., Melack, J. M., Meixner, T., and Schimel, J. P.:](#)  
770 [Assessing nitrogen-saturation in a seasonally dry Chaparral watershed: Limitations of](#)  
771 [traditional indicators of N-saturation, \*Ecosystems\*, 17, 1286-1305, 2014.](#)

772 Houghton, R. A., Hackler, J. L., and Lawrence, K. T.: The US carbon budget: Contributions from  
773 land-use change, *Science*, 285, 574-578, 1999.

774 Hui, D. F., Luo, Y. Q., and Katul, G.: Partitioning interannual variability in net ecosystem  
775 exchange into climatic variability and functional change, *Tree Physiol.*, 23, 433-442, 2003.

776 [Huxman, T. E., Cable, J. M., Ignace, D. D., Eilts, J. A., English, N. B., Weltzin, J., and Willimas,](#)

777 [D. G.: Response of net ecosystem gas exchange to a simulated precipitation pulse in a](#)  
778 [semi-arid grassland: the role of native versus non-native grasses and soil texture, \*Oecologia\*,](#)  
779 [141: 295-305, 2004a.](#)

780 [Huxman, T. E., Snyder, K. A., Tissue, D., Leffler, A. J., Ogle, K., Pockman, W. T., Sandquist, D.](#)  
781 [R., Potts, D. L., and Schwinning, S.: Precipitation pulses and carbon fluxes in semiarid and](#)  
782 [arid ecosystems, \*Oecologia\*, 141: 254-268, 2004b.](#)

783 [Huxman, T. E., Smith, M. D., Fay, P. A., Knapp, A. K., Shaw, M. R., Loik, M. E., Smith, S. D.,](#)  
784 [Tissue, D. T., Zak, J. C., Weltzin, J. F., Pockman, W. T., Sala, O. E., Haddad, B. M., Harte,](#)  
785 [J., Kock, G. W., Schwinning, S., Small, E. E., and Willimas, D. G.: Convergence across](#)  
786 [biomes to a common rain-use efficiency, \*Nature\*, 429, 651-654, 2004c.](#)

787 Jenerette, G. D., Barron-Gafford, G. A., Guswa, A. J., McDonnell, J. J., and Villegas, J. C.:

788 Organization of complexity in water limited ecohydrology, *Ecohydrology*, 5, 184-199, 2012.

789 Jenerette, G. D., Scott, R. L., and Huete, A. R.: Functional differences between summer and

790 winter season rain assessed with MODIS-derived phenology in a semi-arid region, *J. Veg.*

791 *Sci.*, 21, 16-30, 2010.

792 Jenerette, G. D., Scott, R. L., and Huxman, T. E.: Whole ecosystem metabolic pulses following

793 precipitation events, *Funct. Ecol.*, 22, 924-930, 2008.

794 Jobbagy, E. G. and Sala, O. E.: Controls of grass and shrub aboveground production in the

795 Patagonian steppe, *Ecol. Appl.*, 10, 541-549, 2000.

796 [Katul, G. A., Proporato, A., and Oren R.: Stochastic dynamics of plant-water interactions. \*Annu.\*](#)  
797 [\*Rev. Ecol. Evol. S.\*, 38, 767-791, 2007.](#)

798 Kemp, P. R., Reynolds, J. F., Pachepsky, Y., and Chen, J. L.: A comparative modeling study of  
799 soil water dynamics in a desert ecosystem, *Water Resour. Res.*, 33, 73-90, 1997.

800 Kemp, P. R., Reynolds, J. F., Virginia, R. A., and Whitford, W. G.: Decomposition of leaf and  
801 root litter of Chihuahuan desert shrubs: effects of three years of summer drought, *J. Arid*  
802 *Environ.*, 53, 21-39, 2003.

803 Knapp, A. K., Fay, P. A., Blair, J. M., Collins, S. L., Smith, M. D., Carlisle, J. D., Harper, C. W.,  
804 Danner, B. T., Lett, M. S., and McCarron, J. K.: Rainfall variability, carbon cycling, and  
805 plant species diversity in a mesic grassland, *Science*, 298, 2202-2205, 2002.

806 Lauenroth, W. K. and Sala, O. E.: Long-term forage production of North-American shortgrass  
807 steppe, *Ecol. Appl.*, 2, 397-403, 1992.

808 Ma, S. Y., Baldocchi, D. D., Hatala, J. A., Detto, M., and Yuste, J. C.: Are rain-induced  
809 ecosystem respiration pulses enhanced by legacies of antecedent photodegradation in  
810 semi-arid environments?, *Agr. Forest Meteorol.*, 154, 203-213, 2012.

811 Ma, S. Y., Baldocchi, D. D., Xu, L. K., and Hehn, T.: Inter-annual variability in carbon dioxide  
812 exchange of an oak/grass savanna and open grassland in California, *Agr. Forest Meteorol.*,  
813 147, 157-171, 2007.

814 Maestre, F. T., Salguero-Gomez, R., and Quero, J. L.: It is getting hotter in here: determining and  
815 projecting the impacts of global environmental change on drylands Introduction, *Philos. T.*  
816 *R. Soc. B.*, 367, 3062-3075, 2012.

817 [McCalley, C. K., Sparks, J. P.: Abiotic gas formation drives nitrogen loss from a desert](#)  
818 [ecosystem, \*Science\*, 326, 837-840, 2009.](#)

819 McCulley, R. L., Burke, I. C., and Lauenroth, W. K.: Conservation of nitrogen increases with  
820 precipitation across a major grassland gradient in the Central Great Plains of North America,  
821 *Oecologia*, 159, 571-581, 2009.

822 Monger, C., Sala, O. E., Duniway, M. C., Goldfus, H., Meir, I. A., Poch, R. M., Throop, H. L.,  
823 and Vivoni, E. R.: Legacy effects in linked ecological-soil-geomorphic systems of drylands,  
824 *Front. Ecol. Environ.*, 13, 13-19, 2015.

825 ~~Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.:~~  
826 ~~Model evaluation guidelines for systematic quantification of accuracy in watershed~~  
827 ~~simulations, *Transactions of the Asabe*, 50, 885-900, 2007.~~

828 Noy-Meir, I.: Desert ecosystems: environment and producers, *Annu. Rev. Ecol. Evol. S.*, 4,  
829 25-51, 1973.

830 Oesterheld, M., Loreti, J., Semmartin, M., and Sala, O. E.: Inter-annual variation in primary  
831 production of a semi-arid grassland related to previous-year production, *J. Veg. Sci.*, 12,  
832 137-142, 2001.

833 Ogle, K., Barber, J. J., Barron-Gafford, G. A., Bentley, L. P., Young, J. M., Huxman, T. E., Loik,  
834 M. E., and Tissue, D. T.: Quantifying ecological memory in plant and ecosystem processes,  
835 *Ecol. Lett.*, 2014.

836 ~~Oikawa, P. Y., Gratz, D. A., Chatterjee, A., Eberwein, J. E., Allsman, L. A., and Jenerette, G. D.:~~  
837 ~~Unifying soil respiration pulses, inhibition, and temperature hysteresis through dynamics of~~  
838 ~~labile carbon and soil O<sub>2</sub>. *J. Geophys. Res. Biogeosci.*, 115, 521-536, 2014.~~

839 Parton, W. J., Scurlock, J. M. O., Ojima, D. S., Gilmanov, T. G., Scholes, R. J., Schimel, D. S.,

840 Kirchner, T., Menaut, J. C., Seastedt, T., Moya, E. G., Kamnalrut, A., and Kinyamario, J. I.:  
841 Observations and modeling of biomass and soil organic-matter dynamics for the grassland  
842 biome worldwide, *Global Biogeochem. Cy.*, 7, 785-809, 1993.

843 Paruelo, J. M., Lauenroth, W. K., Burke, I. C., and Sala, O. E.: Grassland precipitation-use  
844 efficiency varies across a resource gradient, *Ecosystems*, 2, 64-68, 1999.

845 Peters, D. P. C., Yao, J., Sala, O. E., and Anderson, J. P.: Directional climate change and potential  
846 reversal of desertification in arid and semiarid ecosystems, *Global Change Biol.*, 18,  
847 151-163, 2012.

848 [Porporato, A., Daly, E., and Rodriguez-Iburbe, I.: Soil water balance and ecosystem response to](#)  
849 [climate change. \*Am. Nat.\*, 164, 625-632, 2004.](#)

850 [Porporato, A., and Rodriguez-Iturbe I.: Ecohydrology bearings - invited commentary from](#)  
851 [random variability to ordered structures: a search for general synthesis in ecohydrology,](#)  
852 [Ecohydrology, 6, 333-342, 2013.](#)

853 Potts, D. L., Scott, R. L., Cable, J. M., Huxman, T. E., and Williams, D. G.: Sensitivity of  
854 mesquite shrubland CO<sub>2</sub> exchange to precipitation in contrasting landscape settings,  
855 *Ecology*, 89, 2900-2910, 2008.

856 ~~[Raz Yaseef, N., Yakir, D., Schiller, G., and Cohen, S.: Dynamics of evapotranspiration-](#)~~  
857 ~~[partitioning in a semi-arid forest as affected by temporal rainfall patterns, \*Agr. Forest\*](#)~~  
858 ~~[Meteorol.](#), 157, 77-85, 2012.~~

859 Reichmann, L. G., Sala, O. E., and Peters, D. P. C.: Precipitation legacies in desert grassland  
860 primary production occur through previous-year tiller density, *Ecology*, 94, 435-443, 2013a.

861 Reichmann, L. G., Sala, O. E., and Peters, D. P. C.: Water controls on nitrogen transformations  
862 and stocks in an arid ecosystem, *Ecosphere*, 4, 1-17, 2013b.

863 Reynolds, J. F., Kemp, P. R., Ogle, K., and Fernandez, R. J.: Modifying the 'pulse-reserve'  
864 paradigm for deserts of North America: precipitation pulses, soil water, and plant responses,  
865 *Oecologia*, 141, 194-210, 2004.

866 Reynolds, J. F., Kemp, P. R., and Tenhunen, J. D.: Effects of long-term rainfall variability on  
867 evapotranspiration and soil water distribution in the Chihuahuan Desert: A modeling  
868 analysis, *Plant Ecol.*, 150, 145-159, 2000.

869 Reynolds, J. F., Stafford Smith, D. M., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S.  
870 P. J., Downing, T. E., Dowlatabadi, H., Fernandez, R. J., Herrick, J. E., Huber-Sannwald, E.,  
871 Jiang, H., Leemans, R., Lynam, T., Maestre, F. T., Ayarza, M., and Walker, B.: Global  
872 desertification: Building a science for dryland development, *Science*, 316, 847-851, 2007.

873 Reynolds, J. F., Virginia, R. A., Kemp, P. R., de Soyza, A. G., and Tremmel, D. C.: Impact of  
874 drought on desert shrubs: Effects of seasonality and degree of resource island development,  
875 *Ecol. Monogr.*, 69, 69-106, 1999.

876 Reynolds, J. F., Virginia, R. A., and Schlesinger, W. H.: Defining functional types for models of  
877 desertification. In: *Plant Functional Types: Their Relevance to Ecosystem Properties and*  
878 *Global Change*, Shugart, T. M. and Woodward, F. I. (Eds.), Cambridge University Press,  
879 Cambridge, 1997.

880 [Rodriguez-Iturbe, I., Isham, V., Cox D. R., Manfreda, S., and Porporato A.: Space-time modeling](#)  
881 [of soil moisture: Stochastic rainfall forcing with heterogeneous vegetation. \*Water Resour.\*](#)

882 [Res., 42, doi: 10.1029/2005WR004497, 2006.](#)

883 Sala, O. E., Gherardi, L. A., Reichmann, L., Jobbagy, E., and Peters, D.: Legacies of  
884 precipitation fluctuations on primary production: theory and data synthesis, *Philos. T. R.*  
885 *Soc. B.*, 367, 3135-3144, 2012.

886 Sala, O. E., Lauenroth, W. K., and Parton, W. J.: Long-term soil-water dynamics in the shortgrass  
887 steppe, *Ecology*, 73, 1175-1181, 1992.

888 Schlesinger, W. H.: *Biogeochemistry: An Analysis of Global Change*, Academic Press Inc, San  
889 Diego, CA. , 1991.

890 Scott, R. L., Hamerlynck, E. P., Jenerette, G. D., Moran, M. S., and Barron-Gafford, G. A.:  
891 Carbon dioxide exchange in a semidesert grassland through drought-induced vegetation  
892 change, *J. Geophys. Res. Biogeosci.*, 115, G03026, doi: 10.1029/2010JG001348,  
893 2010.

894 Scott, R. L., Huxman, T. E., Barron-Gafford, G. A., Jenerette, G. D., Young, J. M., and  
895 Hamerlynck, E. P.: When vegetation change alters ecosystem water availability, *Global*  
896 *Change Biol.*, 20, 2198-2210, 2014.

897 Scott, R. L., Jenerette, G. D., Potts, D. L., and Huxman, T. E.: Effects of seasonal drought on net  
898 carbon dioxide exchange from a woody-plant-encroached semiarid grassland, *J. Geophys.*  
899 *Res. Biogeosci.*, 114, G04004, doi: 10.1029/2008JG000900, 2009.

900 Seager, R., Ting, M. F., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H. P., Harnik, N.,  
901 Leetmaa, A., Lau, N. C., Li, C. H., Velez, J., and Naik, N.: Model projections of an  
902 imminent transition to a more arid climate in southwestern North America, *Science*, 316,

903 1181-1184, 2007.

904 Shen, W. J., Jenerette, G. D., Hui, D. F., Phillips, R. P., and Ren, H.: Effects of changing  
905 precipitation regimes on dryland soil respiration and C pool dynamics at rainfall event,  
906 seasonal and interannual scales, *J. Geophys. Res. Biogeosci.*, 113, G03024, doi:  
907 10.1029/2008JG000685, 2008a.

908 Shen, W. J., Reynolds, J. F., and Hui, D. F.: Responses of dryland soil respiration and soil carbon  
909 pool size to abrupt vs. gradual and individual vs. combined changes in soil temperature,  
910 precipitation, and atmospheric [CO<sub>2</sub>]: a simulation analysis, *Global Change Biol.*, 15,  
911 2274-2294, 2009.

912 Shen, W. J., Wu, J. G., Grimm, N. B., and Hope, D.: Effects of urbanization-induced  
913 environmental changes on ecosystem functioning in the Phoenix metropolitan region, USA,  
914 *Ecosystems*, 11, 138-155, 2008b.

915 Shen, W. J., Wu, J. G., Kemp, P. R., Reynolds, J. F., and Grimm, N. B.: Simulating the dynamics  
916 of primary productivity of a Sonoran ecosystem: Model parameterization and validation,  
917 *Ecol. Model.*, 189, 1-24, 2005.

918 Sherry, R. A., Weng, E. S., Arnone, J. A., Johnson, D. W., Schimel, D. S., Verburg, P. S., Wallace,  
919 L. L., and Luo, Y. Q.: Lagged effects of experimental warming and doubled precipitation on  
920 annual and seasonal aboveground biomass production in a tallgrass prairie, *Global Change  
921 Biol.*, 14, 2923-2936, 2008.

922 Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller,  
923 H. L. (Eds.): *Climate Change 2007: The Physical Science Basis*, Cambridge University



924 Press, Cambridge, 2007.

925 Sponseller, R. A.: Precipitation pulses and soil CO<sub>2</sub> flux in a Sonoran Desert ecosystem, *Global*  
926 *Change Biol.*, 13, 426-436, 2007.

927 Swemmer, A. M., Knapp, A. K., and Snyman, H. A.: Intra-seasonal precipitation patterns and  
928 above-ground productivity in three perennial grasslands, *J. Ecol.*, 95, 780-788, 2007.

929 Vargas, R., Baldocchi, D. D., Allen, M. F., Bahn, M., Black, T. A., Collins, S. L., Yuste, J. C.,  
930 Hirano, T., Jassal, R. S., Pumpanen, J., and Tang, J. W.: Looking deeper into the soil:  
931 biophysical controls and seasonal lags of soil CO<sub>2</sub> production and efflux, *Ecol. Appl.*, 20,  
932 1569-1582, 2010.

933 Wiegand, T., Snyman, H. A., Kellner, K., and Paruelo, J. M.: Do grasslands have a memory:  
934 Modeling phytomass production of a semiarid South African grassland, *Ecosystems*, 7,  
935 243-258, 2004.

936 [Willimas, C. A. and Albertson, J. D.: Dynamical effects of the statistical structure of annual](#)  
937 [rainfall on dryland vegetation, \*Global Change Biol.\*, 12, 777-792, 2006.](#)

938 [Williams, C. A., Hanan, N., Scholes, R. J., and Kutsch, W.: Complexity in water and carbon](#)  
939 [dioxide fluxes following rain pulses in an african savanna, \*Oecologia\*, 161, 469-480, 2009.](#)

940 Xu, L. K. and Baldocchi, D. D.: Seasonal variation in carbon dioxide exchange over a  
941 Mediterranean annual grassland in California, *Agr. Forest Meteorol.*, 123, 79-96, 2004.

942 Xu, L. K., Baldocchi, D. D., and Tang, J. W.: How soil moisture, rain pulses, and growth alter the  
943 response of ecosystem respiration to temperature, *Global Biogeochem. Cy.*, 18, GB4002,  
944 doi: 4010.1029/2004GB002281, 2004.

945 Yahdjian, L. and Sala, O. E.: Vegetation structure constrains primary production response to  
946 water availability in the Patagonian steppe, *Ecology*, 87, 952-962, 2006.

947 Yahdjian, L., Sala, O. E., and Austin, A. T.: Differential controls of water input on litter  
948 decomposition and nitrogen dynamics in the Patagonian Steppe, *Ecosystems*, 9, 128-141,  
949 2006.

950 [Yahdjian, L., Sala, O. E.: Size of precipitatin pulses controls nitrogen transformation and losses](#)  
951 [in an arid Patagonian ecosystem, \*Ecosystems\*, 13, 575-585, 2010.](#)

952 Zielis, S., Etzold, S., Zweifel, R., Eugster, W., Haeni, M., and Buchmann, N.: NEP of a Swiss  
953 subalpine forest is significantly driven not only by current but also by previous year's  
954 weather, *Biogeosciences*, 11, 1627-1635, 2014.

955

956

957 **Table 1.** Spearman correlation coefficients between interannual legacy effects and precipitation  
 958 characteristics at an interannual scale. Significant correlations are indicated with \* for  $0.01 < P$   
 959  $\leq 0.05$  and \*\* for  $P \leq 0.01$  —Correlations are significant at the 0.05 and 0.01 levels (2-tailed;  
 960  $n=27$ ), respectively; ns — not significant.

Precipitation characteristics	Dry legacy (previous-year PPT -30%)			Wet legacy (previous-year PPT +30%)		
	$\Delta$ GEP	$\Delta$ R <sub>e</sub>	$\Delta$ NEP	$\Delta$ GEP	$\Delta$ R <sub>e</sub>	$\Delta$ NEP
<u>Previous-year PPT characteristics</u>						
Yearly <u>rainfall</u> -SPI	ns0.134	ns0.033	0.566 <sup>**</sup> 0.270	-0.545 <sup>**</sup> 32	ns-0.180	-0.757 <sup>**</sup> 374
				4		
Warm-GS <u>SPIrainfall</u>	ns0.303	ns0.072	0.579519 <sup>**</sup>	ns-0.430 <sup>*</sup>	ns-0.065	-0.626579 <sup>**</sup>
<u>Yearly Warm-GS</u>	ns-0.069	ns0.137	-0.442399 <sup>*</sup>	-0.446 <sup>*</sup> 07	ns0.053	-0.636 <sup>**</sup> 262
<u>NE&gt;10 mmBEI</u>				5		
Warm-GS NE>10 mm	ns0.329	ns0.067	0.445636 <sup>**</sup>	ns-0.535 <sup>**</sup>	ns-0.227	-0.575619 <sup>**</sup>
<u>Current-year PPT characteristics</u>						
Yearly <u>SPIrainfall</u>	ns0.278	ns0.162	ns0.484 <sup>*</sup>	-0.482466	-0.467600	ns-0.224
				*	**	
<u>WarmCool-GS</u>	ns0.528 <sup>**</sup>	ns0.338	ns0.495 <sup>*</sup>	ns-0.277	-0.399 <sup>*</sup> 31	ns-0.218
<u>SPIrainfall</u>						
Yearly BEI	ns-0.512 <sup>**</sup>	ns-0.285	ns-0.686 <sup>**</sup>	0.409 <sup>*</sup> 359	ns0.352	ns0.255
<u>Cool-GS BEI</u>	-0.519 <sup>**</sup>	-0.286	-0.510 <sup>**</sup>	0.151	0.088	0.214

Yearly NE>10 mm	<del>ns</del> <u>0.331</u>	<del>ns</del> <u>0.178</u>	<del>ns</del> <u>0.512</u> **	<del>-0.394</del> <u>0.567</u>	<del>ns</del> <u>-0.583</u> *	<del>ns</del> <u>-0.398</u> *
				**		
<u>Cool-GS NE&lt;10 mm</u>	<u>0.614</u> **	<u>0.577</u> **	<u>0.398</u> *	<u>-0.105</u>	<u>-0.075</u>	<u>-0.128</u>
<u>PPT difference (<math>\Delta</math>PPT) between current- and previous-year</u>						
<u>Yearly rainfall</u>	<u>0.088</u>	<u>-0.135</u>	<u>0.466</u> *	<u>0.078</u>	<u>-0.088</u>	<u>0.252</u>
<u>Warm-GS rainfall</u>	<u>-0.059</u>	<u>-0.042</u>	<u>0.074</u>	<u>0.206</u>	<u>-0.096</u>	<u>0.326</u>
<u>Cool-GS rainfall</u>	<u>0.326</u>	<u>0.048</u>	<u>0.374</u> *	<u>0.248</u>	<u>0.160</u>	<u>0.209</u>

961 Abbreviations: PPT: precipitation; ~~SPI: standard precipitation index~~; GEP: gross primary  
962 production; R<sub>e</sub>: ecosystem respiration; NEP: net ecosystem production; GS: growing season; BEI:  
963 between-event interval; NE: number of rainfall events. ~~\* and \*\* - Correlations are significant at~~  
964 ~~the 0.05 and 0.01 levels (2-tailed), respectively; ns - not significant.~~

965 **Figure captions**

966 **Figure 1.** ~~Annual and growing season rainfall and corresponding standard precipitation index~~  
967 ~~(SPI) Precipitation characteristics~~ in the 30 years (1981-2010) at the Santa Rita ~~Experimental~~  
968 ~~Range (SRER)~~ mesquite savanna site. ~~(a) Annual and seasonal precipitation amount; (b)~~  
969 ~~Frequency distribution of daily rainfall; (c) Mean and maximum between-event interval (BEI).~~  
970 ~~Horizontal lines within (a) indicate mean annual and seasonal precipitation. The warm growing~~  
971 ~~season (warm-GS) is from Jul through Sep, the cool dry season (cool-DS) from Oct to Nov,~~  
972 ~~the cool growing season (cool-GS) is from Dec through Mar, and the warm dry season~~  
973 ~~(warm-DS) warm-GS from Jul-Apr through Sep-Jun. Dots represent annual or seasonal rainfall~~  
974 ~~and bars the corresponding standard precipitation index Bars in panel (c) represent standard~~  
975 ~~deviations and n is the number of rain event pairs used to calculate the between-event interval in~~  
976 ~~the 30 years.~~

977

978 **Figure 2.** Comparison of the model-simulated water and carbon fluxes with the eddy  
979 covariance observed ~~one~~ ~~at~~ ~~ions~~ at the mesquite savanna site. Left panels show the ~~comparison~~  
980 ~~between the modeled and observed fluxes in four calibration (2007-2007; solid dots) and three~~  
981 ~~validation years (2008-2010; open dots). seasonal and annual fluxes (2004-2007) used for model~~  
982 ~~calibration. Right panels show the relationships of the simulated (solid dots) and observed~~  
983 ~~(open dots) fluxes with precipitation in the seven years seasonal and annual fluxes~~  
984 ~~(2008-2004-2010) used for model validation. R<sup>2</sup> is the coefficient of determination describing~~  
985 the proportion of the variance in measured fluxes explained by the model ~~for the left panels or~~

986 that explained by precipitation for the right panels. ~~CS represents the cool season from Oct to~~  
987 ~~Mar and WS the warm season from Apr to Sep.~~ AET represents actual evapotranspiration; GEP  
988 gross ecosystem production,  $R_e$  total ecosystem respiration, and NEP net ecosystem production.

989

990 **Figure 3.** Interdecadal legacy effects of changing the previous-period (1981-1994)

991 precipitation on the cumulative carbon fluxes of the current period (1995-2010). Interdecadal

992 legacy effects on carbon fluxes (e.g.  $\Delta$ NEP) are calculated as the difference between the

993 current-period flux with previous-period PPT changes and that without previous-period PPT

994 changes. Dashed lines with open symbols represent different levels of decreasing (left panels) the

995 current-period precipitation (left panels)-(PPT). Solid lines with filled symbols represent

996 increasing (right panels) the current-period precipitation (right panels).

997

998 **Figure 4.** Spearman correlations of interdecadal precipitation legacy effects with the

999 precipitation difference between periods ( $\Delta$ PPT). Interdecadal  $\Delta$ PPT is calculated as the mean

1000 PPT of the current period (1995-2010) minus that of the previous period (1981-1994).

1001 Interdecadal legacy effects on carbon fluxes (e.g.  $\Delta$ NEP) are calculated as the difference

1002 between the current-period flux with previous-period PPT changes and that without

1003 previous-period PPT changes. Sample size is 41 for the wet-to-dry period transition (left panels)

1004 and 23 for the dry-to-wet period transition (right panels). GEP represents gross ecosystem

1005 production,  $R_e$  ecosystem respiration, and NEP net ecosystem production.  $R^2$  is the coefficient

1006 of determination and P is probability.

1007

1008 **Figure 5.** Interdecadal precipitation legacy effects on the resource pool dynamics. Left  
1009 panels show the resource pool responses under a 30% of decrease while right panels show those  
1010 under a 30% of increase in the precipitation (PPT) of the current period from 1995-2010.

1011 Legacy effects on pool size (e.g.  $\Delta$ Biomass) are quantified as the difference between the  
1012 current-period pool size with previous-period PPT change and that without previous-period PPT  
1013 change. Dashed lines represent a 30% of decrease while solid lines represent a 30% of increase  
1014 in the precipitation-PPT of the previous period from 1981-1994. SOM represents soil organic  
1015 matter,  $N_{\text{soil}}$  soil mineral nitrogen, and SWC soil water content.

1016

1017 **Figure 6.** Interannual precipitation legacy effects on the ecosystem carbon fluxes. (a) and (b)  
1018 show the lasting duration of dry (left panels) and wet (right panels) legacies, respectively. The  
1019 legacy lasting duration is quantified as the number of years during which the legacy impacts on  
1020 ecosystem fluxes exists after a previous-year PPT change. (c) through (h) show the responses  
1021 of gross ecosystem production (GEP), ecosystem respiration ( $R_e$ ) and net ecosystem production  
1022 (NEP) response to dry (left panels) and wet (right panels) legacies. Bars in the background of  
1023 (a) and (b) represent the previous-yearly standard precipitation index (SPI)PPT amount after a 30%  
1024 decrease and increase, respectively.

1025

1026 ~~**Figure 7.** Spearman correlations of interannual precipitation legacy effects with the~~

1027 precipitation difference between years ( $\Delta$ PPT).— Interannual  $\Delta$ PPT is calculated as current-year  
1028 PPT minus previous-year PPT.— Sample size is 26 for the wet-to-dry year transition (left panels)  
1029 and 27 for the dry-to-wet year transition (right panels).— GEP represents gross ecosystem  
1030 production,  $R_e$  ecosystem respiration, and NEP net ecosystem production.—  $R^2$  is the coefficient  
1031 of determination and P is probability.—

1032

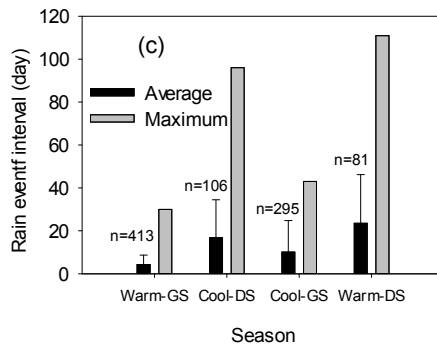
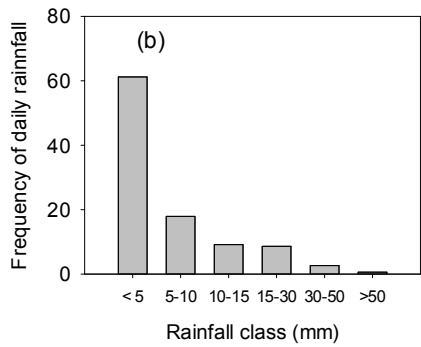
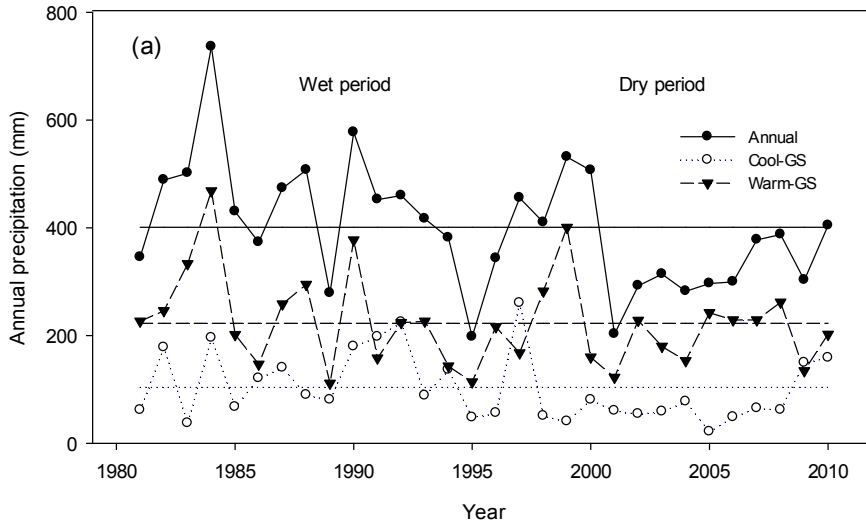
1033 **Figure 78.** Interannual precipitation legacy effects on resource pool dynamics. Left panels  
1034 show the legacy effects on pool dynamics in two representative wet years while right panels for  
1035 two representative dry years. Legacy effects on pool size (e.g.  $\Delta$ Biomass) are quantified as the  
1036 difference between the current-year pool size with previous-year PPT change and that without  
1037 previous-year PPT change. Solid lines represent a 30% decrease while dashed lines represent a  
1038 30% increase in the previous-year precipitation (PPT). SOM represents soil organic matter,  
1039  $N_{\text{soil}}$  soil mineral nitrogen, and SWC soil water content.



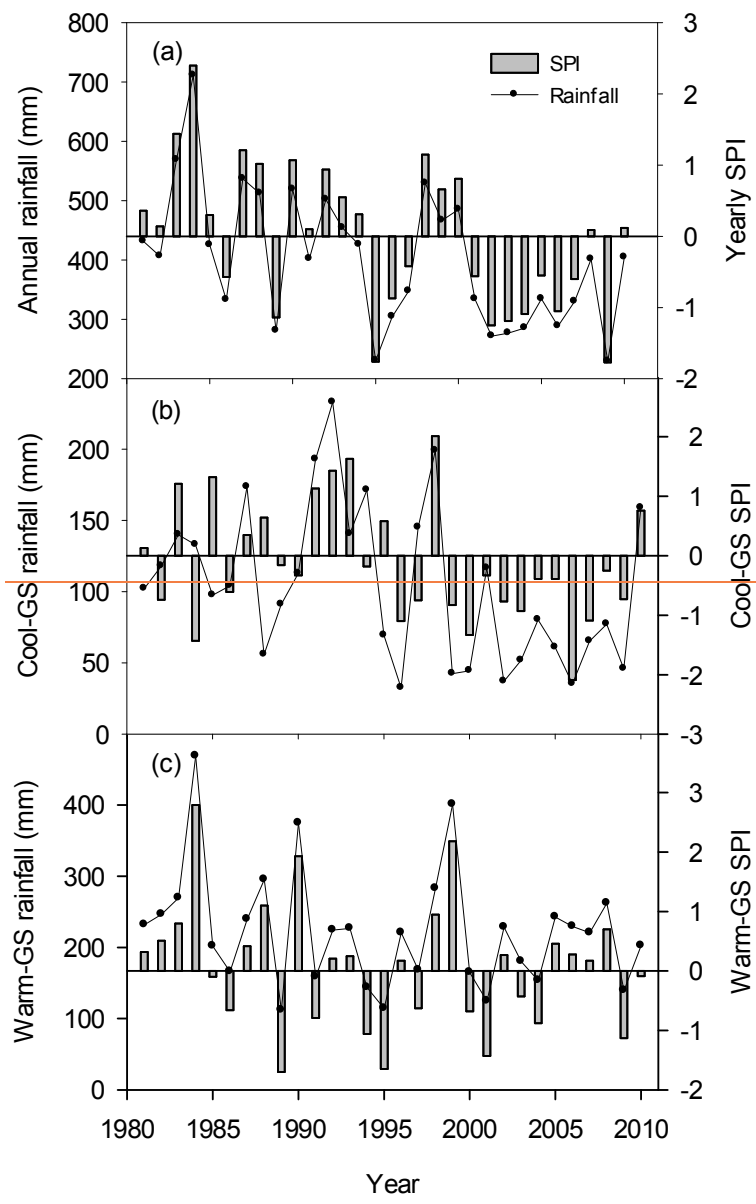
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1041 FIG. 1

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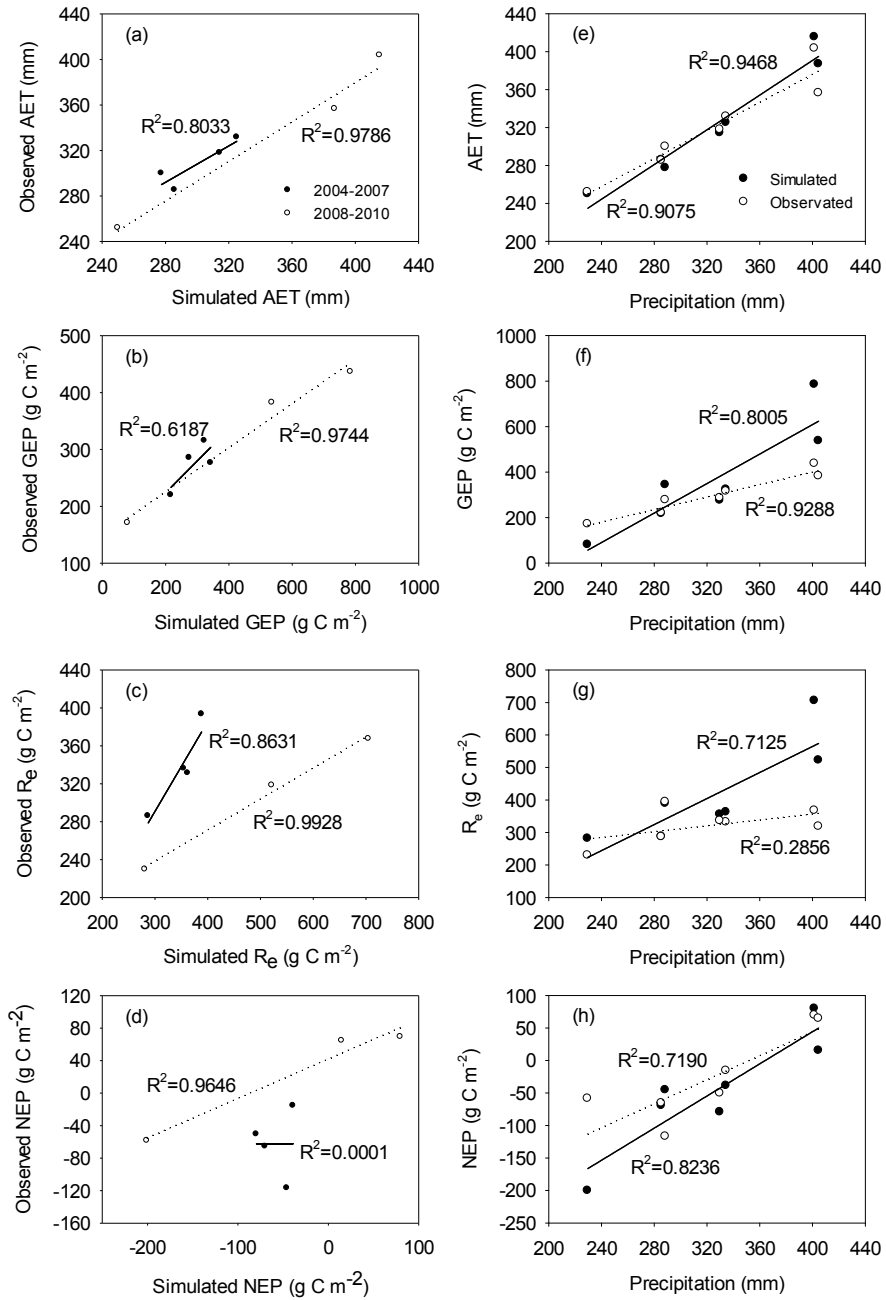


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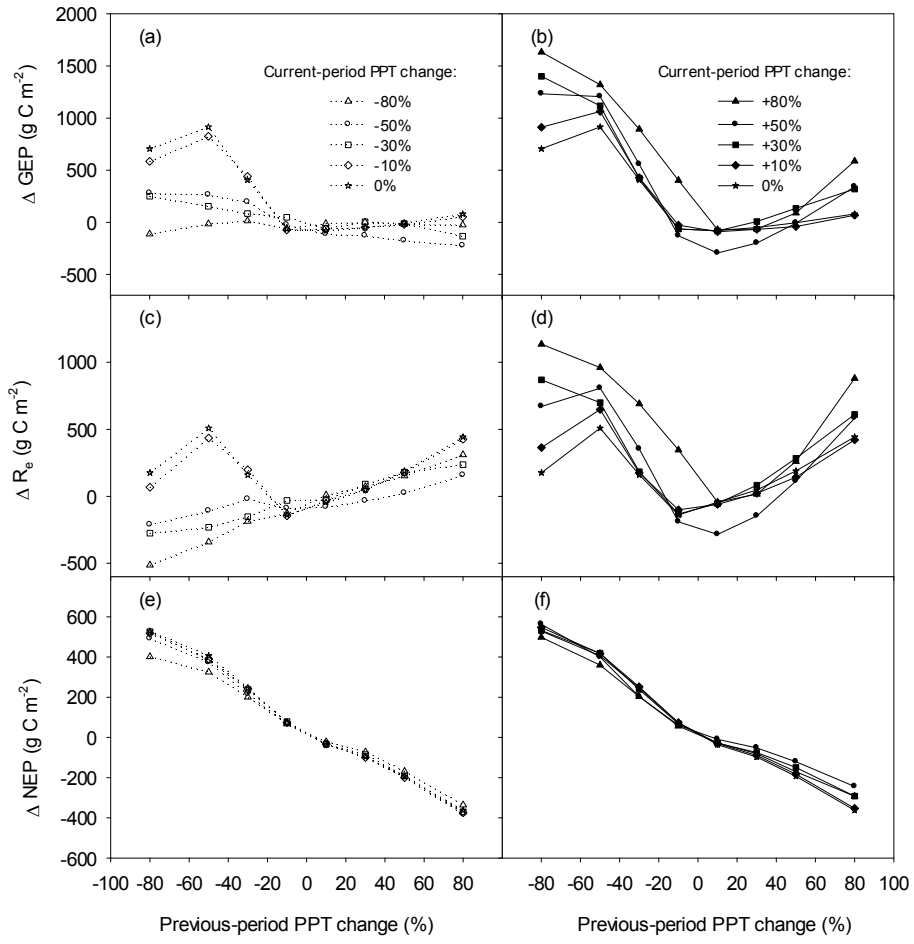
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1047 FIG. 2  
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1051  
1052 FIG. 3  
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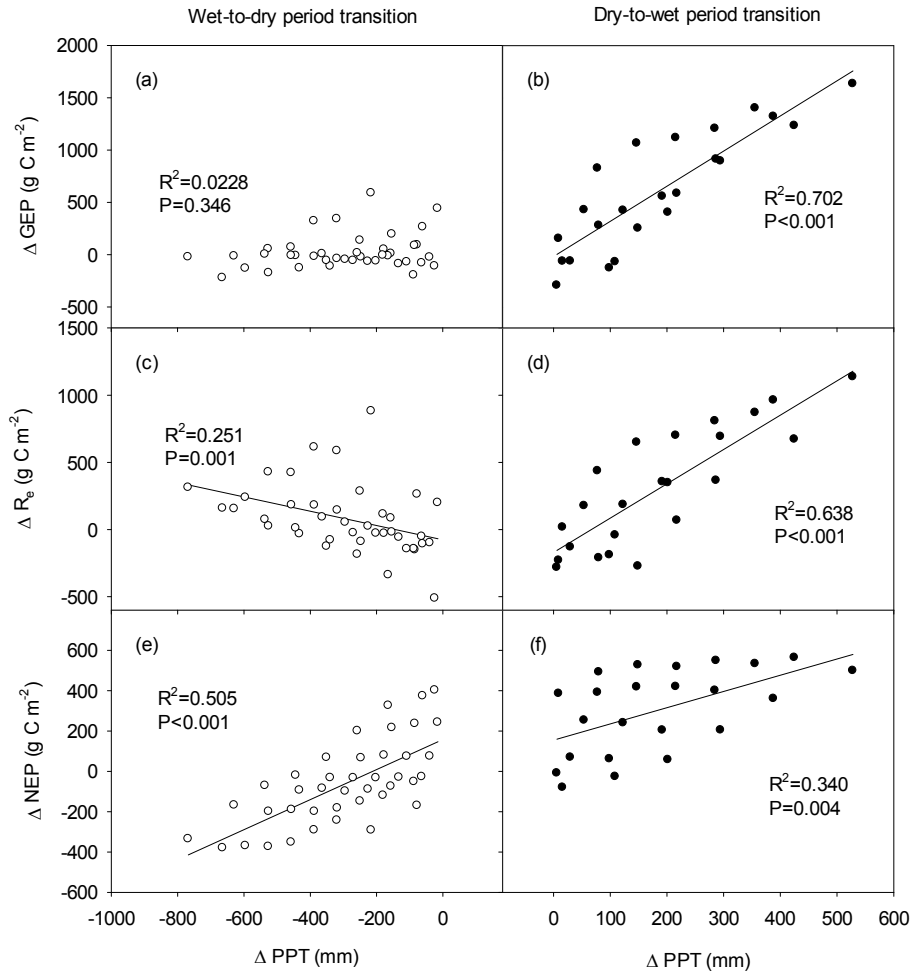


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1057 FIG. 4

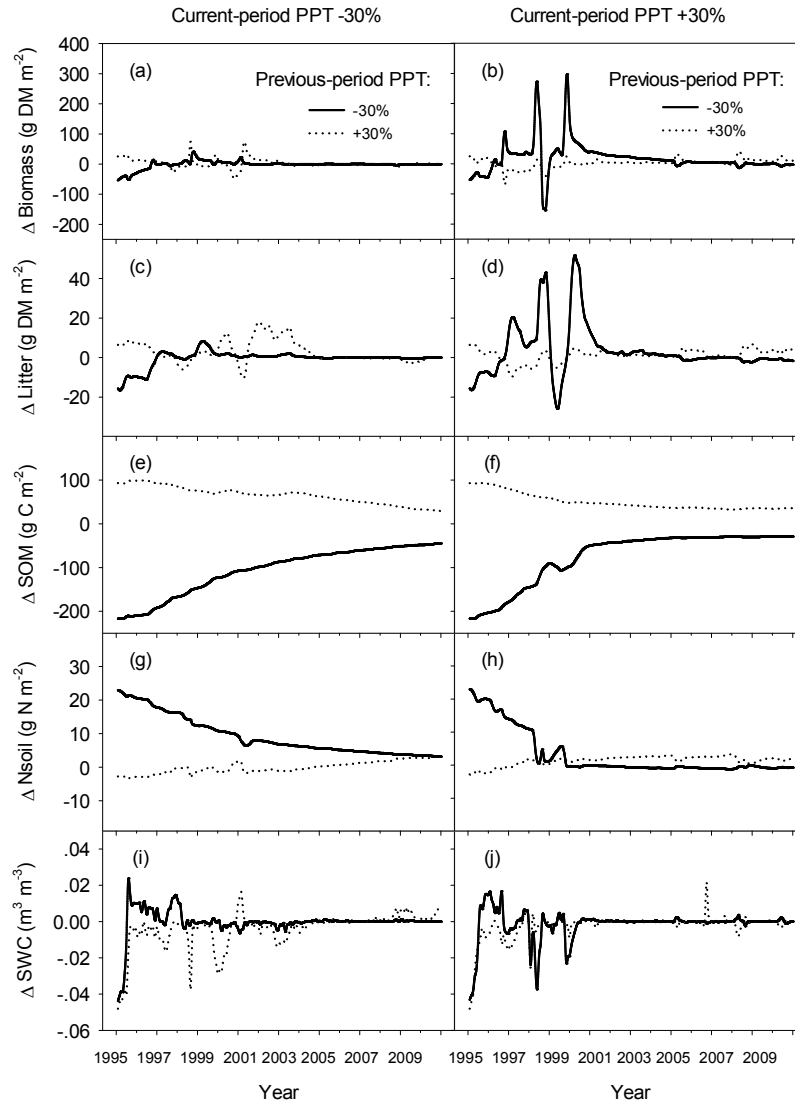
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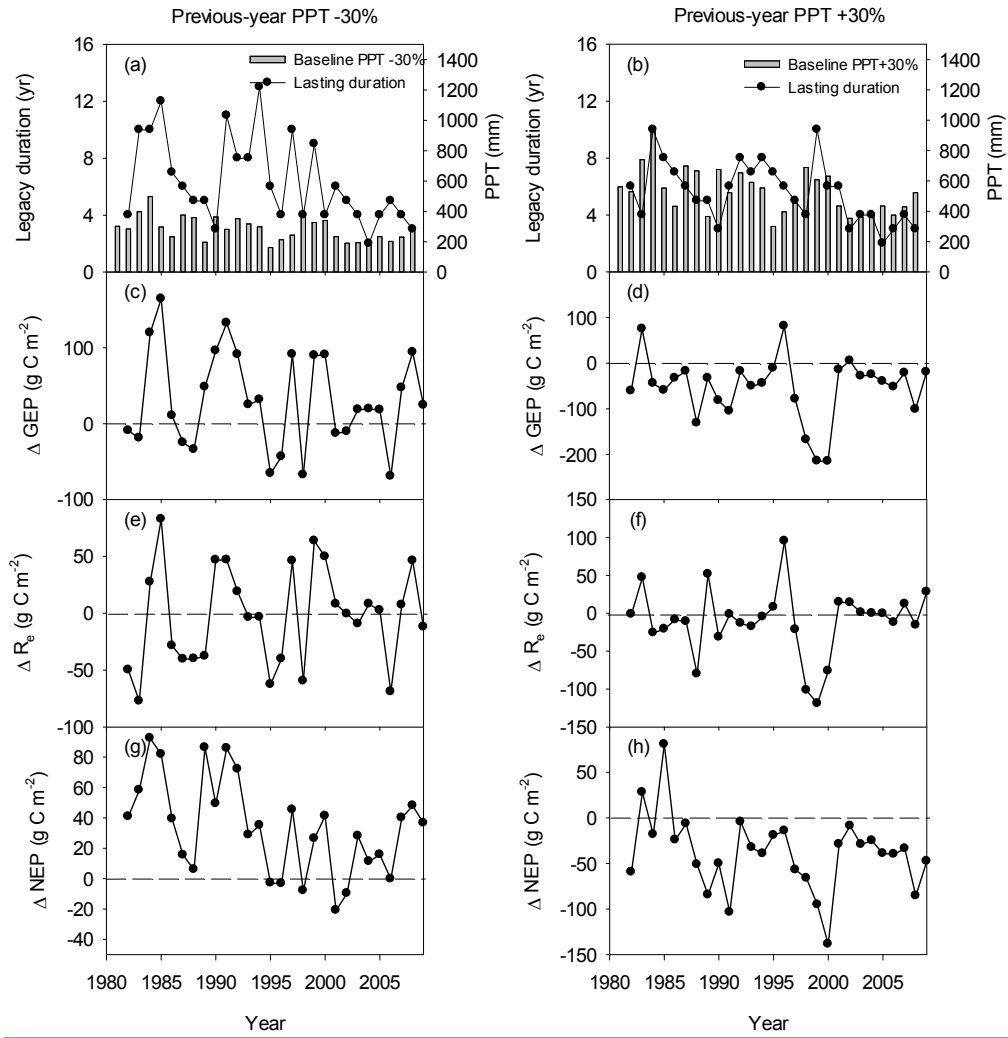
1061  
1062 FIG. 5  
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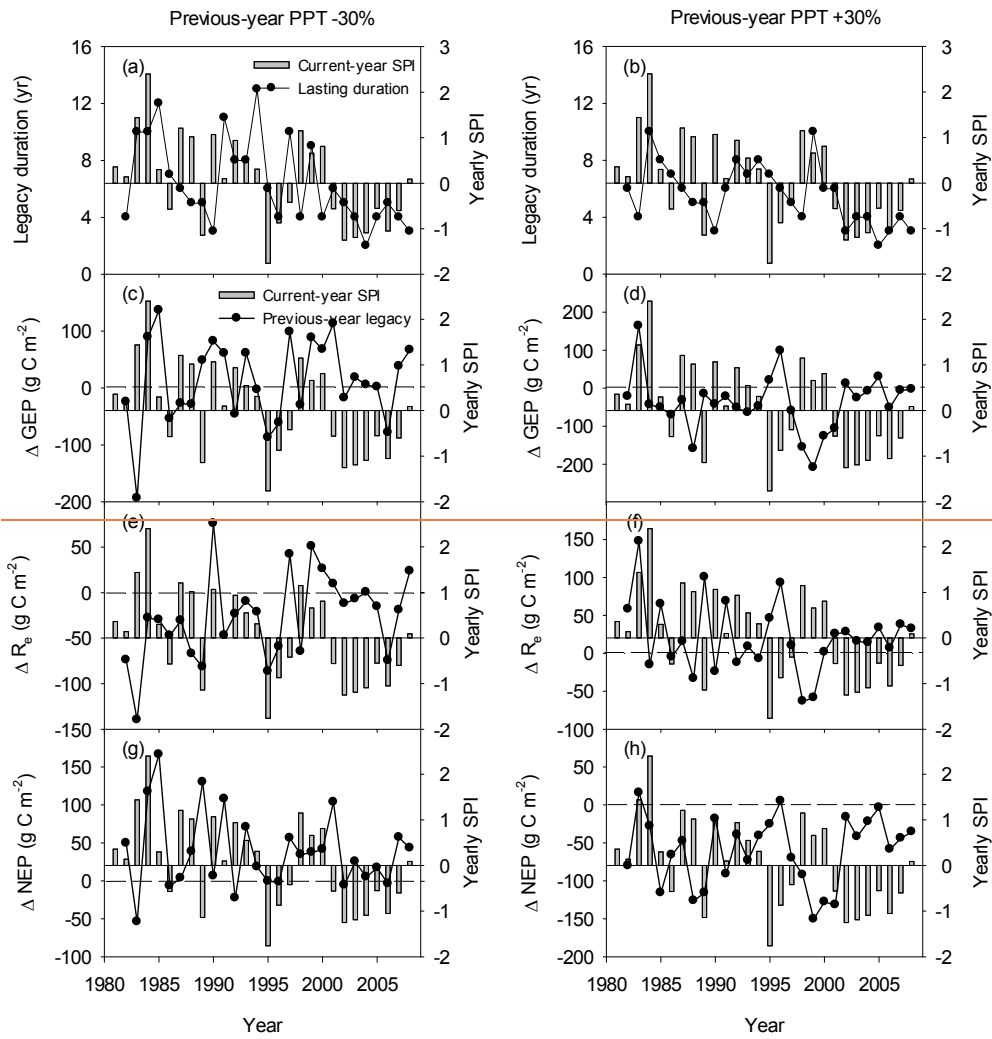
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FIG. 6



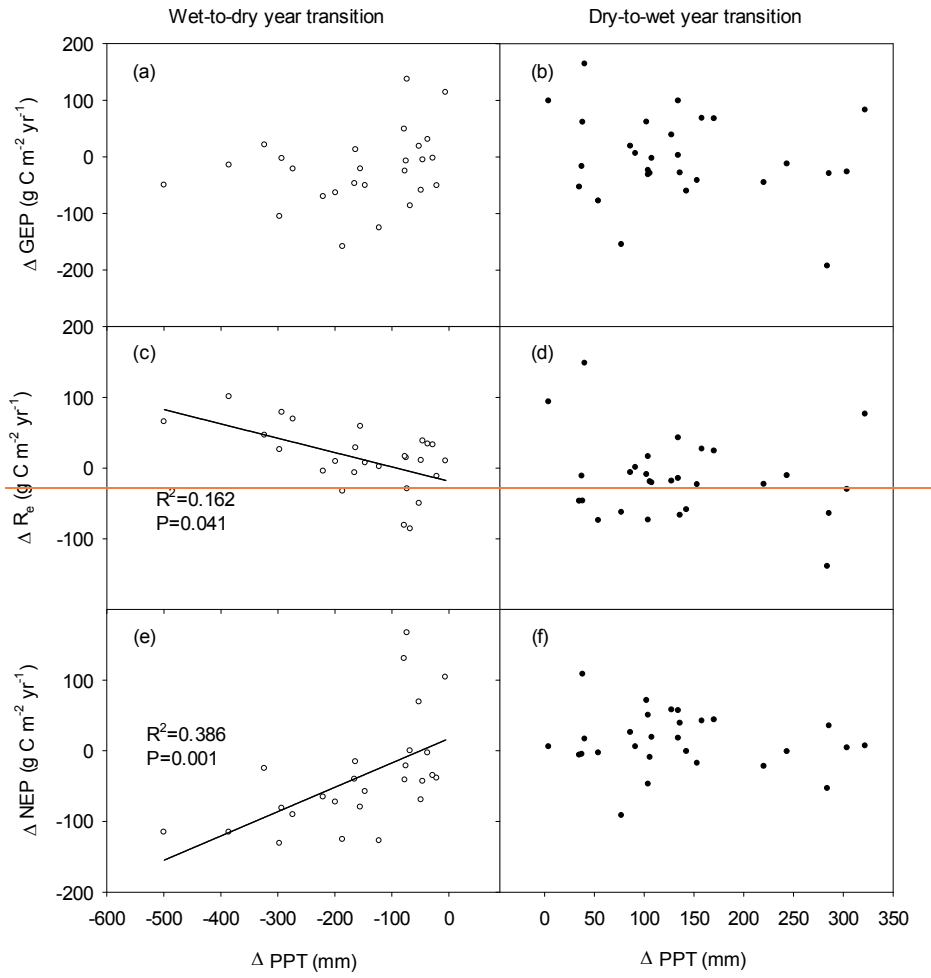
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FIG. 7



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