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. ∆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 ∆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_{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_{soil} during dry periods. On one hand, the accumulated N_{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_{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_{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_{soil} carryover effects because more N_{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.
Abstract

The precipitation legacy effect, defined as the impact of historical precipitation (PPT) on extant ecosystem dynamics, has been recognized as an important driver in shaping the temporal variability of dryland aboveground primary production (ANPP) and soil respiration. How the PPT legacy influences whole ecosystem-level carbon (C) fluxes has rarely been quantitatively assessed, particularly at longer temporal scales. We parameterized a process-based ecosystem model to a semiarid savanna ecosystem in southwestern US, calibrated and evaluated the model performance based on 7 years of eddy covariance measurements, and conducted two sets of simulation experiments to assess interdecadal and interannual scale PPT legacy effects over a 30-yr simulation period. The results showed that decreasing the previous period/year PPT (dry legacy) always imposed positive impacts on net ecosystem production (NEP) whereas increasing the previous period/year PPT (wet legacy) had negative impacts on NEP—a negative PPT legacy effect. The simulated dry legacy impacts were mostly positive on increased subsequent gross ecosystem production (GEP) and negative on reduced ecosystem respiration \( R_e \) but the wet legacy impacts were mostly negative on reduced GEP and positive on increased \( R_e \). Although the direction and magnitude of GEP and \( R_e \) responses to the simulated dry and wet legacies were influenced by both the previous and current PPT conditions, the NEP responses were predominantly determined by the previous PPT characteristics including rainfall amount, seasonality and event size distribution. Larger PPT difference between periods/years resulted in larger legacy impacts, with dry legacies fostering more C sequestration and wet legacies more C release. By analyzing the resource pool (C, N, and H2O) responses to
the simulated dry and wet legacies, we found that the carryover of soil N between periods/years was mainly responsible for the GEP responses while the carryovers of plant biomass, litter and soil organic matter were mainly responsible for the $R_e$ responses. These simulation results suggest that previous PPT conditions can exert substantial legacy impacts on current ecosystem C balance, which should be taken into account while assessing the response of dryland ecosystem C dynamics to future PPT regime changes.

**Keywords:** AmeriFlux, Legacy, carbon flux, lagged effect, biogeochemical carryover, ecosystem modeling, legacy, semiarid.
1 Introduction

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

As a measure of ecosystem C balance, net ecosystem production (NEP) has a value that is positive when an ecosystem accumulates C and negative when an ecosystem loses C. Dryland NEP has been thought to be closely tied to current-year PPT amount, with wetter than average years being a C sink, drier than average years being a C source, and years with average rainfall being C neutral (Flanagan et al., 2002; Hastings et al., 2005). Importantly, at seasonal within annual scales, the distribution of precipitation PPT in addition to the total...
amount can have large influences on ecosystem production (Porporato et al., 2004; Katul et al., 2007). At interannual scales, in addition, the precipitation PPT legacy effect, defined as the impact of past PPT conditions on the current structure and functioning of ecosystems (Lauenroth and Sala, 1992; Sala et al., 2012; Monger et al., 2015), has also been found to play an important role in shaping the temporal variability of dryland ecosystem C fluxes (Knapp et al., 2002; Huxman et al., 2004a, b; Heisler and Weltzin, 2006; Sala et al., 2012; Ogle et al., 2014). For example, Hasting et al. (2005) attributed the C sink status of a desert shrub ecosystem in the early spring of 2002 to the above-average rainfall in the late fall of 2001. Scott et al. (2009) and Hamerlynck et al. (2013) found that the cool season (Dec – Apr) drought was followed by an unusually large net C loss during the following warm monsoon season (Jul - Sep) in a semiarid savanna and a semidesert grassland ecosystems in southwestern US. Moreover, the savanna ecosystem has recently been a net C source and one hypothesized but untested explanation is due to an increase in current respiration of organic C that accumulated in the preceding wetter decade (Scott et al., 2009), but has yet been tested. While these studies reveal the existence of PPT legacy effects on NEP at the seasonal scale, only a few studies have quantitatively assessed the contribution of PPT legacy to the temporal variability of dryland NEP at interannual and interdecadal time scales, has not been quantitatively assessed (Williams and Albertson, 2006), mainly because it is methodologically difficult to separate the past and current PPT impacts on C fluxes with the limited existing observational data (Sala et al., 2012), and there is a general lack of field manipulative experiments to address the PPT legacies at these scales (Reichmann et al., 2013a).
Much of our current understanding of the PPT legacy effects on dryland C fluxes is based on the aboveground net primary production (ANPP). A number of studies have documented that dryland ANPP is not only linearly related to current-year PPT, but also closely related to the PPT amount and seasonality several months to years before (Lauenroth and Sala, 1992; Oesterheld et al., 2001; Huxman et al., 2004c). For example, field studies have found a positive wet-legacy effect where ANPP is higher than expected if preceded by a wetter year, or a negative dry-legacy effect where ANPP is lower than expected if preceded by a drier year (Jobbagy and Sala, 2000; Oesterheld et al., 2001; Wiegand et al., 2004; Sherry et al., 2008; Sala et al., 2012).

Proposed mechanisms explaining such observed positive PPT legacy effects on ANPP mainly involve the structural carryovers of structural attributes between years—the structural attributes, which can include leaf and root biomass (Oesterheld et al., 2001), the composition of species differing in rooting depth and phenology (Paruelo et al., 1999; Jobbagy and Sala, 2000; Jenerette et al., 2014), or the density of seeds, tillers and plant individuals (Oesterheld et al., 2001; Yahdjian and Sala, 2006; Reichmann et al., 2013a). Alternatively, a negative legacy effect occurs when production may be lower than expected if preceded by a wet period (a negative wet legacy effect) or higher than expected if preceded by a dry period (a positive dry legacy effect) (Jenerette et al., 2010). A negative such PPT legacy effects may be influenced more by biogeochemical effects carryovers that influence the resource availability to respond to current PPT (Evans and Burke, 2013; Reichmann et al., 2013b), whereby increased growth in response to a higher PPT can reduce the available nutrients (e.g., nitrogen (N)) for the following period and vice versa. Although various mechanisms have been proposed for the
PPT legacy impacts on ANPP, few of them have been rigorously tested, and the key underlying mechanisms still remain poorly understood (Sherry et al., 2008; Williams et al., 2009; Sala et al., 2012; Monger et al., 2015).

Soil respiration ($R_s$), as a major component of ecosystem C efflux, has also been found to have lagged responses to PPT variations (Huxman et al., 2004b; Sponseller, 2007; Ma et al., 2012; Cable et al., 2013). This is particularly true at the event scale; after a period of drought, a rainfall event can result in a pulse of CO$_2$ efflux that may be orders of magnitude larger than that before the event and then decline exponentially for a few days to weeks (Xu et al., 2004; Jenerette et al., 2008; Borken and Matzner, 2009; Cable et al., 2013; Oikawa et al., 2014). At a seasonal scale, Vargas et al. (2010) found no lags between $R_s$ and soil moisture across 13 vegetation types including four grasslands; but Hamerlynck et al. (2013) presented longer-term ecosystem flux data that suggest seasonal drought legacy affects ecosystem respiration ($R_e$) in a semi-desert grassland in southeastern AZ, US. They posited that the increased C substrate availability resulting from the previous cool-season drought induced plant mortality was responsible for the higher $R_e$ in the following monsoon season. However, very few studies have been devoted to understanding the PPT legacy impacts on dryland respiration at greater than seasonal timescales.

In this study, we conducted simulation experiments with a widely-used dryland ecosystem model, Patch Arid Land Simulator (PALS; Kemp et al. 1997, 2003; Reynolds et al. 2004; Shen et al. 2009), to analyze the PPT legacy effects on ecosystem-level C fluxes including NEP, gross ecosystem production (GEP), and $R_e$. The PALS model was built on the pulse-reserve concept
(Noy-Meir, 1973) and had been used to analyze the impacts of antecedent moisture conditions and the lagged responses of different plant functional types in three North American deserts at the rainfall event scale (Reynolds et al., 2004). We parameterized, calibrated, and evaluated the model based on the long-term eddy covariance measured fluxes at a semidesert savanna ecosystem in southwestern US (Scott et al., 2009) to analyze the PPT legacy effects at interannual and interdecadal scales. Specifically, we aimed to address the following two questions. First, what are the direction and magnitude of ecosystem C flux responses to dry and wet legacies? We expected that the PPT legacy impacts would occur over annual and decadal scales in correspondence to PPT fluctuations at these scales, and the dry and wet legacy impacts would differ in direction and magnitude. Second, how are the direction and magnitude of PPT legacy effects related to the PPT characteristics of both the previous and the current year/period? For PPT characteristics, we were not only interested in the annual and seasonal PPT amount but also between-event interval and event size distribution, since all these variables are widely-recognized key PPT features to dryland ecosystems (Porporato et al., 2004; Katul et al., 2007; Shen et al., 2008). We expected that greater variability in precipitation PPT would lead to corresponding increases in legacy effects… Third, what are the mechanisms responsible for the PPT legacy effects? We assumed that changes in the structural and biogeochemical pools/reserves (C, N, and H2O) resulting from changes in previous year/period PPT would influence current ecosystem C fluxes as conceptualized in the pulse-reserve framework and implemented in the PALS model.
2 Methods

2.1 Model description

PALS is a process-based ecosystem model that consists of four modules: atmospheric forcing, a water cycling and energy budget, plant production and respiration, and soil organic matter (SOM) decomposition and heterotrophic respiration ($R_h$). The four modules are interactively linked by the cycling of C, N, and H$_2$O through the atmosphere-plant-soil continuum. The PALS model explicitly considers seven plant functional types (FTs) commonly found in the North American warm deserts: evergreen shrub, deciduous shrub, perennial forb, perennial C$_3$ and C$_4$ grasses, and native and exotic C$_3$ annual grasses (Reynolds et al., 1997; Shen et al., 2009).

Since the detailed model structure and mechanistic relationships have been presented in several publications (Kemp et al., 1997, 2003; Reynolds et al., 1997, 2000, 2004; Gao & Reynolds, 2003; Shen et al., 2005, 2008a, 2008b, 2009), here we briefly describe the four modules and refer interested audience to the specific literature for detailed description.

The atmospheric driving force module reads in data for atmospheric driving variables (e.g. atmospheric [CO$_2$], N deposition rate, daily maximum and minimum air temperatures, precipitation [PPT], relative humidity, and solar radiation), and based on these driving variables, calculates other important variables such as vapor pressure deficit (VPD) that determines stomatal conductance and soil temperature that influences SOM decomposition and soil respiration. Calculations of VPD and soil temperature can be found in Equations (2) - (7) in Shen et al. (2005).

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

The plant production and respiration module mainly simulates phenology, primary production, growth and maintenance respiration, photosynthate allocation, and litterfall of each plant FT. Three major phenophases (i.e. dates of germination, leafing, and dormancy) are determined in PALS based on the observed dates, air temperature, and precipitation PPT (Shen et al., 2009). Primary production for each FT is calculated based on the leaf area, potential net photosynthetic rate, stomatal conductance, leaf N content modifier, and the difference between intercellular and atmospheric [CO₂]. The plant photosynthesis rate is estimated as a product of stomatal conductance and the partial pressure gradient between atmospheric and intercellular [CO₂]. The stomatal conductance is calculated as an exponential function of leaf water potential that decreases linearly with atmospheric vapor deficit (see Equations (10) - (14) in Shen et al., 2005). Photosynthate is allocated to different plant organs (leaf, stem, and root) using fixed allocation ratios after subtracting the maintenance respiration, which is estimated as a function of live
biomass, basal respiration rate, and modifiers of temperature and plant water potential (Shen et al., 2008a). Growth respiration is calculated based on the growth yield coefficient and the net photosynthate used for growth (Shen et al., 2008a). Litterfall amount is mainly determined as a function of observed dormancy dates, maximum air temperature and drought conditions (Shen et al., 2008a; Shen et al., 2009).

The SOM decomposition and heterotrophic respiration module simulates the decomposition of metabolic and structural litter material, SOM in active, slow and passive pools, and CO₂ emissions associated with these decomposition processes (Kemp et al., 2003 and Shen et al., 2009). The SOM decomposition rate or heterotrophic rate is calculated as a first-order kinetics rate with a decomposition coefficient multiplied by the pool size and the temperature and moisture scalars (see Equations (A4)-(A11) in Shen et al., 2009). In addition, this module also simulates the dynamics of soil mineral N pool by using N mineralization and atmospheric deposition as the major inputs, and plant N uptake and leaching loss as the major outputs.

Among these the N mineralization and plant uptake processes are modeled in more detail while the rates of the other processes are basically assigned with empirical constant values. The N mineralization processes are directly coupled to litter and SOM decomposition processes and are calculated as a product of the C flow rates and the C/N ratio of the corresponding litter or SOM pools (Parton et al., 1993; Kemp et al., 2003). The plant N uptake is a product of water transpiration and N concentration in soil solution (see Equation (8) in Shen et al., 2008b).

2.2 Model parameterization
For this study, we modified and parameterized PALS to represent an upland mesquite savanna ecosystem in the Santa Rita Experimental Range (SRER; 31.8214° N, 110.8661° W, elevation 1116 m), about 45 km south of Tucson, AZ, USA. Soils at this site are a deep sandy loam (Scott et al., 2009), and the mean groundwater depth likely exceeds 100 m (Barron-Gafford et al., 2013). Precipitation (PPT) was therefore considered as the only source of water input into the system. Based on the vegetation composition (Scott et al., 2009), there were five major plant FTs included in PALS: shrub (e.g. Prosopis velutina), subshrub (e.g. Isocoma tenuisecta), C₄ perennial grass (e.g. Digitaria californica), perennial forb (e.g. Ambrosia psilostachya), and C₃ annual grass, among which the velvet mesquite shrub with average height of ca. 2.5 m accounted for ~35% of the total canopy cover and other FTs (mainly perennial grasses) accounted for ~22% (Scott et al., 2009). Therefore, we derived the site-characteristic parameters for the two major FTs (shrub and perennial grass) from previous studies carried out in SRER, with those for the other FTs being adopted from a generic parameter dataset for the PALS model to be used in the North American warm deserts (Reynolds et al., 2004; Shen et al., 2005). These site-specific parameters mainly included plant-related parameters (e.g. canopy cover, C allocation ratio, rooting distribution ratio, and the initial values of living and dead plant biomass pools) and soil-related parameters (e.g. soil chemical and physical properties, C/N ratios, decomposition rates, and initial values of the litter and SOM pools). The values of these parameters are provided in Supplementary Table S1, with cited literature also being listed below the table.

For the climatic variables used to drive the PALS model, we compiled a 30-year meteorological dataset that included daily precipitation (PPT), maximum and minimum air
temperatures (\(T_{\text{max}}\) and \(T_{\text{min}}\)), relative humidity (RH), and total solar radiation (\(S_{\text{rad}}\)) from 1981 to 2010. The \(T_{\text{max}}\), \(T_{\text{min}}\), RH, and \(S_{\text{rad}}\) data from 1981-1990 were observations from the Tucson Weather Station (about 50 km north of the mesquite savanna site and lower elevation) and obtained through the Arizona Meteorological Network online data access (AZMET: http://ag.arizona.edu/azmet). The remaining 20 years (1991-2010) of \(T_{\text{max}}\), \(T_{\text{min}}\), RH and \(S_{\text{rad}}\) data were observations from the Kendall Weather Station (Grassland met site) (about 85 km east of the mesquite savanna site and slightly higher elevation) and obtained through the Southwest Watershed Research Center (SWRC) online data access (http://www.tucson.ars.ag.gov/dap/). The 30-year PPT data were observations from the Santa Rita Watershed rain gage #5 (1.5 km from the site) and obtained also from the SWRC online data access. These different sources of meteorological data were adjusted based on the 7 years (2004-2010) of the meteorological data obtained from the AmeriFlux eddy-covariance flux tower at the mesquite savanna site (US-SRM, see Supplementary Figure S1). At last, we used the AZMET and SWRC data from 1981 to 2003 plus the flux tower data from 2004 to 2010 to drive the model.

Since our simulation experiment was based on the manipulations of the 30-year (1981-2010) PPT data, we report the PPT characteristics here in more detail. In the past 30 years, the mean annual PPT (MAP) amount was 401 mm at the site, slightly greater than the long-term (1937-2007) mean of 377 mm (Scott et al., 2009). Based on the computed SPI, these 30 years were divided into two periods: a wet period from 1981-1994 with mean annual rainfall the a MAP of 465 mm and a dry period from 1995 to 2010 with mean annual rainfall the a MAP of
For the analysis of PPT legacy effects at interdecadal scale, the wet period was treated as the previous period and the dry period as the current period. For the analysis of PPT legacy effects at interannual scale, the annual scale was defined as from July through June of the next year. To analyze the relationship between PPT legacy effects and seasonal rainfall characteristics, each year was further divided into four seasons (with their mean rainfall in parenthesis): the main or the warm growing season from July to September (warm-GS, 224 mm), the cool dry season from October to November (cool-DS, 48 mm), the minor cool growing season from December to March (cool-GS, 104 mm), and the warm dominant dormant dry season from April to June (warm-DS, 27 mm). Based on the seasonal PPT amount, we distinguished four seasons with their mean PPT being listed in parenthesis: the cool growing season from Dec to Mar (cool-GS, 104 mm), the warm dry season from Apr to Jun (warm-DS, 27 mm), the warm growing season from Jul to Sep (warm-GS, 223 mm), and the cool dry season from Oct to Nov (cool-DS, 47 mm). At the site, as in many other dryland regions (Sala et al., 1992; Heisler-White et al., 2008), most rainy days have only light amounts of rainfall events. About 80% of daily rainfall was < 10 mm, with medium- to large-sized events (10 - 50 mm) accounting for about 20% and only 10 events larger than 50 mm in the 30 years (Fig. 1b). The no-rain-day duration between events (hereafter between-event interval or BEI) was ~5 days on average in the warm-GS and ~10 days in the cool-GS (Fig. 1c). The average BEI was ~17 days in the cool-DS and 24 days in the warm-DS; but there could be no rain for three months in these dry seasons (Fig. 1c).

To further assess the degree of dryness/wetness of a particular year or growing season relative-
to the normal annual or seasonal rainfall, we computed the Standard Precipitation Index (SPI) for
the 30 years and the 2 growing seasons of each year using the software SPI_SL_6 (available at
http://drought.unl.edu/MonitoringTools), with SPI ≈ 0 indicating a normal year/season, SPI < 0 a
dry year/season, and SPI > 0 a wet year/season. Based on the computed SPI, the 30 years were
divided into two periods: a wet period from 1981-1994 with mean annual rainfall of 465 mm and
a dry period from 1995 to 2010 with mean annual rainfall of 345 mm (Fig. 1a). The 1995-2010
dry period was dominated by cool-GS drought (Fig. 1b), whereas the warm-GS seemed to be-
wetter in the 1981-1994 wet period (Fig. 1c). These SPI values were used to analyze the
relationships between PPT legacy effect and PPT amount.

2.3 Model calibration and evaluation

After model parameterization, we calibrated the model based on four years (2004-2007) of
CO₂ and H₂O flux data monitored using the eddy covariance technique at the savanna site.
Detailed descriptions of instrumentation, sensor heights and orientations, and data processing
procedures for the eddy covariance data can be found in Scott et al. (2009). During model
calibration, we mainly adjusted the parameter values of photosynthate allocation ratios, live
biomass death rates, and SOM decomposition rates to achieve a best fit between modeled and
observed GEP and Rₑ, since these parameters had been identified as the most sensitive and
uncertain ones (e.g. photosynthate allocation ratios) in influencing the modeled ecosystem
carbon fluxes (Shen et al., 2005). The model performed well in capturing the seasonal variation
patterns of actual evapotranspiration (AET), GEP, Rₑ, and NEP in the four calibration years
Supplementary Figure S2), with faster larger C exchanges fluxes during the warm-GS. At seasonal and the annual scales, simulated AET, GEP, and $R_e$ could explained over 69% of the variations in the observed ones (Fig. 2, left panels). Compared to AET, GEP, and $R_e$, but the correlation between the simulated and observed NEP was very weaker weak (Fig. 2d). This was mainly due to the poor match in 2006 because the model substantially overestimated GEP (120 g C m$^{-2}$ simulated versus 52 g C m$^{-2}$ observed) during the warm-cool-GS of 2006 but underestimated $R_e$ during the cool-GS (Supplementary Figure S3). Further explanations on the possible causes of the GEP overestimation in 2006 shall be provided latter in discussions. If the data of this year were excluded, the explanatory power for annual and seasonal NEP was could reach 5274%. Since our goal was to use an empirically plausible model to understand the long-term temporal variations in ecosystem fluxes, we consider the calibration results acceptable. Year 2006 had extreme cool-GS drought with the SPI = -2.09 (Fig. 1b) and rainfall of 35 mm — less than half of those in the other three years. This cool-GS drought may have caused increased plant mortality similar to that reported for a semi-desert grassland nearby our study-site (Scott et al., 2010; Hamerlynck et al., 2013). We suspect that the model failed to capture such extreme drought impacts and resulted in the poor performance in 2006, since the empirical relations describing plant mortality and climate conditions in PALS account for more normal, rather than extreme, conditions. This is appropriate for our study as we are examining non-extreme influences of legacies.

The model performance was further evaluated by assessing the degree of correlation between the PALS-simulated and flux-tower-measured C and H$_2$O fluxes from 2008 through 2010, which
were not used for model calibration. The coefficients of determination ($R^2$), which describe the proportion of the variance in measured data explained by the model, were all larger than 0.98 at the seasonal and annual scales in the three validation years (2008-2010; Fig. 2, right-left panels).

Model performance is typically considered to be acceptable with $R^2$ value $> 0.5$ (Moriasi et al., 2007). These evaluation results indicate that the model was capable of capturing the temporal variability of observed fluxes at seasonal and the annual scales. Furthermore, we also analyzed the relationships between the observed and simulated fluxes with the corresponding current-year PPT to see how the flux variations were explained by current-year PPT under baseline conditions (i.e. the PPT variations shown in Fig. 1). The explanatory power ($R^2$) for both the observed and simulated fluxes were mostly over 70% (Fig. 2, right panels), which further indicates that the model is capable of capturing the impacts of PPT variability on ecosystem fluxes. The following simulation experiments were therefore designed to discriminate the contributions by previous- and current-year PPT impacts. Since our goal was to use an empirically plausible model to understand long-term temporal variations of ecosystem fluxes, we therefore consider the overall model performance acceptable.

### 2.4 Simulation experiments

We designed two sets of simulation experiments to examine the interdecadal and interannual PPT legacy effects. To analyze the interdecadal legacy effects, we first changed the PPT of the 14-year previous period (1981-1994) by 0%, ±10%, ±30%, ±50% and ±80% (multipliers of existing daily PPT amounts in the record) while keeping the 16-year current-period
(1995-2010) PPT unchanged. After these manipulations, the average PPT of the previous period ranged from 93 mm corresponding to the 80% of decrease to 837 mm corresponding to the 80% of increase. This design detects how changes in previous-period PPT influence the current-period C fluxes and the associated C pool dynamics. On top of each previous period PPT manipulation level, we further changed the current-period PPT by 0%, ±10%, ±30%, ±50%, and ±80%, which resulted in the average current-period PPT varying from 69 mm to 621 mm. This design detects how changes in the current-period PPT influence the legacies resulting from changes in the previous-period PPT. As a result, we made conducted 73 simulation runs corresponding to the 73 combinations of the above previous- and current-period PPT manipulations (9 previous PPT levels times 8 current PPT levels plus 1 baseline run).

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

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

\[ Legacy_{NEP} = \Delta NEP = NEP_{PPT+30\%} - NEP_{PPT+0\%} \]

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

3.1 Interdecadal legacy

Changes in the PPT of the previous period (1981-1994) imposed obvious legacy impacts on the C fluxes of the current period (1995-2010). The direction of the simulated interdecadal dry and wet legacies on GEP and $R_e$ was dependent upon the direction of both the previous- and current-period PPT changes. When the current-period PPT was reduced (Fig. 3, left panels), the simulated dry legacies imposed mostly positive impacts on increased the current-period GEP (Fig. 3a) but negative impacts on decreased $R_e$ (Fig. 3c); whereas wet legacies imposed mostly negative impacts on the current-period GEP (Fig. 3a) but mostly positive impacts on increased $R_e$ (Fig. 3c). When the current-period PPT was enhanced (Fig. 3, right panels), both the dry and wet legacies imposed mostly positive impacts on GEP and $R_e$ (Fig. 3b, d).

Regardless of current-period PPT changes, NEP always responded positively to the increased with dry legacies but and negatively to decreased with the wet legacies (Fig. 3e, f), indicating a consistent that the direction of negative NEP responses to the PPT legacies was predominantly determined by the direction of the previous-period PPT changes.

The simulated absolute magnitude of the PPT legacy influence on ecosystem C fluxes (i.e. GEP, $R_e$, and NEP) generally increased with the absolute magnitude of changes in the previous-period PPT (Fig. 3, Fig. 4). Increasing the current-period PPT generally amplified the legacy effects compared to decreasing the current-period PPT (comparing the left to the right panels of Fig. 3). The magnitude of the PPT legacies was also significantly correlated with the
PPT difference between the previous and current period (ΔPPT, equals to the current-period PPT minus the previous-period PPT; Fig. 4). If the previous period was wetter than the current period (i.e. ΔPPT < 0 or a wet-to-dry period transition), the legacy effect on $R_e$ was negatively related with ΔPPT (Fig. 4c) but that on NEP was positively related with ΔPPT (Fig. 4e), indicating more current-period C release after a wetter previous period. In contrast, if the previous period was drier than the current period (i.e. ΔPPT > 0 or a dry-to-wet period transition), the correlations were all positive for GEP, $R_e$ and NEP (Fig. 4, right panels), indicating more current period C sequestration after a drier previous period.

The resource pool dynamics were also shaped by the alterations in the previous- and current-period PPTs. We only showed the 30% decrease and increase in the previous- and current-period PPT (i.e. 4 out of 72 pairs of PPT change combinations) as representative examples in Fig. 5, because the major response patterns for the other paired combinations were similar. The duration of the PPT legacy impacts generally lasted for about 6-8 years for plant biomass, litter mass and soil water content (SWC), but much longer for soil organic matter (SOM) and soil mineral N ($N_{soil}$) (Fig. 5). Based on the resource pool responses in the early 1-2 years (i.e. 1995 and 1996) of the current period, the dry legacies imposed negative impacts on decreased biomass, litter and SOM (Fig. 5a-f), but positively impacted $N_{soil}$ (Fig. 5g-h).

Contrastingly, the wet legacies imposed positive impacts on increased biomass, litter and SOM (Fig. 5a-f), but negatively impacted $N_{soil}$ (Fig. 5g-h). Similar to the influences on C fluxes, increasing the current-period PPT (Fig. 5, right panels) amplified the PPT legacy impacts on biomass and litter (Fig. 5a-d), and hastened the recovery rates of SOM and $N_{soil}$ to their baseline...
levels (Fig. 5e-h).

3.2 Interannual legacy

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

The correlation analysis showed that not only rainfall amount but also BEI and event size distribution could influence be related to the magnitude of the simulated dry and wet legacies (Table 1). The warm-GS precipitation PPT of a previous-year was detected to have significantly correlated ions with the dry legacies for NEP and the wet legacies for GEP and NEP (Table 1).

Contrastingly, on the other hand, the cool-GS precipitation PPT of a current-year had was found to have important influences on the dry and wet legacies for C fluxes, but not all of them were
statistically significant (Table 1). These results indicate that the legacies were mainly generated in the warm-GS of a previous year, but the current-year cool-GS precipitation could influence the C flux responses to the previous-year generated legacies. Unlike at the interdecadal scale (Fig. 4), our correlation analysis showed that only the dry legacies for NEP had significantly correlations with the PPT difference (ΔPPT) between two consecutive years or cool-GSs (Table 1), indicating that the larger the PPT difference between a previous dry year and a current wet year, the greater the legacy impacts on NEP imposed by the previous dry year. The simulated dry and wet legacies on NEP were only significantly related with the previous-year PPT conditions including annual and warm-GS SPI, BEI, and number of large events (NE>10 mm; P<0.05; Table 1), but not the current-year PPT conditions (Table 1). With respect to GEP and Re responses, only the wet legacies were found to be significantly correlated with some of these PPT variables (P<0.05; Table 1). Further examining the correlation between the PPT legacy effects and the PPT difference between two consecutive years (i.e. ΔPPT = current-year PPT minus previous-year PPT), we found that only Re and NEP responses were significantly correlated with ΔPPT if ΔPPT < 0 (i.e. under a wet-to-dry year transition; Fig. 7c, e).

To analyze the interannual PPT legacy impacts on the dynamics of resource pools (i.e. biomass, litter, SOM, Nsoil, and SWC), two wet years (1983 and 1994) with positive SPI and two dry years (1986 and 1995) with negative SPI (see Fig. 1a) were chosen as examples (see Fig. 1a). The simulated dry legacies had negative impacts on reduced biomass, litter and SOM, but positive impacts on increased Nsoil and SWC in the first current year (Fig. 87). In contrast, the simulated wet legacies imposed just the opposite direction of impacts on the five resource pools.
The simulated PPT legacy impacts on the resource pools could also last for several years, and the direction and magnitude of the legacy impacts in the following years could differ from those in the first year as described above. For example, increasing the PPT of 1995 by 30% caused a positive legacy impact on the biomass of the first following year (i.e. 1996; Fig. 7b) but it became negative in the latter following years (e.g. in 1998; Fig. 8b), further indicating that current-year PPT conditions could influence the direction and magnitude of the previous-year PPT legacies.

4 Discussion

4.1 Direction and magnitude of the simulated PPT legacies

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

(Fig. 7).
PPT (dry legacy) led to more variable effects for both GEP and \( R_e \) that were strongly conditioned on current period PPT such that increasing current PPT was associated with increases in the dry legacy effect. Overall, the effects on GEP were larger than \( R_e \) for reduced prior PPT and smaller for increased prior PPT, which resulted in a consistent negative PPT legacy on NEP regardless of current PPT. The complexity in the legacy effects on ecosystem C cycling we show here are in part influenced by the contrasting PPT legacy responses of C uptake and emission and their distinct interactions with current PPT distributions. 

Despite the fact that However, the dry and wet legacy impacts on the two processes (GEP and \( R_e \)) determining NEP (\( NEP = \text{GEP} - \text{R}_e \)) were largely influenced by both the previous and current PPT changes (Fig. 3a-d, Fig. 6c-f). The main reason was that alterations in current PPT influenced GEP and \( R_e \) in the same direction (e.g. increasing current PPT stimulated both GEP and \( R_e \); see Fig. 3 and Fig. 6), which canceled out the current PPT impacts on the previous PPT legacies for NEP (again \( \text{NEP} = \text{GEP} - \text{R}_e \)). But Nevertheless, the reason of that why the dry overall legacies for NEP were positive/negative whereas the wet legacies for NEP were negative was that ? mainly because the dry legacies were mostly positive/increased for GEP (Fig. 3a-b, Fig. 6c), the wet legacies were mostly negative/for decreased GEP (Fig. 3a-b, Fig. 6d), and the absolute magnitude of the dry and wet legacies for GEP was generally larger than those for \( R_e \) (Fig. 3a-d, Fig. 6c-f), while alterations in previous PPT influenced GEP and \( R_e \) in the opposite direction (Fig. 3a-d, Fig. 6c-f).

These simulation results imply that the direction of the PPT legacy impacts on NEP can be inferred from previous PPT conditions: a previous drier condition may foster more C sequestration in a current wet period/year and a previous wetter condition may cause more C
release in a current dry period/year.

In projecting future dryland C dynamics, the effects of PPT legacies increase the complexity of ecosystem responses to PPT variability. One consistent interaction between legacy and current PPT effects was that based on the eddy covariance measured NEP, Scott et al. (2009) found that the mesquite savanna ecosystem was a net CO$_2$ source during the four below-average-rainfall years from 2004 through 2007. They ascribed the net release of C by the system to the cool-GS drought, but also suspected that the system was likely “burning off” much of the C sequestered during the previous wet period (~1975-1995) (Scott et al., 2009). Our simulation results of the positive wet legacy effects on SOM and negative effects on NEP (Fig. 4e, e) support this hypothesis that the accumulated SOM during the previous wet period (Fig. 5e, f) contributed to the C released during the current dry period. We also found that larger between-period/year PPT differences could result in larger legacy effects (Fig. 4 and Fig. 7), which is in agreement with what have been found in some field studies. For example, the magnitude of drought legacy on ANPP is proportional to the severity of the drought (Yahdjian and Sala, 2006; Swemmer et al., 2007), and dry- or wet-year legacies on ANPP are linearly related to the PPT difference between years (Sala et al., 2012; Reichmann et al., 2013a). Our simulation analysis detected that not only annual PPT amount but also finer scale PPT characteristics such as GS-rainfall, BEI, and event size could be important in determining the interannual-scale PPT legacy effects (Table 1). These simulation results suggest that PPT legacy effects may play a more important role in shaping the temporal variability of dryland ecosystem C fluxes under the projected increase in future PPT variability (Solomon et al., 2007;
Cook and Seager, 2013) but that their characterization remains a challenge.

The influence of PPT legacies to dryland ecosystem C balance may strongly interact with other sources of variability in dryland C balance including current year PPT. Evidence suggests that dryland ecosystems are commonly thought to be a C sink in wet years, a C source in dry years, and C neutral in normal years (Flanagan et al., 2002; Hastings et al., 2005). While recent studies have shown the importance of other factors including growing season length (Xu and Baldocchi, 2004; Ma et al., 2007), seasonal drought (Scott et al., 2009; Scott et al., 2010; Hamerlynck et al., 2013), and other factors such as temperature and vegetation composition (Hui et al., 2003; Hamerlynck et al., 2010; Barron-Gafford et al., 2012; Scott et al., 2014). Our simulation results indicate that PPT legacies may also have important consequences to dryland ecosystem C dynamics balance. These interactions are shown by several examples from our simulations. For example, while PPT was wetter than normal in 1987 \((537 \text{ mm})\) with the SPI of 1.21, but with the simulated NEP of \(-85 \text{ g C m}^{-2} \text{ yr}^{-1}\) (a C source), due to the negative wet legacy impacts on NEP from several previous wet years before \((1982-1985); \text{ see Fig. 6h})\). PPT was nearly normal in 2008 \((402 \text{ mm})\) with the SPI of 0.09, but with the simulated NEP of \(79.680 \text{ g C m}^{-2} \text{ yr}^{-1}\) and the observed NEP of \(69.2 \text{ g C m}^{-2} \text{ yr}^{-1}\) (a C sink), again due to the positive dry legacy impacts on NEP from several previous dry years \((2002-2007); \text{ see Fig. 6g})\). Our findings of substantial PPT legacy effects are consistent with In a recent analysis of 14 years (1997-2011) of eddy covariance measurements, where Zielis et al. (2014) reported that inclusion of previous year’s weather (PPT and temperature) into the linear predicting models for NEP increased the explained variance to 53% compared to 20%
without accounting for previous year’s weather, indicating that previous year’s weather also
played an important role in determining the C balance of the Switzerland subalpine spruce forest.
Although we compared some response patterns generated from this simulation study compared
well with those derived from previous field observations, there exists no field study that, to our
knowledge, is comparable to our simulation experiment to allow us conducting a direct
comparison between the simulated and observed responses provides a similarly comprehensive
analysis of PPT legacies. The simulation experimental design of this study may provides
helpful insights into designing field manipulative experiments to further test the modeled
patterns by focusing on contrasting wet and dry legacies, separating ecosystem production and
decomposition, and exploring the difference in prior and current PPT on the magnitude of the
PPT legacy effect.

4.2 Potential mechanisms of the modeled PPT legacies

There are three basic mechanisms explaining why PPT legacy impacts can occur in the-a
model system like PALS. First, the rate of C fluxes is a function of not only various influential
environmental factors (e.g. PPT and temperature) but also the pool size itself. For example, soil
heterotrophic CO2 efflux (R_h) rate is a product of the decomposition coefficient, the size of the
SOM pool, and two scalar functions accounting for temperature and moisture influences, and
also the size of the SOM pool (Kemp et al., 2003; Shen et al., 2009). Therefore, the Changes in
altered the SOM pool size from previous PPT changes can thereby affects current R_h. Second,
different C pools have different turnover rates that determine whether biogeochemical materials
(e.g. biomass or SOM) can be carried over. If the resources-material (e.g., water, biomass and SOM) produced in a previous legacy year has a turnover rate less than one year, then it would not be carried over to the next year to form a legacy impact. If the resources-material due to slower turnover rate, the resources may be carried over to the current year and influence the C fluxes as explained in the first mechanism. In addition, the turnover rates of different C pools also determine legacy duration. For example, SOM pools in the model have relatively slower turnover rates than biomass pools (Shen et al., 2005; Shen et al., 2008b), thus resulting in the longer-lasting legacy impacts on SOM than on biomass or litter pools (Fig. 5). Third, the interactions between C, N, and H2O availability also determine the direction and magnitude of legacy effects. For example, N carryover as a legacy of a prior dry period (Fig. 5g, h) can impose impacts on the current-period GEP only when the current-period PPT is not so limiting (Fig. 3b). It would have impose little or no legacy impacts on GEP when the current-period PPT is limiting (Fig. 3a). C, N and H2O cycling processes are closely coupled in the PALS model. Carried over resources (e.g., C and N) can therefore interact with current PPT conditions to influence the responses of current fluxes. Based on these are the general model-mechanisms explaining the occurrence of the modeled PPT legacies from a systems perspective. Below we discuss more specifically on the major responsive patterns of response and the responsible biogeochemical carryovers found in this study.

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

The carryover of soil N (N_{soil}) is mainly responsible for the modeled GEP responses. In the PALS model, the photosynthetic rate is linearly related to N availability if plant N demand is not fulfilled (Reynolds et al., 2004; Shen et al., 2005). Therefore, the enhanced N_{soil} as from dry legacies (Fig. 5g, h and Fig. 7g, h) therefore generated resulted in the mostly positive responses of GEP (Fig. 3a, b and Fig. 6c). Conversely, the reduced N_{soil} by wet legacies (Fig. 5g, h and Fig. 8g, h) resulted in the mostly negative responses of GEP (Fig. 3a, b and Fig. 6d). The simulated dry legacies increased N_{soil} mainly through decreasing PPT suppressed plant growth (e.g., the reduced biomass and litter production shown in Fig. 5 and Fig. 7) and therefore limited N uptake. This, which is consistent with many field measurements that N_{soil}
accumulates under drought conditions (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). Although diverse mechanisms of inorganic N accumulation during dry periods have been proposed in field studies, such as including the diffusion restriction of N ions in thin water films of dry soil, the reduced N immobilization by microbial growth and plant uptake, and the reduced N loss from the soil via leaching (Yahdjian et al., 2006), our simulation results suggest that reduced plant uptake might be the main contributor to the $N_{\text{soil}}$ accumulation during dry periods. Given the accumulated $N_{\text{soil}}$ as a dry legacy, how ecosystem C fluxes such as GEP respond to this dry legacy may be influenced by current PPT conditions. If current PPT conditions were favorable (e.g., the increasing current-period PPT treatment shown in Fig. 3b and the relatively wet years shown in Fig. 6c), GEP responded mostly positively with to the dry legacy (or the accumulated N) because both N and $H_2O$ availabilities were favorable for plant growth (or GEP). Contrastingly, if current PPT conditions were unfavorable (e.g., the decreasing current-period PPT treatment shown in Fig 3a and the relatively dry years shown in Fig. 6c), the GEP responses could become negative because of the constrained plant growth and the reduced biomass in previous dry years (see Fig. 5c and Fig. 7b).

Similarly, the mostly negative responses of GEP to wet legacies (or increasing previous PPT, see Fig. 3a, b and Fig. 6d) can be explained by the reduced $N_{\text{soil}}$ from wet legacies (Fig. 5g, h and Fig. 7g, h). The decrease of $N_{\text{soil}}$ with increasing PPT in the PALS model is mainly attributed to the increases in plant N uptake and the N leaching loss that is calculated as a linear function of PPT amount (Shen et al., 2005). Also similar to our simulation results, several field studies...
found that N uptake increases and N$_{\text{soil}}$ decreases under wet conditions in dryland ecosystems (McCulley et al., 2009; McCalley and Sparks, 2009; Yahdjian and Sala, 2010; Reichmann et al., 2013b). However, contrary to our model assumption that N leaching loss is greater in wet than in dry years, some recent field studies reported that the N leaching loss actually is higher in dry than in wet years or at wet sites (McCulley et al., 2009; Evans et al., 2013; Reichmann et al., 2013b; Homyak et al., 2014), resulting in a more “open” N cycle under drier conditions.

Given that these recent field study results are also true for our semidesert savanna ecosystem, the model assumption could potentially cause an overestimation of N$_{\text{soil}}$ carryover effects as shown in Fig. 3 and Fig. 6. But we do not have no observational supports at our study site to specifically justify the model assumption.—Further studies are needed to discriminate the relative contributions of different N processes (e.g., plant uptake, microbial immobilization and mineralization, denitrification, ammonia volatilization, and leaching) to the dynamics of soil inorganic N pools. Nevertheless, this simulation analysis highlights the importance of interactions between N and H$_2$O availabilities in creating the legacy impacts of precipitation PPT and in shaping the temporal variability of dryland ecosystem C fluxes.

The N enhancement as dry legacies also explains why the simulated dry legacy impacts on NEP were positive (Fig. 3e, f and Fig. 6g), particularly under the circumstance of the dry-to-wet period/year transition (Fig. 4e, Fig. 7e). The N$_{\text{soil}}$ carried over from the previous dry period/year and the current wetter conditions ameliorated both the N and H$_2$O limitations on GEP, therefore resulted in more C sequestration in the current period/year—

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

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

5 Conclusions

Through this simulation analysis, we learned that previous PPT conditions can impose substantial legacy impacts on the C balance of dryland
ecosystems, with dry legacies fostering more current C sequestration and wet legacies causing more current C release; ii) the responses of ecosystem C fluxes to the simulated dry and wet legacies are mostly opposite in direction and asymmetrical in magnitude, with dry legacies being greater for GEP than for $R_e$ and wet legacies being greater for $R_e$ than for GEP; iii) the carryover of $N_{soil}$ is mainly responsible for the GEP responses, and the carryovers of biomass, litter and SOM are mainly responsible for the $R_e$ responses; and iv) the simulated PPT legacy effects can last for several years even with a one-year PPT change and therefore the direction and magnitude of interannual PPT legacy effects are less predictable at interannual than at interdecadal scales. These simulation results imply that dryland ecosystems such as these in southwestern US and likely other dryland regions may emit more C that was sequestered in the past into the atmosphere with the predicted decreasing drying trends in future PPT amount the region (Seager et al., 2007; Solomon et al., 2007) dryland ecosystems in southwestern US may emit more C that was sequestered in the past into the atmosphere. With the projected more extreme and variable PPT regime (Seager et al., 2007; Solomon et al., 2007; Diffenbaugh et al., 2008), the temporal variability of ecosystem C fluxes may be further intensified in the region due to the increasing PPT variability and the associated legacy impacts. While this simulation analysis mainly addressed the PPT legacy impacts on dryland ecosystem C fluxes from a biogeochemical perspective, structural shifts in vegetation composition such as woody plant encroachment (Potts et al., 2008; Scott et al., 2014) exotic species invasion (Hamerlynck et al., 2010; Scott et al., 2010), and changes in microbial communities (de Vries et al., 2012; Evans and Wallenstein, 2012; Collins et al., 2014), may also interact with the
biogeochemical processes to shape the PPT legacy effects on the temporal variability of dryland C-fluxes. Future studies incorporating both the structural and biogeochemical aspects and involving multiple temporal scales are needed in order to achieve a more comprehensive understanding of the PPT legacy effects on dryland ecosystem C-dynamics.

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<table>
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<tr>
<th>Precipitation characteristics</th>
<th>ΔGEP</th>
<th>ΔR&lt;sub&gt;c&lt;/sub&gt;</th>
<th>ΔNEP</th>
<th>ΔGEP</th>
<th>ΔR&lt;sub&gt;c&lt;/sub&gt;</th>
<th>ΔNEP</th>
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<tr>
<td><strong>Previous-year PPT characteristics</strong></td>
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<tr>
<td>Yearly rainfall - SPI</td>
<td>ns0.134</td>
<td>ns0.033</td>
<td>0.560&lt;sup&gt;2&lt;/sup&gt;0.270</td>
<td>-0.545&lt;sup&gt;2&lt;/sup&gt;32</td>
<td>ns-0.180</td>
<td>-0.252&lt;sup&gt;2&lt;/sup&gt;374</td>
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<tr>
<td>Warm-GS SPI rainfall</td>
<td>ns0.303</td>
<td>ns0.072</td>
<td>0.579&lt;sup&gt;5&lt;/sup&gt;19&lt;sup&gt;**&lt;/sup&gt;</td>
<td>ns-0.430&lt;sup&gt;**&lt;/sup&gt;</td>
<td>ns-0.065</td>
<td>-0.626&lt;sup&gt;5&lt;/sup&gt;79&lt;sup&gt;**&lt;/sup&gt;</td>
</tr>
<tr>
<td>Yearly-Warm-GS</td>
<td>ns-0.069</td>
<td>ns0.137</td>
<td>-0.442&lt;sup&gt;3&lt;/sup&gt;99&lt;sup&gt;*&lt;/sup&gt;</td>
<td>-0.446&lt;sup&gt;2&lt;/sup&gt;97</td>
<td>ns0.053</td>
<td>-0.636&lt;sup&gt;2&lt;/sup&gt;262</td>
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<tr>
<td>NE&gt;10 mm BEI</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm-GS NE&gt;10 mm</td>
<td>ns0.329</td>
<td>ns0.067</td>
<td>0.445&lt;sup&gt;6&lt;/sup&gt;36&lt;sup&gt;**&lt;/sup&gt;</td>
<td>ns-0.535&lt;sup&gt;5&lt;/sup&gt;</td>
<td>ns-0.227</td>
<td>-0.575&lt;sup&gt;6&lt;/sup&gt;19&lt;sup&gt;**&lt;/sup&gt;</td>
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<td><strong>Current-year PPT characteristics</strong></td>
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<tr>
<td>Yearly SPI rainfall</td>
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<td>ns0.162</td>
<td>ns0.484&lt;sup&gt;*&lt;/sup&gt;</td>
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<td>-0.467&lt;sup&gt;6&lt;/sup&gt;00</td>
<td>ns-0.224</td>
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<tr>
<td>Warm-Cool-GS</td>
<td>ns0.528&lt;sup&gt;**&lt;/sup&gt;</td>
<td>ns0.338</td>
<td>ns0.495&lt;sup&gt;*&lt;/sup&gt;</td>
<td>ns-0.277</td>
<td>-0.399&lt;sup&gt;3&lt;/sup&gt;51</td>
<td>ns-0.218</td>
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<td>SPI rainfall</td>
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<tr>
<td>Yearly BEI</td>
<td>ns-0.512&lt;sup&gt;**&lt;/sup&gt;</td>
<td>ns-0.285</td>
<td>ns-0.686&lt;sup&gt;**&lt;/sup&gt;</td>
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<td>ns0.255</td>
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<td>Cool-GS BEI</td>
<td>-0.519&lt;sup&gt;**&lt;/sup&gt;</td>
<td>-0.286</td>
<td>-0.510&lt;sup&gt;**&lt;/sup&gt;</td>
<td>0.151</td>
<td>0.088</td>
<td>0.214</td>
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<tr>
<td></td>
<td>Yearly NE&gt;10 mm</td>
<td>Cool-GS NE&lt;10 mm</td>
<td>PPT difference (APPT) between current- and previous-year</td>
<td></td>
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<tr>
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<td>ns=0.331</td>
<td>ns=0.178</td>
<td>ns=0.512**</td>
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<td>ns=0.583*</td>
<td>ns=0.398*</td>
<td>ns=0.394567*</td>
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<td></td>
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<td>ns=0.577**</td>
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<td>ns=0.398*</td>
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</tbody>
</table>

**PPT difference (APPT) between current- and previous-year**

<table>
<thead>
<tr>
<th></th>
<th>Yearly rainfall</th>
<th>Warm-GS rainfall</th>
<th>Cool-GS rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.088</td>
<td>-0.059</td>
<td>0.326</td>
</tr>
<tr>
<td></td>
<td>-0.135</td>
<td>-0.042</td>
<td>0.048</td>
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<tr>
<td></td>
<td>0.466*</td>
<td>0.074</td>
<td>0.374*</td>
</tr>
<tr>
<td></td>
<td>0.078</td>
<td>0.206</td>
<td>0.248</td>
</tr>
<tr>
<td></td>
<td>-0.088</td>
<td>-0.096</td>
<td>0.160</td>
</tr>
<tr>
<td></td>
<td>0.252</td>
<td>0.326</td>
<td>0.209</td>
</tr>
</tbody>
</table>

Abbreviations: PPT: precipitation; SPI: standard precipitation index; GEP: gross primary production; \( R_e \): ecosystem respiration; NEP: net ecosystem production; GS: growing season; BEI: between-event interval; NE: number of rainfall events. * and ** Correlations are significant at the 0.05 and 0.01 levels (2-tailed), respectively; ns – not significant.
**Figure captions**

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

**Figure 2.** Comparison of the model-simulated water and carbon fluxes with the eddy covariance observations at the mesquite savanna site. Left panels show the comparison between the modeled and observed fluxes in four calibration (2007-2007; solid dots) and three validation years (2008-2010; open dots). Seasonal and annual fluxes (2004-2007) used for model calibration. Right panels show the relationships of the simulated (solid dots) and observed (open dots) fluxes with precipitation in the seven years seasonal and annual fluxes used for model validation. \( R^2 \) is the coefficient of determination describing the proportion of the variance in measured fluxes explained by the model for the left panels or
that explained by precipitation for the right panels. CS represents the cool season from Oct to Mar and WS the warm season from Apr to Sep. AET represents actual evapotranspiration; GEP gross ecosystem production, $R_e$ total ecosystem respiration, and NEP net ecosystem production.

**Figure 3.** Interdecadal legacy effects of changing the previous-period (1981-1994) precipitation on the cumulative carbon fluxes of the current period (1995-2010). Interdecadal legacy effects on carbon fluxes (e.g. $\Delta$NEP) are calculated as the difference between the current-period flux with previous-period PPT changes and that without previous-period PPT changes. Dashed lines with open symbols represent different levels of decreasing (left panels) the current-period precipitation (left panels)(PPT). Solid lines with filled symbols represent increasing (right panels) the current-period precipitation (right panels).

**Figure 4.** Spearman correlations of interdecadal precipitation legacy effects with the precipitation difference between periods ($\Delta$PPT). Interdecadal $\Delta$PPT is calculated as the mean PPT of the current period (1995-2010) minus that of the previous period (1981-1994). Interdecadal legacy effects on carbon fluxes (e.g. $\Delta$NEP) are calculated as the difference between the current-period flux with previous-period PPT changes and that without previous-period PPT changes. Sample size is 41 for the wet-to-dry period transition (left panels) and 23 for the dry-to-wet period transition (right panels). GEP represents gross ecosystem production, $R_e$ ecosystem respiration, and NEP net ecosystem production. $R^2$ is the coefficient of determination and $P$ is probability.
Figure 5. Interdecadal precipitation legacy effects on the resource pool dynamics. Left panels show the resource pool responses under a 30% of decrease while right panels show those under a 30% of increase in the precipitation (PPT) of the current period from 1995-2010. Legacy effects on pool size (e.g. ΔBiomass) are quantified as the difference between the current-period pool size with previous-period PPT change and that without previous-period PPT change. Dashed lines represent a 30% of decrease while solid lines represent a 30% of increase in the precipitation PPT of the previous period from 1981-1994. SOM represents soil organic matter, N$_{soil}$ soil mineral nitrogen, and SWC soil water content.

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

Figure 7. Spearman correlations of interannual precipitation legacy effects with the
precipitation difference between years ($\Delta$PPT). Interannual $\Delta$PPT is calculated as current year PPT minus previous year PPT. Sample size is 26 for the wet-to-dry year transition (left panels) and 27 for the dry-to-wet year transition (right panels). GEP represents gross ecosystem production, $R_e$ ecosystem respiration, and NEP net ecosystem production. $R^2$ is the coefficient of determination and $P$ is probability.

**Figure 78.** Interannual precipitation legacy effects on resource pool dynamics. Left panels show the legacy effects on pool dynamics in two representative wet years while right panels for two representative dry years. Legacy effects on pool size (e.g., $\Delta$Biomass) are quantified as the difference between the current-year pool size with previous-year PPT change and that without previous-year PPT change. Solid lines represent a 30% decrease while dashed lines represent a 30% increase in the previous-year precipitation (PPT). SOM represents soil organic matter, $N_{soil}$ soil mineral nitrogen, and SWC soil water content.
FIG. 1

(a) Annual precipitation (mm)

(b) Frequency of daily rainfall

(c) Rain event interval (day)

(a) Warm-GS SPI
-2 -1 0 1 2
Warm-GS rainfall (mm)
0 100 200 300 400

(b) Cool-GS SPI
-3 -2 -1 0 1 2
Cool-GS rainfall (mm)
0 50 100 150 200

(c) Yearly SPI
-2 -1 0 1 2 3
Annual rainfall (mm)
200 300 400 500 600 700 800

SPI Rainfall
FIG. 2

(a) Simulated AET (mm)

(b) Simulated GEP (g C m\(^{-2}\))

(c) Simulated \(R_e\) (g C m\(^{-2}\))

(d) Simulated NEP (g C m\(^{-2}\))

(e) Observed AET (mm)

(f) Observed GEP (g C m\(^{-2}\))

(g) Observed \(R_e\) (g C m\(^{-2}\))

(h) Observed NEP (g C m\(^{-2}\))

\(R^2\) values:
- AET: 0.9075
- GEP: 0.9744
- \(R_e\): 0.9928
- NEP: 0.8236

Precipitation (mm)

200 240 280 320 360 400 440

Simulated values:
- AET: 240 280 320 360 400 440
- GEP: 0 200 400 600 800 1000
- \(R_e\): 100 200 300 400 500 600 700 800
- NEP: -160 -120 -80 -40 0 40 80 120

Observed values:
- AET: 240 280 320 360 400 440
- GEP: 100 200 300 400 500
- \(R_e\): 200 300 400 500 600 700 800
- NEP: -160 -120 -80 -40 0 40 80 120
FIG. 3

(a) Current-period PPT change:
-80%
-50%
-30%
-10%
0%

(b) Current-period PPT change:
+80%
+50%
+30%
+10%
0%

(c) 

(d) 

(e) 

(f) 

Previous-period PPT change (%)
FIG. 4

(a) δGEP (g C m$^{-2}$) vs. ΔPPT (mm), R$^2$=0.228, P=0.346

(b) δPPT (mm) vs. NEP (g C m$^{-2}$), R$^2$=0.702, P<0.001

(c) δR$e$ (g C m$^{-2}$) vs. ΔPPT (mm), R$^2$=0.251, P=0.001

(d) δPPT (mm) vs. R$e$ (g C m$^{-2}$), R$^2$=0.638, P<0.001

(e) δNEP (g C m$^{-2}$) vs. ΔPPT (mm), R$^2$=0.505, P<0.001

(f) δPPT (mm) vs. δNEP (g C m$^{-2}$), R$^2$=0.340, P=0.004

Wet-to-dry period transition

Dry-to-wet period transition

R$^2$=0.702
P<0.001

R$^2$=0.638
P<0.001

R$^2$=0.505
P<0.001

R$^2$=0.340
P=0.004
FIG. 5

Current-period PPT -30%  Current-period PPT +30%

(a) Previous-period PPT:  (b) Previous-period PPT:
-30% -30%
+30% +30%

(c)  

(d)  

(e)  

(f)  

(g)  

(h)  

(i)  

(j)  

Previous-period PPT:  
Current-period PPT -30%
Current-period PPT +30%

Year  

Year  

1995  1997  1999  2001  2003  2005  2007  2009  

1995  1997  1999  2001  2003  2005  2007  2009

1061  1063  1065
FIG. 6

Previous-year PPT -30%

(a) Legacy duration (yr)

(b) Legacy duration (yr)

(c) ΔGEP (g C m$^{-2}$)

(d) ΔGEP (g C m$^{-2}$)

(e) ΔR (g C m$^{-2}$)

(f) ΔR (g C m$^{-2}$)

(g) ΔNEP (g C m$^{-2}$)

(h) ΔNEP (g C m$^{-2}$)

Year

Previous-year PPT +30%

Year
Wet-to-dry year transition

Dry-to-wet year transition

(a) 
(b) 
(c) 
(d) 
(e) 
(f) 

$\Delta GEP (gC m^{-2} yr^{-1})$

$\Delta R (gC m^{-2} yr^{-1})$

$\Delta \text{NEP} (gC m^{-2} yr^{-1})$

$R^2=0.162$

$P=0.041$

$R^2=0.386$

$P=0.001$