Impacts of elevated CO_2, climate change and their interactions on water budgets in four different catchments in Australia

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Abstract: Future water availability is affected directly by the effects of climate change on water loss through evapotranspiration (ET) and indirectly via the biological effects of climate change and higher atmospheric CO_2 concentration on plant function. While previous studies of future water availability have considered the direct effects of climate change; few considered the indirect biological effects or the interactions between direct and indirect impacts. In this study, we calibrated an ecohydrological model (WAVES) and used this model to estimate the direct and indirect effects and their interactions of future climate change and elevated CO_2 (eCO_2) on water availability in four different catchments in Australia with contrasting climate regime and vegetation cover. These catchments were: a water-limited forest catchment and an energy-limited forest catchment, a water-limited grass catchment and an energy-limited grass catchment. The future meteorological forcing from 12 GCMs representing a period centred on 2050s was projected and then downscaled to the study catchments. The future CO_2 concentration (i.e., eCO_2) at 2050 was projected to be 550ppm. Results from this study show eCO_2 increases canopy leaf area index (LAI) in all four catchments and increases ET and decreases runoff in the water limited forest catchment and the two grassland catchments, but reduces ET and increases runoff in the energy-limited forest catchment. The effects of future climate on canopy LAI, ET and total runoff were opposing in sign to those of eCO_2 for all four catchments. Our results also suggest that the interactions between the direct and indirect effects on ET are relatively strong in the two grassland catchments but relatively weak in the two forest catchments, possibly because the deep-rooted forest system can utilize more available soil water than grasslands. Interactions on runoff were relatively strong in the two water-limited catchments but weak in the two energy-limited catchments, possibly because ET in the water-limited ecosystems are mainly constrained by water and arid ecosystems have higher water use efficiency. This study highlights that failure to account for impacts of eCO_2 or its interactions with climate change can introduce significant bias into the predictions of future water budgets, especially for the water-limited catchments in Australia.

Key words: elevated atmospheric CO_2 concentration; carbon-water coupling relationship; changing climate; water balance; physiological effects.

1 Introduction

Climate change is predicted to shape new hydroclimatic regimes in many regions of the world (Ramanathan et al., 2001; Dore, 2005; Dai, 2013), and will have significant impacts on water availability (Milly et al., 2005; Bates et al., 2008; Milly et al., 2008). Recent observational studies have shown that elevated atmospheric CO_2 concentration (denoted as eCO_2) may have significant implications for water availability through its physiological effects on plant function associated with the increased water-use-efficiency (WUE) (Eamus, 1991; Field et al., 1995; O'Grady et al., 2011). Modelling results at both plot and global scales have shown that changes in WUE may lead to a discernible increase in water availability or runoff (Gedney et al., 2006; Betts et al., 2007; Cao et al., 2010; Warren et al., 2011). Potential increase in water availability under eCO_2 may be particularly important for water-limited regions (Wullschleger et al., 2002), such as Australia (Eamus et al., 2006). However, the physiological effects of eCO_2 on water budget at catchment scales have rarely been addressed (Bates et al., 2008).

At the leaf scale, eCO_2 reduces stomatal conductance and consequently lower transpiration rate per unit leaf area. This is a water saving effect. Thus, if all other factors remain unchanged, eCO_2 should water availability should increase. This leaf-scale effect has been observed in many experimental studies (Eamus and Jarvis, 1989; Norby et al., 1999; Medlyn et al., 2001; Ainsworth and Long, 2005). Several studies showed that runoff increased significantly caused by this leaf-scale physiological effect of eCO_2 (e.g., Aston (1984), Gedney et al. (2006) and Cao et al. (2010)). At stand or regional scales, however, the physiological processes associated with eCO_2 can stimulate plant growth and increase canopy leaf area index (LAI) via two mechanisms. One is via direct CO_2 fertilization effects (Körner et al., 2007); the other is indirectly via increased water availability resulting from reduced stomatal conductance. Increased LAI may offset the effect of the leaf-scale increased WUE on ecosystem water availability and result in little or no change in ecosystem water budgets (Levis et al., 2000). The net effect of eCO_2 on regional water budgets therefore depends on both responses of stomatal conductance and feedbacks of canopy LAI. How the physiological effects of eCO_2 will manifest at catchment scale is poorly understood and likely to vary across different climate regimes and ecosystems (Nowak et al., 2004; Ainsworth and Long, 2005; Körner et al., 2007; Leakey et al., 2012). The magnitude of the feedbacks of LAI is a key determinant of whether eCO_2 will increase runoff and by how much because leaves are the primary exchanging interface of energy, water and carbon of vegetated land (Woodward, 1990; Piao et al., 2007; Bounoua et al., 2010; Norby and Zak, 2011). However, validation of simulated responses of LAI to eCO_2 is not a major focus of most studies (Cowling and Field, 2003), in spite of the fact that nearly all models have parameterized LAI as controls of plant productivity and canopy transpiration.

Future changes in precipitation, temperature and evaporative demand (determined by radiation, humidity, wind speed and temperature) are direct drivers of catchment water yield (Bates et al., 2008). Increased evaporative demand can enhance regional evapotranspiration and decrease runoff. However, both evapotranspiration (ET) and runoff can increase if precipitation increases. Similarly, canopy LAI may be altered by climate change directly by the changes in meteorological forcing (including temperature, radiation and humidity) (Cowling and Field, 2003) and indirectly through the influence of climate change on regional soil water availability (Knapp et al., 2002; Gerten et al., 2008). Changes in canopy LAI induced by climate change can also exert indirect influences on regional water budgets. Future climate change is projected to vary spatio-temporally in both magnitude and direction (IPCC, 2007), thus sensitivities of both vegetation and water budget to climate change may be markedly different across space and time (Milly et al., 2005; Hyvönen et al., 2007; Bonan, 2008). In addition, complex interactions among the influences of both eCO_2 and climate change on canopy LAI and water budget can dampen or amplify the impacts of either individual factor (Cramer et al., 2001; Gerten et al., 2005; Körner et al., 2007), because physiological effects of eCO_2 at regional scale depend on both canopy LAI and meteorological conditions. However, interactions between climate change and eCO_2 on canopy LAI and water budget have rarely been considered and linear combination of the impacts caused by eCO_2 and other environmental drivers was routinely assumed (e.g., Betts et al. (1997), Eckhardt and Ulbrich (2003), Gedney et al. (2006), Piao et al. (2007) and Kruijt et al. (2008)). Sellers et al. (1996) showed that nonlinear interactions between physiological and radiative effects of double CO_2 on plant growth were noticeable and differed across latitudinal gradients. Luo et al. (2008) demonstrated that interactions among changes in temperature, CO_2 and precipitation on carbon and water dynamics are not consistent among different ecosystems. Dieleman et al. (2012) pointed out that combined effects of the eCO_2 and warming on aboveground biomass were usually less than additive effects of single factors.

Quantifying the changes in future water yield due to either eCO_2 and climate change remains a challenge (Huntington, 2008; Luo et al., 2011), and whether interactive effects between eCO_2 and climate change on both canopy LAI and water budgets are negligible in different climatic and vegetation condition needs further investigation (Körner et al., 2007; Leuzinger et al., 2011; Dieleman et al., 2012). Model simulation is a useful approach to elucidate and predict the physiological effects of eCO_2 and interactions with climate change since physiological effects of eCO_2 at regional scale were poorly understood and atmospheric CO_2 content is projected to rise beyond our observation (Luo et al., 2011). General circulation models with sophisticated land surface models have been used to study the eCO_2 effects on water availability globally (e.g., Sellers et al. (1996), Betts et al. (1997), Gedney et al. (2006), Piao et al. (2007), Betts et al. (2007), Gerten et al. (2008), Cao et al. (2010)), however the results of these studies are inconclusive due to their differences in modelling methodology (including physiological processes of eCO_2, model structure and underlying assumptions) (Gerten et al., 2008; Bounoua et al., 2010; De Kauwe et al., 2013) and poor hydrological performances (Wood et al., 2011; Wang and Dickinson, 2012; Zhou et al., 2012). At catchment scales, previous modelling experiments have consistently predicted an increase in runoff in response to eCO_2 with a relative response ranging from less than 10% (Eckhardt and Ulbrich (2003), Kruijt et al. (2008), and Leuzinger and Körner (2010)) to about 90% (Aston, 1984). Many previous studies of eCO_2 at catchment scale suffer from two weaknesses. First, physiological and hydrological processes parameterized in those models were decoupled or loosely coupled (e.g. Eckhardt and Ulbrich (2003)). As a result, nonlinear interactions between canopy LAI and soil water availability under the eCO_2 and climate change conditions cannot be studied systematically (Gerten et al., 2004; De Kauwe et al., 2013). Secondly, modelling was usually carried out for specific climate regime and vegetation cover. Thus results from those studies may not be applicable to other regions (Wullschleger et al., 2002; McMurtrie et al., 2008).

In this study, a coupled water-carbon ecohydrological model WAVES (Zhang et al., 1996) was used to investigate the effects of eCO_2 and its interactions with future climate change on canopy LAI and water budget. Four small catchments in Australia were selected with contrasting vegetation cover and climate regimes. They included a water-limited (mean annual precipitation is less than mean annual potential evaporation, which indicates a dry climate regime) forest catchment and an energy-limited (mean annual precipitation is larger than mean annual potential evaporation, which implies a wet climate regime) forest catchment as well as a water-limited grass catchment and an energy-limited grass catchment. The future meteorological forcing representing 2050s was projected from 12 GCMs of IPCC AR4 with emission scenario A2, and then downscaled to the study catchments. The future CO_2 concentration under emission scenario A2 (i.e., eCO_2) at 2050s is projected to be 550ppm. In particular, this study has four objectives: (1) to demonstrate whether a well-designed water-carbon coupled model can capture the physiological impacts of both eCO_2 and climate change on canopy LAI and their hydrological impacts on catchment water budgets in different typical ecosystems; (2) to assess effects of eCO_2 on canopy LAI and catchment water yield under different climate regimes and vegetation cover in Australia; (3) to estimate whether impacts of eCO_2 on water budgets in vegetated catchments are small enough to be ignored in comparison to the impacts of future climate change; (4) to investigate whether the interactions between eCO_2 and changes in climate forcing are negligible in predicting future canopy LAI and water yield.

2 Method

2.1 Ecohydrological model: WAVES

The WAVES model is designed to simulate the dynamics of energy, water, carbon, and solute balances of the soil–canopy–atmosphere system at a daily time scale (Zhang et al., 1996; Zhang and Dawes, 1998). The WAVES model was chosen because (1) it has a coupled water-energy-carbon modelling structure with a good balance of complexity and accuracy in both hydrological and physiological processes and thus can capture the dynamic coupling of water and carbon fluxes within soil-plant-atmosphere continuum and suitable for this study (Zhang and Dawes, 1998); (2) it has been well-tested and validated in a number of experimental studies (Zhang et al., 1996; Slavich et al., 1999; Zhang et al., 1999; Zhang et al., 1999; Green et al., 2007; Crosbie et al., 2011; Crosbie et al., 2012; Post et al., 2012).

In WAVES, soil water movement in both the unsaturated and saturated zones is simulated by numerically solving the Richards equation using a finite difference method (Ross, 1990; Dawes and Short, 1993). For each soil type, an analytical soil model proposed by Broadbridge and White (1988) is employed to describe the relationships among water potential, volumetric water content and hydraulic conductivity. Evapotranspiration is estimated using the Penman-Monteith approach as described in Monteith and Unsworth (2008). Leaf stomatal conductance is calculated by the equation developed by Ball (1987) and Leuning (1995) and this is then scaled-up to canopy scale using the method proposed by Sellers et al. (1992). The rate of plant growth is estimated by an integrated rated methodology of Wu et al. (1994), which is a function of light, water and nutrient availabilities. The water extracted by roots for transpiration is distributed along the root profile according to the roots density distribution and water availability in each soil nodes following Ritchie et al. (1986). More detailed modeling strategy and descriptions of WAVES are provided in Zhang et al. (1996) and (Zhang and Dawes, 1998).

The WAVES model used in this study has coded CO_2 as a variable within the stomatal conductance and plant growth modules as described in Hatton et al. (1992) and (Zhang and Dawes, 1998). Canopy conductance (g_c) in WAVES is estimated by:

$$g_c = g_0 LAI + \frac{g_1 A_i}{(C_{si} - \Gamma)(1 + D_{ci}/D_{co})} \frac{1 - \exp(-kLAI)}{k} \quad (1)$$

where g_0 is the residual stomatal conductance, g_1 is an empirical coefficient, A_i is the daily carbon assimilation rate, C_{si} is the CO_2 mole fraction of the air at the canopy surface, Γ is the CO_2 compensation point, D_{ci} is the vapour pressure deficit at the canopy surface, D_{co} is an empirical coefficient, LAI is the canopy leaf area index, k is the attenuation coefficient for light. The g_0, C_{si}, D_{co} and Γ were constant and the same for all four catchments, while g_1 and k were calibrated within their physical meaning recommended by (Zhang and Dawes, 1998). The daily assimilation rate A_i was estimated as in Hatton et al. (1992) as following:

$$A_i = A_{\max} \frac{1 + W_2 + W_3 + W_4}{\frac{1}{m_1 x_1} + \frac{W_2}{x_2} + \frac{W_3}{x_3} + \frac{1}{m_4 x_4}} \quad (2)$$

where $A_{\max}$ is the maximum carbon assimilation rate, W_2 is the weighting factor for water relative to light, W_3 is the weighting factor for nitrogen relative to light, W_4 is the weighting factor for CO_2 relative to light, x_1 is the normalized photosynthesis active radiation availability, x_2 is the normalized water availability, x_3 is the normalized nitrogen availability, x_4 is the normalized CO_2 availability, m_1 is the temperature modifier, and m_4 is the vapour pressure modifier. Under eCO_2 condition, the physiological responses of canopy conductance and assimilation rate in WAVES are fully coupled with climatic regulation on stomata and availability of both water and nutrients to roots. In this study, all the weighting factors and normalized availabilities were calibrated within the ranges of their physical meaning as recommended by (Zhang and Dawes, 1998).

2.2 Catchments and data

The four catchments selected were all small with the dominant vegetation cover as either forest or grass. The locations of the four catchments are shown in Figure 1. The energy-limited forest catchment used in this study is a tributary of Bellinger River in the northeast of New South Wales (NSW) with an area about 150 km^2. Mean annual precipitation is 1830 mm, and aridity index (ratio of mean annual potential evapotranspiration and mean annual rainfall) is about 0.7 (Chiew et al., 2009). More than 90% of the catchment area is covered by forest identified from the National Vegetation Information System (NVIS, http://www.environment.gov.au/erin/nvis/index.html). The energy-limited grass catchment used in this study is the Fisher River, upstream of Lake Mackenzie in the north of Tasmania (TAS) with an area of 37.5 km^2. Mean annual precipitation is 1860 mm, and aridity index is about 0.25 (CSIRO, 2009). The vegetation in the Fisher River is dominated by native grass (*ca*. 60%) and sparse shrub and woodlands (30%) (Brown et al., 2006). The topography is plateau with many rock outcrops and chains of lakes. The water-limited forest catchment selected for this study is West Brook upstream of Glendon Brook River in the south-east of the NSW, with an area of 73 km^2. Mean annual precipitation is 750 mm and aridity index is about 1.7 (Zhang et al., 2011). The vegetation cover identified from NVIS is eucalypt tall open forests (41.5%) and eucalypt open forests (58.5%); however, the forests are not dense. The topography of the West Brook is a ridge and valley complex and moderately steep hill slopes, with a mean slope about 6 degrees. The water-limited grass catchment chosen for this study is the Fletcher River at Dromedary of Fitzroy River in the north-west coast of West Australia (WA), with an area of 68.2 km^2. Mean annual precipitation is 1000 mm, and the aridity index is about 2.2. The catchment is completely covered by Hummock Grasslands (100%) identified from NVIS (Department of the Environment and Water Resources, 2007). The detailed descriptions of the climatic, geological and vegetation characteristics of each catchment are presented as following and the basic information are summarized in Table 1.

Insert Table 1 here.

The soil information for each catchment were identified from the Australian Soil Resources Information System (ASRIS, http://www.asris.csiro.au/index_other.html), including soil types, texture, horizons and thickness McKenzie et al. (2000). The depth of different layers was determined by averaged thickness of different horizons. Based on the ASRIS, two soil layers were identified for all the four catchments but with different thickness. The upper and lower layer were 0.3 m and 0.6 m for the energy-limited forest catchment; 0.2 m and 1.0 m for the energy-limited grass catchment; 0.4 m and 0.4 m for the water-limited forest catchment; and 0.4 m and 0.5 m for the water-limited grass catchment. Another clay layer was set underlying these two layers. The total depth of soil column was up to 5.0 m in the two forest catchments and 3.0 m in the two grass catchments. The dominant soil type of each layer was also identified from ASRIS. This dominant soil type was used to determine the initial soil parameters.

The meteorological data needed to run the WAVES model included daily precipitation, daily maximum and minimum temperature, daily vapour pressure deficit, daily rainfall duration, and daily solar radiation. Daily precipitation, daily maximum and minimum temperature were obtained from the "SILO Data Drill" of the Queensland Department of Natural Resources and Water (http://www.longpaddock.qld.gov.au/silo/) (Jeffrey et al., 2001). The daily vapour pressure deficit and solar radiation are estimated according to daily temperature measurements following (Kimball et al., 1997) and (Thornton and Running, 1999). Observed streamflow data were collected from different studies and projects to calibrated model. The leaf area index (LAI) data of each catchment were obtained from MODIS Land Product Subsets (MOD15A2, Collection 5) (http://daac.ornl.gov/MODIS/modis.shtml) with a quadrate of 7×7 km on the centre of catchment. The Savitzky-Golay filtering method was employed to smooth the raw LAI derived from MOD15A2 combined with quality control data using TIMESET (Jönsson and Eklundh, 2004). The smoothed mean LAI time series of each catchment from 2000 to 2005 is shown Figure 4.

2.3 Future meteorological forcing data

The 12 GCMs used in this study are listed in Table S1 in the auxiliary material. These GCMs were selected because projections of them performed better than others compared with historical climate of Australia (Crosbie et al., 2011; Vaze et al., 2011). Four meteorological variables were projected to represent future climatic conditions centred on 2050 (2040-2060) including precipitation, daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), and solar radiation. The constant scaling method proposed by Santer et al. (1990) (also called the delta or perturbation method) was used to downscale GCM outputs to future daily time series for the study catchments. This method generates future climate time series by scaling observed historical time series with constant scaling factors, which are estimated from the historical observed time series and projected time series. Constant scaling factors of each variable were estimated at seasonal time-scales of each GCM. Three global warming scenarios (low, median, and high), which indicate different rate of climate change, were applied to provide a range of possibilities of future change.

Future precipitation and radiation at a specific day (x'_n) were estimated using equation 3a, and future daily maximum and minimum temperature at a specific day (x'_n) were estimate in terms of equation 3b.

$$x'_n = x_n\left(1 + t_k f_{i,j}/100\right) \tag{3a}$$

$$x'_n = x_n + t_k f_{i,j} \tag{3b}$$

where x_n and x'_n are observed and projected climatic variables at a specific date *n*; t_k (°C) is waring temperature of *k*-th global warming scenario (1 ≤ *k* ≤ 3, i.e., low, median and high); $f_{i,j}$ is constant scaling factor of *i*-th season (1 ≤ *i* ≤ 4, i.e., spring, summer, autumn and winter) of *j*-th GCM (1 ≤ *j* ≤ 12), $f_{i,j}$ is in %/°C (percentage change per degree Celsius of global warming) for precipitation and radiation and in °C/°C (degree Celsius increases per degree Celsius of global warming) for maximum and minimum temperature. According to the IPCC projections (CSIRO and BoM, 2007), low, median and high global warming scenarios were 0.84°C, 1.4°C and 2.24°C, respectively. Thus, 36 scenarios are assembled for each catchment and daily pattern of scaled time series were kept the same as observed series.

The seasonal scaling factors (or changes) of four meteorological variables from 12 GCMs are shown in Figure S1 in auxiliary materials. The climatic changes derived in this study are all in close agreement with previous estimates by CSIRO and BoM (2007). Assemble mean change in precipitation and potential evaporation (using Priestley and Taylor (1972)) are shown in Figure 2 in terms of the four projected meteorological variables. Precipitation was projected to increase in the water-limited forest catchment only about 1.0%. Precipitation decreased by about 1.5%, 5% and 1% in energy-limited forest catchment, energy-limited grass catchment and water-limited grass catchment, respectively. Potential evaporation was increased in all the four catchments. It increased about 5% in the energy-limited grass catchment and approximately 2% in other three catchments.

Insert Figure 2 here.

2.4 Parameter estimation

For the two forested catchments, both overstorey and understorey were considered. The overstorey layer is dominated by tall eucalyptus trees at two sites. The understorey layer includes grass and/or liana, and it was treated as a perennial C3 grass layer. For the two grass catchments, only one vegetation layer was considered. The vegetation was set as C3 perennial grass in the energy-limited catchment and as C4 annual grass in the water-limited grass catchments. For each vegetation type, there are 26 vegetation parameters used in representing the physiological and phenological processes of plant growth in WAVES. The vegetation parameters include canopy albedo, soil albedo, rainfall interception coefficient, light extinction coefficient, maximum plant available soil water potential, *etc*.

Some vegetation parameters and all the soil parameters were further optimised by minimizing the differences between modelled and observed streamflow data and smoothed MODIS LAI data together using the shuffled complex evolution (SCE-UA) method (Duan et al., 1992). The calibrated vegetation parameters include rainfall interception coefficients, maximum carbon assimilation rate, specific leaf area, respiration coefficient of leaf and root, leaf mortality rate and aerodynamic resistance. Previous study found that all these parameters have significant influences on the simulated plant-water interactions in WAVES (Zhang and Dawes, 1998). All the calibrated parameters were allowed to vary within their ranges as recommended by Dawes et al. (1998). Both bias and Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) were incorporated into the objective function of the SCE-UA method as in Viney et al. (2009) to quantify the dynamic and systematic differences between simulated and observed streamflow and LAI series to identify optimal soil and vegetation parameters.

2.5 Modeling experiments

For a catchment, runoff (R) is influenced by climate (M) and atmospheric CO_2 (C):

$$R = f(M, C) \tag{4}$$

Using Taylor approximation, changes in runoff at catchment scales under future climate (ΔR_M) or increased CO_2 (ΔR_C), or both climate and increased atmospheric CO_2 (ΔR_{MC}) can be expressed as:

$$\Delta R_M \approx \frac{\partial f}{\partial M}\Delta M + \frac{1}{2!}\frac{\partial^2 f}{\partial M^2}\Delta M^2 + \cdots + \frac{1}{n!}\frac{\partial^n f}{\partial M^n}\Delta M^n \quad (5a)$$

$$\Delta R_C \approx \frac{\partial f}{\partial M}\Delta C + \frac{1}{2!}\frac{\partial^2 f}{\partial M^2}\Delta C^2 + \cdots + \frac{1}{n!}\frac{\partial^n f}{\partial M^n}\Delta C^n \quad (5b)$$

$$\Delta R_{MC} \approx \Delta R_M + \Delta R_C + \underbrace{\frac{\partial^2 f}{\partial C \partial M}\Delta C \Delta M + \cdots}_{interactions} \quad (5c)$$

where ΔM is change in climate and ΔC is change in CO_2. The first two terms in equation 5c, which are Equation 5a and 5b, represent sensitivities of runoff to changes in climate forcing and CO_2, respectively. The rest of the terms in equation 5c represent interactions between *M* and *C*. Changes in evapotranspiration (ET) and LAI can also be estimated using equations similar to (5) as they are both influenced by climatic and CO_2.

Four modelling experiments with different climate forcing and CO_2 were designed to investigate the impacts exerted by future climate change (ΔM) and eCO_2 (ΔC). Basic descriptions of the modelling experiments are listed in Table 2.

Insert Table 2 here.

As shown in Table 2, Experiment 1 (Expt1) was used as the baseline for assessing the impacts of changes in climate and atmospheric CO_2 concentration on canopy LAI and catchment water budget. Experiment 2 (Expt2) was the same as Expt1 except CO_2 concentration was increased to 550 ppm, a level similar to most FACE experiments. Experiment 3 (Expt3) was designed to quantify the impact of change in climatic conditions. Expt3 is similar to most assessments of the climatic impacts on water resources studies. Experiment 4 (Expt4) considers the effects of both future atmospheric CO_2 concentration and climatic conditions. The differences between Expt2 and Expt1 represent the sensitivity to eCO_2, which stands for ΔR_C (namely equation 5a and the first approximation term in equation 5c). The differences between Expt3 and Expt1 represent the sensitivities to future climate change, which corresponds to ΔR_M (namely equation 5b and the second approximation term in equation 5c). The differences between Expt4 and Expt1, which stands for ΔR_{MC}, include not only the sensitivities to both climate change and eCO_2 but also interactions between two drivers (i.e., interaction terms in equation 5c).

3 Results

3.1 Model calibration over baseline period: Results of Expt1

The WAVES model was calibrated over the baseline period using observed daily streamflow and 8-day MODIS LAI. Model simulations, i.e. Expt1, are for current CO_2 and climate conditions (1995 ~ 2006). Modelled monthly runoff agrees well with the observations for all four catchments using the optimized parameters (see Figure 3). The slope between modelled and observed monthly runoff is not statistically significant different from 1 for the two grassland catchments and wet forest catchment, but is greater than 1 for the dry forest catchment. Therefore our model tends to overestimate the monthly runoff for the dry forest catchment. Nash-Sutcliffe efficiencies of simulated monthly streamflow with optimal parameters were 0.89, 0.66, 0.74 and 0.70, and biases of water balance were −12.4%, −1.2%, −0.3%, and −2.4% for energy-limited forest, water-limited forest, energy-limited grass, and water-limited grass catchments, respectively.

Insert Figure 3 and 4 here.

Figure 4 shows that the 8-day variation of canopy LAI modelled by WAVES agree reasonably well the MODIS LAI, but with smaller amplitude than the MODIS LAI for all four catchments. The Nash-Sutcliffe efficiencies were 0.67, 0.36, 0.34 and 0.82, and biases of water balance were −0.1%, −0.03%, 1.0%, and −0.9% for LAI for energy-limited forest, water-limited forest, energy-limited grass, and water-limited grass catchments, respectively. The above results indicated that WAVES is capable of simulating both streamflow and LAI variations in catchments under different climatic regime and vegetation types.

3.2 Sensitivities of LAI, ET and runoff to eCO_2 and climate change

The mean of ensemble sensitivities of LAI, ET and runoff in percentage to eCO_2 or climate change are shown in Figure 5. The eCO_2 increased canopy LAI in all four catchments. Evapotranspiration increased and runoff decreased in all catchments except the energy-limited forest catchment, in which ET decreased and runoff increased. Therefore the effect of reduced stomatal conductance on ET under eCO_2 was greater for the energy-limited forest catchment but less for the other three catchments than the increased LAI. The increase in LAI was smallest (1.8%) in the energy-limited forest catchment and largest (21.2%) in the water-limited grass catchment. The increases in LAI were 12.7% and 14.7% in water-limited forest catchment and energy-limit grass catchment, respectively (Figure 5a). Total evapotranspiration changed −1.4%, 0.6%, 3.9% and 10.1% and runoff changed 1.8%, −2.9%, −1.1% and −18.2% due to eCO_2 in the energy-limited forest catchment, water-limited forest catchment, energy-limited grass catchment and water-limited grass catchment, respectively (Figure 5b and 5c).

Insert Figure 5 here

Under climate change, canopy LAI decreased in all four catchments (Figure 5a). Total evapotranspiration increased in energy-limited forest catchment but decreased in other three catchments (Figure 5b). Note that precipitation increased slightly only in the water-limited forest catchment and potential evaporation increased in all four catchments (Figure 2). Thus increased ET in the energy-limited forest was primarily caused by increase in potential evaporation, while decrease in ET in the water-limited forest can be attributed to adverse impacts of climate change on canopy LAI. However, decrease in ET in two grass catchment resulted from decrease in both canopy LAI and rainfall. Consequently, catchment runoff decreased in two energy-limited catchments but increased in two water-limited catchments (Figure 5c). These changes imply that future climate change reduce canopy LAI, which resulted in changes both in direction and magnitude in ET and runoff among catchments. The decrease in canopy LAI was smallest (2.7%) in energy-limited catchment and largest (25.5%) in water-limited grass catchment. The changes in ET were 0.5%, −0.3%, −2.0% and −8.4%, changes in runoff were −1.4%, 3.4%, −5.8% and 15.6%, due to climate change in energy-limited forest catchment, water-limited forest catchment, energy-limited grass catchment and water-limited grass catchment, respectively (Figure 5b and 5c). Relatively, the eCO_2 induced changes in LAI, ET and runoff were approximately equivalent in magnitude but in an opposing direction to that caused by changes in climate alone, except for changes in runoff in the energy-limited grass catchment.

3.3 Interactive effects of the eCO_2 and climate change on LAI, ET and runoff

The additive effects of eCO_2 and climate change (namely summing up of changes of Expt2 and Expt3) and relative changes of Expt4, which include additive effects of both eCO_2 and climate change and interactive effects between the two drivers, are shown in Figure 6. Differences between Expt4 and additive effects are interactive effects between eCO_2 and climate change. Figure 6 shows that the interactive effects between the two drivers were significant, especially for LAI and ET in the two grassland catchments and runoff in the two water-limited catchments. Our results suggest that the assumption that linear combination of individual effects is very unlikely to apply to predictions of LAI and ET in either of the two grassland catchments and runoff in either of the two water-limited catchments. The interactive effects on LAI in the two forest catchments were small (<0.2%), but were relatively larger in two grass catchments. The interaction was about 1% in the energy-limited grass catchment and −5.4% in the water-limited grass catchment. The interactions on ET were −0.22%, 0.35%, 1.5% and −1.6% in energy-limited forest catchment, water-limited forest catchment, energy-limited grass catchment and water-limited grass catchment, respectively. The interactive effects on runoff were relatively small (<0.5%) in the energy-limited catchments and were larger than 2% in water-limited catchments. Furthermore, the directions of additive effects and changes under Expt4 condition were in opposing directions in the two water-limited catchments. These results suggest that prediction of runoff in two water-limited catchments was not only biased but also may in opposite direction, if interactive effects between eCO_2 and climate were neglected.

Insert Figure 6 here

4 Discussion

4.1 Plant growth responses to elevated CO_2 and climate change.

Sensitivities of LAI to eCO_2 suggest that plant growth was enhanced in all four catchment, as has been suggested previous studies (e.g. Luo et al. (2008) and Piao et al. (2007)). This is possibly caused by both direct fertilization effects of eCO_2 (Eamus and Jarvis, 1989; Woodward, 1990), which is induced by increased supply of carbon for photosynthesis, and indirect water effects of eCO_2 through its physiological effects on stomatal conductance, which reduce water use and thus can ameliorate water stress under water-limited condition (Wullschleger et al., 2002; Gerten et al., 2005; Crosbie et al., 2012). Increases in LAI of the two water-limited catchments were larger than increases in the energy-limited catchments. This is likely to arise because the indirect water effects (i.e. increased soil moisture content arising from reduced stomatal conductance) were more pronounced in water-limited catchments than energy-limited catchments as water is one of main constrains on plant growth in water-limited regions (Wullschleger et al., 2002; Eamus and Palmer, 2007;

Macinnis-Ng et al., 2011). Larger increases in LAI in water-limited regions under eCO_2 have been observed in field experiments (Morgan et al., 2004; Morgan et al., 2011).

Sensitivities of LAI to climate change indicate that projected future climate change had adverse impacts on canopy LAI in all four catchments. Changes in this study agreed well with previous assessments that climate change may influence vegetation growth detrimentally (Gerten et al., 2005; Fischlin et al., 2007; Luo et al., 2008). Predicted reductions in LAI in these catchments were principally associated with rising temperature and its concomitant effects on water availability for growth. Higher temperature may result in unfavourable conditions for plant growth including higher rate of heterotrophic respiration (Bonan, 2008), reduction in assimilation rate (Landsberg and Sands, 2011) and aggravating water stress and enhancing transpiration (O'Grady et al., 2011; Crosbie et al., 2012). The LAI change in the energy-limited grass catchment was very likely caused by not only rising temperature but also decreased rainfall (about −5%, Figure 2). Changes in seasonality of precipitation (especially in spring and summer, Figure S1), may also affect plant growth adversely (Knapp et al., 2002; Gerten et al., 2008). Predicted decrease in LAI in the water-limited grass catchment was consistent with the observed growth decline in the southern Spain induced by rapid climate change (Jump et al., 2006). Therefore, we conclude that the coupled water-carbon model WAVES reasonably captured the responses of vegetation in contrasting ecosystems to eCO_2 and changing climate.

The LAI was more sensitive to climate change in the energy-limited forest catchment and water-limited grass catchment but more sensitive to eCO_2 in the other two catchments in term of the direction of additive effects on LAI (Figure 6a). The interactive effects between eCO_2 and climate change exist because both drivers can influence plant growth alone and interactively. For instance, rising temperature can pose positive or negative impacts on plant growth depending on climatic regimes and vegetation conditions (Fischlin et al., 2007; Bonan, 2008), meanwhile it can also influence both direct fertilization effects and indirect water effects of eCO_2 on plant growth (Leuzinger et al., 2011; O'Grady et al., 2011). The eCO_2 can enhance plant growth, at the same time, it can also modulate the impact of climate change on plant growth by alter WUE (Crosbie et al., 2012).

4.2 Shift of water budgets due to elevated CO_2 and climate change

The physiological effects of eCO_2 on catchment water budgets operate directly through reductions in canopy transpiration and indirectly through changes in canopy LAI (Katul et al., 2012). Our modelling results show that reductions in ET and increases in runoff only occurred in the energy-limited forest under eCO_2 (i.e., Expt2, Figure 5b and 5c). Decreased ET in this catchment resulted from decreases in stomatal conductance, which reduced canopy transpiration and outweighed any increase in water consumption associated with increased LAI (~2%), resulting in increased runoff in this catchment. For the other three catchments, increased ET is likely to be related to the significant increase in LAI under eCO_2 conditions, which outweighed the effect of stomatal closure.

Climate change can influence water budgets directly though changes in climate forcing including precipitation and temperature, and indirectly via impacts on canopy LAI, which can alter the partitioning of precipitation into different components of ET and water yield (Zhang et al., 2001; Bonan, 2008; Cheng et al., 2011). Both ET and runoff decreased in the energy-limited grass catchment in Expt3. Decrease in ET in this catchment were possibly caused by decreases in both precipitation (~5%) and LAI (~10%), but reduced runoff was principally caused by decreased precipitation alone. In the water-limited grass catchment, reduced ET was possibly induced by decreases in LAI (~26%), and increase in runoff (~16%) can be attributed to decreased ET.

Under Expt4, changes in ET in all the four catchments were in the same direction as that in Epxt2. This suggests that eCO_2 is more dominant than climate change in controlling ET in these vegetated catchments. Ainsworth and Long (2005) showed that stomatal conductance was reduced by approximately 20% in response to CO_2 enrichment across multiple FACE experimental sites. Although ecohydrological influences of eCO_2 were very likely attenuated at stand level and catchment scales (Field et al., 1995; Leuzinger et al., 2011), larger eCO_2 effects on ET observed in all four catchments are possibly due to the fact that these catchments were all completely vegetated and projected average climate changes were moderate in these four catchments. In terms of direction of changes in runoff under Expt4 and Expt2, eCO_2 has larger influence on runoff in two forest catchment (Figure 5c and 6c). The effects eCO_2 were more dominant than climate change on ET but less dominant on runoff in the energy-limited grass catchment is possibly due to LAI of grassland is more sensitive to climate change (Figure 5a) and projected change in rainfall in this catchment was significant (Figure 2a). Our results suggest that incorporating the impacts of eCO_2 on water budgets are very important for correctly predicting of future water availability of vegetated land.

4.3 Interactive effects between climate change and eCO_2

Modelling results in this study show that interactive effects of climate change and eCO_2 on plant growth can be neglected (<0.5%) in forested catchments but is quite significant in grassed catchments (2%~2.6%, Figure 6a). Interactions between the two drivers were small in forested catchment and likely a result of forests with deep roots that can utilize more available soil water. As a result, forests are more resilient to climate change than grasslands (Zhang et al., 2001; Cheng et al., 2011). With respect to interactive effects between eCO_2 and climate change, interactions on ET can be neglected in the two forested catchments and interactions on runoff can be neglected in the two energy-limited catchments. Interactive effects on ET in forested catchments can be neglected possibly because interactive effects on LAI in these two catchments were unnoticeable. In water-limited regions, ecosystem structure and function are mainly constrained by water (Eamus et al., 2006) thus water-limited ecosystems have higher rain-use efficiency (Huxman et al., 2004; Troch et al., 2009). Small interactive effects on plant water use can result in significant differences in runoff (Cramer et al., 2001; Wullschleger et al., 2002; Bounoua et al., 2010). That is why interactive effects on runoff in water-limited catchments cannot be neglected.

The magnitudes of the interactive effects on canopy LAI, ET and runoff were much smaller than the magnitudes of single-factor effects. It is similar to the conclusion drawn by Luo et al. (2008) from modelled interactive effects among precipitation, temperature and CO_2, and by Wu et al. (2011) from multiple manipulated experiments. However, additive and interactive effects of eCO_2 and climate change are basically in the same magnitude because the effects of climate change and eCO_2 were opposing in sign. The assumption that the effects of climate change and eCO_2 are linearly addictive is not appropriate for changes in LAI and ET in grassland catchments or runoff in water-limited catchments, where interactive effects of eCO_2 and climate change cannot be neglected compared with additive effects.

5 Conclusions

In this study, impacts of elevated CO_2 (eCO_2) on canopy LAI and water budget (evapotranspiration and runoff) were investigated using a well-tested ecohydrological model (WAVES). Future climate changes were considered and interactions between eCO_2 and climate change were estimated in four different ecosystems in Australia with contrasting climate regime and vegetation cover. Results from this study show eCO_2 increased canopy

LAI in all four catchments and increased ET and decreased runoff in the water-limited forest catchment and the two grassland catchments, but reduces ET and increases runoff in the energy-limited forest catchment. The effects of future climate on canopy LAI, ET and total runoff were opposite in sign to those of eCO_2 for all four catchments. Our results also suggest that the interactions between the direct and indirect effects on ET were relatively large in the two grassland catchments but relatively weak in the two forest catchments, and were relatively strong on runoff in the two water-limited catchments but weak in the two energy-limited catchments. This study highlights that failure to account impacts of eCO_2 or its interactions with climate change can introduce significant bias into the predictions of future water budgets, especially for the water-limited catchments in Australia.

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References:

Ainsworth, E.A. and Long, S.P., 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytol., 165(2): 351-372.

Aston, A.R., 1984. The effect of doubling atmospheric CO2 on streamflow: A simulation. J. Hydrol., 67(1-4): 273-280.

Ball, J.T., 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Biggins, J. (Eds.), Prog. Photosynthesis Res. Proc. Int. Congress 7th, Providence, 10-15 Aug 1986.

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P., 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva.

Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D. and Gedney, N. et al., 2007. Projected increase in continental runoff due to plant responses to increasing carbon dioxide. Nature, 448(7157): 1037-1041.

Betts, R.A., Cox, P.M., Lee, S.E. and Woodward, F.I., 1997. Contrasting physiological and structural vegetation feedbacks in climate change simulations. Nature, 387(6635): 796-799.

Bonan, G.B., 2008. Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. Science, 320(5882): 1444 -1449.

Bounoua, L., Hall, F.G., Sellers, P.J., Kumar, A., Collatz, G.J. and Tucker, C.J. et al., 2010. Quantifying the negative feedback of vegetation to greenhouse warming: A modeling approach. Geophys. Res. Lett., 37(23): L23701.

Broadbridge, P. and White, I., 1988. Constant rate rainfall infiltration: A versatile nonlinear model: 1. Analytic solution. Water Resour. Res., 24(1): 145-154.

Brown, A.E., Hairsine, P.B. and Freebairn, A., 2006. The development of the Tasmanian Land Use Change and Stream Flow (TasLUCaS) tool: Report to the Tasmanian Natural Resource Management Committees, CSIRO Land and Water, Canberra, ACT.

Cao, L., Bala, G., Caldeira, K., Nemani, R. and Ban-Weiss, G., 2010. Importance of carbon dioxide physiological forcing to future climate change. PNAS, 107(21): 9513 -9518.

Cheng, L., Xu, Z., Wang, D. and Cai, X., 2011. Assessing interannual variability of evapotranspiration at the catchment scale using satellite-based evapotranspiration data sets. Water Resour. Res., 47(9): W09509.

Chiew, F.H.S., Teng, J., Vaze, J., Post, D.A., Perraud, J.M. and Kirono, D.G.C. et al., 2009. Estimating climate change impact on runoff across southeast Australia: Method, results, and implications of the modeling method. Water Resour. Res., 45: W10414.

Cowling, S.A. and Field, C.B., 2003. Environmental control of leaf area production: Implications for vegetation and land-surface modeling. Global Biogeochem. Cycles, 17(1): 1007.

Cramer, W., Bondeau, A., Woodward, F.I., Prentice, I.C., Betts, R.A. and Brovkin, V. et al., 2001. Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. Global Change Biol., 7(4): 357-373.

Crosbie, R., McCallum, J., Walker, G. and Chiew, F., 2012. Episodic recharge and climate change in the Murray-Darling Basin, Australia. Hydrogeol. J., 20(2): 245-261.

Crosbie, R.S., Dawes, W.R., Charles, S.P., Mpelasoka, F.S., Aryal, S. and Barron, O. et al., 2011. Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. Geophys. Res. Lett., 38(11): L11406.

Crosbie, R.S., Pollock, D.W., Mpelasoka, F.S., Barron, O.V., Charles, S.P. and Donn, M.J., 2012. Changes in Köppen-Geiger climate types under a future climate for Australia: hydrological implications. Hydrol. Earth Syst. Sci., 9(6): 7415-7440.

CSIRO, 2009. Water availability for the Mersey-Forth region: Report four of seven to the Australian Government from the CSIRO Tasmania Sustainable Yields Project, CSIRO Water for a Healthy Country Flagship, Canberra, ACT.

CSIRO and BoM, 2007. Climate Change in Australia: Technical Report 2007, CSIRO & BoM, Canberra.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nature Clim. Change, 3(1): 52 − 58.

Dawes, W., Zhang, L. and Dyce, P., 1998. WAVES: An integrated energy and water balance model (User Manual), CSIRO Land and Water, Canberra, Australia.

Dawes, W.R. and Short, D.L., 1993. The efficient numerical solution of differential equations for coupled water and solute dynamics: the WAVES model, CSIRO Division of Water Resources, Canberra.

De Kauwe, M.G., Medlyn, B.E., Zaehle, S., Walker, A.P., Dietze, M.C. and Hickler, T. et al., 2013. Forest water use and water use efficiency at elevated CO_2: a model-data intercomparison at two contrasting temperate forest FACE sites. Global Change Biol., 19(6): 1759-1779.

Department of the Environment and Water Resources, 2007. Australia's Native Vegetation: A summary of Australia's Major Vegetation Groups, 2007, Australian Goverment, Canberra, ACT.

Dieleman, W.I.J., Vicca, S., Dijkstra, F.A., Hagedorn, F., Hovenden, M.J. and Larsen, K.S. et al., 2012. Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO_2 and temperature. Global Change Biol., 18(9): 2681-2693.

Dore, M.H.I., 2005. Climate change and changes in global precipitation patterns: What do we know? Environ. Int., 31(8): 1167-1181.

Duan, Q., Sorooshian, S. and Gupta, V., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resour. Res., 28(4): 1015-1031.

Eamus, D., 1991. The interaction of rising CO_2 and temperatures with water use efficiency. Plant Cell Environ., 14(8): 843-852.

Eamus, D. and Jarvis, P.G., 1989. The direct effects of increase in the global atmospheric CO_2 concentration on natural and commercial temperate trees and forests. Adv. Ecol. Res., 19: 1-55.

Eamus, D. and Palmer, A.R., 2007. Is climate change a possible explanation for woody thickening in arid and semi-arid regions? Research Letters in Ecology, 2007.

Eamus, D., Hatton, T., Cook, P. and Colvin, C., 2006. Ecohydrology: vegetation function, water and resource management. CSIRO Publishing, Collingwood, VIC, Australia, 360 pp.

Eckhardt, K. and Ulbrich, U., 2003. Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. J. Hydrol., 284(1 − 4): 244-252.

Field, C.B., Jackson, R.B. and Mooney, H.A., 1995. Stomatal responses to increased CO_2: implications from the plant to the global scale. Plant Cell Environ., 18(10): 1214-1225.

Fischlin, A., Midgley, G.F., Price, J.T., Leemans, R., Gopal, B. and Turley, C. et al., 2007. Ecosystems, their properties, goods, and services. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 211-272.

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C. and Stott, P.A., 2006. Detection of a direct carbon dioxide effect in continental river runoff records. Nature, 439(7078): 835-838.

Gerten, D., Lucht, W., Schaphoff, S., Cramer, W., Hickler, T. and Wagner, W., 2005. Hydrologic resilience of the terrestrial biosphere. Geophys. Res. Lett., 32(21): L21408.

Gerten, D., Luo, Y., Le Maire, G., Parton, W.J., Keough, C. and Weng, E. et al., 2008. Modelled effects of precipitation on ecosystem carbon and water dynamics in different climatic zones. Global Change Biol., 14(10): 2365-2379.

Gerten, D., Rost, S., von Bloh, W. and Lucht, W., 2008. Causes of change in 20th century global river discharge. Geophys. Res. Lett., 35(20): L20405.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W. and Sitch, S., 2004. Terrestrial vegetation and water balance--hydrological evaluation of a dynamic global vegetation model. J. Hydrol., 286(1-4): 249-270.

Green, T.R., Bates, B.C., Charles, S.P. and Fleming, P.M., 2007. Physically Based Simulation of Potential Effects of Carbon Dioxide − Altered Climates on Groundwater Recharge. Vadose Zone J., 6(3): 597 -609.

Hatton, T.J., Walker, J., Dawes, W.R. and Dunin, F.X., 1992. Simulations of Hydroecological Responses to Elevated CO_2 at the Catchment Scale. Aust. J. Bot., 40(5): 679-696.

Huntington, T.G., 2008. CO_2-induced suppression of transpiration cannot explain increasing runoff. Hydrol. Process., 22(2): 311-314.

Huxman, T.E., Smith, M.D., Fay, P.A., Knapp, A.K., Shaw, M.R. and Loik, M.E. et al., 2004. Convergence across biomes to a common rain-use efficiency. Nature, 429(6992): 651-654.

Hyvönen, R., Ågren, G.I., Linder, S., Persson, T., Cotrufo, M.F. and Ekblad, A. et al., 2007. The likely impact of elevated [CO_2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytol., 173(3): 463-480.

IPCC, 2007. Climate Change 2007 - The Synthesis Report: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland.

Jeffrey, S.J., Carter, J.O., Moodie, K.B. and Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environ. Modell. Softw., 16(4): 309-330.

Jönsson, P. and Eklundh, L., 2004. TIMESAT - a program for analyzing time-series of satellite sensor data. Comput. Geosci., 30(8): 833-845.

Jump, A.S., Hunt, J.M. and Penuelas, J., 2006. Rapid climate change-related growth decline at the southern range edge of Fagus sylvatica. Global Change Biol., 12(11): 2163-2174.

Katul, G.G., Oren, R., Manzoni, S., Higgins, C. and Parlange, M.B., 2012. Evapotranspiration: A process driving mass transport and energy exchange in the soil-plant-atmosphere-climate system. Rev. Geophys., 50(3): RG3002.

Kimball, J.S., Running, S.W. and Nemani, R., 1997. An improved method for estimating surface humidity from daily minimum temperature. Agr. Forest Meteorol., 85(1－2): 87-98.

Knapp, A.K., Fay, P.A., Blair, J.M., Collins, S.L., Smith, M.D. and Carlisle, J.D. et al., 2002. Rainfall Variability, Carbon Cycling, and Plant Species Diversity in a Mesic Grassland. Science, 298(5601): 2202 -2205.

Körner, C., Morgan, J. and Norby, R., 2007. CO_2 Fertilization: When, Where, How Much? In: J.G. Canadell, D.E. Pataki and L. Pitelka (Eds.), Terrestrial Ecosystems in a Changing World. Global Change — The IGBP Series. Springer Berlin Heidelberg, pp. 9-21.

Kruijt, B., Witte, J.M., Jacobs, C.M.J. and Kroon, T., 2008. Effects of rising atmospheric CO_2 on evapotranspiration and soil moisture: A practical approach for the Netherlands. J. Hydrol., 349(3-4): 257-267.

Landsberg, J. and Sands, P., 2011. Chapter 2 - Weather and Energy Balance. In: J. Landsberg and P. Sands (Eds.), Physiological Ecology of Forest Production. Elsevier, pp. 13-48.

Leakey, A.D., Bishop, K.A. and Ainsworth, E.A., 2012. A multi-biome gap in understanding of crop and ecosystem responses to elevated CO_2. Curr Opin Plant Biol, 15(3): 228-236.

Leuning, R., 1995. A critical appraisal of a combined stomatal-photosynthesis model for C3 plants. Plant Cell Environ., 18(4): 339-355.

Leuzinger, S. and Körner, C., 2010. Rainfall distribution is the main driver of runoff under future CO2-concentration in a temperate deciduous forest. Global Change Biol., 16(1): 246-254.

Leuzinger, S., Luo, Y., Beier, C., Dieleman, W., Vicca, S. and Körner, C., 2011. Do global change experiments overestimate impacts on terrestrial ecosystems? Trends Ecol. Evol., 26(5): 236-241.

Levis, S., Foley, J.A. and Pollard, D., 2000. Large-Scale Vegetation Feedbacks on a Doubled CO_2 Climate. J Climate, 13(7): 1313-1325.

Luo, Y., Gerten, D., Le Maire, G., Parton, W.J., Weng, E. and Zhou, X. et al., 2008. Modeled interactive effects of precipitation, temperature, and [CO_2] on ecosystem carbon and water dynamics in different climatic zones. Global Change Biol., 14(9): 1986-1999.

Luo, Y., Melillo, J., Niu, S., Beier, C., Clark, J.S. and Classen, A.T. et al., 2011. Coordinated approaches to quantify long-term ecosystem dynamics in response to global change. Global Change Biol., 17(2): 843-854.

Macinnis-Ng, C., Zeppel, M., Williams, M. and Eamus, D., 2011. Applying a SPA model to examine the impact of climate change on GPP of open woodlands and the potential for woody thickening. Ecohydrology, 4(3): 379-393.

McKenzie, N.J., Jacquier, D.W., Ashton, L.J. and Cresswell, H.P., 2000. Estimation of soil properties using the Atlas of Australian Soils, CSIRO Land and Water, Canberra, ACT.

McMurtrie, R.E., Norby, R.J., Medlyn, B.E., Dewar, R.C., Pepper, D.A. and Reich, P.B. et al., 2008. Why is plant-growth response to elevated CO_2 amplified when water is limiting, but reduced when nitrogen is limiting? A growth-optimisation hypothesis. Funct. Plant Biol., 35(6): 521-534.

Medlyn, B.E., Barton, C.V.M., Broadmeadow, M.S.J., Ceulemans, R., De Angelis, P. and Forstreuter, M. et al., 2001. Stomatal conductance of forest species after long-term exposure to elevated CO_2 concentration: a synthesis. New Phytol., 149(2): 247-264.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W. and Lettenmaier, D.P. et al., 2008. Stationarity Is Dead: Whither Water Management? Science, 319(5863): 573-574.

Milly, P.C.D., Dunne, K.A. and Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature, 438(7066): 347-350.

Monteith, J. and Unsworth, M., 2008. Principles of environmental physics, 3rd. Elsevier, 440 pp.

Morgan, J.A., LeCain, D.R., Pendall, E., Blumenthal, D.M., Kimball, B.A. and Carrillo, Y. et al., 2011. C4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. Nature, 476(7359): 202-205.

Morgan, J.A., Pataki, D.E., Körner, C., Clark, H., Grosso, S.J. and Grünzweig, J.M. et al., 2004. Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO_2. Oecologia, 140(1): 11-25.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — A discussion of principles. J. Hydrol., 10(3): 282-290.

Norby, R.J. and Zak, D.R., 2011. Ecological Lessons From Free-Air CO_2 Enrichment (FACE) Experiments. Annu. Rev. Ecol. Evol. Syst., 42: 181-203.

Norby, R.J., Wullschleger, S.D., Gunderson, C.A., JOHNSON, D.W. and Ceulemans, R., 1999. Tree responses to rising CO_2 in field experiments: implications for the future forest. Plant Cell Environ., 22(6): 683-714.

Nowak, R.S., Ellsworth, D.S. and Smith, S.D., 2004. Functional responses of plants to elevated atmospheric CO_2 – do photosynthetic and productivity data from FACE experiments support early predictions? New Phytol., 162(2): 253-280.

O'Grady, A.P., Tissue, D.T. and Beadle, C.L., 2011. Canopy processes in a changing climate. Tree Physiol., 31(9): 887 -892.

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudré, N., Labat, D. and Zaehle, S., 2007. Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. PNAS, 104(39): 15242 -15247.

Post, D.A., Chiew, F.H.S., Teng, J., Viney, N.R., Ling, F.L.N. and Harrington, G. et al., 2012. A robust methodology for conducting large-scale assessments of current and future water availability and use: A case study in Tasmania, Australia. J. Hydrol., 412 – 413(0): 233-245.

Priestley, C.H.B. and Taylor, R.J., 1972. On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. Mon. Weather Rev., 100(2): 81-92.

Ramanathan, V., Crutzen, P.J., Kiehl, J.T. and Rosenfeld, D., 2001. Aerosols, Climate, and the Hydrological Cycle. Science, 294(5549): 2119-2124.

Ritchie, J.T., Jones, C.A., Kiniry, J.R. and Dyke, P.T., 1986. Model inputs. In: C.A. Jones, J.R. Kiniry and P.T. Dyke (Eds.), CERES-Maize: a simulation model of maize growth and development. Texas A&M University Press.

Ross, P.J., 1990. Efficient numerical methods for infiltration using Richards' equation. Water Resour. Res., 26(2): 279-290.

Santer, B.D., Wigley, T.M.L., Schlesinger, M.E. and Mitchell, J.F.B., 1990. Developing climate scenarios from equilibrium GCM results, Max-Planck-Institut für Meteorologie, Hamburg, Germany.

Sellers, P.J., Berry, J.A., Collatz, G.J., Field, C.B. and Hall, F.G., 1992. Canopy reflectance, photosynthesis, and transpiration. III. A reanalysis using improved leaf models and a new canopy integration scheme. Remote Sens. Environ., 42(3): 187-216.

Sellers, P.J., Bounoua, L., Collatz, G.J., Randall, D.A., Dazlich, D.A. and Los, S.O. et al., 1996. Comparison of Radiative and Physiological Effects of Doubled Atmospheric CO_2 on Climate. Science, 271(5254): 1402 -1406.

Slavich, P.G., Walker, G.R., Jolly, I.D., Hatton, T.J. and Dawes, W.R., 1999. Dynamics of Eucalyptus largiflorens growth and water use in response to modified watertable and flooding regimes on a saline floodplain. Agr. Water Manage., 39(2 – 3): 245-264.

Thornton, P.E. and Running, S.W., 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. Agr. Forest Meteorol., 93(4): 211-228.

Troch, P.A., Martinez, G.F., Pauwels, V.R.N., Durcik, M., Sivapalan, M. and Harman, C. et al., 2009. Climate and vegetation water use efficiency at catchment scales. Hydrol. Process., 23(16): 2409-2414.

Vaze, J., Teng, J. and Chiew, F.H.S., 2011. Assessment of GCM simulations of annual and seasonal rainfall and daily rainfall distribution across south-east Australia. Hydrol. Process., 25(9): 1486-1497.

Viney, N.R., Perraud, J.M., Vaze, J., Chiew, F.H.S., Post, D.A. and Yang, A., 2009. The usefulness of bias constraints in model calibration for regionalisation to ungauged catchments. In: Anderssen, R.S., Braddock, R.D. and Newham, L.T.H. (Eds.), Interfacing Modelling and Simulation with Mathematical and Computational Sciences. 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Cairns, Australia.

Wang, K. and Dickinson, R.E., 2012. A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability. Rev Geophys, 50(2): RG2005.

Warren, J.M., Pötzelsberger, E., Wullschleger, S.D., Thornton, P.E., Hasenauer, H. and Norby, R.J., 2011. Ecohydrologic impact of reduced stomatal conductance in forests exposed to elevated CO_2. Ecohydrology, 4(2): 196-210.

Wood, E.F., Roundy, J.K., Troy, T.J., van Beek, L.P.H., Bierkens, M.F.P. and Blyth, E. et al., 2011. Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water. Water Resour. Res., 47(5): W05301.

Woodward, F.I., 1990. Global change: Translating plant ecophysiological responses to ecosystems. Trends Ecol Evol, 5(9): 308-311.

Wu, H., Rykiel Jr., E.J., Hatton, T. and Walker, J., 1994. An integrated rate methodology (IRM) for multi-factor growth rate modelling. Ecol. Model., 73(1-2): 97-116.

Wu, Z., Dijkstra, P., Koch, G.W., Penuelas, J. and Hungate, B.A., 2011. Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. Global Change Biol., 17(2): 927-942.

Wullschleger, S.D., Tschaplinski, T.J. and Norby, R.J., 2002. Plant water relations at elevated CO_2 – implications for water-limited environments. Plant Cell Environ., 25(2): 319-331.

Zhang, L. and Dawes, W., 1998. WAVES: An integrated energy and water balance model, CSIRO Land and Water, Canberra, Australia.

Zhang, L., Dawes, W.R. and Hatton, T.J., 1996. Modelling hydrologic processes using a biophysically based model—application of WAVES to FIFE and HAPEX-MOBILHY. J. Hydrol., 185(1-4): 147-169.

Zhang, L., Dawes, W.R. and Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res., 37(3): 701-708.

Zhang, L., Dawes, W.R., Slavich, P.G., Meyer, W.S., Thorburn, P.J. and Smith, D.J. et al., 1999. Growth and ground water uptake responses of lucerne to changes in groundwater levels and salinity: lysimeter, isotope and modelling studies. Agr. Water Manage., 39(2-3): 265-282.

Zhang, L., Hume, I.H., O'Connell, M.G., Mitchell, D.C., Milthorpe, P.L. and Yee, M. et al., 1999. Estimating episodic recharge under different crop/pasture rotations in the Mallee region. Part 1. Experiments and model calibration. Agr. Water Manage., 42(2): 219-235.

Zhang, Y.Q., Viney, N., Chen, Y. and Li, H.Y., 2011. Collation of streamflow data for 719 unregulated Australian catchments, CSIRO: Water for a Healthy Country National Research Flagship, Canberra, ACT.

Zhou, X., Zhang, Y., Wang, Y., Zhang, H., Vaze, J. and Zhang, L. et al., 2012. Benchmarking global land surface models against the observed mean annual runoff from 150 large basins. J. Hydrol., 470－471(0): 269-279.

Tables and Figures

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Table 1 | Key features of the four catchments compared in this study.

		energy-limited		water-limited	
		forest	grass	forest	grass
state	-	NSW	TAS	NSW	WA
latitude(S)	degree	30.34	41.70	32.46	17.09
longitude(E)	degree	152.53	146.42	151.28	125.04
catchment area	km^2	150	37.5	72.9	68.2
mean slope	degree	12	1	5.5	2.5
mean elevation	m	300	1140	250	247
mean annual precipitation	mm	1830	1860	750	1020
aridity index	mm/mm	0.7	0.25	1.7	2.16
mean annual temperature	°C	12.5	5.9	17.8	26.8
photosynthesis pathway	-	C3	C3	C3	C4
vegetation growth type	-	perennial	perennial	perennial	annual
leaf area index (maximum)	m^2/m^2	6.0	1.25	2.5	1.25
vegetation layers	-	2	1	2	1
modelled soil depth	m	5.0	3.0	5.0	3.0
soil types	-	3	3	3	3
number of soil nodes	-	25	25	25	25
runoff records		1995-2005	1995-2005	1995-2005	1995-1999
baseline CO_2 concentration	ppm	370	370	370	370

Table 2 | A summary of the four scenarios applied in this study.

No.	**Climate**	**CO_2**	**Descriptions**
Expt1	Observed	Current (cCO_2, 370 ppm)	The model was run with observed daily meteorological data, current ambient CO_2 concentration, and optimized model parameter values. Results of Experiment 1 represent water balance under current climatic and CO_2 conditions. Experiment 1 provides the reference for assessing the impact of climate change and CO_2 concentration on water balance.
Expt2	Observed	Elevated (eCO_2, 550 ppm)	The same as Experiment 1, except the CO_2 concentration was elevated to 550 ppm. Experiment 2 was designed to estimate the impact of elevated CO_2 under current climate condition. It is similar as FACE experiments.
Expt3	Projected	Current (cCO_2, 370 ppm)	The same as Experiment 1, except future climate forcing projected from GCMs were considered. Experiment 3 is designed to estimate impact of future climate change on water balance without considering impact of CO_2 and to separate the impacts of changing climate and CO_2 concentration.
Expt4	Projected	Elevated (eCO_2, 550 ppm)	The model was run with future climate forcing obtained from GCMs, elevated CO_2 concentration, and optimized model parameter values. Experiment 3 was designed to investigate the effect of changes in both climatic variables and CO_2 concentration on water balance.

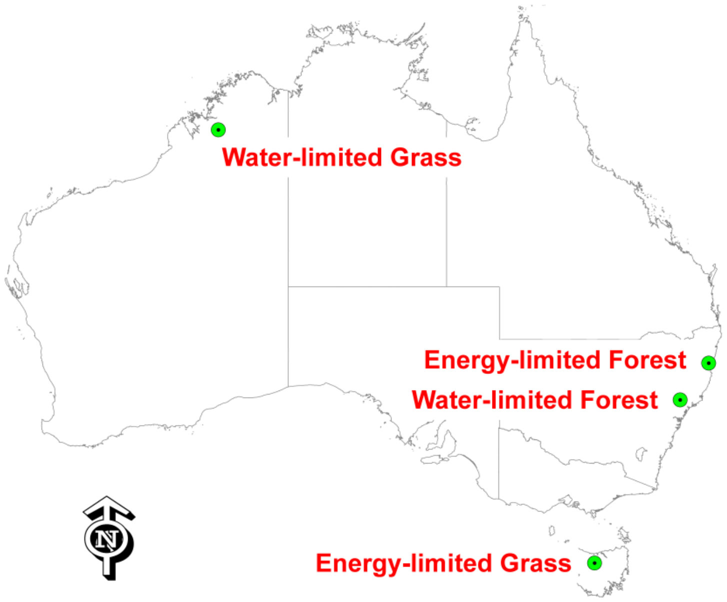
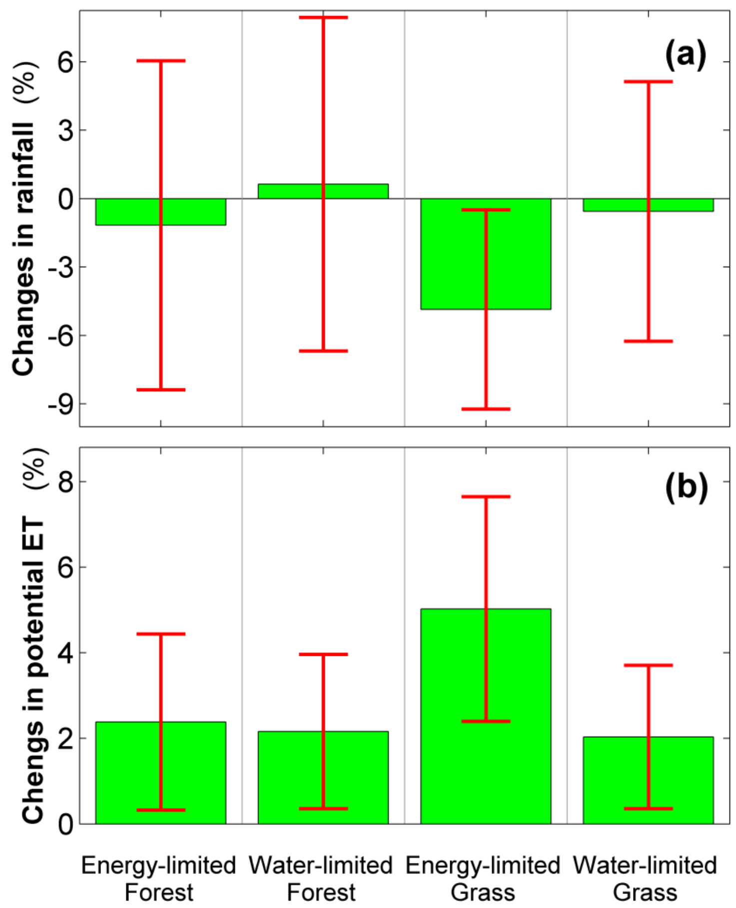


Figure 1 | A schematic map showing the locations of four different ecosystems studied.



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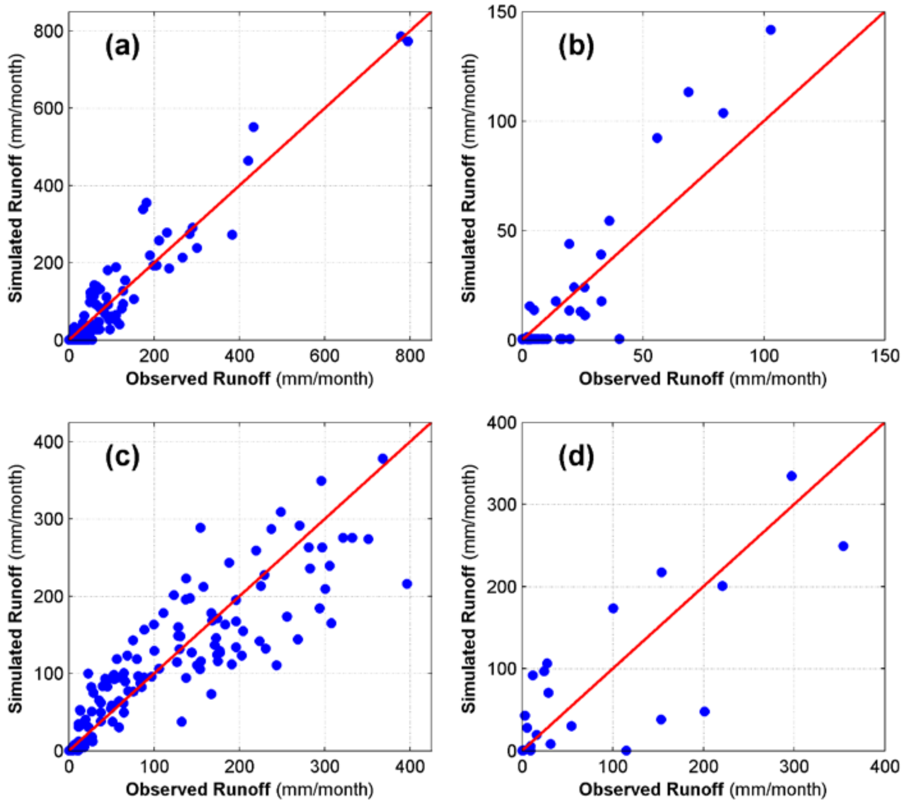

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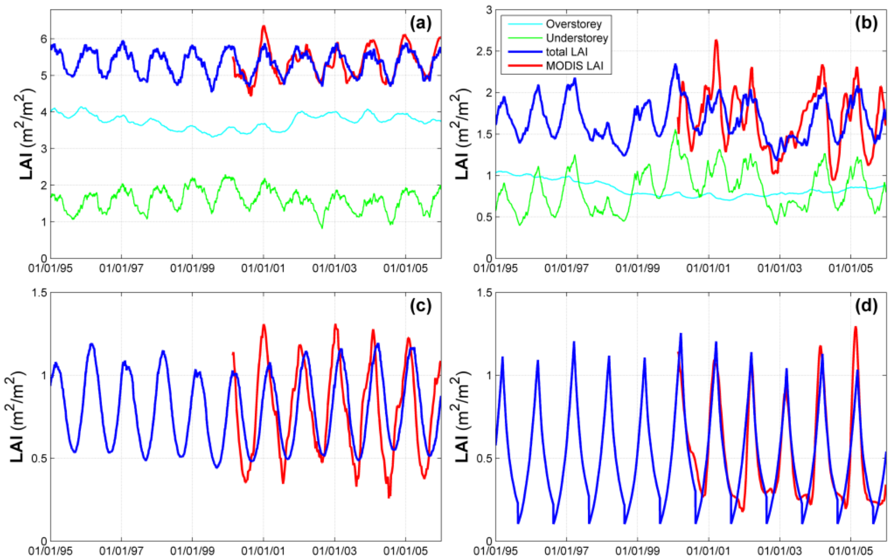

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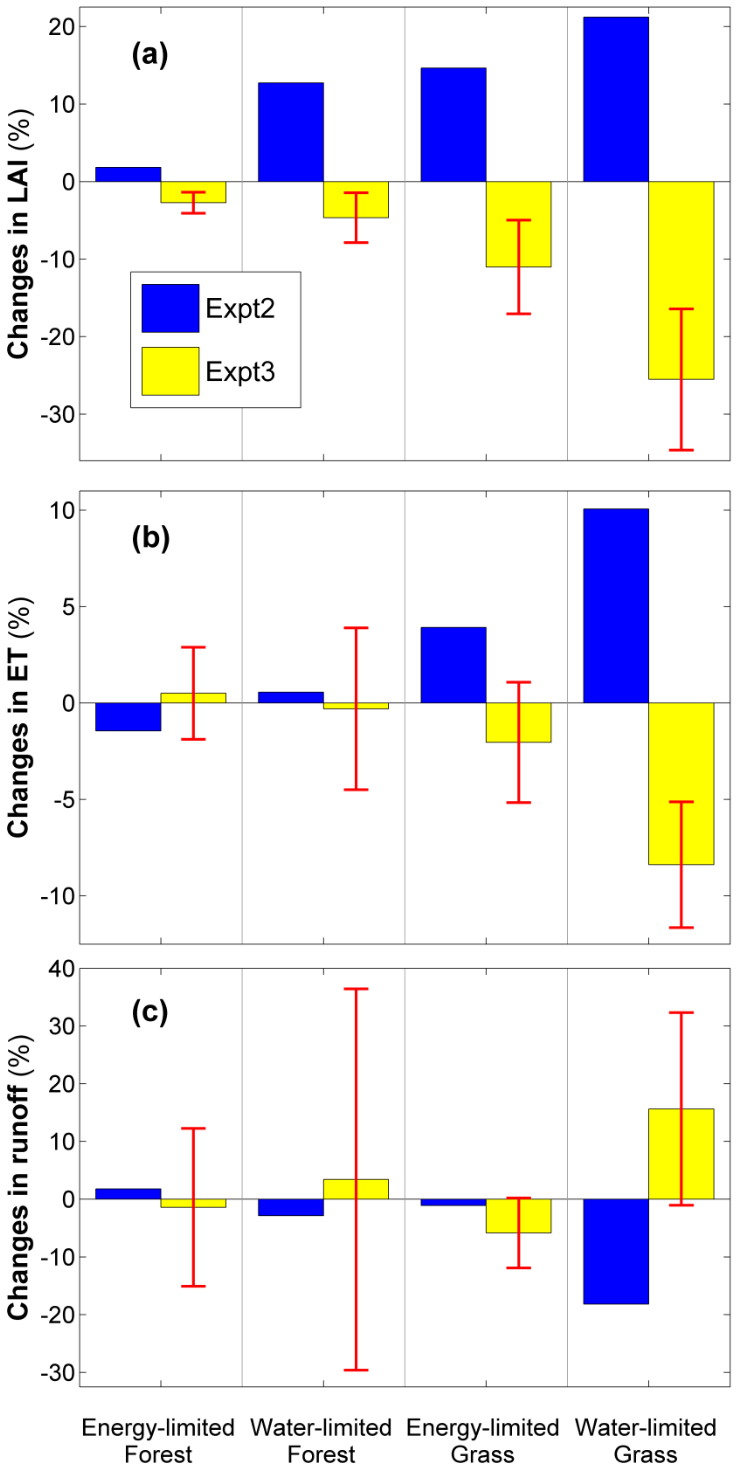

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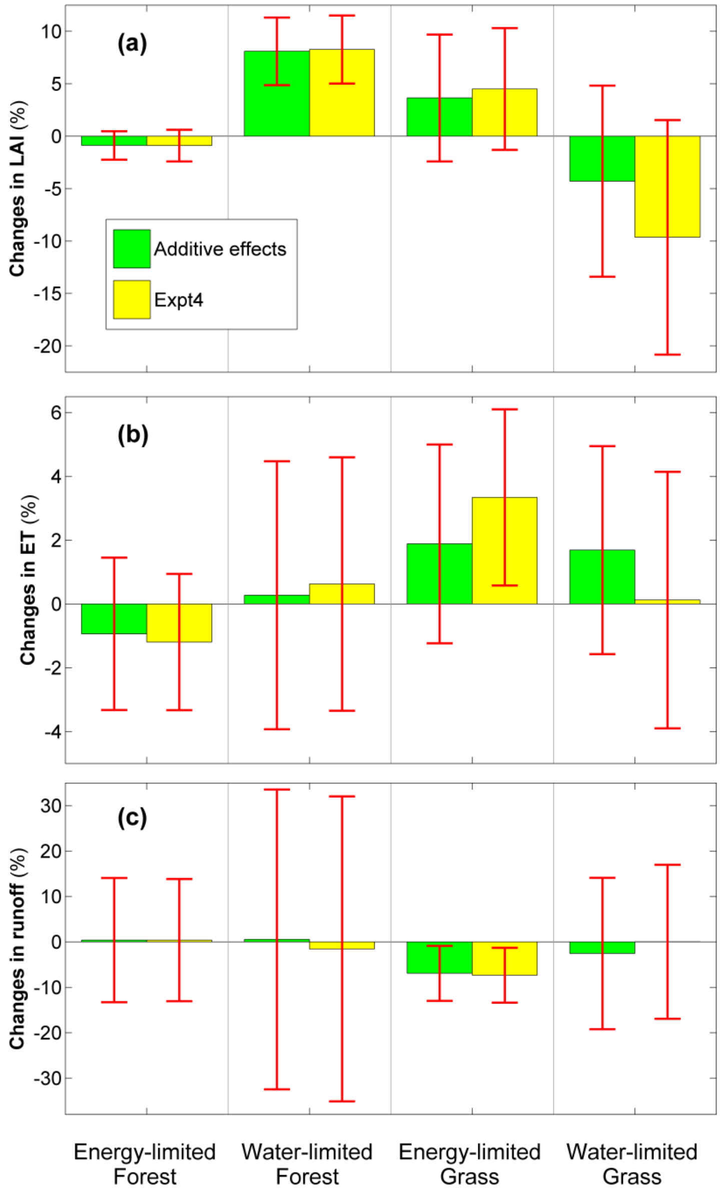

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Table S1 | Summary of the GCMs used in this study

No.	GCM	Modelling group & Country	
1	BCM 2.0	BCCR	Bjerknes Centre for Climate Research, Norway
2	CGCM 3.1	CCCma	Canadian Climate Centre, Canada
3	CM 3.0	CNRM	Centre National de Recherches Meteorologiques, France
4	Mk 3.0	CSIRO	CSIRO, Australia
5	Mk 3.5	CSIRO	CSIRO, Australia
6	CM 2.1	GFDL	Geophysical Fluid Dynamics Lab, USA
7	CM 3.0	INM	Institute of Numerical Mathematics, Russia
8	CM 4.0	IPSL	Institut Pierre Simon Laplace, France
9	MIROC 3.2	NIES	National Institute for Environmental Studies, Japan
10	ECHO_G	MIUB	Meteorological Institute, University of Bonn, Germany
		METRI	Meteorological Research Institute of KMA, Korea
		M&D	Model and Data Groupe at MPI-M, Germany
11	ECHAM5	MPI-M	Max-Planck-Institut for Meteorology, Germany
12	PCM	NCAR	National Center for Atmospheric Research, USA

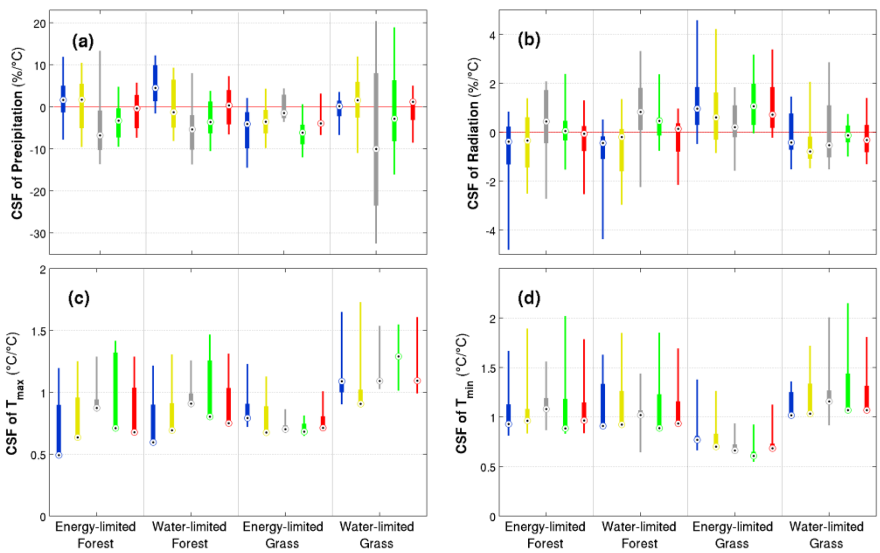

Figure S1 | The constant scaling factor (CSF) of (a) precipitation (PPT), (b) solar radiation, (c) daily maximum temperature (T_{max}), or (d) daily minimum temperature (T_{min}), which were estimated from the projections of 12 global climate models for 2050's for each of the four catchments and different seasons. The box plots in blue, earth yellow, grey, green, and red represent the CSF of summer (DJF), autumn (MAM), winter (JJA), spring (SON), and annual mean, respectively.