

Effects of spatial and temporal climatic variability on terrestrial carbon and water fluxes in the Pacific Northwest, USA



Sinkyu Kang^{a,*}, Steven W. Running^b, John S. Kimball^b, Daniel B. Fagre^c,
Andrew Michaelis^b, David L. Peterson^d, Jessica E. Halofsky^e, Sukyoung Hong^f

^a Department of Environmental Science, Kangwon National University, Chuncheon, Kangwon-do 200-701, Republic of Korea

^b Numerical Terradynamic Simulation Group (NTSG), College of Forestry and Conservation, The University of Montana, Missoula, MT, USA

^c USGS Northern Rocky Mountain Science Center, West Glacier, MT, USA

^d U.S. Forest Service, Pacific Northwest Research Station, Seattle, WA, USA

^e School of Forest Resources, University of Washington, Seattle, WA, USA

^f Soil and Fertilizer Management Division, National Academy of Agricultural Science, Rural Development Administration, Suwon, Republic of Korea

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ABSTRACT

The Pacific Northwest (PNW) of the conterminous United States is characterized by large variations in climate and topography, and provides an ideal geographic domain for studying interactions between regional climate and vegetation dynamics. We examined vegetation carbon (C) and water dynamics along PNW climate and topographic gradients using a process-based biogeochemical model, BIOME-BGC, the algorithms of which form bases for a fully-prognostic treatment of carbon and nitrogen cycles in Land Community Model (CLM). Simulation experiments were used to (1) analyze spatial and temporal variability of terrestrial carbon (C) stocks and flux, (2) investigate primary climatic variables controlling the variability, and (3) predict effects of future climate projections on vegetation productivity and water flux variables including evapotranspiration and water supply. The model experiments focused on two 18-year (1980–1997 and 2088–2105) simulations using future climate predictions for A2 (+4.2 °C, –7% precipitation) and B2 (1.6 °C, +11% precipitation) emissions scenarios through year 2100. Our results show large west to east spatial variations in C and water fluxes and C stocks associated with regional topography and distance from coastal areas. Interannual variability of net primary productivity (NPP) and evapotranspiration (ET) are 57% and 33%, respectively, of the 18-year mean annual fluxes for 1980–1997. The annual NPP and ET are positively correlated with precipitation but inversely proportional to vapor pressure deficit; this suggests that modeled NPP and ET are predominantly water limited in the PNW. The A2 scenario results in higher NPP and ET of 23% and 10%, respectively, and 15% lower water outflow. The B2 scenario results in higher NPP and ET of 12% and 15%, respectively, and 2% lower water outflow, despite projected increases in precipitation. Simulation experiments indicate that most PNW ecosystems are water limited, and that annual water outflow will decrease under both drier (A2) and wetter (B2) scenarios. However, higher elevations with high snowpacks of long duration may buffer the loss of water resources in some areas, even if precipitation is lower.

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1. Introduction

The functions of terrestrial ecosystems and climate are closely linked, and numerous studies have examined the influence of climatic variability and change on ecosystem function at the global or continental scale (e.g., Braswell et al., 1997; Kucharik et al., 2000; Bachelet et al., 2001, 2003; Cramer et al., 2001; Lucht et al.,

2006). However, there is increasing interest in predictions of the effects of climatic variability and change at the regional scale (Fagre et al., 2003), because studies at this scale provide important information about ecosystem response to climatic variability and change that can be masked in coarser scale studies (Bachelet et al., 2001). It is also more feasible to implement mitigation and adaptation strategies at regional and sub-regional scales (e.g., Millar et al., 2007; Joyce et al., 2009).

It is particularly important to investigate effects of climatic variability and change in mountainous regions, because mountains support a high diversity of ecosystems, provide a wide range of

* Corresponding author. Tel.: +82 33 250 8578.

E-mail address: kangsk@kangwon.ac.kr (S. Kang).

ecological services to human populations (Beniston and Fox, 1996), and are especially vulnerable to climate change (IPCC, 2007). Mountains accumulate larger amounts of precipitation, often in the form of snow, than surrounding lowlands and serve as “water towers” by supplying river systems and providing fresh water for humans. Increasing temperatures with climate change are expected to cause more precipitation falling as rain rather than snow (Mote, 2003), earlier snowmelt and snowmelt-driven streamflow (Stewart et al., 2005), and reduced spring snowpack (Mote, 2003; Mote et al., 2005; Barnett et al., 2008). For the mountainous regions of the western United States, snowmelt provides approximately 70% of annual streamflow (Mote et al., 2008). Both increased winter rain (as opposed to snow) and shifts to earlier spring snowmelt are expected to result in higher winter and spring streamflows and lower summer streamflows in snowmelt-dominated and transient (rain/snow) watersheds. This reduction in summer streamflow would have major implications for water supply, fisheries, wildlife, and agriculture, making increased understanding and regional predictions of changes in water flux with climate variability and change critical.

Increased temperatures and atmospheric CO₂ levels with climate change will also influence other plant and ecosystem processes, such as photosynthesis, water use efficiency, and biogeochemical cycling (Long, 1991; Amthor, 1995; Kirschbaum, 2004). Changes in these and other processes will influence vegetation dynamics, ecosystem productivity and carbon storage (Cao and Woodward, 1998; Cramer et al., 2001; IPCC, 2007). For example, increased atmospheric CO₂ concentrations could have a direct plant “fertilization” effect by increasing water use efficiency, thus increasing net primary production (NPP) (Idso, 1991; Kirschbaum, 2004). However, climate warming may also result in decreased soil moisture in mountainous regions of the western United States (Wetherald and Manabe, 2002; Manabe et al., 2004). Process-based models can help in understanding these complex interactions. By providing information on the influence of climatic variability and change on carbon stocks and fluxes, process-based models can also suggest how ecosystem processes, productivity, and services will be influenced by climate change.

Regional modeling studies using process-based models have been reported at various spatial scales from watershed to sub-continental scales. White et al. (1997a,b) and Baron et al. (2000) simulated current and future carbon and water fluxes in Rocky Mountain areas using RHESSys model (Tague and Band, 2004). Nemani et al. (2009) provided a case study investigating carbon and water fluxes under current and projected future climate conditions in Yosemite National Park in U.S.A. The sub-continental carbon and water fluxes were also simulated for East Asia (Ito, 2008), Canadian boreal forest (Kang et al., 2005), and tropical forests (Ichii et al., 2005). The regional modeling applications provide us new opportunity to enhance our understanding on carbon and water dynamics across climatic and topographic gradients at spatial scales that can be comparable with management practice units. Nevertheless, some research gaps exist for future enhancements of regional modeling schemes such as (1) incorporating high spatial resolution input data of climate and soil information, (2) investigating climatic and topographic controls on coupled carbon-water dynamics and, (3) considering historical disturbances, and (4) developing regional model validation dataset from both pristine and disturbed areas. Nemani et al. (2009) proposed a comprehensive regional modeling system to fill the research gaps. This study focus to address the above-mentioned first and second research gaps for the Pacific Northwest (PNW) region of the continental United States.

The PNW region is a biologically, topographically, and climatically diverse region that encompasses steep topographic and

climatic gradient, with strong west-to-east temperature and precipitation variability within and across the Olympic, Cascade, and Rocky Mountains (Fig. 1). The large regional variations in climate and topography that characterize the PNW make it an ideal geographic region for studying interactions between regional climate and ecosystem function. In this study, we examined vegetation carbon and water dynamics along climatic and topographic gradients in the PNW using the process-based biogeochemical model, BIOME-BGC (White et al., 2000; Thornton et al., 2002). Simulation experiments were used to: (1) analyze spatial and temporal variability in carbon stocks and flux variables of carbon, (2) investigate the primary climatic variables controlling this variability, and (3) predict effects of different climate change scenarios on vegetation productivity and water flux variables, including evapotranspiration and water supply. Simulations were conducted for two 18-year periods (1980–1997, 2088–2105) and two different climate change scenarios (A2 and B2; Table 1).

2. Methods

Simulation experiments were designed to have two 18-year (1980–1997 and 2088–2105) simulations for the A2 and B2 emission scenarios (*sensu* IPCC, 2007). The A2 scenario is characterized by hotter and drier climate in the PNW (+4.2 °C, −7% precipitation) for the year 2100, and the B2 scenario is characterized by moderately warmer and wetter conditions (1.6 °C, +11% precipitation).

2.1. Study area description

The spatial domain for this study encompasses a 1000 km by 200 km portion of the PNW, spanning 12° (113–125 W) of longitude and 2° (47–49 N) of latitude, including portions of northern Washington, Idaho, and western Montana, USA (Fig. 1). The study domain encompasses Olympic, North Cascades and Glacier National Parks (NP), which include the major mountain environments of the PNW and extend along a general longitudinal transect from the Pacific coastal mountains to the Cascade Range and Rocky Mountains. These mountain ranges extend in a north-south direction roughly parallel to the Pacific coast and exert a major influence on regional climate and land cover variability.

Climatic diversity is largely a function of distance from the Pacific Ocean and physiographic relief, with relatively steep west-east temperature and moisture gradients across the major mountain ranges. The coastal mountains have a general maritime climate with extensive precipitation in the form of rain and snow on windward slopes driven by orographic uplift of moist cyclonic air masses moving predominantly west to east off the Pacific. Inland areas east of the Cascade Range and east-facing slopes of the major ranges exhibit a more continental climate with lower precipitation and higher seasonal temperature variability than coastal areas and west-facing slopes.

Natural vegetation patterns within the region correspond with the major PNW physiographic and climatic regimes. Lower elevations with moderate to high precipitation are dominated by coniferous forests, while semi-arid and arid intermountain areas consist of predominantly shrub-steppe vegetation cover. Upper elevation mountain areas consist of subalpine forest and alpine tundra. Deciduous tree species are found in all locations, primarily in riparian and disturbed areas, but comprise a small proportion of total forest cover. Lower elevation forests outside the national parks have been subject to logging over the past 50–120 years, and are still dominated by coniferous species, but of younger ages than in unlogged areas. Periodic disturbance by fire, insects, and wind contribute to a mosaic of age classes across the forested portion of the PNW.

The study domain is classified as 68% evergreen needleleaf forest (ENF), 16% grassland (including agricultural land), 9% shrubland, 7% deciduous broadleaf forest (DBF) (including mixed forest, MX), and 0.2% other biomes based on the MODIS land cover classification (Fig. 1). Both vegetation and surface meteorological variables have considerable spatial heterogeneity corresponding to topographic gradients ranging from sea level to 3207 m elevation. The 18-year mean daily air temperature and mean annual precipitation from 1980 to 1997 ranged from −5.4 to 11.5 °C and from 124 to 7081 mm y^{−1}, respectively, with cooler temperatures and higher precipitation at higher elevations. The rainfall fraction of total annual precipitation varies from 7 to 100% and is generally higher near the Pacific coast and at lower elevations. Interannual variability in average air temperatures for the domain is approximately ±2.7 °C, and variability in precipitation, vapor pressure deficit and solar radiation is ±592 mm, ±218 kPa, and ±0.7 MJ m^{−2} d^{−1}, respectively (Fig. 2a). Interannual variability in surface meteorology is relatively high compared to regional means for temperature (44%, mean = 6.1 °C), precipitation (50%, mean = 1183 mm y^{−1}), VPD (31%, mean = 699 Pa), and solar radiation (10%, mean = 7.5 MJ m^{−2} d^{−1}).

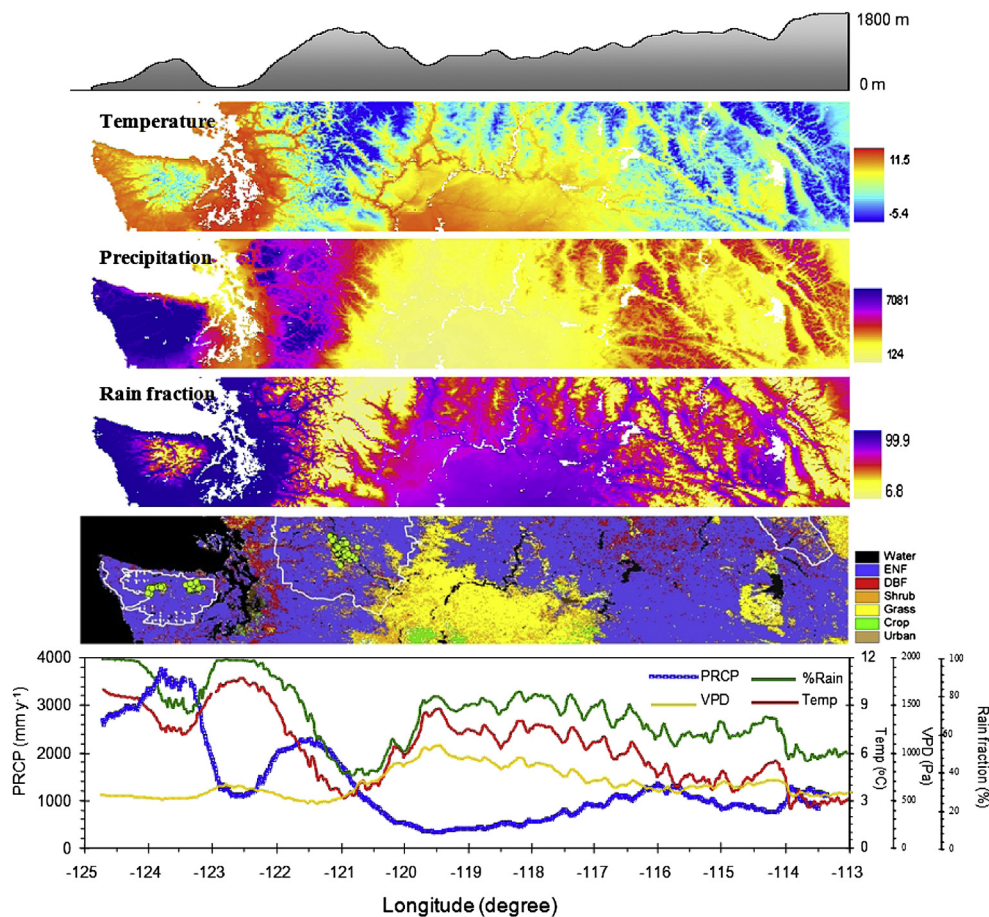


Fig. 1. Spatial patterns of 18-year mean daily air temperature (°C), precipitation (mm y⁻¹) and estimated rainfall fraction of annual precipitation (%) averaged over the 1980–1997 period. The spatial domain spans 113–125 W of longitude and 47–49 N of latitude. MODIS 16-class land cover map (MOD12) aggregated into seven general biomes representing: open water, evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), mixed forest (MX), shrub, grassland, and urban. The white polylines demarcate the boundaries of the Olympic, North Cascade, and Glacier National Parks from west to east. Longitudinal variations in average precipitation (mm y⁻¹), temperature (°C), vapor pressure deficit (Pa) and rainfall fraction (%) are also shown (bottom). The upper plot shows the corresponding longitudinal gradient in mean elevation (m) for the PNW domain.

2.2. Spatial data collection

We assembled a digital geospatial data array of dominant land cover class, digital elevation (DEM), soil properties (effective soil depth and fractions of sand, silt, and clay), and daily surface meteorology (air temperature, humidity, precipitation, incident solar radiation) as the major drivers of BIOME-BGC simulations of daily water and carbon cycle dynamics. Regional topography (elevation, slope, aspect, azimuth) at 1-km resolution was defined from a USGS 30 arc-second (GTOPO30) DEM of the world (USGS, 1998). A regional land cover map was used to define major PNW biomes for the model simulations and was prepared by

Table 1
Climate change scenarios of seasonal mean temperature and precipitation between year 2000 and 2100, prepared by using the Hadley Centre (UK) climate model, HadCM3, based on the ISAM model annual CO₂ abundance data from 2000 to 2100 for A2 and B2 scenarios.

	Season	A2	B2
Temperature change (°C)	Spring	+3.0	+1.0
	Summer	+6.7	+2.1
	Autumn	+4.6	+1.6
	Winter	+2.5	+1.8
	Average	+4.2	+1.6
Precipitation change (%)	Spring	+2	+17
	Summer	−34	+24
	Autumn	−7	+5
	Winter	+11	−1
	Average	−7	+11
Atmospheric CO ₂ conc. in 2100 (ppm)		856	621

aggregating the MODIS 16-class land cover map (MOD12 collection 4, Friedl et al., 2002) into seven general biomes representing: evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forest, shrub, and grassland (Myneni et al., 1997). Soil properties were derived from the USDA NRCS (1995) database, in which effective soil depth was determined by assessing soil rock fraction and was used to define effective rooting depth for model simulations. Daily surface meteorological data for the model simulations were obtained from an 18-year (1980–1997) digital daily time series (DAYMET) of 1-km resolution, spatially gridded daily surface weather data for the continental USA (Thornton et al., 1997). All geospatial data were reprojected to a consistent geographic decimal degree (DD) projection with 0.0125° resolution (approximately 1-km resolution) prior to model simulations.

The DAYMET database provides daily meteorological data at 1 km resolution that includes daily minimum and maximum temperature, precipitation, daytime mean vapor pressure deficit (VPD), and incident solar radiation (Thornton et al., 1997). DAYMET interpolates temperature and precipitation first and then estimates VPD and solar radiation using the same algorithms applied to MT-CLIM (Running et al., 1987). A regional comparison of DAYMET results against daily weather station observations over the Northwestern USA showed mean absolute errors of 0.7 °C and 1.2 °C and 13.4 cm with biases of +0.1 °C and −0.1 °C and −2.1 cm for annual average maximum and minimum temperature and annual total precipitation, respectively (Thornton et al., 1997). Currently, the DAYMET data has been updated for 1980–2011 and expanded to include the United States, Mexico, and Canada (<http://daymet.ornl.gov/>), which give future opportunity to expand model simulations with more than 30-year spatial meteorological dataset.

For BIOME-BGC model validation, we collected field leaf area index (LAI) measurements for 1999–2001 from each two watersheds in Olympic NP and North Cascades NP in the PNW, respectively (Fig. 1). The field LAI measurements were conducted for 139 sites located in two respective watersheds at each NP, but only 95 site measurements were used in this study because the other sampling sites were located within classified water pixels of the overlying 1 km resolution MODIS land

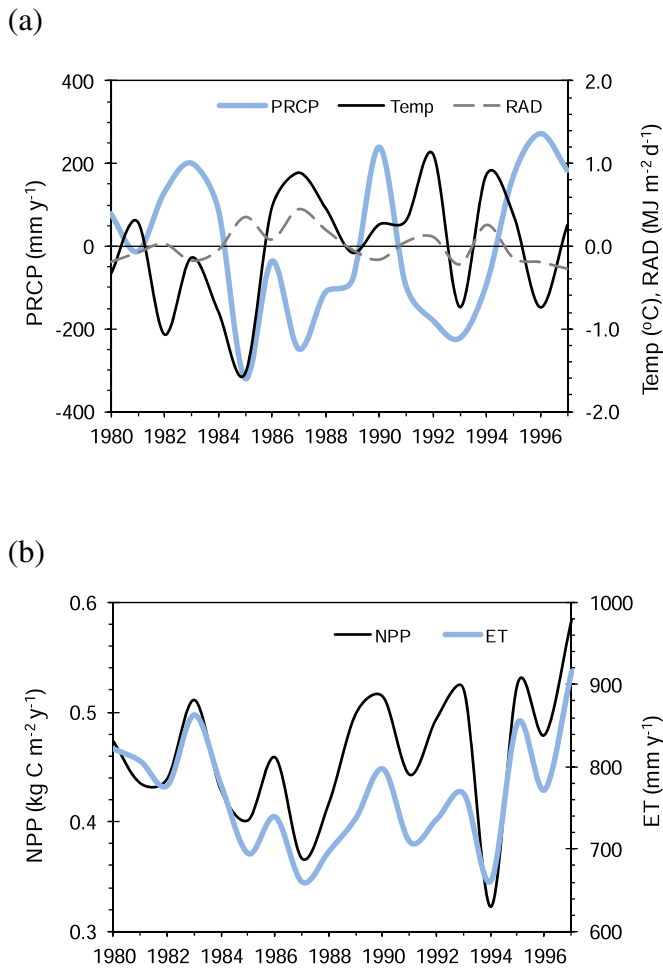


Fig. 2. Annual anomalies of (a) precipitation (PRCP, mm y^{-1}), air temperature (Temp, $^{\circ}\text{C}$), and incident shortwave solar radiation (RAD, $\text{MJ m}^{-2} \text{d}^{-1}$), and (b) NPP and ET for 1980–1997. The solid linear line indicates a significant ($P < 0.05$) temporal trend in mean annual air temperature of approximately 0.4°C per decade for the region.

cover map. The vegetation types at the LAI measurement sites included ENF (78 sites), MX (8), and grassland (6). Because the spatial scale of field LAI measurements is not comparable to that of the simulations, we utilized the watershed-mean LAI in comparison with the simulated LAI for each land cover type. Sparse LAI measurements for MX and grassland types increase uncertainty in the LAI validation results for those land cover types.

2.3. Model description

BIOME-BGC is a general ecosystem process model designed to simulate fluxes and storage of water, carbon and nitrogen for terrestrial biomes ranging from single plot to global scales. Details of the model are presented elsewhere (White et al., 2000; Thornton et al., 2002) and include applications for multiple biome types and spatial scales. The model is designed to realistically simulate soil-plant carbon (C) and nitrogen (N) cycling, but with simplifying assumptions to facilitate application at regional scales using a limited number (34) of biome specific physiological constants. All plant, litter, and soil C, N, and water pools and fluxes are entirely prognostic. The plant/ecosystem surface is represented by a single, homogeneous canopy, snow (when present) and soil layers. Understory vegetation is not distinguished from the aggregate canopy layer, though the homogeneous canopy is further divided into respective portions of sunlit and shaded canopies. The model uses a daily time-step with daily maximum and minimum air temperature and precipitation as the primary inputs from which mean daily shortwave radiation, vapor pressure deficit, and day/night average temperatures are estimated. Biophysical processes represented by the model include: photosynthetic C fixation from atmospheric CO_2 ; N uptake from the atmosphere and soil; C/N allocation to growing plant parts; seasonal phenology, decomposition of fresh plant litter and soil organic matter; plant mortality, growth, litterfall, decomposition and disturbance (i.e., fire and management); solar radiation interception and partitioning into sunlit and shaded leaf fractions; rainfall routing to leaves and soil; snow accumulation and

melting; drainage and runoff of soil water; evaporation of water from soil and wet leaves; evapotranspiration partitioning into transpiration, snow, soil and canopy evaporation components. The BIOME-BGC model has been successfully applied and validated over a range of diverse biomes, spatial scales and climate regimes (e.g., White et al., 2000), including all major biomes within the PNW domain (Schimel et al., 1997; White et al., 1997a,b; Nemani et al., 2002). The algorithms of BIOME-BGC form bases for a fully-prognostic treatment of carbon and nitrogen cycles in Land Community Model (CLM), the land component of the Community Earth System Model (CESM) (Oleson et al., 2010).

In this study, we utilized version 4.1.1 BIOME-BGC that was successfully validated for the PNW domain in previous studies. Thornton et al. (2002) applied the same BIOME-BGC model version to simulate disturbance effects (i.e. harvest and fire), while Kang et al. (2005) modified this version to incorporate historical fire disturbance. However, in this study, we did not consider the effect of disturbance and management in simulating vegetation carbon and water dynamics. This is partly due to difficulty in collecting historical disturbance maps for the PNW domain, and also due to uncertainty in future disturbance regime.

2.4. Simulation experiments

Historical atmospheric CO_2 concentrations were defined from statistical analysis of Mauna Loa flask measurements and ice core data (Enting et al., 1994; Wigley, 2000) and ranged from 294 ppm (1890) to 363 ppm (1997). A gridded daily surface meteorological database for 1980–1997 (DAYMET) was used to initialize model simulations and define model historical daily meteorological inputs. The BIOME-BGC model was implemented for each grid cell within the PNW domain (Fig. 1) consisting of 960 columns and 160 rows, and 0.0125° spatial resolution. Except for water, urban, and barren pixels, the BIOME-BGC simulations were run for a total of 131,487 pixels. Lateral connections between pixels and water routing to river systems were not considered in the simulation.

Simulation experiments were conducted in four steps. First, we ran the model in spin-up mode by cycling the gridded 18-year meteorological database with a fixed 1890-era atmospheric CO_2 concentration repeatedly until the simulated total ecosystem carbon content was relatively stable. Second, the results of these simulations provided the initial state for subsequent model simulations from 1890 to 1997 using the gridded 18-year meteorological database and historical atmospheric CO_2 concentrations from 294 ppm (1890) to 363 ppm (1997). Model results from the last 18 years (1980–1997) of the 108-year simulation were selected for further analysis, including regional assessment of spatial and temporal variations in net primary productivity (NPP) and evapotranspiration (ET). Third, we validated the model with annual-mean maximum LAI modeled for the 1980–1997 period by using field LAI measurements for 1999–2001 in Olympic NP, North Cascades NP, and Glacier NP. In addition, satellite-driven (MODIS) estimates of gross primary productivity (GPP) and NPP from 2001 to 2003 were prepared for the study area and compared with the 18-year mean GPP and NPP to test reliability of model predictions. Finally, a climate change response simulation was conducted for 1998 to 2105 using two different climate change scenarios (Table 1). The final 18-year (2088–2105) sequences of the 108-year simulations were used to examine the effects of the climate change scenarios on NPP and ET, relative to 1980–1997 conditions.

The two climate change scenarios were produced from the Hadley Centre climate model, HadCM3. The A2 and B2 scenarios assume increased atmospheric CO_2 from 369 ppm (year 2000) to 856 and 621 ppm, respectively, in 2100. These differences result in changes in mean annual temperature of $+4.2^{\circ}\text{C}$ (A2) and $+1.6^{\circ}\text{C}$ (B2) and mean annual precipitation of -7% (A2) and $+11\%$ (B2), with different seasonalities in climate (Table 1). We constructed 108-year (1998–2105) daily meteorological time series from the 18-year (1980–1997) DAYMET record by assuming a gradual change with fixed linear rates of temperature and precipitation increases or decreases for spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). For the climate change simulations, atmospheric CO_2 concentration varies depending on each CO_2 increase scenario. We also implemented a simulation assuming steady-state conditions using 1980–1997 meteorology and constant (1998) atmospheric CO_2 concentration for the 1998–2105 simulation, thus providing a control scenario for analyzing the relative impacts of climate change on NPP and ET.

For model validation, stringent validation requirements (Kleijnen et al., 1998) were applied by alternative regression analysis method to determine agreements between observed and modeled LAI, and between MODIS derived and BIOME-BGC modeled GPP and NPP. Basic regression analysis uses the observed and model values, and novel regression analysis uses the difference and the sum of the observed and model values (Kleijnen et al., 1998; Bennett et al., 2013). In this study, we used the basic regression analysis to test whether the model values significantly explain variations found in the observed values (i.e. significance of coefficient of determination, r^2). The novel regression analysis was applied to test whether the observed and model values have identical means and variances, in other words, whether the difference and sum of the values are uncorrelated (Kleijnen et al., 1998). For this test, we conducted the general linear regression analysis for the values of the difference and sum to examine whether the intercept and slope values were equal to

zero statistically at a 95% significance level (i.e. $p = 0.05$), which means the difference and sum are statistically uncorrelated.

2.5. Simulation analyses

For the 1980–1997 simulation, we examined spatial and temporal patterns of C stocks (above and below-ground vegetation, soil, and the sum of soil and vegetation C pools), C fluxes (GPP and NPP), and water fluxes (ET, transpiration, and evaporation). We conducted a spatial pattern analysis of model outputs emphasizing the longitudinal variation of ecosystem carbon and water variables, which also accounts for the primary PNW west-east regional gradients in topography, climate, and land cover. Model gridded outputs for the 18-year (1980–1997) time series were aggregated by longitudinal bands at 0.0125° resolution and then compared to precipitation and temperature data using statistical correlation analysis (IDL Version 7.1.1, ITT Visual Information Solutions) to assess relative climatic controls on west-east variability in simulated carbon stocks and fluxes.

Temporal correspondence between model simulations and environmental parameters (precipitation, air temperature, solar shortwave radiation) were assessed for individual grid cells and the entire PNW domain. Pearson correlation coefficients were calculated on a grid cell-by-cell basis between mean annual NPP and ET simulations and precipitation, temperature, and shortwave radiation, in order to assess spatial patterns of correspondence between climatic variables and estimated fluxes. We also assessed statistical relations of aerially averaged results to identify the primary environmental drivers of regional fluxes for the entire PNW domain.

Model simulations of potential future (1998–2105) conditions were evaluated by comparing results of the two climate change simulations with the control simulation in terms of relative changes in carbon fluxes (NPP, GPP, and heterotrophic respiration) and water fluxes (ET, transpiration, canopy and soil evaporation, and outflow). We also evaluated differences among the major PNW biomes in terms of their relative contributions to regional productivity, ET, and water outflow, and their potential response under future climate conditions. The model estimated outflow is the difference between precipitation and the sum of ET and soil water storage change. Hence, outflow is a source of runoff and water supply to river systems, though hydrologic routing of estimated runoff for river discharge was not considered in this investigation.

3. Results and discussion

3.1. Spatial variability in carbon and water

3.1.1. Model validations

Model predictions of maximum annual LAI agree well with watershed-averaged LAI derived from field measurements in ENF, MX, and grassland biomes ($r^2 = 0.95$, $p < 0.001$) (Fig. 3a). The model simulations explained up to 95% of observed variability in the field LAI measurements. The projected LAI results for field vs. BIOME-BGC simulations are $5.7 (\pm 2.4)$ vs. $6.1 (\pm 0.4)$ $\text{m}^2 \text{m}^{-2}$ for ENF, $4.5 (\pm 2.5)$ vs. $5.0 (\pm 2.1)$ $\text{m}^2 \text{m}^{-2}$ for MX, and $0.8 (\pm 0.8)$ vs. $0.3 (\pm 0.2)$ $\text{m}^2 \text{m}^{-2}$ for grassland, respectively. The model simulations capture similar between- and within-biome differences in vegetation canopy characteristics and associated climate–vegetation interactions for the focal areas in relatively pristine national parks. The regression analysis also showed reasonable agreements in the means and variances between field observed and model LAI with significance levels (p) of 0.19 and 0.07 for the intercept and slope of the difference and sum values, respectively.

Model predictions are generally higher for GPP and lower for NPP than MODIS derived GPP and NPP estimates for woody biomes including ENF (mean bias = +439 and $-5 \text{ g C m}^{-2} \text{y}^{-1}$ for GPP and NPP, respectively), DBF and MX (+252 and $-45 \text{ g C m}^{-2} \text{y}^{-1}$), and shrub (+187 and $-165 \text{ g C m}^{-2} \text{y}^{-1}$) (Fig. 3b and c). For grassland, both GPP and NPP are predicted lower than MODIS estimates (-317 and $-191 \text{ g C m}^{-2} \text{y}^{-1}$). The modeled GPP and NPP explained 92% and 99% of respective variations in the MODIS parameters. The MODIS GPP and NPP and field LAI observations, however, showed much greater within-biome variability (horizontal bars in Fig. 3). The regression analyses indicated that the MODIS and model means and variances are not statistically different for GPP but are significantly different for NPP. The significance levels for the intercept and slope were 0.13 and 0.07 for GPP and 0.009 and 0.02 for NPP, respectively. These results indicate that the model

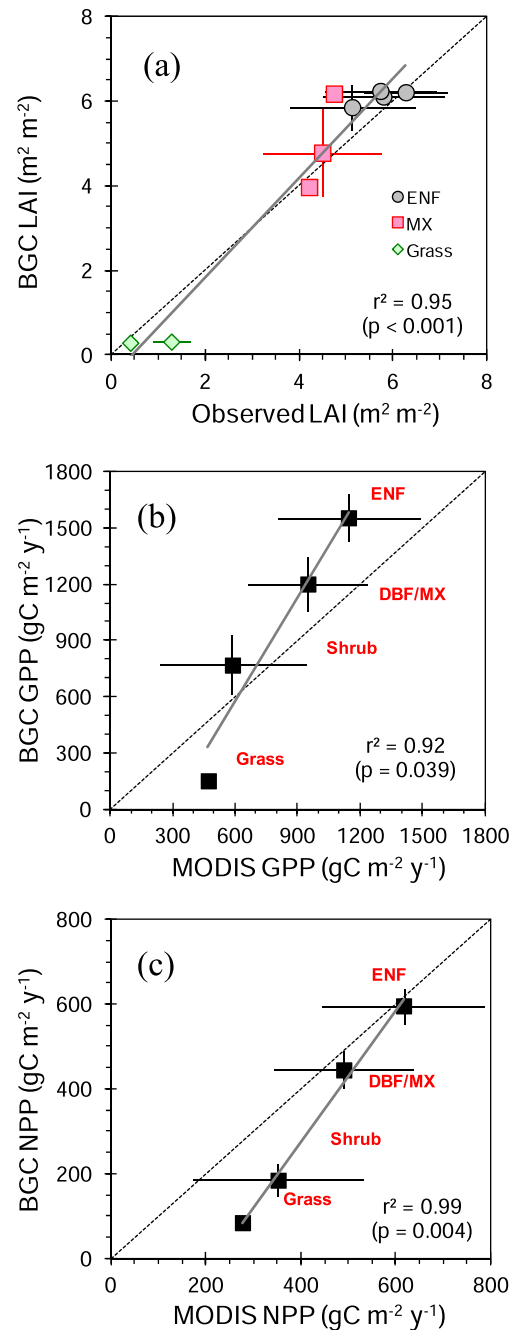


Fig. 3. Comparison of the model predictions with (a) observed leaf area index (LAI, $\text{m}^2 \text{m}^{-2}$), (b) MODIS GPP ($\text{g C m}^{-2} \text{y}^{-1}$), and (c) MODIS NPP ($\text{g C m}^{-2} \text{y}^{-1}$) for different biomes across the PNW domain. The observed LAI data were collected for several pristine watersheds in Olympic NP, North Cascades NP, and Glacier NP, where we assume that current vegetation is similar to potential vegetation conditions represented by the model simulations. MODIS GPP and NPP from 2001 to 2003 were averaged for each biome in the study region. Horizontal and vertical bars represent standard deviations within each watershed for LAI and GPP and NPP for the PNW. Regression relationships between modeled and MODIS GPP and NPP are denoted (solid gray lines) with coefficients of determination (r^2) and significance (p value).

simulations adequately explained observed variations of LAI, GPP, and NPP, but favorably predicted the observed parameter means and variances only for LAI and GPP.

Because MODIS GPP and NPP products contain uncertainties for some biomes and geographical locations, MODIS may not provide a robust validation of model predictions. For example, Heinsch et al. (2006) compared MODIS GPP with flux tower GPP measurements

across different biome types in North America and reported that MODIS GPP showed mean biases of +22, +17, +127, −1, and 0 $\text{g C m}^{-2} \text{y}^{-1}$ for ENF, savanna, open shrubland, MX, and grassland biomes, respectively. Zhao et al. (2005) reported that MODIS NPP was comparable to the Ecosystem Model-Data Intercomparison (EMDI) NPP dataset. These comparisons indicate that despite documented uncertainties in MODIS productivity products, the MODIS driven estimates show reasonable accuracy for regional or global-scale estimates and hence, provide a useful standard for evaluating other independent model predictions.

In principle, the BIOME-BGC simulations from this study describe potential vegetation condition because of model initialization to relative steady-state conditions for simulated total ecosystem C content. The potential vegetation is likely to have higher biomass and LAI, so we hypothesized that model predictions result in higher GPP but lower NPP than actual vegetation relative to (MODIS observation based estimates of these parameters) that reflect disturbance history and management impacts (Thornton et al., 2002). Our comparisons generally support this hypothesis (Fig. 3b and c), which indicates that the model simulations can capture differences in biome-specific productivity for potential vegetation in the PNW.

On the other hand, there are some critical aspects of these simulations that should be considered in interpreting the model results. First, we did not consider disturbance effects (e.g. fire and harvest) in shaping current and future vegetation status. In previous studies, BIOME-BGC was applied to simulate carbon and water dynamics in disturbed landscapes (Thornton et al., 2002; Kang et al., 2005). Explicit consideration on disturbance effects, however, requires site-specific historical records on diverse disturbance types that were unavailable for this investigation. Hence, we targeted simulations of potential vegetation conditions and then evaluated the model results within relatively pristine national park areas. Because we did not apply future disturbance scenarios, our

projected simulations do not consider how disturbances will shape future landscapes but only reflect direct sensitivity of simulated carbon and water dynamics to projected future climate conditions.

The model validation scheme used in this investigation is suitable for verifying regional patterns and relative productivity differences among different PNW biomes and along environmental gradients in relation to sparse ground observations and independent satellite data driven estimates of these processes. However, because the model simulations represent potential vegetation conditions, comparisons of these results against observational records provide only limited information on model performance. Compiling various hydrological and ecological data from pristine regions would be useful for enhancing model performance evaluations, though most ecosystems are characterized by non-steady state conditions due to various levels of disturbance and recovery.

3.1.2. Variation in longitudinal gradients

The model results have considerable spatial variability in estimated C and water stocks and fluxes that correspond with the west-east topographic gradient. The ET, GPP, and NPP simulations are highest in the west, intermediate in the east, and lowest in the central portion of the study area (Fig. 4a and b). ET is higher on the western side of mountain ranges and directly proportional to annual precipitation. Evaporation is the dominant component of ET in coastal areas of the domain, while transpiration is dominant in other areas, indicating greater vegetation control of ET in more arid central and eastern portions of the PNW.

The NPP/GPP ratio ranges from 0.34 to 0.43, with a mean of 0.38 and is generally higher in cooler climate zones, which is coincident with decreasing NPP/GPP ratio in temperature ranges from -20°C to 10°C reported by Zhang et al. (2009). GPP and NPP/GPP vary by 7- and 1.5-fold, respectively, across the study area. In contrast to ET and GPP, total ecosystem C stocks, including soil and vegetation, is higher in the east ($\sim 70 \text{ kg C m}^{-2}$) than in the west ($\sim 60 \text{ kg C m}^{-2}$)

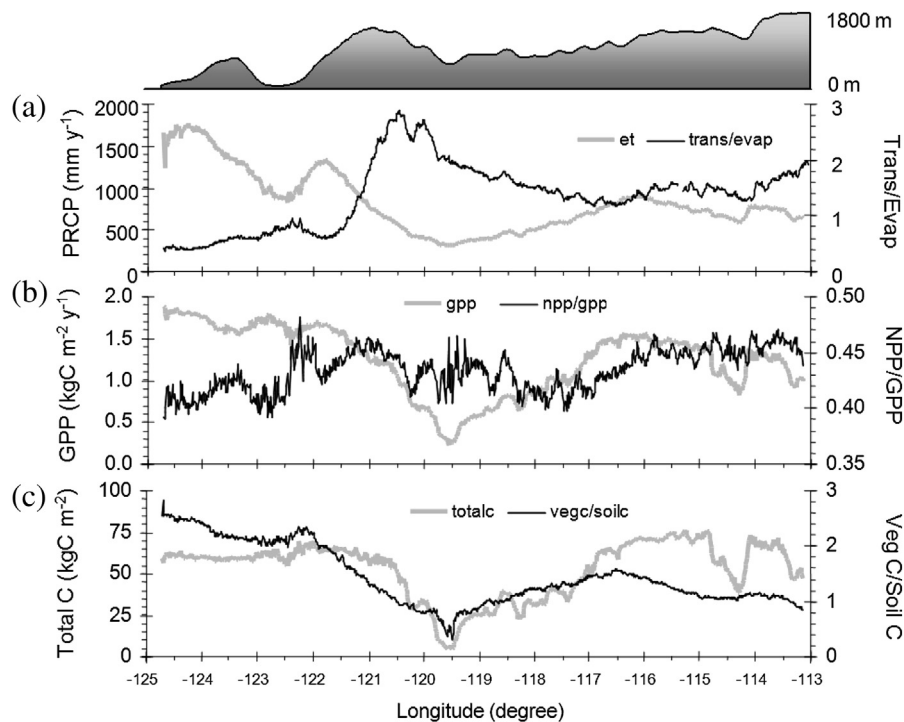


Fig. 4. Longitudinal variations in BIOME-BGC derived (a) evapotranspiration (mm y^{-1}) and the ratio of transpiration to evaporation, (b) GPP ($\text{kg C m}^{-2} \text{y}^{-1}$) and the ratio of NPP to GPP, and (c) total carbon stocks (kg C m^{-2}) and ratio of vegetation to soil carbon. The shaded graph shows the longitudinal-mean elevation gradient (0–1800 m) from the Pacific coast to the Rocky Mountains.

and varies by approximately 18-fold across the domain (Fig. 4c). Forested areas of the western portion of the domain have a higher proportion of total C storage in vegetation biomass, and forests in the eastern portion of the domain have higher proportional storage as soil C. Longitudinal variability in simulated C stocks and fluxes corresponds closely with regional precipitation and temperature patterns (see Fig. 5). Areas with mean precipitation lower than 1300 mm y^{-1} have strong positive relationships for precipitation and both C fluxes (Fig. 5a) and C stocks (Fig. 5b). Temperature is a better indicator of longitudinal variations in simulated C variables in areas with higher precipitation, where GPP, NPP, and vegetation C increase but soil C decreases with temperature (Garten et al., 1999).

3.1.3. Variation in elevation gradients

Simulated C stocks and C and water fluxes have high variability in relation to elevation changes across the PNW (Fig. 6). Total and soil C stocks are generally maximized at mid elevations:

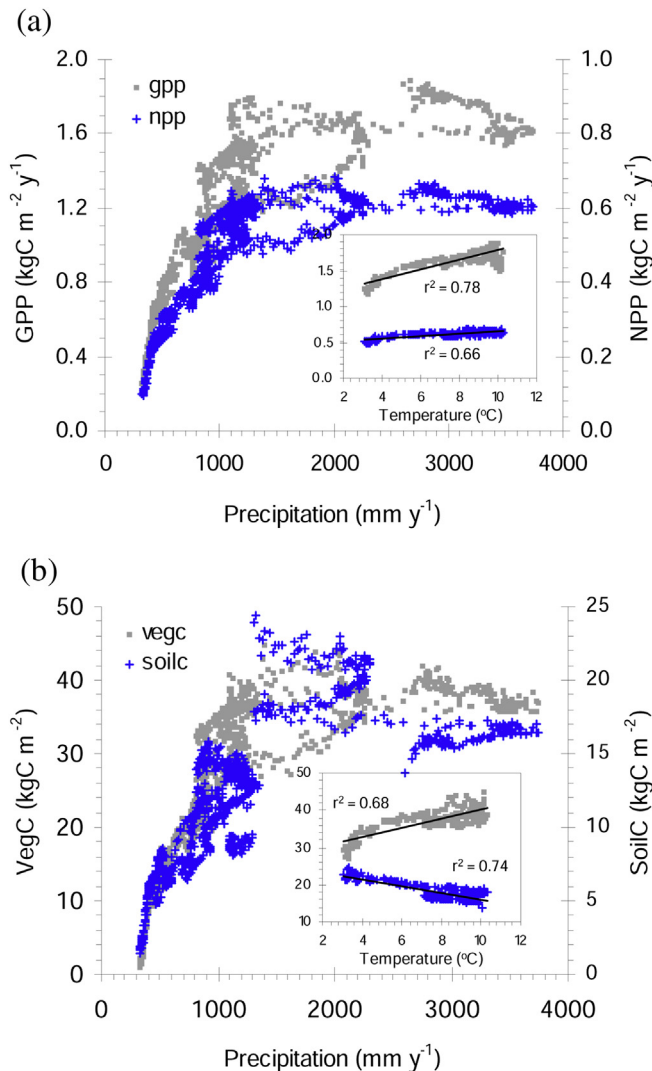


Fig. 5. Scatter plots of the relationships between longitudinal-mean variables: (a) precipitation (mm y^{-1}) vs. GPP and NPP ($\text{kg C m}^{-2} \text{ y}^{-1}$), and (b) precipitation vs. vegetation and soil carbon stocks (kg C m^{-2}). The embedded graphs are scatter plots between the carbon variables and temperature ($^{\circ}\text{C}$) for precipitation conditions above 1300 mm y^{-1} . Under these conditions, temperature was a better indicator of variability in productivity and carbon stocks, whereas precipitation was a better indicator under drier ($<1300 \text{ mm y}^{-1}$) conditions.

$>70 \text{ kg C m}^{-2}$ between 1600 and 1900 m, and $>30 \text{ kg C m}^{-2}$ between 1800 and 2000 m. Areas above 2500 m and between 400 and 800 m contain smaller C stocks, which correspond to high mountain and central dry areas, respectively. The soil fraction of total C content is directly proportional to elevation, ranging from 27 to 64% (Fig. 6a), whereas the vegetation fraction of total C decreases with increasing elevation. Annual GPP and NPP are highest below 200 m and from 1000 to 2000 m (Fig. 6b). The NPP/GPP ratio generally increases with elevation from 0.36 to 0.50, similar to the values reported for other regional studies (Waring et al., 1998; Gifford, 2003).

Annual precipitation is relatively high along the Pacific coast and is directly proportional to elevation above 500 m, with regional maximums above 2500 m (Fig. 1). Predicted outflow, defined the difference between precipitation and the sum of ET and soil water storage, represents the amount of water available for runoff and streamflow. The relationship between model outflow and elevation is similar to precipitation, whereas both ET and transpiration are inversely proportional to elevation above 2000 m (Fig. 6c) and coincide with low productivity and C stocks at high elevation. Low ET at high elevation and predominance of snowfall result in a relatively large (up to 87%) proportion of precipitation as outflow, compared to only 26% for inland semi-arid areas between 500 and 800 m (Fig. 6d). The relative importance of transpiration increases steadily from 34 to 68% of ET, but decreases to a regional minimum of approximately 8% above 2200 m (Fig. 6c).

3.1.4. Variation among national park areas

Table 2(a) summarizes the estimated NPP, ET, outflow, total C, and soil C for the three national parks and PNW regional domain. Total C stocks average 52.5 kg C m^{-2} , compared with 57.9 kg C m^{-2} (Olympic NP), 60.8 kg C m^{-2} (North Cascades NP), and 62.7 kg C m^{-2} (Glacier NP) for the three national parks. The relative proportion of soil C to total C is highest in Glacier NP (42%) and lowest in Olympic NP (28%). NPP, ET and hydrologic outflow are highest in Olympic NP, followed by North Cascades NP and Glacier NP. Hydrologic outflows from the national parks are higher than other areas of the PNW. These results suggest that high mountain areas represented by these national parks have particularly important roles in storing terrestrial C and supplying water to river systems.

3.2. Interannual variation of carbon and water fluxes

Interannual variability in aerial mean NPP and ET show strong, direct correspondence with each other ($r = 0.81$, $p < 0.01$). The deviation of annual ET ranges from -104 to 150 mm y^{-1} for the PNW region and represents 33% of long-term (18-year) average ET conditions (766 mm y^{-1}). Annual deviation in NPP ranges from -139 to $123 \text{ g C m}^{-2} \text{ y}^{-1}$ and represents 57% of the 18-year mean annual flux ($462 \text{ g C m}^{-2} \text{ y}^{-1}$). Model simulations of NPP, ET, and radiation use efficiency (i.e., GPP/photosynthetically active radiation) are positively correlated with rainfall ($p < 0.01$) but inversely proportional to VPD and radiation ($p < 0.01$) (Table 3), which indicates that the PNW is predominantly water limited for NPP and ET. Aerial mean water use efficiency (i.e., GPP/transpiration) is weakly correlated with the climatic variables, except for temperature ($r = 0.52$, $p < 0.05$).

Interannual variability in ET and NPP simulations correspond to changes in precipitation, temperature, and shortwave radiation, whereas the relative strength and direction of these relationships vary considerably across the PNW (Fig. 7). Correlation patterns are significantly different among the climatic variables. Annual ET corresponds strongly and directly with annual precipitation in southern coastal and semi-arid central regions of the PNW,

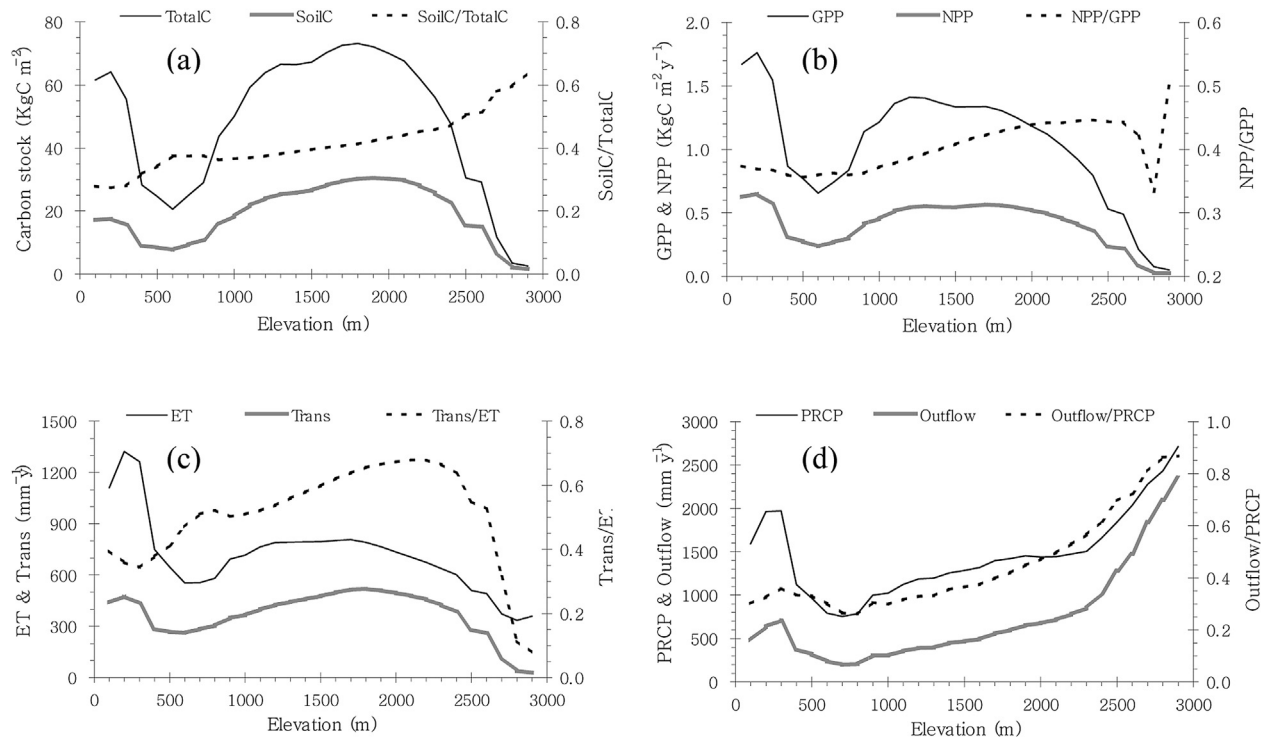


Fig. 6. Variations in mean annual C and water variables with elevation for the entire PNW including: (a) soil and total (vegetation + soil) C stocks, and their ratio; (b) GPP, NPP, and their ratio; (c) ET, transpiration (Trans), and their ratio; and (d) precipitation, outflow, and their ratio. All variables were averaged at 100-m elevation intervals.

whereas ET is more strongly associated with temperature and solar radiation in colder, energy limited ecosystems at higher elevations, including national park areas. Both ET and NPP have similar spatial patterns of correspondence with climatic variables, except for the southern coastal area of the Olympic Peninsula where no single climatic variable is dominant in explaining NPP interannual variability.

The positive NPP anomaly corresponded with increased precipitation in the PNW, except for years 1992–1993 (Fig. 2). Despite less precipitation from 1991 to 1994 and cooler temperatures in 2003, NPP showed a positive anomaly for 1992–1993. Similarly, Gu et al. (2003) reported enhanced Harvard Forest photosynthesis in 1992 and 1993 due to increased diffuse radiation caused by volcanic aerosols following the Pinatubo eruption.

3.3. Potential climate change effects on carbon and water fluxes

3.3.1. A2 scenario

The A2 scenario is characterized by increased temperature (+4.2 °C) and decreased annual precipitation (−7%) with hot (+6.7 °C) and dry (−34%) summer conditions relative to 1980–1997 conditions (Table 1). Overall, carbon and water fluxes were enhanced under the A2 scenario relative to the control simulations, except for transpiration and outflow (see Fig. 8). The A2 scenario results in 23% and 10% increases in NPP and ET, respectively, above current conditions over the entire domain, whereas the spatial pattern of the responses to these changes vary by land cover type. The 15% decrease in outflow is larger than expected, given the 7% decrease in A2 precipitation. Transpiration decreases under the A2

Table 2

Comparisons of mean carbon stocks and carbon and water fluxes across the PNW study domain, Olympic National Park (NP), North Cascades NP, Glacier NP, and other PNW areas outside park boundaries.

	NPP (kg C m ⁻² y ⁻¹)	ET (mm y ⁻¹)	Outflow (mm y ⁻¹)	Total C (kg m ⁻²)	Soil C (kg m ⁻²)	Soil C/Total C
(a) Means for 1980–1997 simulation						
Olympic NP	0.59	1409	2087	57.9	16.5	0.28
North Cascades NP	0.52	832	686	60.8	23.2	0.38
Glacier NP	0.50	775	547	62.7	26.4	0.42
Other area	0.44	722	271	50.2	18.8	0.37
PNW average	0.46	767	407	52.2	19.4	0.37
(b) Means for 2088–2105 simulation with A2 scenario						
Olympic NP	0.73	1640	2094	61.7	16.2	0.26
North Cascades NP	0.64	972	600	64.3	22.9	0.36
Glacier NP	0.63	865	447	66.1	26.1	0.40
Other area	0.54	761	216	52.4	18.6	0.36
PNW average	0.56	828	350	54.6	19.2	0.35
(c) Means for 2088–2105 simulation with B2 scenario						
Olympic NP	0.66	1649	2182	59.7	16.3	0.27
North Cascades NP	0.58	970	665	62.6	23.1	0.37
Glacier NP	0.57	911	540	64.6	26.3	0.41
Other area	0.49	816	259	51.6	18.8	0.36
PNW average	0.51	873	399	53.6	19.4	0.36

Table 3
Pearson correlation coefficients between mean annual NPP and ET and meteorological variables in the PNW study domain for 1980–1997; *p* values are in parentheses.

	Precipitation	Rainfall	VPD	Temperature	Radiation
NPP	0.50 (0.03)	0.65 (0.003)	−0.81 (<0.001)	−0.08 (>0.1)	−0.82 (<0.001)
ET	0.74 (<0.001)	0.90 (<0.001)	−0.76 (<0.001)	−0.16 (>0.1)	−0.85 (<0.001)
Radiation use efficiency	0.60 (0.009)	0.75 (<0.001)	−0.83 (<0.001)	−0.03 (>0.1)	−0.90 (<0.001)
Water use efficiency	0.01 (>0.1)	0.26 (>0.1)	−0.14 (>0.1)	0.52 (0.02)	−0.31 (>0.1)

scenario but is offset by a large increase in canopy evaporation, resulting in higher ET and lower outflow. The reduction in transpiration is attributed to a 34% decrease in summer precipitation. Both canopy and soil evaporation are enhanced under the A2 scenario, although canopy evaporation has much larger increases (36%) than soil evaporation (3%). Increased rates of canopy evaporation are attributed to increased canopy interception of precipitation from increased NPP, LAI, and the rainfall fraction of total precipitation. Increased canopy interception and evaporation of precipitation also result in decreased soil water availability for soil evaporation and transpiration. Relatively warm (+2.5 °C) and moist (+11%) winter conditions under the A2 scenario also increase winter canopy evaporation, offsetting decreases in summer evaporation and resulting in an overall increase in annual evaporation.

Simulations of mean water use efficiency (WUE) across the PNW study domain increase by 58% under the A2 scenario, but also vary according to individual land cover classes. The largest WUE increase occurs in ENF (+63%), followed by DBF (+43%) and grassland (+16%) cover types (Fig. 9). WUE is enhanced through the

fertilization effects of increased atmospheric CO₂ concentrations on GPP, and increased canopy stomatal reductions of water losses under warmer and drier climate conditions. The model response to the A2 scenario also reveals complex interactions between WUE and C and water fluxes that result in a non-linear response of outflow. For ENF, increased WUE under the A2 scenario is caused by increased NPP, canopy interception, canopy evaporation, and ET, which also result in associated reductions in outflow. However, the relative effects of increased WUE on annual outflow are greatly reduced for DBF and grassland cover types because the deciduous characteristics of these classes enables a general increase in warm winter outflow, resulting in only minor (1%) reductions in annual flows, despite a 7% reduction in annual precipitation and a large (23%) increase in canopy evaporation.

3.3.2. B2 scenario

The B2 scenario has increased temperature (+1.6 °C) and annual precipitation (+11%) with a wetter (+24%) summer climate relative to 1980–1997 conditions. Overall, when compared with the control

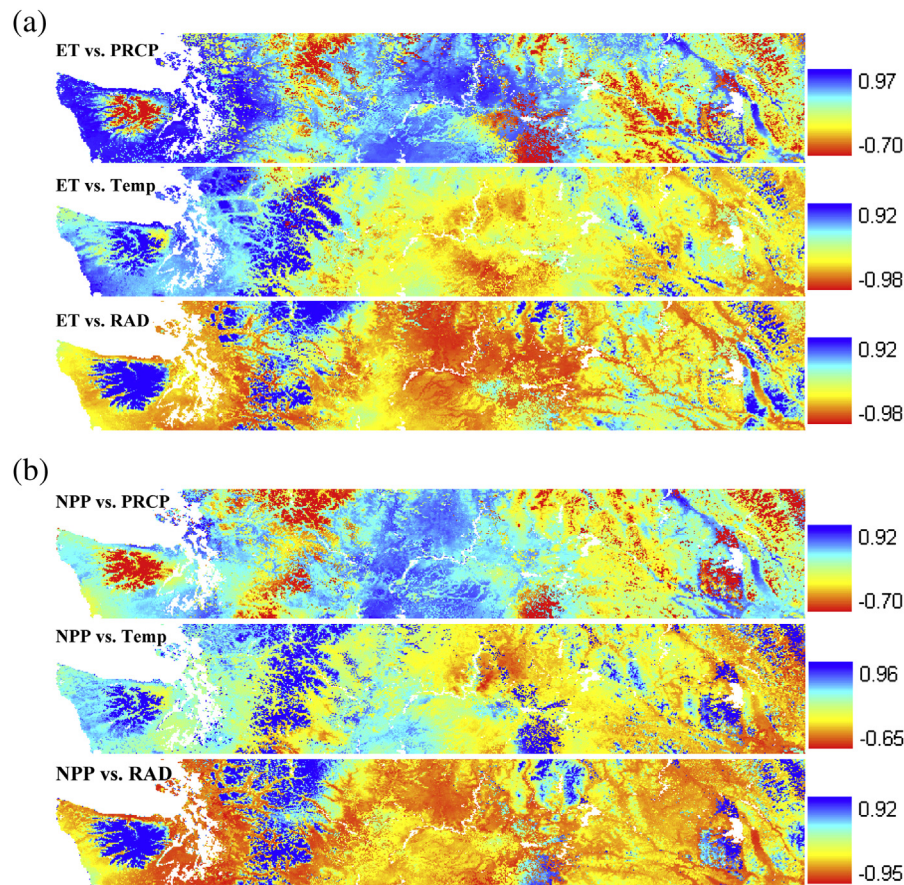


Fig. 7. Spatial maps showing grid cell-wise Pearson correlation coefficients of (a) evapotranspiration (ET, mm y^{−1}) vs. precipitation (PRCP, mm y^{−1}), temperature (Temp, °C), and incident shortwave solar radiation (RAD, MJ m^{−2} d^{−1}); (b) net primary production (NPP, kg C m^{−2} y^{−1}) vs. precipitation (PRCP, mm y^{−1}), temperature (Temp, °C), and incident shortwave solar radiation (RAD, MJ m^{−2} d^{−1}) for 1980–1997. The map domain is 113–125 W of longitude and 47–49 N of latitude.

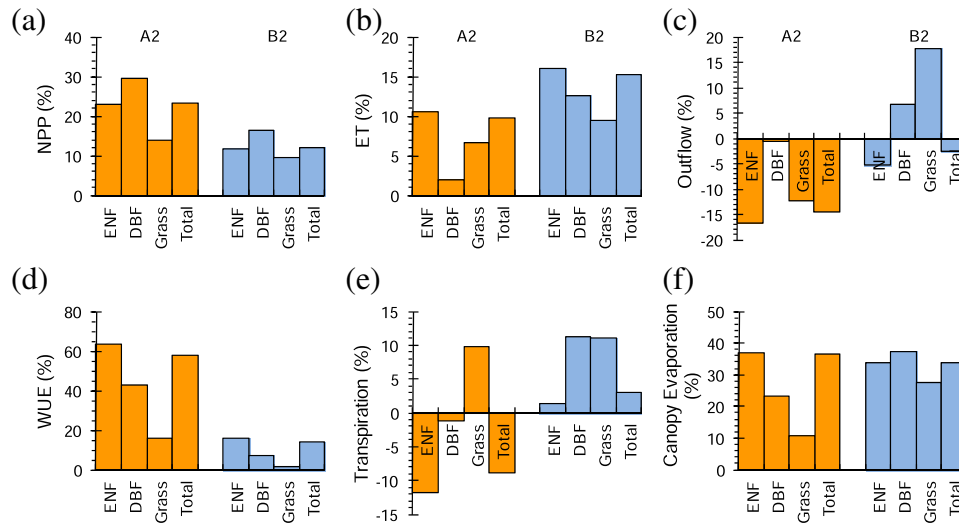


Fig. 8. Biome-specific increased or decreased rates (%) of climate change simulations to the control simulation for the A2 and B2 scenarios: (a) NPP, (b) ET, (c) outflow, (d) water use efficiency (WUE), (e) transpiration, and (f) canopy evaporation. Total value is the aerial mean for the whole study area.

simulation, C and water fluxes are enhanced under the B2 scenario, except for outflow (Fig. 8). The B2 scenario results in increased aerial average NPP (+12%) and ET (+15%), and a 2% decrease in regional outflow, although the relative responses of individual land cover classes to these changes differed. Relative increases in NPP and ET for the B2 scenario are attributed to more favorable growing season conditions under a warmer and wetter climate. Despite a relatively large increase in annual precipitation, however, outflow still shows a general decrease under the B2 scenario. The negative outflow response is attributed to enhanced ET from increased vegetation productivity and associated increases in both transpiration and evaporation, offsetting any gains from a wetter climate. Canopy evaporation increases by 34%, overwhelming any potential enhancement in excess water supply from increased precipitation.

Aerial mean WUE increases by 14% under the B2 scenario and is smaller than the WUE response under the A2 scenario. The

reduced WUE response is attributed to a smaller B2 projected increase in atmospheric CO₂ (621 ppm) than the A2 scenario (856 ppm). Similarly, the largest increase in WUE is in ENF (+16%), followed by DBF (+7%) and grassland (+2%) vegetation (Fig. 8). Overall increases in temperature and plant-available moisture for photosynthesis and higher atmospheric CO₂ result in increased GPP and associated WUE. Enhanced canopy development (LAI) under the B2 scenario also results in considerable increases in ET, primarily through increased canopy evaporation for ENF (+34%), DBF (+37%), and grassland (+27%) vegetation; this results in reduced outflow despite the B2 increase in precipitation.

3.3.3. Effects of climate change in national park areas

The projected climate change response of the three national parks relative to other PNW areas shows larger increases in NPP (+23–27%

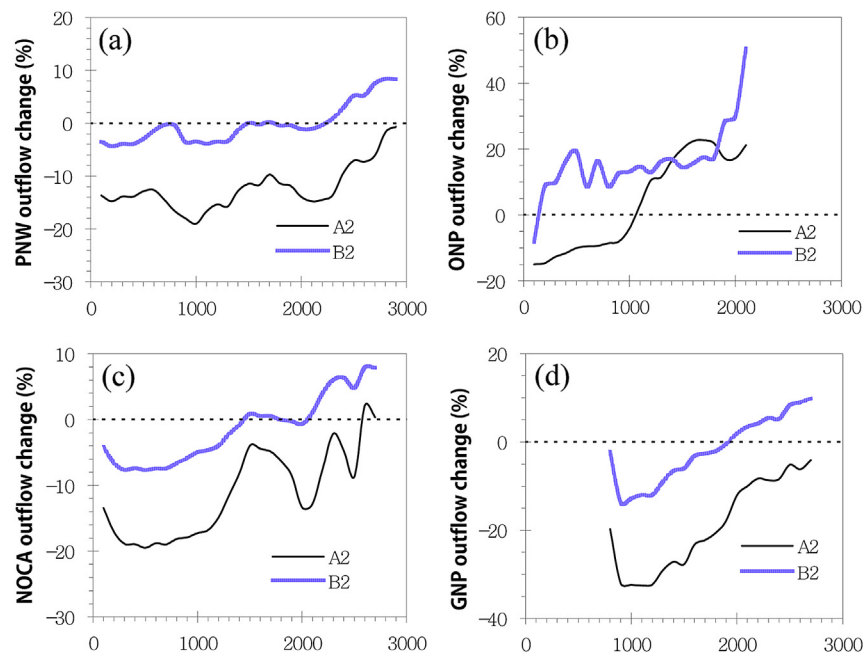


Fig. 9. Percent changes of outflows simulated under A2 and B2 climate scenarios for years 2088–2105 with respect to 1980–1997 simulations. The values were averaged by 100-m elevation interval for (a) entire PNW, (b) Olympic NP, (c) North Cascades NP, and (d) Glacier NP. Minus value denotes outflow reduction with a particular scenario.

vs. +22%), ET (+12–17% vs. +5%), and total carbon stocks (+5.3–6.6% vs. +4.5%), and larger decreases in soil C (–1.5 to 1.5% vs. –0.9%) for the A2 scenario. The park areas also show a similar pattern under the B2 scenario, with larger increases in ET (+17–18% vs. +13%) and total C (+2.9–3.1% vs. +2.7%) and larger decreases in soil C (–0.4 to –0.9% vs. –0.4%) relative to other areas of the PNW (Table 2).

Relative responses to the A2 and B2 scenarios are similar among the three national park areas and the entire PNW domain. NPP, ET and total terrestrial C stocks increase under projected climatic conditions, whereas soil C storage decreases (Table 2). The only difference in these general responses occurs in Olympic NP, where A2 and B2 scenarios result in respective 0.4% and 4.6% increases in outflow, compared to mean outflow reductions of 20% and 4% for other areas.

The PNW region has considerable reductions of outflow under the A2 scenario for all elevations, while outflows under the B2 scenario decrease below 1500 m elevation and increase above that elevation (Fig. 9a). The elevation-related distribution of outflow changes with respect to the A2 and B2 scenarios are similar for North Cascades NP (Fig. 9c) and Glacier NP (Fig. 9d) but different for Olympic NP (Fig. 9b). Outflow response for Olympic NP increases in areas above 1100 m for A2 and above 200 m for B2, relative to current conditions. This indicates that, in Olympic NP, the modeled water balance would be changed to increase outflow under projected future conditions, even under the reduced precipitation of the A2 climate. Although outflow declines for both North Cascades NP and Glacier NP under both scenarios, these reductions are lower than the estimated 20% (A2) and 4% (B2) outflow reductions for other PNW areas outside the parks (e.g., Table 2). Our simulations indicate that the terrestrial water balance varies considerably across the PNW, depending on elevation and geographic locations, vegetation type and for different climate change scenarios.

4. Summary and conclusions

Using the process-based biogeochemical model BIOME-BGC, we quantified the effects of two projected climate scenarios on vegetation C and water dynamics in the PNW. The most important findings from our simulation experiments are summarized below.

- (1) Large west-to-east spatial variations in the modeled C and water fluxes and C stocks are found, and these variations are generally associated with mountainous topography and distance from the west coast. The modeled carbon fluxes and stocks are strongly positively correlated with precipitation in areas where precipitation is $<1300 \text{ mm y}^{-1}$, whereas they are correlated more strongly with temperature than precipitation in areas where precipitation is $>1300 \text{ mm y}^{-1}$.
- (2) Interannual variability of NPP and ET are 57% and 33% of the 18-year mean annual fluxes for 1980–1997, respectively, and are positively correlated with rainfall but inversely proportional to VPD, indicating that the PNW is predominantly water limited for NPP and ET in the context of the BIOME-BGC simulation.
- (3) The A2 climate change scenario (hotter [+4.2 °C], drier [–7%] climate) results in increased NPP (23%), increased ET (10%), and decreased outflow (15%) for the PNW. The modeled carbon and water flux components may explain mechanisms of the above changes at a process level. The model simulations indicate that decreased transpiration is offset by a large increase in canopy evaporation, resulting in increased ET, which also results in decreased soil water availability for transpiration. The large increase in canopy evaporation is caused by increased NPP and LAI, and the associated large increase in canopy interception of precipitation.

- (4) The B2 scenario (warmer [+1.6 °C], wetter [+11%] climate), results in increased NPP (12%), increased ET (12%), and decreased outflow (2%), despite increased precipitation. The future simulation experiments show that the enhanced ET from increased vegetation productivity and associated increases in both transpiration and evaporation offset any gains from a wetter climate resulting in overall decrease in hydrologic outflows and potential water available for runoff and streamflow.
- (5) The modeled carbon and water dynamics of the national parks are characterized by higher total and vegetation C stocks, and higher NPP, ET, and outflow than those of non-park areas in the PNW. The projected climate change response of the three national parks includes increased NPP, ET, and total C, but larger decreases in soil C for both A2 and B2 scenarios than in other PNW areas. Although outflow declines for both North Cascades NP and Glacier NP under both scenarios, these reductions are lower than the outflow reductions for other PNW areas. In contrast, Olympic NP supplies additional water resources under projected future conditions, even under the reduced precipitation of the A2 scenario.

It is worthy of noting some limitations and lessons from our simulations. Model validation on current status of carbon and water dynamics was conducted only with limited LAI observations from relatively pristine NP areas at a watershed scale and with regional MODIS primary productivity estimates over the larger PNW study domain. Because our analysis focused on interpreting future changes of vegetation carbon and water dynamics, the model performance needs to be evaluated for various flux and state variables of current vegetations conditions. Our model simulations did not consider disturbance effects (e.g., fire and harvest), lateral water flow between pixels, and runoff routing of outflow water to river systems. These limitations constrain realistic interpretations of the modeled carbon and water dynamics of the PNW study region, which confines our simulation results to investigating sensitivity of potential vegetation carbon and water dynamics to climate change and variability.

These limitations provide a basis for developing more comprehensive regional modeling schemes, including use of more extensive field data collections for model validation, especially, across regions with different climatic and disturbance regimes, developing consistent regional historical disturbance records and plausible future disturbance scenarios at spatial scales consistent with landscape heterogeneity, and incorporating water routing for better representing terrestrial and aquatic linkages. More realistic region-scale simulations may provide further opportunities to enhance our understanding of mechanisms of ecosystem response to climate change (Bachelet et al., 2001; Fagre et al., 2003) and disturbance (Kang et al., 2005), and also make it feasible to implement mitigation and adaptation strategies at regional and sub-regional scales (Millar et al., 2007; Joyce et al., 2009).

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