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# A comprehensive analysis of interseasonal and interannual energy and water balance dynamics in semiarid shrubland and forest ecosystems

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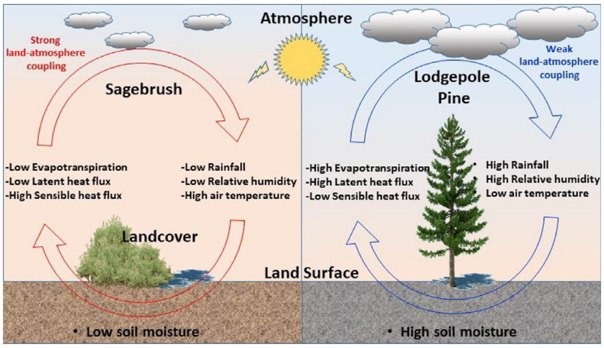
## HIGHLIGHTS

- Interannual variability in energy fluxes was due to precipitation.
- Sagebrush had weak soil moisture-temperature coupling and had a stronger advection.
- Sagebrush had severe water deficit conditions from the Budyko analysis.
- Strong asymmetric relationship from the complementary analysis for sagebrush
- Dominant controls are soil evaporation at sagebrush and transpiration at lodgepole pine.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Accurate estimation of ecosystem-scale land surface energy and water balance has great importance in weather and climate studies. This paper summarizes seasonal and interannual fluctuations of energy and water balance components in two distinctive semiarid ecosystems, sagebrush (SB) and lodgepole pine (LP) in the Snake River basin of Idaho. This study includes 6 years (2011–2016) of eddy covariance (EC) along with modeled estimates. An analysis of the energy balance indicated a higher energy balance ratio (0.88) for SB than for LP (0.86). The inclusion of canopy storage ($C_S$) increased the association between turbulent fluxes and available energy in LP. Green vegetation fraction (GVF) significantly controlled evapotranspiration (ET) and surface energy partitioning when available energy and soil moisture were not limited. Seasonal water balance in the Budyko framework showed severe water-limited conditions in SB (6–9 months) compared to LP (6–7 months). Based on the validated Noah land surface model estimates, direct soil evaporation ($E_{Soil}$) is the main component of ET (62 to 79%) in SB due to a large proportion of bare soil (60%), whereas at the lodgepole pine site, it was transpiration ($E_{Tran}$, 42–52%). A complementary ratio (CR) analysis on ET and potential ET (PET) showed a strong asymmetric CR in SB, indicating significant advection. Both SG and LP showed strong coupling between soil moisture (SM) and air temperature ($T_a$). However, a weak coupling was observed in SB when the soil was dry and $T_a$ was high. This weak coupling was due to the presence of net advection. The results presented here have a wider application: to help us understand and predict the survival, productivity, and hydroclimatology of water-limited ecosystems.

## 1. Introduction

The land surface, a transition layer between the subsurface soil column and atmospheric boundary layer (ABL), regulates the complex

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loop of coupled energy and water feedback processes. At the land surface, precipitation is partitioned into evapotranspiration (ET), runoff, and recharge. Similarly, the net radiation ($R_N$) near the land surface is partitioned into sensible heat flux (SH), latent heat flux (LH), ground heat flux (GH), and thermal radiation. Turbulent heat flux comprises LH and SH, which regulate the flow and thermodynamic structure of ABL and hence atmospheric circulation (Lee, 2015). GH controls the thermal storage of the surface and the subsurface soil column. LH (latent heat of vaporization × ET) represents the amount of water evaporated into the atmosphere in terms of energy units. The partitioning of the energy and water budget determines the state of the land surface, which mediates the coupling between land and ABL (Charney, 1975; Gentine et al., 2013; Koster et al., 2006; Milly and Dunne, 1994; Pielke et al., 2002; Porporato, 2009; Robock et al., 1995; Wang et al., 2007). The spatiotemporal variations in land surface properties—such as vegetation cover, soil moisture, available energy and emissivity—and spatial heterogeneity in topography are the major drivers that modify land surface energy and water partitioning (Chehbouni et al., 1999; Gentine et al., 2013; Ward et al., 2014; Yang and Wang, 2014; Huang et al., 2017). The central theme of land-atmospheric coupling is the sensitivity of ET to soil moisture (Teuling et al., 2006). Thus, the quantification of surface energy and water balance at the land surface has great importance in numerical weather predictions, climate studies, and understanding the impact of soil–vegetation–atmosphere interactions on the local and regional weather and climate (Betts et al., 1997; Idso et al., 1975; Maurer et al., 2001; Pielke et al., 2002; Sridhar et al., 2002; Ward et al., 2014).

In arid and semiarid environments, the ecosystems are hydrologically closed on timescales longer than seasons (Huntington et al., 2011; Kurc and Small, 2004; Reynolds et al., 2000; Sala et al., 1992). That is, in water-limited environments, ET is approximately equal to precipitation on an annual timescale (Budyko, 1971; Kurc and Small, 2004; Phillips, 1994). ET varies greatly through annual and seasonal time cycles due to variations in meteorological, vegetation, and soil moisture conditions (Anderson et al., 2012; Ceperley et al., 2017; Nagler et al., 2007). In a water-limited ecosystem, where potential ET (PET) is larger than precipitation, ET is mainly controlled by the soil moisture status. However, when soil moisture is not limited, meteorological and vegetational (phenological) conditions control ET (Kurc and Small, 2004; Shuttleworth, 1991). Vegetation plays an important role in terrestrial energy and water cycles by controlling surface energy partitioning in response to surface and sub-surface soil moisture and meteorological conditions. ET comprises vegetation canopy evaporation ($E_{Can}$), direct soil evaporation ($E_{Soil}$), and plant transpiration ($E_{Tran}$), which constitutes 62% of the annual water balance globally (Eagleson, 1978; Jaksa et al., 2013; Kim and Ek, 1995; Sridhar, 2013; Sridhar et al., 2002; Verstraeten et al., 2008). Long-term ecosystem-scale observations of land surface energy and water fluxes are necessary for a comprehensive understanding of ET-related processes and variables. Given the broad importance of the accurate estimation of land surface turbulent heat and moisture fluxes, ecosystem-scale observations of surface energy and water balance components are surprisingly scarce (Kurc and Small, 2004, 2007).

The quantification of land surface turbulent fluxes can be achieved through different methods, including eddy covariance (EC) (Moncrieff et al., 1997; Offerle et al., 2006; Twine et al., 2000; Wilson et al., 2001); remote sensing using systems such as satellites, radars, aircraft, and lifted kites (Maronga et al., 2013); Bowen ratio (BR); and large-aperture scintillometer (LAS) measurements (Beyrich et al., 2002; Chehbouni et al., 1999; Lee et al., 2015; Meijninger et al., 2006; Samain et al., 2011; Zhang and Zhang, 2015; Zeweldi et al., 2010). EC provides direct measurements of the transfer of land surface turbulent fluxes into the atmosphere from a point-scale over a homogenous land surface (Foken, 2008; Lee et al., 2006; Offerle et al., 2006). However, there is some uncertainty associated with the EC method when measuring area-averaged fluxes over a heterogeneous land surface due to insufficient sampling of large-scale atmospheric motion (Beyrich et al., 2002; Kohsiek et al., 2006; Mauder et al., 2013). ET can be directly measured in the field using weighing lysimeters (Gebler et al., 2015). Land surface models (LSM) are widely used to estimate the surface energy and water balance when observations are limited. Among the many methods of quantifying ET, a basic and popular approach is to multiply PET by the ratio of ET to PET or to develop a complementary relationship (CR) between ET and PET (Brutsaert and Stricker, 1979; Crago et al., 2010; Hobbins et al., 2001; Huntington et al., 2011; Jaksa et al., 2013; Pettijohn and Salvucci, 2009). CR is a relatively simple method based upon a general feedback mechanism between ET and PET. Based on the CR approach, under given atmospheric conditions in the absence of large-scale advection (Aminzadeh and Or, 2017; Lhomme, 1997), a decrease in ecosystem-scale ET would increase PET. That is, when the soil is relatively dry, the excess energy after the ET process modifies the surface air temperature and vapor pressure deficit and increases PET by establishing a complementary relationship (Aminzadeh and Or, 2017; Brutsaert, 2005; Pettijohn and Salvucci, 2009). Similarly, when the surface soil is saturated, ET increases and approaches PET.

Detailed knowledge of the ecohydrological responses of different ecosystems in a watershed from consideration of seasonal and annual plant water consumption and linking to the available water resources is necessary for water management and land-atmospheric interaction studies, especially in water-limited environments (Valayamkunnath et al., 2018). Studies based on field observations contribute critical information about how different ecosystems behave in energy and water balance dynamics, especially the vegetation response to soil moisture, ET, and rainfall. Different studies based on field observations have discussed the energy and water balance, ET partitioning, and vegetation dynamics in semiarid environments. However, most of these studies (Baldocchi et al., 2004; Cavanaugh et al., 2011; Dugas et al., 1996; Gash et al., 1991; Kabat et al., 1997; Kurc and Small, 2004; Malek and Bingham, 1997; Minderlein and Menzel, 2015; Moran et al., 2009; Ryu et al., 2008; Stannard et al., 1994; Taylor, 2000; Valayamkunnath et al., 2018) were conducted in semiarid shrubland or grassland environments, and relatively few studies of the energy and water balance have been completed in semiarid forest (Ha et al., 2015; Small and McConnell, 2008; Valayamkunnath et al., 2018; Yaseef et al., 2010) or woodland (Mitchell et al., 2009; Scott et al., 2004; Yepez et al., 2003) environments. However, a descriptive understanding of meteorological and vegetational influences on seasonal and interannual energy and the water balance, on soil moisture and air temperature (land–atmosphere) interaction, and on evapotranspiration partitioning based on long-term (>5 years) field observation is limited, especially in semiarid shrublands or forest ecosystems.

Recently released long-term (6 years) EC data for sagebrush and lodgepole pine ecosystems in the Snake River basin of Idaho, USA, have allowed us to investigate and differentiate inter-seasonal and inter-annual energy and water balances and biophysical and meteorological factors influencing energy and water balances in two ecosystems. The Snake River basin is a semiarid region covering Idaho, Oregon, Nevada, Wyoming, Montana, and Washington. The main land cover types of the Snake River basin include grasslands (cheatgrass), shrubland (sagebrush), conifer forests (lodgepole pine), and irrigated agricultural lands. This semiarid region is characterized by hot (average temperature: 21–23 °C), dry (average rainfall: 13–80 mm) summers and cold winters (Valayamkunnath et al., 2018). The annual precipitation ranges from 200 to 440 mm in the central and western regions and from 410 to 700 mm in the eastern mountains of the Snake River basin. Most annual precipitation occurs during the winter and is the main source of water to meet the region's irrigation water demands (Jaksa and Sridhar, 2015; Teng et al., 2012; Valayamkunnath et al., 2018). Approximately 91% of the agricultural land in the Idaho Snake River basin utilizes surface and subsurface water resources to meet its crops' water requirements because the central region receives