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Roles of spatially varying vegetation on surface fluxes within a small mountainous catchment

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Abstract

Understanding the role of ecosystems in modulating energy, water and carbon fluxes is critical to quantifying the variability in energy, carbon, and water balances across landscapes. This study compares and contrasts the seasonal surface fluxes of sensible heat, latent heat and carbon fluxes measured over different vegetation in a rangeland mountainous environment within the Reynolds Creek Experimental Watershed. Eddy covariance systems were used to measure surface fluxes over low sagebrush (*Artemesia arbuscula*), aspen (*Populus tremuloides*) and the understory of grasses and forbs beneath the aspen canopy. Peak leaf area index of the sagebrush, aspen, and aspen understory was 0.77, 1.35, and 1.20, respectively. The sagebrush and aspen canopies were subject to similar meteorological forces, while the understory of the aspen was sheltered from the wind. Estimated cumulative evapotranspiration from the sagebrush, aspen understory, and aspen trees were 399 mm, 205 mm and 318 mm. A simple water balance of the catchment indicated that of the 700 mm of areal average precipitation, 442 mm was lost to evapotranspiration, and 254 mm of streamflow was measured from the catchment; water balance closure for the catchment was within 7 mm. Fluxes of latent heat and carbon for all sites were minimal through the winter. Growing season fluxes of latent heat and carbon were consistently higher above the aspen canopy than from the other sites. While growing season carbon fluxes were very similar for the sagebrush and aspen understory, latent heat fluxes for the sagebrush were consistently higher. Higher evapotranspiration from the sagebrush was likely because it is more exposed to the wind. Sensible heat flux from the aspen tended to be slightly less than the sagebrush site during the growing season when the leaves were actively transpiring, but exceeded that from the sagebrush in May, September and October when the net radiation was offset by evaporative cooling. Results from this study illustrate the influence of vegetation on the spatial variability of surface fluxes across mountainous rangeland landscapes.

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1 Introduction

Mountainous headwater catchments often display considerable variability in soils, geology, vegetation and precipitation. This variability in ecosystems across the landscape translates to variability in surface fluxes of energy and mass across these catchments.

5 Understanding the role of ecosystems in modulating energy, water and carbon fluxes is critical to quantifying the energy flux, carbon storage, and water balances of these headwaters. Comparison of surface fluxes across the ecosystems within these catchments provides a framework for quantifying the water balance and net energy and mass fluxes from and within these catchments.

10 Eddy covariance (EC) systems have gained popularity as a means to measure the surface energy, water and carbon fluxes. Historically, these systems have been used for short-term, intensive field campaigns; however the use of EC systems is increasing within the hydrological community as sensors have become more rugged and reliable. Long-term EC sites provide a unique contribution to the hydrological characterization 15 of a site and to the study of the environmental and climatological controls on surface exchange between terrestrial ecosystems and the atmosphere.

Landscape variability and complex terrain often necessitates deployment of EC systems at less than ideal sites in order to quantify fluxes in headwater catchments. Complex terrain complicates EC measurements due to potential violations of stationarity and homogeneity assumptions. In the past decade, application of EC to measure 20 fluxes of heat, water, and carbon has been extended to more complex sites (Baldocchi et al., 2000a; Pomeroy et al., 2003; Turnipseed et al., 2003; Marks et al., 2008; Reba et al., 2009). Several studies have found the method capable of accurately quantifying fluxes below the forest canopy (Baldocchi et al., 2000b; Marks et al., 2008; Reba et al., 2010) and have partitioned fluxes within the canopy by having separate EC systems 25 above and below the canopy (Blanken et al., 1997; Constantin et al., 1999; Blanken et al., 2001; Wilson et al., 2000).

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Few studies have used EC systems to quantify the variability in surface fluxes within headwater catchments. Reba et al. (2010) described the variability in measured turbulent fluxes over snow for sagebrush and the understory of an aspen canopy within the Reynolds Mountain East Catchment. Their work focused on winter fluxes and the snow cover energy and mass balance as affected by wind shelter, canopy and terrain. However, they did not address growing season fluxes or fluxes above the aspen canopy. An EC system has since been deployed above this aspen stand. Herein, we compare energy and carbon fluxes for a sagebrush site, the aspen understory, and the above-canopy aspen site throughout an entire year to bridge the analysis between the winter analysis conducted by Reba et al. (2010) to the larger hydrologic and ecosystem issues for snow-dominated headwater catchments. The focus of this paper is to compare and contrast the seasonal surface energy and carbon fluxes across the Reynolds Mountain East Catchment headwaters catchment characterized by large variability in precipitation and vegetation cover to elucidate the roles that the different vegetation types have in modifying the timing and magnitude of the energy and carbon fluxes.

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exposed ridges and sagebrush areas tend to be windswept and accumulate approximately a meter of snow during the winter. Conversely, the area immediately upslope of the aspen typically accumulates 6 m of snow, which sustains the aspen and fir trees in this topographically-sheltered area (Fig. 1).

5 Three eddy covariance sites were established to monitor fluxes across the RME catchment as part of a long-term study to characterize the hydrology of this mountainous headwater catchment. The wind-exposed sagebrush site was operated from October 2002 until January 2008. Measurements below the aspen were initiated in December 2004 and above the aspen in February 2007. Analyses of this study focus primarily
10 on 2007 when all three systems were operational; data for above the aspen were extrapolated to complete the 2007 water year (October 2006 through September 2007). The sites are representative of the two major landscape units in the catchment.

Vegetation at the sagebrush site consists of about half sagebrush with the remainder
15 consisting of equal amounts of native grasses and forbs. Vegetation is approximately 60 cm in height with a leaf area index (LAI) of 0.77 based on point frame measurements. The slope varies from 3 to 5 percent. The aspen site consists of an aspen
20 grove with an understory of grasses and forbs. An inventory of the trees in the immediate vicinity (0.20 ha) of the eddy covariance system indicated a density of 1280 trees/ha with an average diameter of 14.6 cm at a height of 1.3 m. Average height was 9.5 m and the maximum tree height was 15 m. Stem area index (SAI) of the trunks and limbs
25 based on LAI-2000 measurements prior to the growing season was 0.5. Leaf area index (LAI) of the aspen was measured during the growing season using an LAI-2000; maximum LAI of the aspen was 1.35 in August. Understory vegetation LAI measurements indicated an LAI of approximately 1.2 for the grasses and forbs.

Eddy covariance systems used to measure turbulent fluxes consisted of a three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific, Inc., Logan UT) and an open path infrared gas analyzer (IRGA; Model LI-7500, LI-COR, Inc., Lincoln, NE) sampled at 10 Hz. The EC systems were located at 5 m above the ground surface at the sagebrush site, and 4.5 m and 19.25 m at the aspen site. Short and
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long wave radiation, air temperature and humidity were collected every 30 min using a four-component net radiometer (CNR-1, Kipp and Zonen, Delft, The Netherlands), and a temperature and humidity probe (HMP45C, Viasala, Helsinki, Finland). Ground heat flux was measured with up to six heat flux sensors (HFP01, Hukseflux, Netherlands) installed 0.08-m deep within the soil and three sets of self-averaging thermo-couples installed at 0.02 and 0.06-m deep. A single set of soil heat flux sensors were shared by the understory and above aspen sites. Soil moisture used to compute volumetric heat capacity of the soil was measured hourly at 0.03 m using Hydra-probe II soil moisture sensors. The understory site also included sensors in the soil profile down to approximately 1 m; the soil moisture profile at the sagebrush site was measured periodically to a depth of 1.2 m using a neutron probe.

2.2 Processing eddy covariance and energy balance data

The surface energy balance can be described by the surface energy balance equation: $R_n - G - \Delta S_{sp} - \Delta S_c = -(H + LE)$, where R_n is net radiation, G is soil heat flux at the surface, S_{sp} is the change in heat stored within the snowpack if present, ΔS_c is change in heat stored within the vegetation canopy, and H and LE are turbulent sensible and latent heat fluxes. All fluxes are assumed positive in the downward direction. Post-processing of the 30-min EC data followed the protocols described by Reba et al. (2009). They consisted of sonic temperature correction (Schotanus et al., 1983), density correction (Webb et al., 1980), and coordinate rotation (Kaimal and Finnigan, 1994). Soil heat flux measured at 0.08 m was corrected for heat storage above the heat flux plates. Heat stored within the canopy was computed from the empirical equation $\Delta S_c = C(\Delta T / \Delta t) + D$ based on Blanken et al. (1997) and used in several studies (Arain et al., 2003; Wu et al., 2007), where ΔT is the change in temperature over the observed time period Δt , and C and D account for heat storage characteristics of the trees, shrubs, and air column within the canopy. Values of C for the aspen, aspen understory, and sagebrush were 9.5, 2.4 and 1.7 J/C, respectively; D was assumed negligible. For comparison, Arain et al. (2003) used values of 13.5 J/C for C and 1.66 W m^{-2} for D in

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a black spruce stand with 5900 trees/ha, and Wu et al. (2007) used value of 16.2 J/C and 1.5 W m^{-2} for a mixed forest having a mean canopy height of 26 m. Quality of the EC data assessed by energy balance closure was limited to periods without snow cover because snow temperatures and energy stored within the snowpack were not available to assess ΔS_{sp} . Wind direction had very little effect on energy balance closure for the sagebrush and aspen understory, however the above aspen tower was located near the northeast edge of the aspen grove. Therefore periods when the wind did not originate from the direction of the aspen (170° to 290° from north) were removed from analysis for the above aspen site. Data from the sagebrush and aspen understory sites were screened for winds originating within a 90° sector in the direction of the tower.

Data were screened for representative periods during each month of 2007 when plotted turbulent fluxes from the three sites looked reasonable. Composite hourly averages were computed for typically 10 to 20 day periods within each month. These periods were selected because they had high data quality with generally complete EC and meteorological data. Data were not available from the aspen understory site for some of the months due to power supply problems.

3 Results

3.1 Meteorological conditions

Average meteorological conditions for each month of 2007 are plotted for each site in Fig. 2. Total wind-corrected precipitation measured during 2007 was 704 mm at the sagebrush site and 759 mm at the aspen site, which are 89% and 75% of normal. Typical of the mountainous western US, conditions are characterized by cool wet winters and hot dry summers as indicated by the separation between air temperatures and dew point temperatures (Fig. 2). Meteorological conditions are very similar for the sagebrush and above aspen, while the solar radiation and wind speed are

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moderated considerably for the aspen understory. Solar radiation measured below the aspen reaches a maximum in May prior to the aspen trees leafing out. Typical wind speeds below the aspen are 1 m s^{-1} while those above the aspen and sagebrush are around 4 m s^{-1} . Average understory temperatures tend to be lower than the other sites, except for May; solar radiation penetration prior to aspen leaf-out resulted in high solar radiation values beneath the aspen for this month likely contributed to the higher temperatures.

3.2 Energy balance closure and footprint analysis

Eddy covariance systems are well known for their inability to close the energy balance (Twine et al., 2000; Wilson et al., 2002). Energy balance closure for the months free of snow was assessed following the lead of Wilson and Baldocchi (2000) by regressing $R_n - G - S_c$ on $-(H + LE)$ during periods when snow was not present. Figure 3 gives a plot of the monthly average hourly values of $R_n - G - S_c$ versus $-(H + LE)$ for May through October; the resulting regressions are given in Table 1. Although the slope for the sagebrush (0.84) is quite good and that for the above aspen site is acceptable (0.74), the slope of 0.38 for the aspen understory site suggests a general lack of energy closure. The lack of energy balance closure for the aspen understory site can be attributed to unrepresentative net radiation measurements. Gaps in the canopy exposed the net radiometer in the understory to direct radiation during the mid-afternoon hours (typically hours 13 to 17 as well as hour 9), as illustrated in Fig. 4, due in part to the site being located toward the eastern edge of the aspen. Incoming solar radiation measured at the sensor was therefore not representative of the average solar radiation flux received beneath the aspen canopy, so closure cannot be expected during these hours. Upon excluding these hours from the energy balance closure analysis, the slope of the regression line improves to 0.70. Even so, spatial measurement of radiation beneath the canopy, similar to the approach used by Baldocchi et al. (2000b), would be preferred. Thus, net radiation comparisons for the aspen understory, particularly during

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the afternoon hours, should be done with caution; however there is nothing to suggest that the turbulent fluxes beneath the canopy are not reliable.

Magnitude of the canopy storage term S_c was a minor component of the energy balance, ranging from 2 W m^{-2} during the winter months to 7 W m^{-2} during the summer for the above aspen site. This accounted for approximately 10% of R_n during the winter and 3% during the summer; the magnitude of S_c typically accounted for 1% or less of R_n at the sagebrush site and 1 to 2% at the aspen understory.

A footprint analysis for the three sites was conducted similar to that described by Blanken et al. (2001) and Schuepp et al. (1990). Under neutral conditions, distance from the instruments exerting the maximum influence on measured fluxes was 54 m for the sagebrush site, 46 m for the aspen understory, and 36 m for the above aspen site. Under typical unstable daytime conditions, these distances reduced to 42 m, 36 m, and 28 m, respectively. Fetch is not a concern for most wind directions at the sagebrush site, however the aspen sites are limited to approximately 160 m of fetch for acceptable wind directions. For unstable conditions, approximately 70% of the flux upwind of the towers originated within this fetch, however this dropped to approximately 60% under neutral conditions.

3.3 Seasonal comparison of fluxes

Average monthly energy and carbon fluxes for each site are plotted in Fig. 5. Average net radiation was consistently higher above the aspen throughout the year compared to the other sites, due to its higher leaf area index and complex canopy. Albedo above the aspen ranged from 0.12 during the growing season to 0.45 during the snow-covered period, while that for the sagebrush 0.17 to 0.77. Average net radiation above the sagebrush was negative during months with snowcover and low sun angles (November through February) when albedo reached its highest. Tree trunks and limbs of the aspen contributed to the lower winter albedo and absorbed sufficient solar radiation to prevent negative net radiation for any month. Data were not available from the understory site for much of the snow-covered period, but the data did indicate negative net radiation in

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February and only slightly positive net radiation during November. More of the aspen trunks were buried by snow in February, resulting in the negative net radiation.

Figure 4 presents the average diurnal trace in the radiation fluxes for each month throughout the year. The dominant component in net radiation is the incoming solar radiation because the long-wave radiation measurements tend to cancel each other. The problems presented by the gaps in the canopy for measurement of the understory radiation is apparent in Fig. 4, as incoming solar radiation for many of the mid-afternoon hours are very close to the above canopy measurements. Although incoming solar radiation is lower during the winter months, reflected radiation is actually higher due to the high albedo of the snow.

Incoming and emitted long-wave radiation fluxes plotted in Fig. 4 present some interesting contrasts between the three sites. As expected, downward long-wave radiation is nearly identical above the sagebrush and aspen, however the sheltering provided by the aspen canopy is evident from the much higher downward long-wave radiation for the aspen understory. Upward long-wave radiation is nearly identical for the sagebrush and aspen understory early in the year until the snowcover becomes discontinuous at the sagebrush site in March or April. During this period, solar radiation absorbed by the aspen caused upward long-wave radiation from the aspen to be slightly higher (approximately 2%). Vegetation cover at the sagebrush site is sparse, allowing more soil to be exposed after snowmelt; this combined with the lower latent heat flux from the drier sagebrush site (Fig. 5) caused upward long-wave fluxes from the sagebrush to be substantially higher than the other sites throughout the growing season (Fig. 4). The evaporative cooling effect of the combined tree/grass system substantially lowers the surface temperature and upward long-wave radiation flux viewed by the above aspen net radiometer compared to the other sites. The reduced upward long-wave radiation persists through the growing season and even until December when snowcover resumes.

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Figure 6 presents the average diurnal trace in the energy and carbon fluxes for each month throughout the year. As mentioned previously, net radiation measured in the understory is likely not representative of the understory; due to gaps in the canopy, direct radiation penetrated the canopy during the afternoon hours throughout the growing season (March through August), skewing the net radiation measurements. Morning measurements tended to be lower than the other two sites while afternoon measurement approached or exceeded net radiation above the canopy.

Turbulent fluxes of sensible and latent heat are relatively small during the snow-covered period and tend to offset each other, so that the net turbulent flux ($H+L,E$) is quite small, as noted by other investigators (Garen and Marks, 2005; Link and Marks, 1999; Marks et al., 2002). Evapotranspiration and latent heat fluxes get an early start at the sagebrush site compared to the other locations as a result of early snowmelt and the perennial leaves on the sagebrush. By May, latent flux is very similar at all three sites, and the above aspen flux quickly surpasses the sagebrush site by June. The fact that latent heat fluxes for the aspen understory and above aspen sites are similar in May suggest that the aspen trees had not yet started to transpire, and the entire latent heat flux measured above the canopy originates from the understory. Latent heat flux clearly peaked in June at the sagebrush and above aspen canopies, while May and June fluxes are similar for the aspen understory (Figs. 5 and 6). Leveling off of latent heat flux in June under the aspen canopy coincides with a drop in net radiation at this site (Fig. 5); by June, leaf cover of the aspen shades the understory vegetation sufficiently to reduce evaporative demand. Latent heat flux above the aspen is consistently higher through the growing season, but is very nearly similar to the sagebrush site in September when the leaves fall from the aspen and much of the latent heat flux likely originates from the understory. Latent heat flux is actually higher from the sagebrush site during April and October compared to the other sites, due to the perennial leaf cover of the sagebrush.

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Average daily sensible heat fluxes tend to be lower over the aspen compared to the sagebrush during the months when the aspen leaves are actively transpiring (Fig. 4); average daily fluxes ranged from 73 to 88% less than that over the sagebrush during the months from June to August. Interestingly, the diurnal trend in sensible heat flux above the aspen and sagebrush sites are quite similar during the non-snow period (April through November, Fig. 6). This might be expected, given that the two sites are subject to nearly identical meteorological forces. Average daily fluxes were more negative above the aspen than the sagebrush during May, September and October. Absorption of solar radiation during these months was not offset by transpiration of the aspen, resulting in a higher proportion of the energy being dissipated by sensible heat flux. However the Bowen ratio, defined as the ratio of sensible to latent heat fluxes, are identical for the two sites during May (1.1) and September (2.2). Although the aspen had higher net radiation, the two sites partitioned the available energy between the turbulent fluxes similarly. In October, the Bowen ratio of the aspen rose further to 3.8 while that for the sagebrush dropped to 1.7; the decrease in October for the sagebrush was likely due to the sagebrush utilizing the precipitation that fell in September and October.

Bowen ratios suggest increased water stress as the growing season progressed. A typical value for well-watered vegetation is 0.2 (Campbell, 1977). Average daily Bowen ratios reached a minimum in June with values of 0.26, 0.55 and 0.63 for the aspen, aspen understory, and sagebrush, respectively. By August, soil moisture storage within the top 1 meter had dropped to nearly its minimum; Bowen ratios rose to 0.93, 2.26 and 1.71, respectively, for August. The high Bowen ratio for the understory in August is due in part to the fact the understory had begun to senesce.

As expected, soil heat flux is small and slightly negative throughout the snow-covered period. Soil heat flux becomes positive and displays a diurnal trend when snowcover becomes discontinuous, which occurs in March at the sagebrush site and late April beneath the aspen. The sagebrush site, having more bare soil exposed, displays larger amplitude in the diurnal trace in soil heat flux. Net soil heat flux for both sites (the

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aspen sites shared a single set of soil heat flux instrumentation) becomes negative in October. In November, midday soil heat flux under the sagebrush falls below that for the aspen understory (Fig. 6), which coincides with net radiation becoming negative at the sagebrush sites (Fig. 5).

5 The diurnal trace for carbon flux is rather noisy early in the year, but displays some interesting trends beginning in May. As with the latent heat flux, carbon flux from the aspen understory and above aspen sites are very similar in May, suggesting that nearly all of the latent heat and carbon flux originates below the aspen canopy. During this time, the aspen trees have not leafed out yet, but the grasses and forbs are flourishing.

10 Carbon storage of the understory vegetation surpassed that of the sagebrush while the aspen understory vegetation was actively growing. Beginning in June, carbon flux to the sagebrush and aspen understory is very similar for the remainder of the growing season, even though evapotranspiration is higher from the sagebrush canopy. Being more sheltered from the wind, the understory vegetation can use the available water

15 more efficiently than the sagebrush at the more exposed site. Once the aspen begins to leaf out, carbon storage in the aspen canopy is substantial until the leaves drop and net carbon flux becomes essentially zero during October and November for the aspen sites.

3.4 Water budget for 2007 water year

20 Data presented in Figs. 5 and 6 are based on the 2007 calendar year, however water balance data are typically reported based on the water year. Evapotranspiration for the 2007 water year (October 2006 through September 2007) is presented in Table 2 and all components of the water balance are plotted in Fig. 7. Unfortunately evapotranspiration data from the above aspen site are not available for the beginning of the water year

25 (October through January 2007), so data were estimated based on the sagebrush site and the ratio of evapotranspiration from the above aspen site to the sagebrush for the same months in 2007. Fortunately these three months are some of the lowest rates for evapotranspiration, thereby minimizing the overall error introduced by the estimation.

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Seasonal timing of the water balance components are illustrated in Fig. 7. Typical of the Western US, the sites started the water year with a very dry soil profile, and soil storage increased with autumn precipitation. Soil moisture at the sagebrush site peaked in December and decreased during January due to the abnormally low precipitation. Soil moisture storage began a gradual decline beginning in March at the sagebrush site and at the end of April at the aspen site, which coincided with the end of snowmelt at the respective sites and the onset of active plant transpiration. Streamflow peaked in April and dropped rapidly as the soil profile began to dry.

Based on areal coverage of the vegetation, an areal average evapotranspiration of 442 mm was computed for the catchment. Latent heat flux from the sagebrush was very nearly the same as that above the aspen for most of the year (Fig. 5), so the areal average evapotranspiration mimics that from the sagebrush until June. Due in part to its larger coverage within the catchment, sagebrush accounts for approximately 60% of the total evapotranspiration from the catchment, while the aspen understory accounts for 15% and the trees account for 25%.

Precipitation measured at the sagebrush site was 690 mm for the 2007 water year and 718 mm at the aspen site, yielding an areal average precipitation of 700 mm. Water stored in the soil profile decreased by 19 mm at the aspen site, while that at the sagebrush site actually increased by 12 mm due to September precipitation. The net result is an estimated 1 mm increase in soil water storage for the catchment. Measured streamflow for the 2007 water year was 254 mm. A simple water balance results in an excess of 7 mm exiting the basin above the annual precipitation. The tight closure of the water balance is somewhat fortuitous given the uncertainty in the ET estimates and areal distribution of the precipitation. Chauvin et al. (2010) reported an average 10% error in the water balance for a 24-year study of a separate intensively measured catchment within the Reynolds Creek Watershed. The tighter water balance closure in the present study may be attributed to direct measurement as opposed to simulation of the evapotranspiration component, but more likely to a much greater percentage of the precipitation contributing to streamflow (36% compared to 8%). Evapotranspiration in

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the present study accounted for approximately 63% of the precipitation, which is much lower than the 82% reported by Chauvin et al. (2010). However, cumulative evapotranspiration from the sites is very comparable to that reported by Chauvin et al. (2010), who reported an average of 382 mm from a low sagebrush site, and 521 mm from an aspen site.

4 Summary and conclusions

This study highlights the influence of vegetation and site conditions on surface energy and carbon fluxes across small landscapes. Differences in the surface energy and carbon fluxes between the three sites were modulated by the characteristics of the three vegetation types. Perennial leaves of the sagebrush enabled higher rates of evapotranspiration and latent heat flux during the early and late portions of the growing season compared to the aspen site. Conversely, the aspen understory experienced the highest net radiation, carbon, evapotranspiration, and latent heat fluxes in May, prior to the aspen trees leafing out. Latent heat and carbon flux at the aspen site during this period originated almost entirely from the understory. The presence of the aspen also modulated the partitioning of the turbulent fluxes at the site; sensible heat flux from the aspen tended to be slightly less than the sagebrush site during the growing season when the leaves were actively transpiring, but exceeded that from the sagebrush in May, September and October when net radiation was not offset by evaporative cooling of the aspen leaves.

Carbon flux to the sagebrush and aspen understory was very similar for much of the growing season, even though evapotranspiration was higher from the sagebrush canopy. Being more sheltered from the wind, the understory vegetation used the available water more efficiently than the sagebrush at the more exposed site. Carbon flux to the aspen trees far surpassed that used by either the aspen understory or sagebrush.

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Total estimated evapotranspiration was 399, 205 and 318 mm from the sagebrush, understory, and aspen trees, respectively for the 2007 water year. The higher total evapotranspiration from the sagebrush can be attributed to its perennial leaves and the exposed nature of the site. Given its higher cumulative evapotranspiration and larger areal coverage within the catchment, it is clearly the dominant usage of water within the catchment. A simple water balance of the catchment indicated that of the 700 mm of areal average precipitation, 442 mm was lost to evapotranspiration, and 254 mm of streamflow was measured from the catchment. Results from this study illustrate the influence of vegetation on the spatial variability of surface fluxes across mountainous rangeland landscapes.

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References

Arain, M. A., Black, T. A., Barr, A. G., Griffis, T. J., Morgenstern, K., and Nesic, Z.: Year-round observations of the energy and water vapour fluxes above a boreal black spruce forest, *Hydrol. Process.*, 17, 3581–3600, 2003.

Baldocchi, D. D., Finnigan, J., Wilson, K., Paw U, K. T., and Falge, E.: On measuring net ecosystem carbon exchange over tall vegetation on complex terrain, *Bound.-Lay. Meteorol.*, 96, 257–291, 2000a.

Baldocchi, D. D., Law, B. E., and Anthoni, P.: On measuring and modeling energy fluxes above the floor of a homogeneous and heterogeneous conifer forest, *Agr. Forest Meteorol.*, 102(2–3), 187–206, 2000b.

Blanken, P. D., Black, T. A., Yang, P. C., den Hartog, G., Neumann, H. H., Nesic, Z., Novak, M. D., Staebler, R., and Lee, X.: Energy balance and surface conductance of a boreal aspen forest: partitioning overstory and understory components, *J. Geophys. Res.*, 102, 28915–28927, 1997.

Blanken, P. D., Black, T. A., Neumann, H. H., den Hartog, G., Yang, P. C., Nesic, Z., and Lee, X.: The seasonal water and energy exchange above and within a boreal aspen forest, *J. Hydrol.*, 245, 118–136, 2001.

Campbell, G. S.: An Introduction to Environmental Biophysics, Springer-Verlag, New York, p. 136, 1977.

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Chauvin, G. M., Flerchinger, G. N., Link, T. E., Marks, D., Winstral, A. H., and Seyfried, M. S.: Long-term Water Balance and Conceptual Model of a Semi-Arid Mountainous Catchment, *Hydrol. Process.*, in review, 2010.

5 Constantin, J., Grelleb, A., Ibroma, A., and Morgensterna, K.: Flux partitioning between understorey and overstorey in a boreal spruce/pine forest determined by the eddy covariance method, *Agr. Forest Meteorol.*, 98–99, 629–643, 1999.

Garen, D. C. and Marks, D.: Spatially distributed energy balance snowmelt modelling in a mountainous river basin: estimation of meteorological inputs and verification of model results, *J. Hydrol.*, 315, 126–153, 2005.

10 Kaimal, J. C. and Finnigan, J. J.: *Atmospheric Boundary Layer Flows-Their Structure and Measurement*, Oxford University Press, New York, 289 pp., 1994.

Link, T. E. and Marks, D.: Distributed simulation of snowcover mass-and energy-balance in the boreal forest, *Hydrol. Process.*, 13, 2439–2452, 1999.

15 Marks, D., Winstral, A., and Seyfried, M.: Simulation of terrain and forest shelter effects on patterns of snow deposition, snowmelt and runoff over a semi-arid mountain catchment, *Hydrol. Process.*, 16, 3605–3626, 2002.

Marks, D., Reba, M., Pomeroy, J., Link, T., Winstral, A., Flerchinger, G., and Elder K.: Comparing simulated and measured sensible and latent heat fluxes over snow under a pine canopy, *J. Hydrometeorol.*, 9(6), 1506–1522, 2008.

20 Pomeroy, J., Toth, B., Granger, R., Hedstrom, N., and Essery, R.: Variation in surface energetics during snowmelt in complex terrain, *J. Hydrometeorol.*, 4(4), 702–716, 2003.

Reba, M. L., Marks, D., Pomeroy, J., and Link, T. E.: An assessment of corrections to turbulent fluxes over snow by eddy covariance in mountain environments, *Water Resour. Res.*, 45, W00D38, doi:10.1029/2008WR007045, 2009.

25 Reba, M. L., Link, T. E., Marks, D., and Pomeroy, J.: Comparison of measured turbulent fluxes over snow at a wind-exposed and nearby sheltered site using eddy covariance, *Hydrol. Earth Syst. Sci. Discuss.*, in preparation, 2010.

Schuepp, P. H., Leclerc, M. Y., MacPerson, J. I., and Desjardins, R. L.: Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation, *Bound.-Lay. Meteorol.*, 50, 355–373, 1990.

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Schotanus, P., Nieuwstadt, F. T. M., and De Bruin, H. A. R.: Temperature measurement with sonic anemometer and its application to heat and moisture fluxes, *Bound.-Lay. Meteorol.*, 26, 81–93, 1983.

Slaughter, C. W., Marks, D., Flerchinger, G. N., Vactor, S. S. V., and Burgess, M.: 35 years of research data collection at the Reynolds Creek Experimental Watershed, Idaho, USA, *Water Resour. Res.*, 37(11), 2819–2824, 2001.

Twine, T. E., Kustas, W. P., Norman, J. M., Cook, D. R., Houser, P. R., Meyers, T. P., Prueger, J. H., Starks, P. J., and Wesely, M. L.: Correcting eddy-covariance flux underestimates over a grassland, *Agr. Forest Meteorol.*, 103, 279–300, 2000.

Turnipseed, A. A., Anderson, D. E., Blanken, P. D., Baugh, W. M., and Monson, R. K.: Airflows and turbulent flux measurements in mountainous terrain part 1. Canopy and local effects, *Agr. Forest Meteorol.*, 119, 1–21, 2003.

Webb, E. K., Pearman, G. I., and Leuning R.: Correction of flux measurements for density effects due to heat and water vapor transfer, *Q. J. Roy. Meteor. Soc.*, 106, 85–100, 1980.

Wilson, K. B. and Baldocchi, D. D.: Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America, *Agr. Forest Meteorol.*, 100, 1–18, 2000.

Wilson, K. B., Hanson, P. J., and Baldocchi, D. D.: Factors controlling evaporation and energy partitioning beneath a deciduous forest over an annual cycle, *Agr. Forest Meteorol.*, 102, 83–103, 2000.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B. E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., and Verma, S.: Energy balance closure at FLUXNET sites, *Agr. Forest Meteorol.*, 113, 223–243, 2002.

Wu, J., Guan, D., Han, S., Shi, T., Jin, C., Pei, T., and Yu, G.: Energy budget above a temperate mixed forest in Northeastern China, *Hydrol. Process.*, 21, 2425–2434, 2007.

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Table 1. Characteristics of energy budget closure by regressing $-(H+LE)$ vs. (R_n-G-S) .

Site	Slope	Intercept	R^2
Sagebrush	0.84	22.5	0.96
Aspen understory	0.38	19.2	0.76
Aspen understory (excluding mid-afternoon hours)	0.70	12.6	0.80
Above aspen	0.74	29.5	0.95

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Table 2. Monthly evapotranspiration (mm) from each site for 2007 water year and the areal average based on 66% sagebrush and 34% aspen (Asterisked values are estimated from neighboring sites; values for the aspen trees are computed by difference between the understory and above aspen values.).

Month	Sagebrush	Aspen Understory	Above Aspen	Aspen Trees	Areal Average
Oct 2006	16.6	7.4	13.7*	6.3	3.9
Nov 2006	20.5	9.3	18.0*	8.7	13.8
Dec 2006	13.6	7.4	11.2*	3.8	18.7
Jan 2007	3.1	2.2	5.3*	3.1	34.0
Feb 2007	12.8	6.5	15.7	9.2	61.9
Mar 2007	18.4	6.6	19.4	12.8	112.4
Apr 2007	37.0	11.0	28.2	17.2	72.3
May 2007	61.3	45.8	63.2	17.4	47.7
Jun 2007	88.9	46.7	158.0	111.3	29.1
Jul 2007	60.5	32.8	95.2	62.4	16.1
Aug 2007	39.2	16.7	64.1	47.4	19.9
Sep 2007	27.4	12.5*	32.6	20.1	13.1
Total	399.2	205.1	523.6	318.5	441.5

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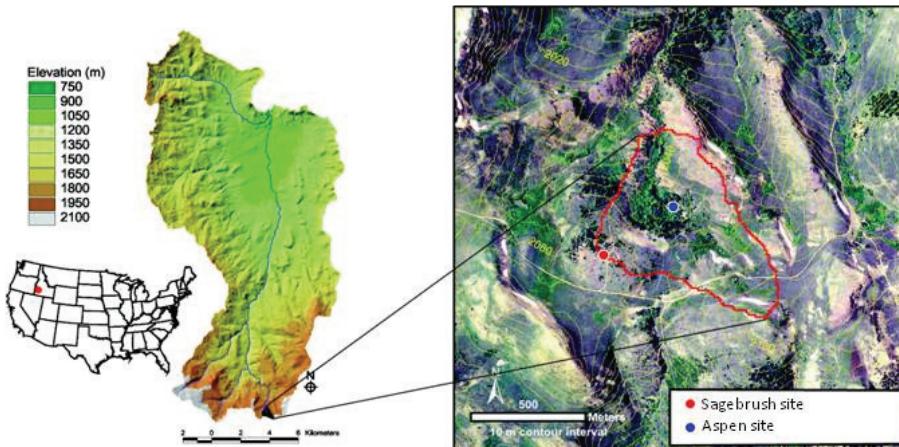


Fig. 1. Location map of Reynolds Mountain East Catchment.

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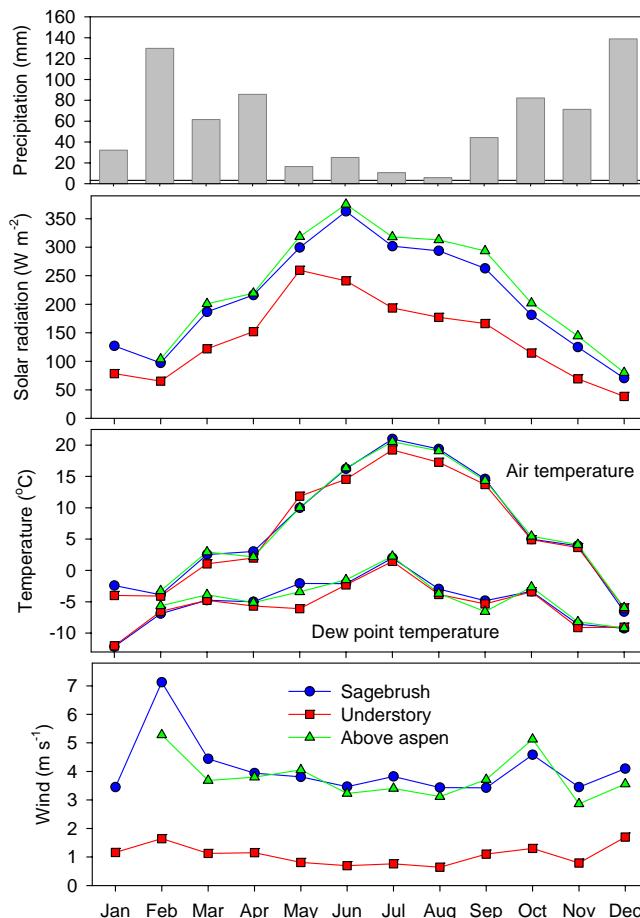


Fig. 2. Monthly meteorological averages for the three study sites within Reynolds Mountain East.

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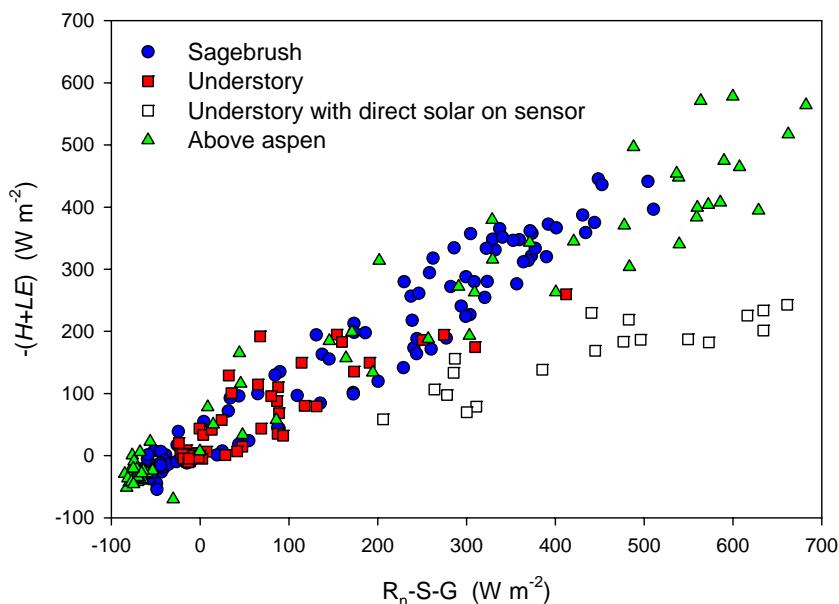


Fig. 3. Scatter plot of monthly averaged hourly values of $-(H+LE)$ vs. $(R_n - G - S)$.

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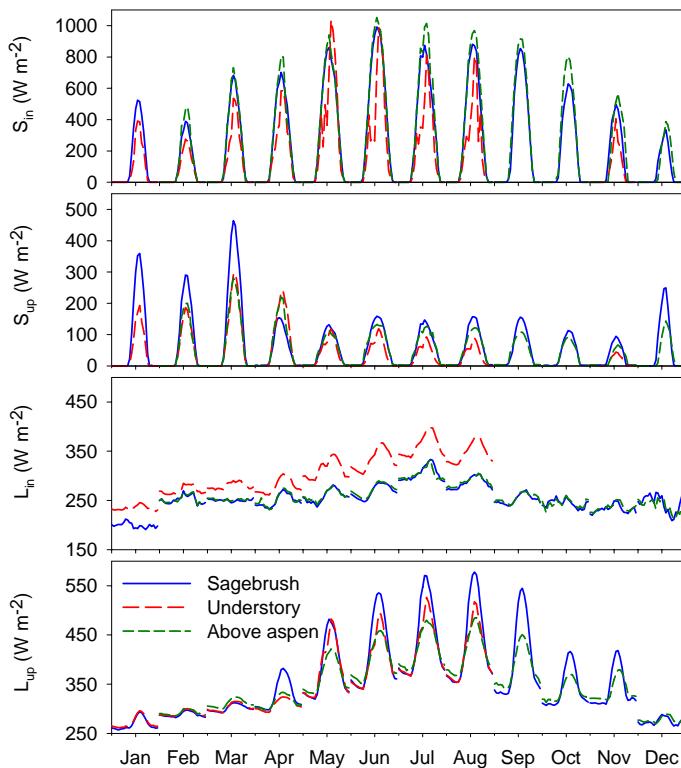


Fig. 4. Average diurnal variation in incoming (S_{in}) and reflected (S_{up}) solar radiation and incoming (L_{in}) and emitted (L_{up}) long-wave radiation fluxes for the three study locations.

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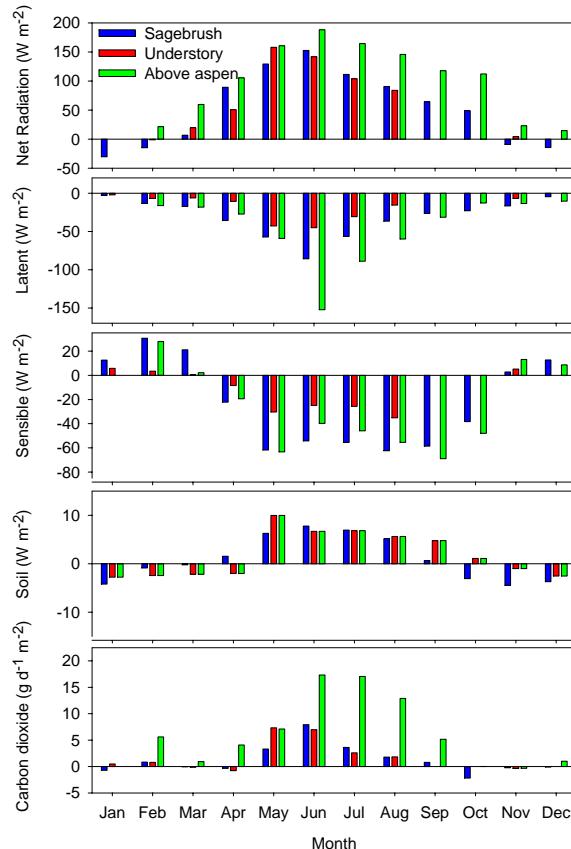


Fig. 5. Average surface energy and carbon fluxes measured for each month of the study period fluxes for the three study locations (Data are not available for the aspen understory during September, October and December, nor for above the aspen during January.).

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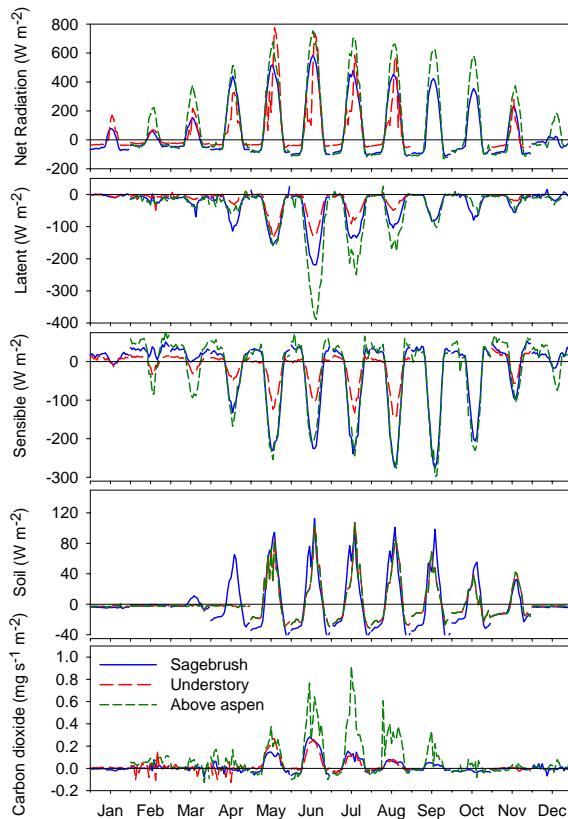


Fig. 6. Average diurnal variation in measured surface energy and carbon fluxes for the three study locations.

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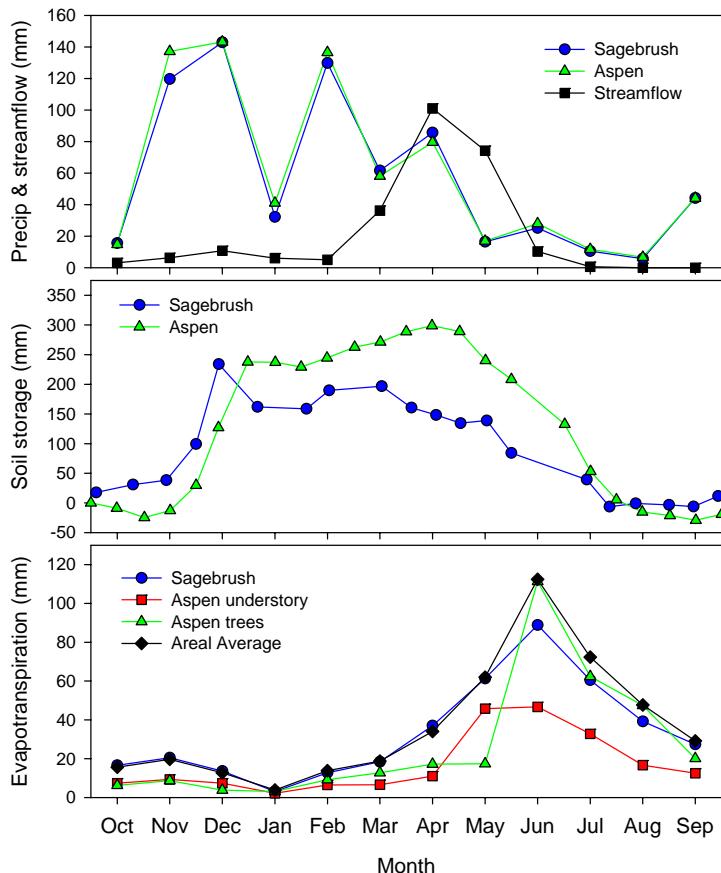


Fig. 7. Monthly variation in water balance components, including precipitation, streamflow, change in soil water storage from the beginning of the water year, and evapotranspiration from each major plant type.