SOIL CO_2 EFFLUX AND WATER USE EFFICIENCY ACROSS DIVERSE COVER TYPES IN SOUTHERN APPALACHIAN HARDWOOD FORESTS

Ruba C. Bilal, John R. Seiler, Brian D. Strahm, and John A. Peterson[1]

Abstract—We are investigating biogeochemical cycling in a mixed hardwood forest in the Ridge and Valley physiographic province in Montgomery County, Virginia. The broad aim of the study is to understand how carbon, water and nutrient cycles vary among diverse stand types in a relatively small spatial area. The specific objectives here are to determine patterns in soil CO_2 efflux or respiration (R_s) and water use efficiency among cover types. Four 0.02 ha sample plots, replicated four times, were established in four cover types – white oak (WO, *Quercus alba*), Scarlet oak (SO, *Q, coccinea*), chestnut oak (CO, *Q. montana*) and mixed pine – oak (PO, *Pinus* spp., *Quercus* spp.). In each plot, diameter at breast height was measured on all trees greater than 5.1 cm. R_s was measured monthly. Foliage from two dominant or co-dominant trees in each plot was sampled for water use efficiency using $\delta^{13}C$ discrimination analysis. Soil temperature alone explained 93 percent of the variation in R_s and the variance due to cover type was not significant. Water use efficiency was greatest in SO where $\delta^{13}C$ was -26.6 per- mille which was significant different than CO (-28.3) and WO (-28.5) values.

INTRODUCTION

Natural hardwood stands constitute a considerable proportion of US forests, yet much is unknown about factors controlling carbon and nutrient cycling in this ecosystem. Largely because of changes in water availability, as influenced by upslope subsidies, productivity and species composition in these forests change over very short distances from ridge top to cove landscape positions. Currently these forests are experiencing pressure from land use and environmental changes which influence their functioning and the services derived from them (Turner and others 2003). Most models that predict influences of land use and global change on the fluxes of carbon, water, and nutrients do not include considerations at the finer scale of cover types in these very diverse temperate forest ecosystems. Studies have shown the responses of carbon, water and nutrient cycling differed from one species to another. Raich and Tufekcioglu (2000) found that soil respiration rates differ among plant biomes and this was because vegetation has influence upon soil microclimate, the quantity of detritus and litter fall. At a global scale, Raich and Tufekcioglu (2000) found that soil respiration (Rs) increases with litter fall in relatively mature ecosystem, suggesting that soil respiration increased in sites with greater rates of detritus production, plant detritus provide the energy that drives the respiration. This trend at a local scale has been suggested to be poorly correlated (Reiners 1968, Ellis 1969) due to local factors such as soil type, inter-site habitats, species composition, or land use history may obscure correlations that are obvious at broader scales. The associations of temperature and moisture content to respiration have been reported differently. Davidson and others (1998) found the spatial and temporal variation in soil respiration in temperate forests, ranging from 5.3-8.5 Mg ha^{-1} yr^{-1} across soil drainage classes. In this system, an exponential function predicting soil CO_2 efflux using soil temperature accounted for about 80 percent of seasonal variation in efflux across the sites (Davidson and others 1998).

Water use efficiency (WUE) is a ratio of net CO_2 assimilation and transpiration and it generally increases during drought conditions. WUE can be indirectly estimated at the leaf level via carbon isotope discrimination which favors lighter isotopes to the heavier ones (Monclus and others 2005). At a particular site, ranking of leaves of C_3 species according to their discriminative values should give a ranking of their WUE at the leaf level (Monclus and others 2005).

This study is undertaken to examine R_s and WUE as measured with ^{13}C isotope discrimination in four cover types (stand types), white oak (WO, *Quercus alba* L.), scarlet oak (SO, *Quercus coccinea* Muench.), chestnut oak (CO, *Quercus montana* Willd.) and mixed pine-oak (PO, *Pinus* spp. and *Quercus* spp.) in the ridge and valley physiographic province in southwest Virginia. Our results will improve our understanding of how carbon and water use differ across the dominant cover types in natural southern Appalachian hardwoods and how

[1]PhD research student, Virginia Tech, College of Natural Resources and Environment, Department of Forestry; Professor Forest Biology; Associate Professor Forest Soils; Research Specialist.

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external forces might impact future ecosystem function. Our specific hypotheses are 1) R_s will be largely driven by soil temperature and moisture, 2) this R_s relationship will differ among the cover types, and 3) WUE of species will be largely driven by the soil moisture gradient.

SITE LOCATION

The study site is located in the ridge and valley physiographic province in Montgomery County, Virginia. The geology is composed primarily of limestone and sandstone. Specifically, the soils are a mixture of Berks (Typic Dystrudepts) and Weikert (Lithic Dystrudepts), which are acidic and well drained soils with low available water holding capacity and low nutrient status (Copenheaver and others 2006). The elevation in this region varies from 152m at the valley to more than 732m (Fenneman 1938). The specific study area is a predominately southern facing slope. The mean annual temperature is 10.8 ˚C, (January mean is -0.6 ˚C and the July mean is 21.7 ˚C). The average annual precipitation is 1020 mm with maximum being in April and September and annual frost free days are 162 (Rhoades 1995).

EXPERIMENTAL DESIGN

We examined four common cover types: white oak, scarlet oak, chestnut oak and mixed pine-oak. Within each of these cover types, four circular 1/50 ha plots were established. The experimental design used is a randomized complete block with four replications (fig. 1).

MATERIALS AND METHODS

Aboveground Biomass

In each plot, all trees with >5.1 cm diameter at breast height (DBH; at 1.37m above the ground), were measured for diameter. The precise point at which the diameter measurement was taken was tagged for the subsequent remeasurements. Algometric equations developed by Jenkins and others (2003) and Ter-Mikaelian and Korukhin (1997) were used to calculate aboveground dry mass from DBH.

Water-Use Efficiency

Water use efficiency was estimated using a stable carbon isotope ($\delta^{13}C$) discrimination technique (Sands and Mulligan, 1990). In mid-July, growing season foliage was sampled from the upper third of the crown of dominant and co-dominates tree species in each plot using a shotgun. Two dominant or co-dominant trees representing the cover type designation in each plot were chosen, with the exception of the mixed oak-pine plots where four trees were used, two each from Table Mountain pine (*Pinus pungens* Lamb.) and chestnut oak. Leaves were oven dried at 65˚C, ground to a fine powder, and analyzed for $\delta^{13}C$ on an Isoprime-100 Isotope Ratio Mass Spectrometer (Elementar Americas Inc, Mt. Laurel, NJ 08054-3409).

Soil CO_2 Efflux

Soil CO_2 efflux was measured monthly at three sub-samples in every plot. A modified Li-Cor 6200 CO_2 gas

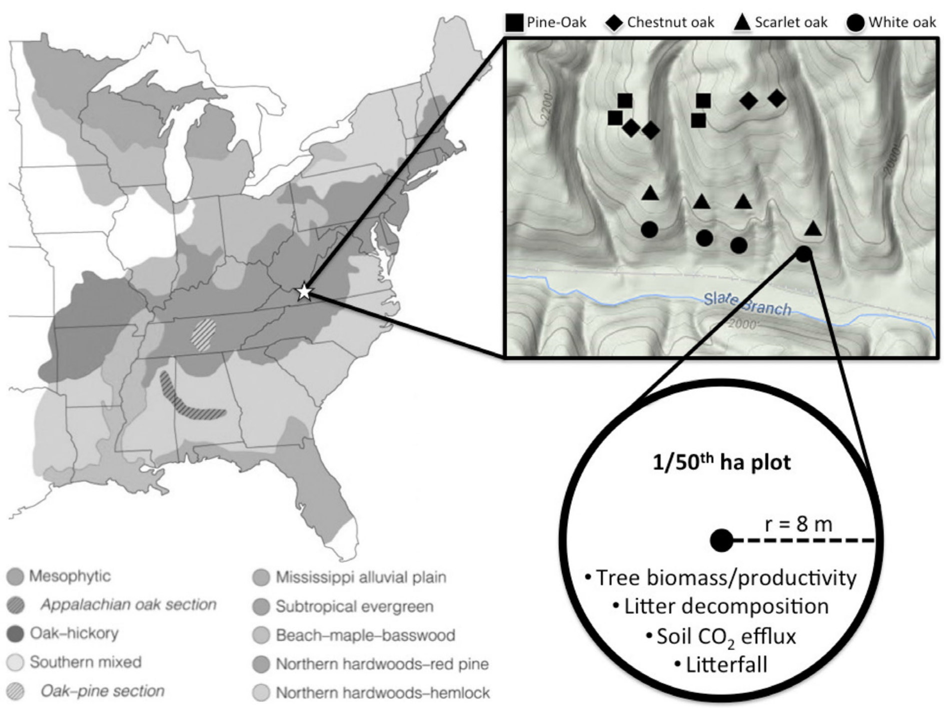

Figure 1—Study site location, Montgomery County, Virginia and the distribution of the sample plot within the larger mesophytic forest ecoregion (adapted from Smith and Smith 2012).

analyzer with a 24.5 cm diameter chamber was used (Tyree and others 2014). Soil temperature and moisture content were measured at 12 cm and 0-10 cm depth, respectively, at each sub-sample point.

STATISTICAL ANALYSES

One-way analysis of variance (AVOVA) was used to test the significances of the above ground biomass across the canopy types. Tukey's HSD was used to separate the means at a statistical significance of 5 percent. R_s data were analyzed with multiple linear regressions to determine relationships with soil temperature, moisture content and stand characteristics. Significant differences in means were determined by ANOVA and HSD at 5 percent significant difference.

Foliar $\delta^{13}C$ was analyzed on an Isoprime-100 Isotope Ratio Mass Spectrometer (Elementar Americas Inc, Mt. Laurel, NJ 08054-3409). One-way ANOVA determined the significances of water use efficiencies of the dominant trees across stand types, LSD determined the statistical mean differences at significant level of 5 percent.

RESULTS AND DISCUSSION

Cover types were accurately delineated (fig. 2). The above ground biomass of each cover type is largely dominated (over 75 percent in all cases) by their respective species names (fig. 2). In the PO stand, 69 percent of the stand biomass is pine and 27 percent oak. The cover type distribution in respect to their stem number and aboveground biomass is associated with availability of moisture content along the gradient. Whittaker (1956) showed moisture controls the distribution along the gradient in Appalachian hardwood forest, with the areas on lower slopes having higher stems/ha than upper slopes. In this study the number of stems/ha increased with elevation, WO (280), SO (395), PO (495) and CO (530). The decrease in stem density at lower elevation may be associated with changes in past stand use such as influences from nearby mining, and harvesting (Copenheaver and others 2006); stands at the lower slope position are more accessible due to a nearby railway and road.

WUE is the amount of carbon fixed per unit water transpired (Sands and Mulligan 1990), which indirectly can be estimated via carbon isotope discrimination. Plants which show less ^{13}C discrimination have greater WUE (table 1). SO had significantly higher $\delta^{13}C$ discrimination indicating it has higher WUE than other species (table 1). However, soil moisture content was not the lowest in SO (12.31 percent) and was nearly as high as WO (12.67 percent). This suggests that soil moisture contents alone do not directly explain water use efficiency. Some studies have shown WUE vary from xeric to mesic environments. Plants growing under xeric condition, where moisture content is low,

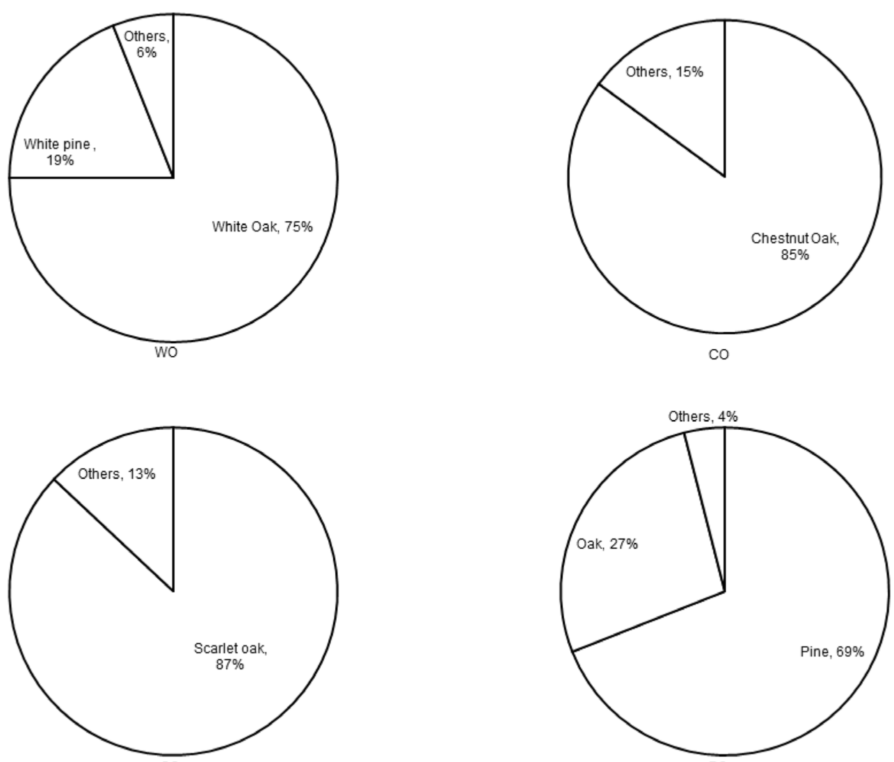

Figure 2—Aboveground biomass percentage for four ridge and valley cover types, white oak (WO), pine-oak (PO), scarlet oak (SO) and chestnut oak (CO) examined in the study.

Table 1—Mean δ13C discrimination and soil moisture for four ridge and valley tree cover types

Cover Type	δ13C discrimination	Mean Soil Moisture (July-October)
Scarlet oak	-26.60 A	12.31
Pine-Oak:		
Table mountain pine	-27.81 AB	10.29
Chestnut oak	-28.51 B	
Chestnut oak	-28.28 B	9.35
White oak	-28.45 B	12.67

experience higher WUE than plants growing under mesic conditions as in the case of radiata pines (Sands and Nambiar 1984). Principally stomatal closure during drought reduces transpiration rate more than the photosynthesis rate and WUE increases. Many factors influence WUE such as vapor pressure deficit (Sandford and Jarvis 1986), wind speed (Smith 1980) and vegetation height increases (Kriedemann and Barrs 1983). Further, our measure of soil moisture content may not be adequately estimating water availability on these rocky upland sites.

R_s varied greatly over the seven months of measurements with few differences between cover types (fig. 3a). In July and August, efflux rates were greatest in CO and WO. WO R_s fell sharply in September; Rs fell sharply in all cover types in October and then remained low through the winter months.

Soil temperature followed the same pattern for all cover types (fig. 3b) while soil moisture (fig. 3c) between the cover types varied more than temperature. WO and SO generally had higher soil moisture and CO and P-O generally lower moisture (fig. 3c, table 1).

R_s tracked soil temperature closely (fig. 3a and 3b) and when modeled, soil temperature alone explained 93 percent of the variance in R_s (fig. 4). Despite soil moisture varying among covers types (fig. 3c), moisture did not explain a significant amount of variation in R_s. Cover type also did not influence the R_s and temperature relationship. This is likely because soil temperature was very consistent across cover types (fig. 3b). Similar results have been shown by others studies, Davidson and others (2000) reported on exponential function of CO_2 efflux to soil temperature accounting 80 percent of seasonal variation in efflux across sites and a decline in R_s was associated with a decrease in soil matric potential. Boone and others (1998) reported water content was unrelated to R_s (R^2=0.86, temperature alone and R^2= 0.90, temperature and moisture content) but there was a strong correlation between temperature and R_s. Likewise, Templeton and others (2015) found soil temperature to be the most important driver and soil moisture explaining a very small amount of variation in R_s in loblolly pine stands. Some studies reported differently, Martin and Bolstad (2005) found that in deciduous trees, R_s was correlated to soil temperature, moisture and site conditions and that Rs varied with severity, timing and duration of drought. Witkamp (1966) and Kramer and Boyer (1995) reported the complex interdependency that existed between soil temperature, water content, soil properties and structures in influencing the rate of soil respiration, and Wildung and others (1975) reported soil temperature and moisture being the principle factors in influencing the plant root decomposition and the rate of CO_2 evolution in the soils. The results of the present study indicate no interaction between soil temperature and soil moisture content on R_s. Our study was for seven months covering late summer, fall and winter. In a much longer time frame with a greater range in soil moisture an influence of soil moisture on R_s may develop.

CONCLUSIONS

- R_s tracked closely with soil temperature. Soil temperature alone explained 93 percent of the variance in Rs.
- Cover type did not influence Rs. One model fit all cover types.
- Water use efficiency as indicated by δ13C discrimination was greatest in scarlet oak. Elevation-driven soil moisture gradients alone were not sufficient in explaining water use efficiencies of the canopy dominant species.

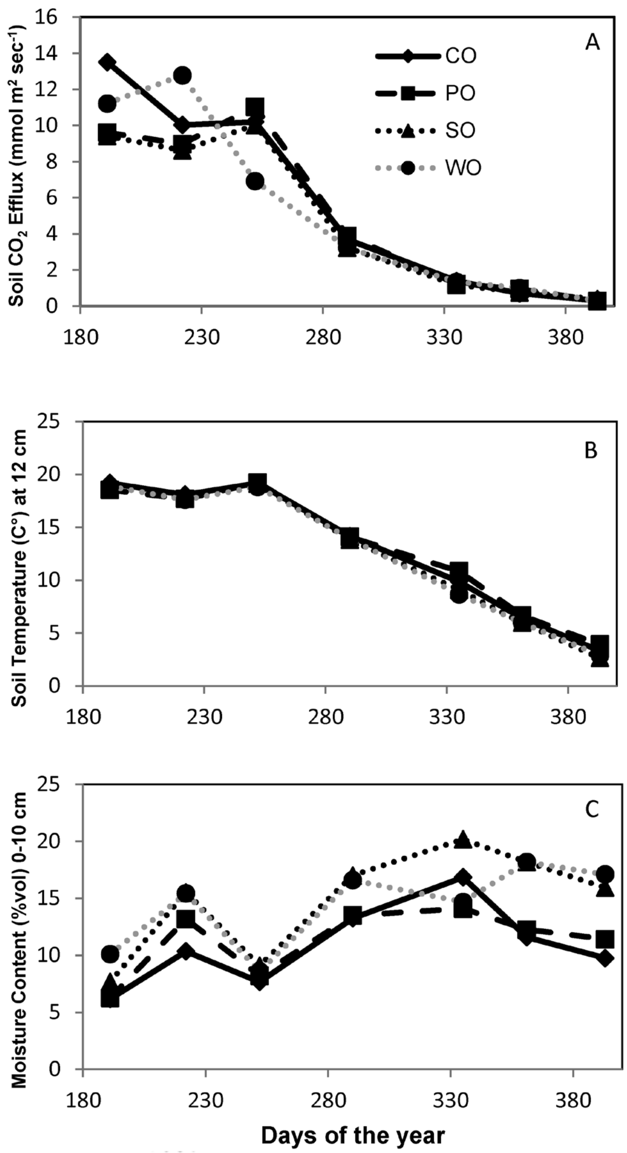

Figure 3—The relationship between soil CO_2 efflux (a), soil temperature (b) and soil moisture content (c) in four common Appalachian cover types; White oak (WO), Scarlet Oak (SO), Chestnut Oak (CO) and Pine Oak (PO; mixture of pine and oak).

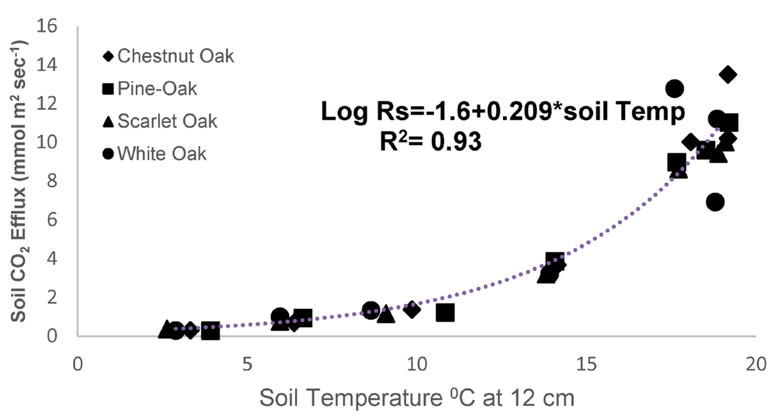

Figure 4—Relationship between soil temperature and soil CO_2 efflux (Rs) in four common Appalachian cover types.

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