SOIL EFFLUX IN A SOUTHERN APPALACHIAN HARDWOOD FOREST

ISABEL R. HILLMAN

Abstract. Soil efflux is a major component of the global carbon cycle. I studied efflux in a southern Appalachian hardwood stand to determine factors influencing efflux rates. Both portable and automated systems were used to measure efflux, and the impact of temperature, DOY, soil moisture, elevation, and vegetation was determined. Temperature was found to have the greatest influence on soil efflux, accounting for 89% of the total variability efflux, although efflux also declined linearly with DOY during the fall months. Soil moisture was also found to have additional affects, reducing efflux under dry conditions. Vegetation and elevation had little influence, although elevation was weakly correlated with efflux. In scaling to the stand level, an annual total of 1082.10 grams of Carbon per square meter was found.

Key words: Efflux, global carbon cycle, soil moisture.

INTRODUCTION

Soil efflux, the movement of CO_2 from soil into the atmosphere, is a key factor in the global carbon cycle as the second largest terrestrial carbon flux (Bond-Lamberty and Thomson 2010). There is an estimated two to three times more carbon in the global soil pool than in the atmosphere (Zhang et al. 2013). In certain hardwood forests, soil efflux comprises approximately 60-80% of the entire ecosystem's respiration (Davidson et al. 1998). Total soil respiration is the sum of autotrophic respiration and heterotrophic respiration (Zhang et al. 2013). CO_2 is produced belowground by roots, organisms in the soil, and mycorrhizae. At the surface, belowground respiration is combined with surface litter respiration to deliver total respiration (Raich and Schlesinger 1992).

There is interest in studying variation in efflux due to the changing global climate, and how changes in efflux rates will affect environments (Davidson et al. 1998). Respiration rates vary temporally on hourly, diurnal, and seasonal scales, over the age of an ecosystem; and spatially from meters to ecoregions, causing significant regional differences (Vose and Bolstad 2007). Efflux is influenced by interplaying environmental factors such as temperature, soil moisture and vegetation composition (Davidson et al. 1998, Vose and Bolstad 2007, Lamberty and Thomson 2010). Respiration is positively correlated with temperature and can be limited by soil moisture content (Raich and Schlesinger 1992). Since efflux is a combination of heterotrophic respiration from decomposing organic matter and autotrophic respiration from root metabolism, higher respiration rates are expected in areas of high root biomass. Global trends can be explained by these factors; high efflux occurs in regions of high temperature and high moisture such as the tropics, and low efflux is found in cold or dry regions, such as deserts and tundra. Generally, lower latitudes experience greater rates of efflux than higher latitudes (Raich and Schlesinger 1992).

Past studies have shown that the complex relationship between soil respiration and temperature has a diel hysteresis (Phillips et al. 2010, Barron-Gafford et al. 2011, Savage et al. 2012). Diel patters show a lag between time of peak soil temperature and peak soil respiration (Phillips et al. 2010). The lag may be caused by the time it takes for CO_2 produced in soil to diffuse to the soil surface (Phillips et al. 2010, Savage et al. 2012). Diel patterns are known to fluctuate with season, and with the presence of absence of canopy cover (Savage et al. 2012).

CO_2 efflux in some regions has been studied extensively, but there are many gaps in research where further study is needed (Raich and Schlesinger 1992). The southern Appalachian Mountains afford a unique environment to study soil respiration. In this region, wide variation in ecosystems is found, and can provide insight to factors affecting soil respiration between ecosystems over a relatively small distance (Wang et al. 2012). Within southern Appalachian forests there are many different ages of forests due to past logging activity. There is variation in forest type based on elevation, slope, and soil composition. In addition, seasonal variation offers opportunity to observe various temperatures and effects of vegetation as deciduous flora defoliates in fall and refoliates in spring (Vose and Bolstad 2007).

Utilizing a region with varied ecosystems provides insight into differences in soil flux in areas with different amounts of disturbance (Vose and Bolstad 2007). Forest disturbance can result in a lack of soil fertility, negatively affecting vegetation (Butnor et al. 2003). Disturbance can also reduce primary productivity, and alter carbon inputs from detritus, which also modifies efflux (Nuckolls et al. 2009).

In this paper, we will analyze the relationship between CO_2 efflux with soil temperature and moisture in a mature, southern Appalachian broadleaf forest, and compare our results with work done by Vose and Bolstad (2007). We will expand on the previous study by increasing the spatial range of measurements and increasing the frequency of measurements from bi-monthly to weekly. We hypothesize that higher frequency sampling will show a similar temperature-response function, but unlike the previous study, we will observe soil moisture limitations on efflux. We will also determine if biophysical factors, such as vegetation and topography, near sampling locations can explain variability in efflux. We hypothesize that we will measure higher efflux rates in plots with greater basal area due to an increased contribution from root respiration. We do not expect to see major changes resulting from elevation differences because the elevation changes in our study area are relatively small. However, elevation may influence soil moisture, and we expect to see differences in soil moisture from wetter low elevation points to dryer upslope areas. In addition, we will quantify lags between peak soil temperature and peak efflux, and examine these for temporal trends. We anticipate seeing peak efflux lag behind soil temperature, and lag times to decrease when soil moisture is low, due to faster diffusion through the soil. From the data collected, we will be able to estimate annual soil CO_2 efflux from the stand.

METHODS

Measurements were taken at Coweeta Hydrologic Laboratory in Macon County, North Carolina during the summer and fall of 2013. The southern Appalachian hardwood forest was approximately 75 years of age, and consisted of vegetation typical of the region. In most of the study site, Rhododendron was the predominate vegetation form, indicating an acid cove forest (Schafale 2012). Elevation ranged from 702 m above sea level to 754 m above sea level, with an average of 718 m. Average annual precipitation in the area is 179.54 cm, and average annual temperatures range from 3.57- 21.88°C (Coweeta Hydrologic Lab 1934-2007).

Half of the measurements were taken weekly using the Li-6400 portable photosynthesis system (LI-COR, Lincoln, NE, USA) along two transects. Transect A consisted of 14 plots spaced approximately 25 m apart, Transect B contained 13 plots spaced in the same manner. No measurements were taken at Plot 1 of both transects, as they were located at a data collection tower. A piece of PVC pipe 10 cm in diameter and 5 cm in height was located at the center of

each plot. The PVC collar was inserted 4 cm into the ground to stabilize the Li-Cor system while measurements were being taken. Li-Cor measurements were taken by placing the extension on top of the PVC pipe and temperature probe 10 cm into the soil at each plot. For each measurement, three replicate cycles were taken and target CO_2 was set to the ambient atmospheric level. During each of the three rotations, CO_2 was cycled out of the chamber and through desiccant and CO_2 scrubber compartments. Each cycle provided a temperature and efflux measurement, giving three data points for each plot in total. Three soil moisture measurements were taken around the PVC collar simultaneously with temperature and efflux using a Time Domain Reflectomotry (TDR) device (Hydrosense, Campbell Scientific, Australia). The TDR uses an electric signal passed along two probes of 20 cm in length, the time it takes for the signal to move along the probe provides the soil moisture measurement.

The remaining measurements utilized two Automated Carbon Efflux System (ACES, USDA Forest Service, US Patent 6692970), which provide data for soil temperature and efflux. Each system was connected to one control chamber and 15 active chambers, which were moved between two locations twice a week. The ACES system took continuous measurements on a 160 minute cycle, moving between each plot on a 10 minute interval and providing one efflux and temperature value per measurement. Chambers were 25 cm in diameter, with a small hole in the top allowing for pressure to equilibrate within the chamber. Each chamber was covered with a piece of reflective solar radiation shield to minimize sunlight within the chamber. Located inside each chamber was a temperature probe, inserted 5 cm into the soil. An exhaust pump was used to circulate air to chambers between measurements to prevent CO_2 accumulation within the chamber (Butnor et al. 2005).

To provide additional information about the environment surrounding each plot on Transects A and B, vegetation recordings were taken. All vegetation was documented by species and diameter at breast height in a one-meter radius around the center of each plot. The same measurements were taken in a three meter radius from the center of each plot, but excluded any vegetation smaller than 2cm in diameter. Vegetation surrounding each plot of the ACES system was classified as open or within a rhododendron thicket.

Temperature measurements from certain plots for two distinct weeks were missing because the Li-Cor temperature probe broke. To find substitute values for these times, gap-filling methods were utilized. To gap-fill, the plots with missing data were compared to plots containing all data points. A linear regression was run between the two and the pair with the r^2 value closest to 1 was chosen. The regression equation was used to provide a temperature value for the missing measurements.

To test the response of efflux to soil temperature and moisture, we used an approach similar to Oishi et al. (2013) where efflux increased exponentially with temperature and was also affected by a function of soil moisture:

$$\text{Efflux} = a*\exp^{(b*\text{Tsoil})} * F_{sm}$$

where a and b are fitted parameters, Tsoil is soil temperature at 10 cm, and F_{sm} is a second-order polynomial function of soil moisture. For each transect location, a and b parameters were first estimated, then the soil moisture function was fit using residual values (measured efflux divided by efflux estimated from the temperature-response function). When residual values were equal to one it indicated that measured value and estimated value are the same. When residual values are greater than one, the measured value was higher than the estimated value. If the residual value is less than one then some factor besides temperature is acting on efflux and keeping the value lower than expected (Oishi et al. 2013).

RESULTS

Total measurements taken exceeded 400 on the Li-Cor system. Twenty-seven measurements were taken along both transects each week from mid July to early November 2013, DOY 204-319. Spatial variation accounted for differences in vegetation, slope, and soil composition leading to efflux variations within a single day's measurements. Efflux measurements generally did not vary more than 2 μmol on the same day for all plots. Temporal changes from the summer to winter seasons drive changes in respiration outputs in vegetation (Uvarov et al. 2006). Efflux declines as day of year increased and temperature decreased (Fig. 1). The lowest soil temperatures were found on DOY 298, producing an average efflux of 1.65 μmol for that day. Warmest soil temperatures on transect A were found on DOY 224, with an average efflux of 6.53 μmol, and on DOY 205 for transect B with average efflux of 6.78 μmol. Measurements taken here followed similar trends to the data taken by the ACES system. Spatial variation was relatively low compared to temporal variation.

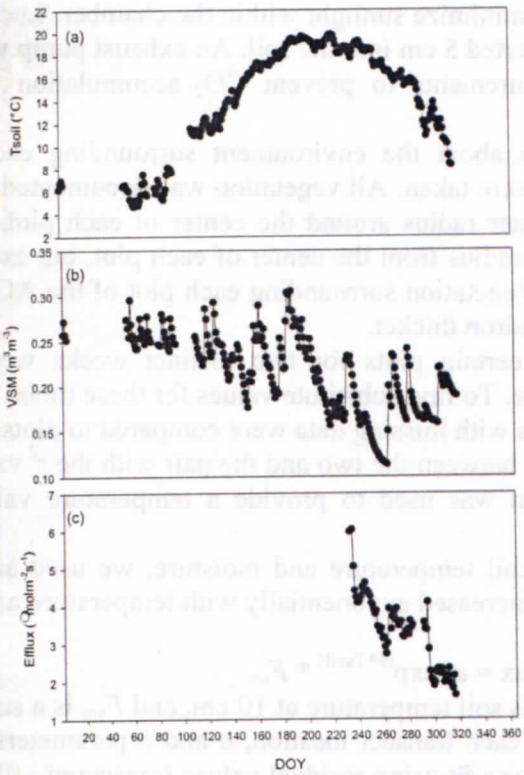

FIG. 1. Annual (a) soil temperature, (b) soil moisture content, and (c) efflux values taken from the ACES system. Shows temporal variation and correlation between soil temperature and efflux.

Soil temperature was compared to efflux using an exponential function (Fig. 3). All relationships had high r^2 values, with the lowest being 0.69 at plot B14, and the highest being 0.96 at plot B6. The average r^2 value for all plots was 0.89, indicating a strong relationship between soil temperature and efflux at all sites. From these measurements, temperature accounts for approximately 89% of efflux across all plots. We also observed a linear decline in efflux over the study period at several plots, so we tested whether a linear regression with DOY produced a better relationship with efflux than the exponential temperature function. The lowest r^2 value was found at B14 again, at 0.57, and the highest was found at B9 with a value of 0.95. The average r^2 value for all plots was 0.84. This value shows a strong relationship between DOY and efflux but is slightly weaker than the relationship between soil temperature and efflux. DOY r^2 values were higher than temperature to efflux value at only five plots. Having higher temperature r^2 values at 22 plots provides evidence that temperature plays a greater role

than a constant, linear decline during the fall. Soil moisture was also found to influence efflux. Using an estimated efflux based on soil temperature, I estimated a residual value by dividing measured efflux by estimated efflux based on the temperature-response function (Fig. 2). Residual values represented variability not explained by the regression between soil temperature and efflux (Fig. 4). When soil moisture was compared to residual values, it accounted for some of the variability not explained by soil temperature, although very little (Table 1). A linear relationship between the two produced an r^2 value of 0.07. This suggests that soil moisture can limit efflux, and lower efflux values are expected when soil moisture is lower at the same temperature.

TABLE 1. Exponential function parameters, r^2 values, and estimates of efflux at 18°C using parameters for all plots using Efflux = a*exp(b*Temperature).

Plot	A value	B Value	R2	18 degree efflux
A2	0.4502	0.1353	0.93321	5.141457757
A3	0.4820	0.1159	0.81798	3.882148879
A4	0.4651	0.1275	0.84989	4.615855189
A5	0.3950	0.1465	0.90165	5.518634662
A6	0.1531	0.1948	0.81196	5.102527594
A7	0.1823	0.1834	0.88347	4.948568796
A8	0.3107	0.1488	0.95667	4.524343743
A9	0.2459	0.1537	0.8453	3.910908384
A10	0.3155	0.1586	0.85951	5.480538722
A11	0.2353	0.1723	0.94316	5.230495507
A12	0.2014	0.1840	0.91916	5.526406037
A13	0.0718	0.2377	0.86871	5.179607064
A14	0.1824	0.1791	0.89002	4.582509614
A15	0.7151	0.1284	0.92509	7.212871325
B2	0.4567	0.1423	0.86891	5.916064463
B3	0.2423	0.1493	0.89343	3.560216469
B4	0.2377	0.1504	0.89913	3.562469896
B5	0.1952	0.1691	0.83084	4.096239653
B6	0.4805	0.1318	0.96228	5.152448041
B7	0.3871	0.1460	0.95521	5.35980599
B8	0.8064	0.1272	0.95314	7.959965123
B9	0.5156	0.1229	0.93925	4.710414894
B10	0.5989	0.1456	0.93793	8.232908548
B11	0.4531	0.1275	0.89379	4.496761957
B12	0.3822	0.1627	0.91174	7.147686607
B13	0.4085	0.1603	0.94566	7.316533391
B14	0.3829	0.1261	0.69343	3.705501397

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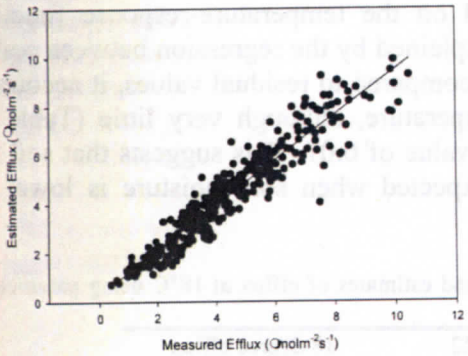

FIG. 2. Measured efflux values from all transects vs. estimated efflux values when temperature is 18°C based off exponential function. Trend line is linear relationship between measured and estimated efflux values.

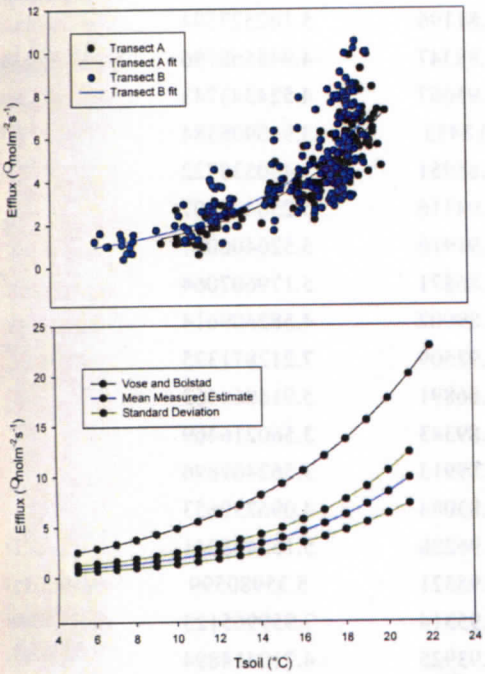

FIG. 3. (a) Soil temperature vs. efflux values for transects A and B. Exponential trend lines for both transects. (b) Soil temperature vs. efflux using mean estimated efflux values from our study, and the same parameters from the Vose and Bolstad study (2007). Black lines indicate standard deviations from Vose and Bolstad measurements.

Spatial variability in efflux was partially explained by biophysical factors. Vegetation composition varied at each plot; some plots were within rhododendron thickets, some were not. In order to compare efflux among plots over the entire study period, I standardized this value by using the exponential functions to estimate efflux at 18°C (mean soil temperature for the early phase of the study). Linear regressions between a reference efflux at 18°C and all vegetation characteristics were insignificant, with $P>0.3$ at all plots. Elevation between plots varied from 702-754 meters above sea level. Efflux at 18°C and elevation showed a weak linear trend, with

P=0.067. No trend was found between soil temperature and elevation, but soil moisture decreased as elevation increased, with P=0.027 (Fig. 4). This range in elevation represents topographic variability, but does not represent large-scale changes in elevation seen over the entire region, or in larger mountain ranges.

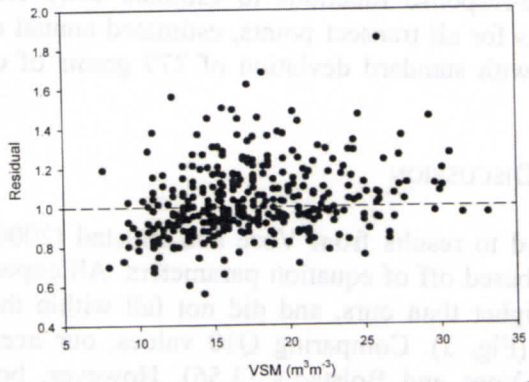

FIG. 4. Soil moisture vs. residual values for both transect's measurements. Dotted line at Y value of 1 to provide reference for values above and below 1.

ACES and transect measurements provided very similar values for soil temperature. When temperature measurements from ACES were compared to transect A measurements, the linear regression produced an r^2 value of 0.98, and for transect B produced an r^2 value of 0.99. This indicates that soil temperature is very similar along both transects or that the measurement systems from both machines are comparable. Efflux measurements from the ACES and transects also produced high r^2 values, but slightly lower than those for soil temperature. ACES compared to transect A gave an r^2 value of 0.81, and compared to transect B gave an r^2 value of 0.83. This shows slightly more variability in efflux measurements between systems, or between plots. Soil moisture showed the most variability between ACES and transect measurements. ACES compared to transect A resulted in an r^2 value of 0.70, and when compared to transect B resulted in an r^2 value of 0.63. This means there is more soil moisture variability between sites, or the two systems read soil moisture differently.

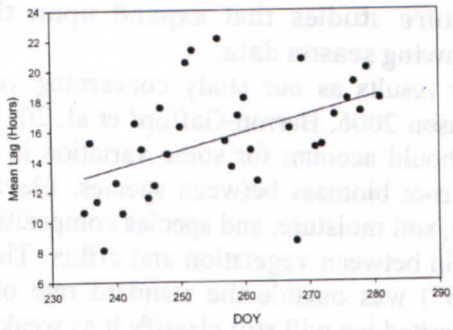

FIG. 5. DOY vs. mean lag time. Shows a slight increase in lag time as DOY increases.

Lag times were analyzed from the ACES data from DOY 235-282. Lags between peak soil temperature and peak efflux varied greatly (Fig. 5). The shortest lags were approximately 8

hours on DOY 238 and 268, and the longest lag was about 22 hours on DOY 256. There was a slight increase in average lag as DOY increased. The average time of maximum soil temperature was 17.8 (5:00 pm), and the average time of peak efflux was 12.8 (12:00 noon). The lag time for the averages is approximately 17 hours. Lags showed a slight decrease as soil moisture increased, but the trend was very weak.

Using the exponential temperature-response functions to estimate daily efflux totals under non-limiting soil moisture conditions for all transect points, estimated annual efflux was 1082 grams of carbon per square meter, with standard deviation of 279 grams of carbon per square meter.

Discussion

Our measurements, when compared to results from Vose and Bolstad (2006), showed substantial differences in expected efflux based off of equation parameters. All expected efflux values based off their parameters were higher than ours, and did not fall within the range of standard deviation of our measurements (Fig. 3). Comparing Q10 values, our average value across all plots was higher (4.79) than Vose and Bolstad's (3.56). However, both study's parameters led to increases in efflux as temperature increased over a range of 5°C to 22°C. Vose and Bolstad did not find limitations on efflux from soil moisture, although they did note that variability of soil moisture could account for some variability in efflux between plots. Our data began to indicate that soil moisture could limit efflux, but further study is necessary to find a definitive relationship. Recent studies have shown that soil moisture can explain some efflux not explained by temperature (Uvarov et al. 2006) including in temperate forests of similar age and species composition (Oishi et al. 2013).

The DOY-efflux relationship showed that from late summer through the fall, efflux declines at nearly a constant daily rate. In other words, phenological cycles in this forest system may determine the temporal variability in efflux for the period including the end of the growing season and leaf senescence. The temperature-efflux relationship suggests that efflux is a function of temperature, and that temperature variation can explain most variation seen in efflux rates. Data taken in our study supports both the DOY-efflux relationship and the temperature-efflux relationship. Similar to past studies, we found higher efflux rates in August than in November (Davidson et al. 1998, Coleman et al. 2002, Garten and Hanson 2006). Over this time period, temperature also decreased. We found that efflux decreased as temperature decreased and DOY increased, supporting both relationships. Future studies that expand upon this research should incorporate springtime and early growing season data.

Other published data has had similar results as our study concerning vegetation and elevation (Garten et al. 1999, Garten and Hanson 2006, Barron-Gafford et al. 2011, Ngao et al. 2012). Variation in vegetation composition should account for some variation in efflux due to differing respiration rates and differences in root biomass between species. Elevation changes can account for differences in soil temperature, soil moisture, and species composition. However, our data did not show a significant relationship between vegetation and efflux. The relationship found between elevation and efflux (P=0.067) was outside the standard rate of significance (P=0.05), but since our study was relatively limited we will still classify it as weakly significant. In regions of greater elevation change, we expect to see greater differences in efflux. Had we conducted our study to include sample points from a stand with similar species near the top of the basin, we may have seen a more significant influence from an elevation gradient.

Since our results did not identify simple biophysical factors that explained spatial variability in efflux, future studies could take into account several additional factors' influence on efflux. Other studies have interpreted the effect of soil nitrogen content, soil porosity, and pH on efflux (Garten et al. 1999, Ngao et al. 2012). Future work could be expanded to account for some of these additional factors, and possibly the addition of considering the slope of each plot's location. Slope could affect the movement of water through and over soil, and impact soil moisture.

Lag times between maximum soil temperature and mean peak efflux were highly variable, but showed a weak trend over time. Other studies have been able to quantify lag times (Phillips et al. 2010). Greater inspection of our data, soil moisture influence, and additional data from a greater time period could provide an estimate of lag time as it varies during the year.

Our stand estimate of 1082.10 grams of carbon per square meter was considerably lower than the estimates made by Vose and Bolstad (2006). Their annual estimate was 1623 grams of carbon per square meter. Vose and Bolstad's (2006) parameters led to higher efflux values than ours at the same temperature, so it was expected for their annual estimate to be higher as well.

Conclusion

Study of this particular hardwood forest has led to the conclusion that temperature plays the largest role in influencing soil efflux, accounting for about 89% of efflux. DOY can also contribute, but was found to be slightly less well correlated than temperature. Soil moisture explained some of the variation in efflux not explained by temperature. Elevation and vegetation composition of each plot played little role in determining efflux rates. The estimated annual total efflux for the stand was 1082 grams of Carbon per square meter.

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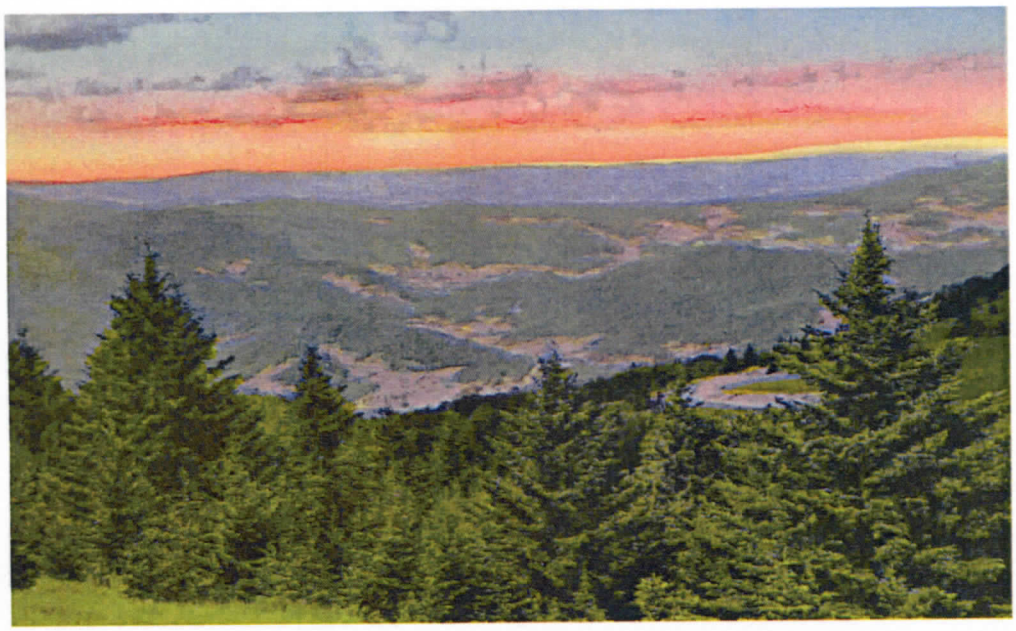

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