VARIABILITY IN MICROCLIMATE AND CARBON DYNAMICS IN HARDWOOD FORESTS MANAGED WITH THE IRREGULAR SHELTERWOOD REPRODUCTION METHOD

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Abstract

How do forest edges compare to intact interior forests in terms of carbon dynamics, and how is the microclimate altered through the creation of forest edges? Woody plants and trees can act as a carbon sink by using live and dead tissue to store varying amounts of carbon. However, factors such as age, species, respiration rates, and death alter the amount of carbon sequestered by the forest (Gorte, 2009). Additionally, widespread forest fragmentation has resulted in 20% of forests worldwide being located within 100 meters (m) of a forest edge (Haddad et al., 2015). Despite this fragmentation, current carbon models consider forests to be intact and therefore neglect edge effects (Reinmann & Hutyra, 2016), potentially increasing the amount of error in models of current carbon sequestration in our forests (Chaplin-Kramer et al., 2015). However, there are few studies to date on the effects of forest edges on carbon sequestration, and those that exist have produced conflicting results, which may indicate that results are sensitive to particular ecosystems or regions (Meeussen et al., 2021).

In this research, we investigated differences in carbon sequestration and depth of edge effects by studying microclimate variables, growth, and decomposition along a transect implemented within subtropical study sites receiving the irregular shelterwood reproduction method. Across transects, photosynthetically active radiation (PAR) was found to be altered for up to 15 m in either direction from a physical edge. Air and soil temperature appeared to be altered for approximately 20 m into uncut forests. However, determining depth of edge effects for additional microclimate variables, growth, and decomposition was more difficult. This may have occurred due to the small size of implemented gaps or natural canopy gaps within the uncut forests. Furthermore, nominal differences in carbon storage (C) on north and south facing edges indicate that edge aspect may have impacted amounts of C stored. Differences in microclimate variables and C observed across small distances suggest that small scale changes in

silvicultural practices could have a greater than expected impact on net carbon sequestration and storage when implemented at larger scales.

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Chapter 1: Introduction

Between 1970 and 2000, CO_2 [carbon dioxide] emissions grew at an average annual increase of 1.3% each year. However, over the next consecutive 10 years the average annual increase of CO_2 emissions was 2.2% each year (IPCC, 2014). Although the growth rate decreased to 1.3% between 2010 and 2019, overall greenhouse gas emissions continued to climb to the highest levels seen; nearly half of the CO_2 emissions since 1850 have occurred in the past three decades (IPCC, 2023). Across agricultural and forestry land use types (AFOLU), forestry offers the largest potential to mitigate climate changes through CO_2 sequestration. Contributions from the AFOLU sector provided mitigation of 1.4% of global CO_2 emissions from 2010 to 2019, with the majority of these contributions coming from the forestry sector. Despite these advancements, a variety of challenges and unknowns are still faced within reducing CO_2 emissions through forestry (IPCC, 2021). Although it is widely established that United States forests are logical carbon sinks, there are some ongoing complications which include measuring carbon storage above naturally occurring amounts when applying carbon credits, monitoring carbon sequestration, and mitigating carbon losses within the forest (Gorte, 2009).

The impacts of increasing CO_2 have significant direct effects on the environment, and indirect effects on social constructs (IPCC, 2021). The main factors responsible for a large portion of negative environmental and social construct changes are rising temperatures, air pollution, and land fragmentation (IPCC, 2007). As air temperatures increase, this creates a positive feedback loop in both marine and terrestrial ecosystems. In marine environments, ice caps in the arctic continue to melt as albedo is altered. As a result, the Artic Ocean is predicted to be ice free by the middle of the 21st century (Holland et al., 2010), which will cause significant impacts to marine wildlife (Arrigo et al., 2012) and increased sea-levels which, in turn, threaten coastal ecosystems, terrestrial wildlife, infrastructure, and livelihoods. These impacts can cause economic hardships for coastal populations as the cost of repairs or altered living arrangements

are made (Doney et al., 2012). In terrestrial environments, altered biomes and pollinator loss are among the direct negative impacts of rising air temperatures. As a result, food stability is anticipated to decrease which will thereby impact the economic value of impacted crops (Giannini et al., 2017). In addition, portions of the United States are expected to see altered fire regimes (Fill et al., 2019), which can pose health hazards (Fann et al., 2018) and economic hardships (NIFC, 2020) alike, while simultaneously contributing to CO_2 emissions. Furthermore, once global surface temperatures reach 1.5 degrees Celsius above pre-industrial temperatures, biodiversity and ecosystem services have limited mitigation potential, which would, in turn, make further global warming mitigation even more difficult. The most recent consensus by IPCC (2023) revealed that in 2020, global surface temperatures had reached 1.1 degrees Celsius above pre-industrial temperatures, indicating that reductions in carbon dioxide levels need to occur in the near future if AFOLU is to be considered for use as an effective carbon sink.

Tropical forests are known to have large carbon sequestration abilities when compared to temperate forests, with differences appearing to be driven by decomposition rates and species diversity (Gorte, 2009). However, modern forests are also highly fragmented, and nearly 20% of forests worldwide occur within 100 m of a forest edge (Haddad et al., 2015). If deforestation rates are held constant, it is projected that 50% of forests worldwide would occur within 100 m of a forest edge by the year 2100 (Fischer et al., 2021). Despite modern advances, current carbon prediction models neglect differences in edge effects (Reinmann & Hutyra, 2016). These edges have not yet been sufficiently studied to determine guidelines for edge effect limitations or to what extent microclimate variables fluctuate across the edge. One study by Chaplin-Kramer et al. (2015) based upon tropical forests found a decrease in biomass and carbon storage along forest edges, with effects lasting up to 500 m into the forest. A previous study within similar climate regions also found a significant decrease in biomass (Laurence et al., 1997), but these results are not strictly limited to tropical forests. An earlier study on boreal

forests showed increased mortality along forest edges which would decrease overall carbon sequestration abilities of the forested area (Jönsson et al., 2007). In fact, it has been said that forest edges may only sequester half of the amount of carbon as their interior counterparts (Schmidt et al., 2017). However, a study by Reinmann & Hutyra (2016) in southern New England found a significant increase in biomass and carbon storage along deciduous temperate forest edges that would account for regional increases of 10% biomass and carbon sequestration ability. Likewise, temperate coniferous forest edges were also shown to have increased biomass along forest edges when compared to their interior counterparts (Bowering et al., 2006). It should be noted that basal area (BA), or the cross-sectional area of a tree at breast height, is often used as a metric of estimating biomass and carbon since it is easy to calculate in the field (Torres & Lovett, 2012).

Decomposition within forests also plays a significant role in carbon cycling, as decaying woody debris and organic matter emit carbon and regulate soil carbon storage (Berg & McClaugherty, 2008). Although there are a number of factors responsible for decomposition rates, climate has been thought to be one of the main drivers for several decades (Couˆteaux, 1995). While multiple studies have found decomposition to be correlated with soil temperature and soil moisture (Drewnik, 2006; Kim et al., 2010), other factors such as leaf litter composition (Berg & McClaugherty, 2008), soil pH (Zunino et al., 1982), and elevation (Shanks & Olson, 1961) have been suggested as factors influencing decomposition rates. Furthermore, as soil temperatures rise in response to climate change, decomposition rates on forest edges are expected to increase, which would only further the positive feedback loop and ultimately create imbalances in our understanding of carbon cycling (Reinmann et al., 2020; Smith et al., 2019). The gravity of the situation is compounded by increased forest fragmentation (Garvey et al., 2021) and lack of model inclusion of soil carbon fluxes (Smith et al., 2019). One study by Crockatt and Bebber (2015) found that decomposition rates increased as the distance from the edge of the forest

increased. They found the difference in decomposition to be up to 25% different, which would drastically modify the amount of carbon that is being stored along forest edges. Similarly, Garvey et al. (2021) found that urban forest edges had lower decomposition rates, but that this was not true of rural forest edges. In contrast, other studies such as Smith et al. (2019) discovered higher decomposition rates on forest edges, and Putz et al. (2014) estimated that forest edge carbon losses could account for up to 24% of total carbon losses associated with deforestation, showing there is some uncertainty on carbon respiration dynamics as well.

Furthermore, forest stand management can have implications for carbon sequestration potential. Site index, soil characteristics, species composition, stand age, stand density, and overall stand health play important roles in carbon sequestration (Kern et al., 2021). Forest management practices such as clear-cutting can influence carbon dynamics (Binkley, 1984), and studies have found that management can have positive or negative effects on carbon sequestration potential, depending on management practices (Moore et al., 2012). Regardless, both human and natural disturbances create fragments at some level (Hart & Grissino-Mayer, 2009).

There are many different silvicultural practices within forestry, but what type of practice is applied to a stand depends on the management goals. These stands can then be managed as even-aged or uneven-aged stands, as appropriate for the desired goals. An even-aged stand is comprised largely of trees that are all the same age or diameter class, while uneven-aged stands are generally referred to as more than three age classes within a stand (Bettinger et al., 2016). The irregular shelterwood reproduction method is one type of silvicultural practice that is used to create an uneven-aged stand, which is often desirable for ecosystem-based goals. While all shelterwood methods share a common goal of regenerating mixed species stands, the irregular shelterwood method maintains overhead or side canopy for an extended period of time to promote vertical and horizontal complexity within the stand (Schültz, 2002) This is commonly

used to promote tree species that have a tolerant or intermediate shade tolerance level (Raymond et al., 2009).

Although the definition and scale of microclimate variables depends largely upon the hypothesis being investigated (Mislan & Helmuth, 2008), it can generally be thought of as "… the suite of climatic conditions measured in localized areas near the earth's surface" (Naiman et al., 2010). However, these conditions can be altered through disturbances, whether anthropogenic or natural, and alter microclimates variables such as temperature, light, wind speed, and moisture, and others (Chen et al., 1999). Therefore, to understand the implications that silvicultural treatments have on their environment, variables must be examined at microclimate scale (Rose, 2000; Dam, 2001). Furthermore, gap studies have varied widely in approaches, scales, and variables investigated, ultimately leading to a fractured and incomplete analysis of microclimate variables across gaps (Abd Latif & Blackburn, 2009).

Our study is located within East Tennessee, a region that, to our knowledge, has not previously been studied in terms of carbon sequestration on forest edges. From a geographical perspective, one might expect the results of carbon sequestration to be muted in comparison with the geographical extremes presented in the above previous studies. However, Tennessee has abundant floral biodiversity, with over 2,800 native vascular plants throughout the state (Wofford & Chester, 2002). With this in mind, we will be testing four main hypotheses for this project:

(1) Microclimate variables can be used to show the depth of edge effects.
(2) Carbon dynamics along forest edges will differ from carbon dynamics within the uncut portion of the forest.
(3) Basal area (BA) on forest edges will be different from that in uncut forest due to differences in microclimate conditions, primarily light.

(4) Decomposition along forest edges will be different than that in uncut forest due to differences in microclimate conditions, particularly soil moisture.

The objectives of this project are (1) to examine the depth of edge effects in irregular shelterwoods in a subtropical forest ecosystem, (2) to test that carbon storage (C) along forest edges varies from carbon storage within intact forests, (3) to determine conditions that affect carbon dynamics along forest edges by measuring BA, decomposition, and microclimate variables including photosynthetically active radiation (PAR), air temperature, soil temperature, soil moisture, relative humidity, and canopy cover (4) and to study the effects of the irregular shelterwood reproduction method on carbon storage in East Tennessee.

Chapter 2: Methods

Site Description

A total of six sites were studied within the University of Tennessee Arboretum Forest (35.9935° N, 84.2201° W) located in Oak Ridge, Tennessee (Figure 1). The forest type of the study sites is described as Oak-Hickory Forest (USDA Forest Service, 2019). The site index for base age 50 white oak was 70 feet (Soil Survey Staff 2022). Across all of the sites, the seven species with at least 0.5 m^2/ha were oaks (*Quercus spp.*), tulip-poplar (*Liriodendron tulipifera*), and maples (*Acer spp.*) (Table 1). All sites were located on soils belonging to the Fullerton-Pailo complex. Slopes ranged from 5-35 percent. Only one site had a greater than 20% slope. Sites with 5-12% slope had a gravelly silt loam in the upper 38 cm of soil. Soils on all other slopes were defined as having a gravelly silt loam soil texture for the first 18 cm that transitioned into a gravelly clay below this depth (Soil Survey Staff, 2023). The study region is considered to have a subtropical climate, which is defined as having temperatures above 10 degrees Celsius for at least eight months of the year (IPCC, 2006). A weather station is located on the University of Tennessee Arboretum property, and this station has recorded an annual average of 156.36 cm of precipitation and an average of at least 10 degrees Celsius over 8 months during the past two decades (NCDC, 2020). In 2022, the University of Tennessee Arboretum weather station (NOAA-ATDD) recorded nine months averaging at least 10 degrees Celsius, as of September 2023, seven months had reached an average of at least 10 degrees Celsius. In 2022, there was an annual precipitation of 149.56 cm. Microclimate variables were recorded each year in June-August. In 2022, the study period had average temperatures of 26 degrees Celsius and precipitation totaled 39.56 cm. In 2023, the study period had average temperatures of 23.1 degrees Celsius and precipitation totaled 40.64 cm (NCEI, 2023).



Figure 1. Generalized (a) and specific (b) study site locations

Table 1. Species comprising at least 0.5 m^2/ha on the study sites

Species	Latin	Trees/Hectare	Average Basal Area/Tree	Average Basal Area/Hectare
chestnut oak	*Quercus montana*	28	0.155 m^2	4.321 m^2/ha
tulip-poplar	*Liriodendron tulipifera*	2009	.001 m^2	2.836 m^2/ha
white oak	*Quercus alba*	65	0.023 m^2	2.020 m^2/ha
black oak	*Quercus velutina*	16	0.124 m^2	1.977 m^2/ha
red maple	*Acer rubrum*	818	.002 m^2	1.157 m^2/ha
northern red oak	*Quercus rubra*	7	0.115 m^2	0.765 m^2/ha
sugar maple	*Acer saccharum*	209	.001 m^2	0.571 m^2/ha

Study Design

The main study design was a complete block design in which each site represented a block. On each site, a single transect was established across seven different levels of canopy structure created through implementation of the irregular shelterwood reproduction method. This consisted of uncut forests on either end of the transect, a gap harvested in either 2013 or 2014, hereafter referred to as 'old cut', a gap harvested in either 2022 or 2023, hereafter referred to as 'recent cut', and the edges between all of these areas, hereafter referred to as the uncut/old cut edge, old/recent cut edge, and the uncut/recent cut edge as appropriate (Figure 2). Gaps created ranged from 0.15-0.25 ha each. The transects extended 40 m into the uncut areas on either side of the old- and recent cuts unless physical constraints prevented transect segments of this length. All transect segments were located with "0" points corresponding to the physical edge, which was defined by the outermost tree bole. Where edges were less defined, an in-field average outermost tree bole was estimated and marked as point "0". Uncut forest is defined as not having had timber harvests in the past 30 years, while old- and recent cuts were performed between 2013 and 2014 and 2022 and 2023, respectively. All measurements were obtained in the summers of 2022 and 2023, and each transect was sampled within three months of harvesting the recent plots.

Data Collection and Materials

Along each transect, diameter at breast height (DBH) was recorded by species for all woody stems occurring within five m radius circular plots located every 10 m along each transect (Figure 2). All diameters were taken using calipers or diameter tape, as appropriate, and measurements were recorded to the nearest millimeter. Diameter measurements were used to calculate basal area (BA) and used to estimate biomass using equations developed by Chojnacky et al. (2014). Ultimately, the biomass estimates were converted to carbon storage

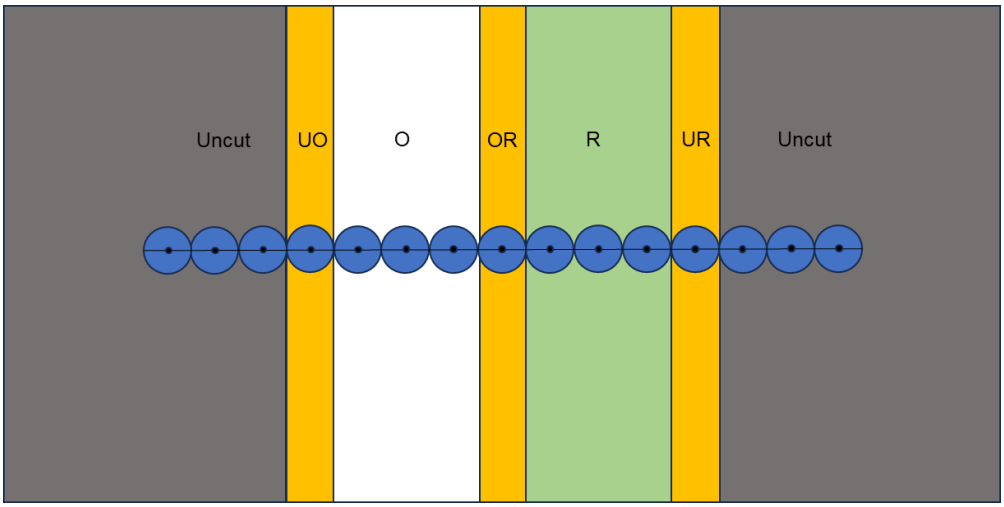


Figure 2. Schematic of a Sampling Transect

From left to right transect segments are: north facing uncut forest, uncut/old cut edge, old cut, old/recent cut edge, recent cut, uncut/recent cut edge, and south facing uncut forest.

(C) by multiplying biomass by a constant of 0.47, which is appropriate for the study area (IPCC, 2006).

Microclimate variables were measured every five m along the transect tape. All microclimate variables were taken on entirely sunny days with no cloud cover and within two hours of solar noon. Additionally, all microclimate variables along a single transect were taken on the same day, and generally took less than one hour to complete for a single transect. This was done to minimize time related differences in PAR readings. Air temperature and relative humidity were measured using a Kestrel 3000 pocket weather meter (Nielsen-Kellerman, Chester, PA). Soil temperature was measured using a Reotemp 300 series SS soil temperature thermometer with a 15.24 cm stem (Reotemp Instrument Corporation, San Diego, CA). Photosynthetically active radiation (PAR) was measured using a LP-80 ACCUPAR Ceptometer (Meter Group Inc., Pullman, WA), and canopy cover was measured using the CanopyCapture (2018) application. Soil moisture was measured with a Model 6050X1 Trase System with model 6005L2 20 cm buriable waveguides (Soil Moisture Corporation, Santa Barbara, CA). Waveguides were buried between 8-10 cm below the mineral soil surface. All soil moisture data was collected within 48 hours of a rain event that produced at least 2.54 centimeters of rainfall during the period that soil moisture waveguides were buried. All above-ground measurements (e.g., PAR, AT, etc.) were taken facing South at 1 m above-ground. Soil temperature measurements were taken in an area that was cleared of leaf litter, and the stem was inserted perpendicular to the soil surface. Decomposition of 90mm diameter Whatman Grade 3 cellulose paper (GE Healthcare, Chicago, IL) was quantified by the mass lost after placement in the field for 33 days. Cellulose papers were weighed and enclosed in fiberglass screening with a 0.02794 cm mesh size (Saint-Gobain Adfors, Grand Island, NY) and closed with an office stapler. Gaps between staples did not exceed one cm. The fiberglass screening envelopes were tagged with 2.54 cm x 8.89 cm Jim-Gem aluminum tags (Forestry Suppliers Inc., Jackson, MS) and placed horizontally between the

mineral soil surface and the bottom of the organic soil horizon. All fiberglass envelopes were staked to the ground with one to two metal stakes, depending on site factors, and installed as close to flagged transect points as possible. Upon extraction from the field, cellulose papers were dried at 50 degrees Celsius for five days and then weighed. All masses were recorded to the nearest 1/10,000 of a gram. Decomposition for five out of the six transects had the same date of installation on June 29, 2023 and removal on August 1, 2023. Decomposition along the sixth transect was implemented one month later on July 29, 2023 and removed on August 31, 2023, due to delays in harvesting the recent gap.

Chapter 4: Analysis

Data Analysis

All microclimate variables, DBH, and decomposition values were entered into Microsoft Excel (2021) where simple mathematical calculations were carried out to convert diameters to BA, obtain biomass estimates (Chojnacky et al., 2014), and obtain estimates of stored carbon (IPCC, 2006). After all calculations were performed, line graphs illustrating raw data of all microclimate variables, BA, C, and decomposition values were created to visually analyze patterns and relationships between independent and dependent variables. Histograms of each variable across treatment sections (e.g., uncut, uncut/old cut edge, old cut, etc.) were created with standard error bars to evaluate significant differences across treatments corresponding to the different canopy types.

Statistical Analysis

All microclimate variables, BA, C, and decomposition were analyzed in SAS 9.4 (2013). Preliminary analysis included frequencies, means, and correlations (Table 2) between variables. All variables were checked for normality using Shapiro-wilk's test of normality. Multiple regression using the proc reg function was utilized to determine variables impacting carbon dynamics. An ANOVA test was then performed using the proc glm function to compare carbon dynamics across the seven types of treatment sections and Tukey's post-hoc test was performed to analyze differences across treatments for each variable. A standard level of significance ($p < 0.05$) was applied for all tests.

Table 2. Correlations between Study Variables

Pearson Correlation Coefficients, N = 42 Prob > |r| under H0: Rho=0											
	Carbon	Basal	AVG_Decomp	Site	Treatment	AVG_PAR	AVG_Air_T	AVG_RH	AVG_Soil_T	AVG_Canopy	AVG_SM
Carbon	1.00000	0.89871 <.0001	-0.09974 0.5297	-0.08762 0.5811	0.26139 0.0945	-0.13959 0.3780	-0.04394 0.7823	0.20955 0.1829	0.06292 0.6922	0.34774 0.0240	-0.10431 0.5109
Basal	0.89871 <.0001	1.00000	-0.15838 0.3165	-0.17234 0.2751	0.11682 0.4613	-0.25679 0.1007	-0.05752 0.7175	0.25662 0.1009	0.04168 0.7932	0.46065 0.0021	-0.02629 0.8688
AVG_Decomp	-0.09974 0.5297	-0.15838 0.3165	1.00000	-0.11597 0.4645	0.06878 0.6652	0.33356 0.0309	0.07319 0.6451	0.00673 0.9663	0.04881 0.7589	-0.22095 0.1597	0.18560 0.2393
Site	-0.08762 0.5811	-0.17234 0.2751	-0.11597 0.4645	1.00000	0.00000 1.0000	-0.03486 0.8265	-0.05148 0.7461	-0.21490 0.1717	-0.16264 0.3035	-0.09401 0.5537	-0.05812 0.7147
Treatment	0.26139 0.0945	0.11682 0.4613	0.06878 0.6652	0.00000 1.0000	1.00000	0.34136 0.0269	0.07075 0.6561	-0.02610 0.8697	0.16424 0.2987	-0.35080 0.0227	-0.13736 0.3857
AVG_PAR	-0.13959 0.3780	-0.25679 0.1007	0.33356 0.0309	-0.03486 0.8265	0.34136 0.0269	1.00000	0.33614 0.0295	-0.21818 0.1651	0.41556 0.0062	-0.79406 <.0001	0.22115 0.1593
AVG_Air_T	-0.04394 0.7823	-0.05752 0.7175	0.07319 0.6451	-0.05148 0.7461	0.07075 0.6561	0.33614 0.0295	1.00000	0.49230 0.0009	0.91708 <.0001	-0.23337 0.1369	0.50984 0.0006
AVG_RH	0.20955 0.1829	0.25662 0.1009	0.00673 0.9663	-0.21490 0.1717	-0.02610 0.8697	-0.21818 0.1651	0.49230 0.0009	1.00000	0.60408 <.0001	0.31596 0.0415	0.10547 0.5062
AVG_Soil_T	0.06292 0.6922	0.04168 0.7932	0.04881 0.7589	-0.16264 0.3035	0.16424 0.2987	0.41556 0.0062	0.91708 <.0001	0.60408 <.0001	1.00000	-0.23681 0.1311	0.45273 0.0026
AVG_Canopy	0.34774 0.0240	0.46065 0.0021	-0.22095 0.1597	-0.09401 0.5537	-0.35080 0.0227	-0.79406 <.0001	-0.23337 0.1369	0.31596 0.0415	-0.23681 0.1311	1.00000	0.04350 0.7844
AVG_SM	-0.10431 0.5109	-0.02629 0.8688	0.18560 0.2393	-0.05812 0.7147	-0.13736 0.3857	0.22115 0.1593	0.50984 0.0006	0.10547 0.5062	0.45273 0.0026	0.04350 0.7844	1.00000

Chapter 5: Results

Photosynthetically Active Radiation

PAR was relatively uniform across uncut forests, old cuts, and the uncut/old cut edge for most transects, although transects “A” and “E” had a few outliers. These outliers are true in-field differences, and therefore make determining the depth of edge effects for PAR on these transects difficult to visually assess. Overall, PAR was very uniform across old cuts. Interestingly, across the recent cuts and the adjacent edges, PAR was varied even when assessed at an individual transect level. However, for most transects, PAR can be seen rapidly diminishing in value across the edges adjacent to the recent cut. Across transects the extent of edge effects appear to be 15 m or less into the old cut or the uncut forests, with the exception of a few outliers as mentioned above. Transects “D” and “F” did appear to reach an equilibrium point within recent harvests, indicating that edge effects on PAR from the uncut forest and old cuts extended 5-10 m into the recent harvest. However, it was not possible to visually assess the depth of PAR edge effects into the recent cuts for most of the transects (Figure 3).

Canopy Cover

Most transects had noticeably uniform canopy cover in old cut areas, with the exception of a few outliers in transect “C” and “D”. In fact, this value was often higher in old cut areas than in uncut areas along the same transect. However, outliers in uncut forest as well as variation within the recent cut make determining depth of edge effects of canopy cover difficult. It should be noted, however, that often PAR and canopy cover within a transect are nearly mirror images of one another (Figure 4).

Air Temperature

For the majority of transects, the depth of edge effects is observed to be on average 10-15 m into the uncut forest, extending from any gap. However, along transects “B” and “E”, differences

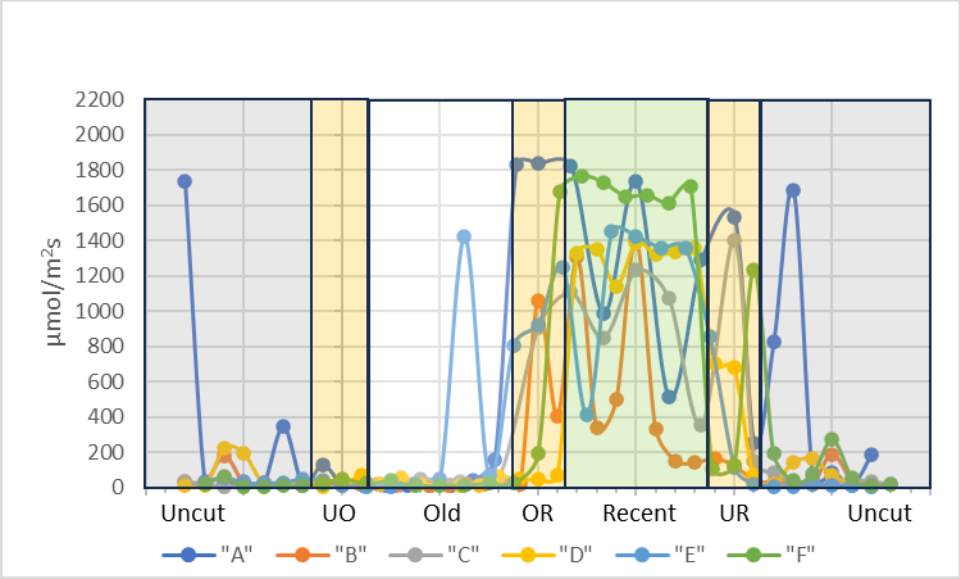


Figure 3. Photosynthetically Active Radiation across Transects

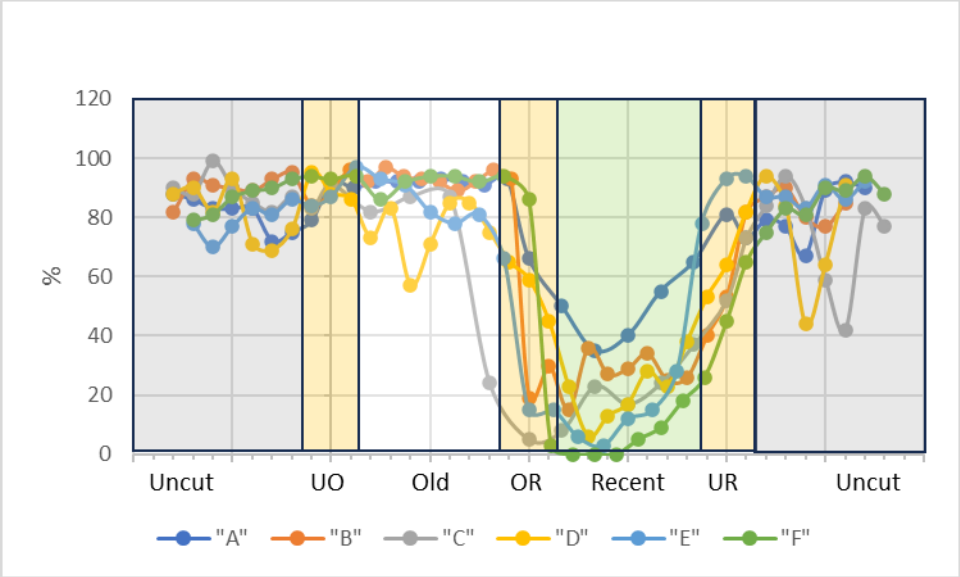


Figure 4. Canopy Cover across Transects

in air temperature across the transect were relatively stable, and therefore differences were not great enough to be visually assessed. There is some implication to suggest that edge effects from the uncut forest onto gaps extend approximately 15 m as well, although data are not consistent enough to have conclusive results. Reasonably, highest nominal air temperature values were often recorded within recent cuts or an adject edge (Figure 5).

Relative Humidity

Air temperature and relative humidity have an inverse relationship where relative humidity is often highest where air temperature is lowest. Across transect “A”, the depth of edge effects extend 10-15 m away from the recent cut, however the impacts from the old cut are less clear. Other transects, such as transect “D” seem to implicate that the depth of edge effects for relative humidity are reached within 10-15 m in any direction of a gap, although outliers make this less certain. In fact, in some transects, such as transect “E”, the depth of edge effects on the north facing uncut forest appears to extend 5 m, while variation on the south facing uncut forest is not easily discernable, therefore aiding in the uncertainty in the depth of edge effects of relatively humidity (Figure 6).

Soil Temperature

Soil temperatures along transects “A”, “C”, and “E” were increased for 10-15 into the uncut forests away from a gap. Along transect “D” these effects were extended for 20 m. However, other transects such as the north facing uncut forest along transect “C” or transects “B” and “F”, differences were difficult to visually assess. Transect “F”, however, appears to implicate that the depth of edge effects extends for approximately 15 m in any direction of a gap (Figure 7).

Soil Moisture

Soil moisture across transects and treatments experienced high levels of variability. The exception is that the recent cut in transect “C” was relatively consistent, but variation in either

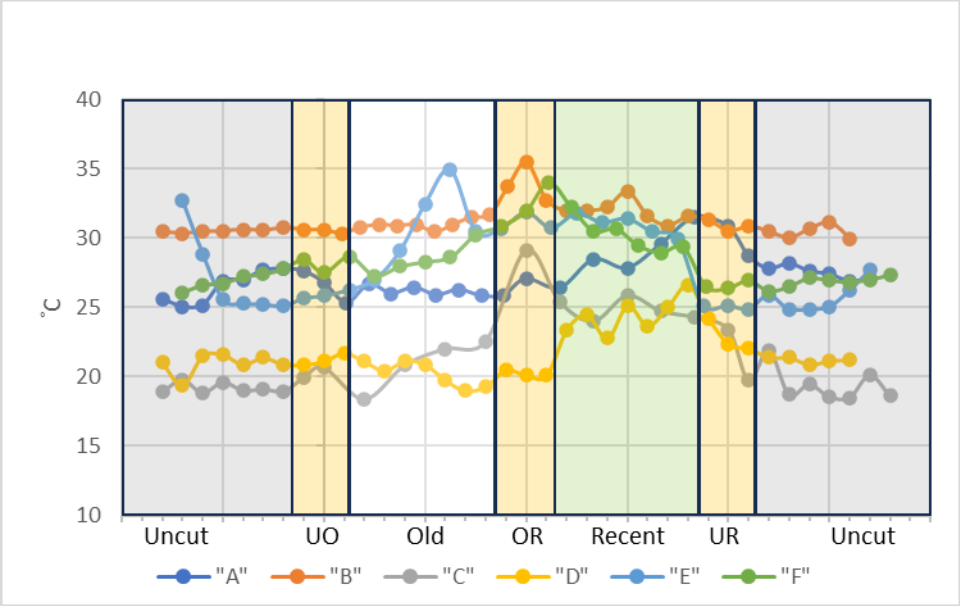


Figure 5. Air Temperature Across Transects

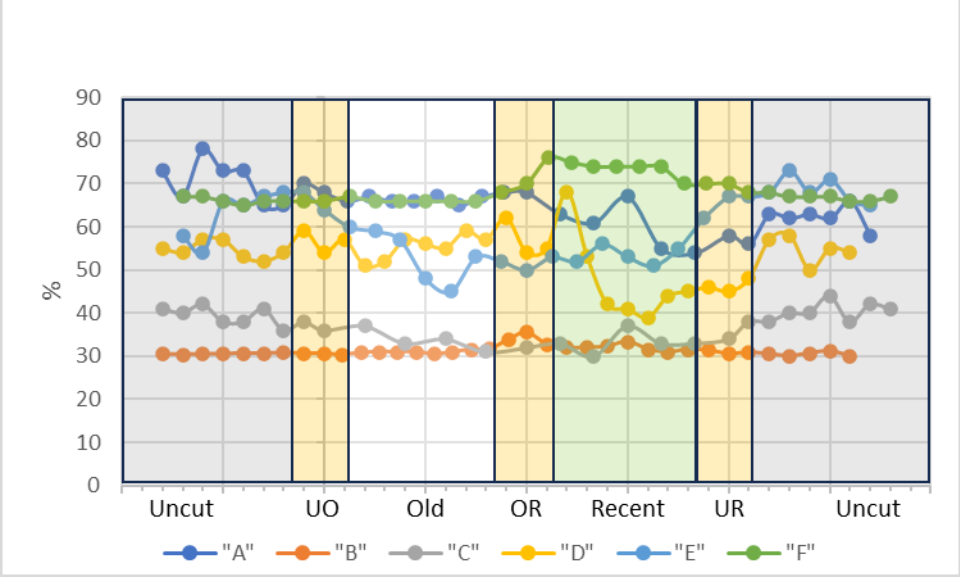


Figure 6. Relative Humidity Across Transects

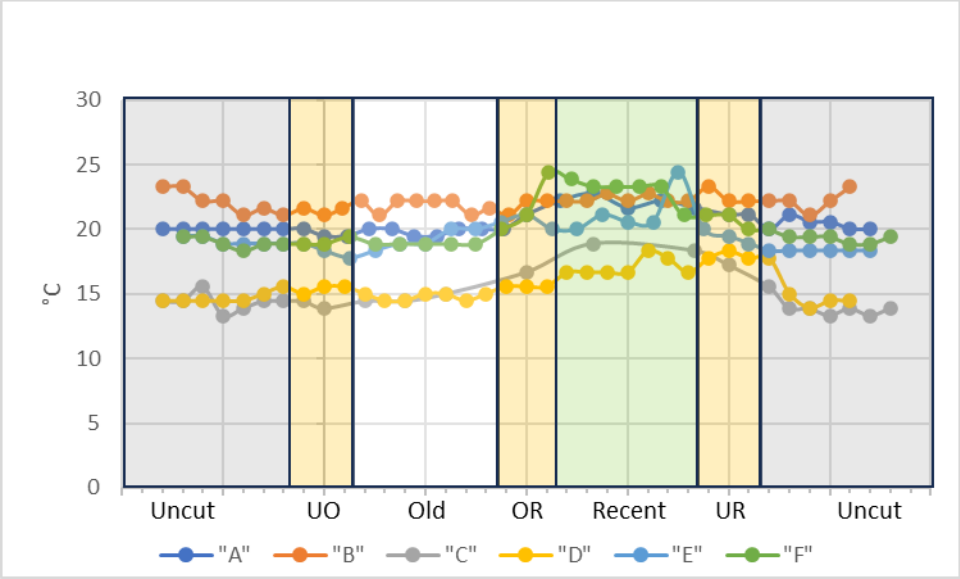


Figure 7. Soil Temperature Across Transects

direction of the recent cut makes it impossible to determine the depth of edge effects for soil moisture (Figure 8).

Decomposition

Like soil moisture, decomposition experienced a significant amount of variation across transects that was not related to the treatment segment. Although some transects has specific trends, such as overall lower nominal levels of decomposition in uncut forests when compared to the gaps along transect “D”, other transects such as “E” appeared to experience the opposite, with higher nominal levels of decomposition occurring in gaps rather than in uncut forest. Additionally, the high levels of variation within any transect made visually determining the depth of edge effects on decomposition impossible (Figure 9).

Basal Area

The south facing uncut forests, or those closest to the recent cut, often experienced the highest levels of BA within the first 15 m into the uncut forest from the physical edge. However, this was not necessarily true of the north facing uncut forest, or the portion closest to the old cut. This portion of the old cut forest often had the greatest recorded value at the end point of the transect, with the exception of two transects. BA was predictably low in old- and recent cuts, but differences in old- and recent cuts are discernable across all transects (Figure 10).

Carbon Storage

Similar to BA, stored C often experienced differences between the north facing and south facing uncut forests. Generally, the greatest values of stored C on the south facing uncut forests are seen within the first 15 m of a physical edge. However, the north facing uncut forests were often observed to have the greatest stored C at the furthest data point recorded, around 35 m away from a physical edge. Additionally, variation within C storage in uncut forests made visually determining depth of edge effects difficult along some transects. Although the difference in C

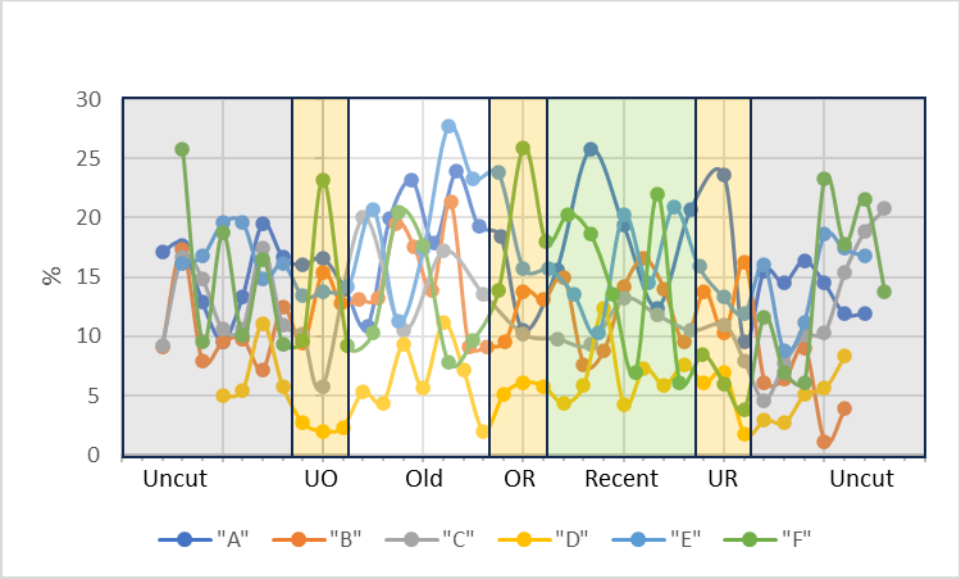


Figure 8. Soil Moisture Across Transects

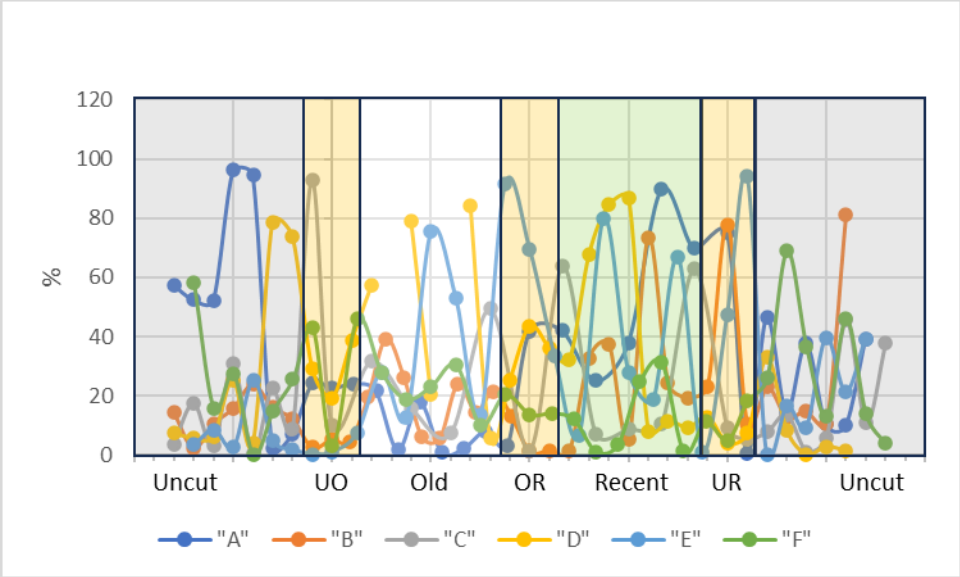


Figure 9. Decomposition Across Transects

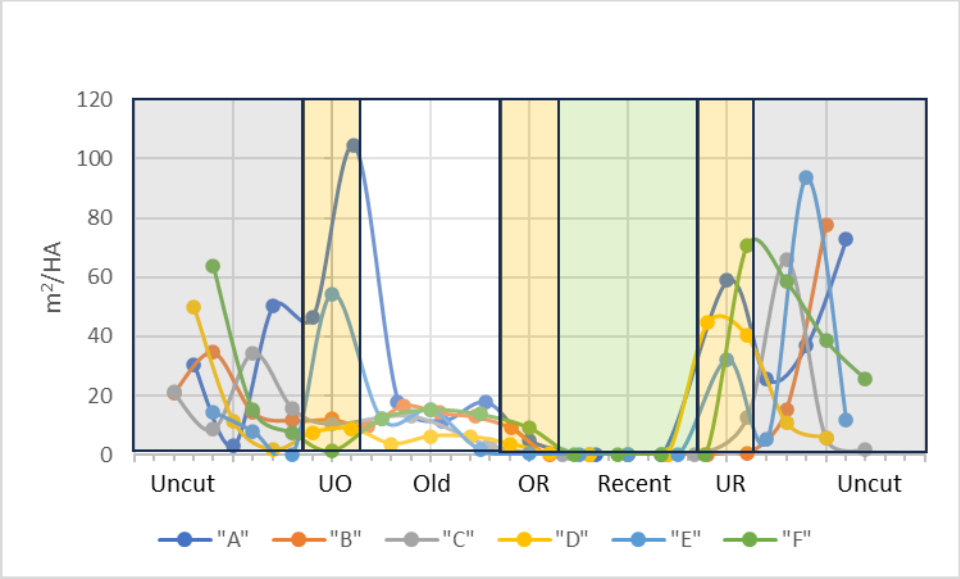


Figure 10. Basal Area Across Transects

storage between old cuts and recent cuts is not as noticeable as it is in BA, there is some visual difference occurring (Figure 11).

Regression Results

A simple linear regression was performed for dependent variables C, BA, and decomposition. Canopy cover and treatment were found to be factors associated with predicting C storage (adjusted R^2 = 0.2520, p = 0.0013) modeled with the equation C = -0.7776 + 0.0109*canopy cover + 0.1218*treatment. Predictions for BA were similar, with canopy cover and treatment as factors in the model (adjusted R^2 =0.2647, p = 0.0009) modeled by the equation BA = -0.1664 + 0.0032*canopy cover + 0.0224*treatment. Only one factor, PAR, was found to be associated with predicting decomposition (adjusted R^2 = 0.0890, p = 0.0309) modeled by the equation decomposition = 22.4959 + 0.0111*PAR.

ANOVA results

Differences in mean PAR across treatments were found to be significant (R^2 = 0.807, $p < 0.001$) where recent harvests had significantly more PAR than the uncut/recent edges. Uncut/recent edges also had greater PAR than uncut, old cuts, and the uncut/old cut edge areas (Figure 12). Mean air temperature in recent cuts and the old/recent cut edge differed from uncut forest areas and the uncut/old cut edge (R^2 = 0.901, $p < 0.001$) (Figure 13). Similarly, mean soil temperature in recent cuts and the adjacent edges (old/recent cut edge and uncut/recent cut edge) were significantly greater than all other treatment areas (R^2 = 0.947, $p < 0.001$) (Figure 14). However, mean soil moisture was only significant by site (R^2 = 0.800, $p < 0.001$) rather than treatment (p = 0.135) (Figure 15). Mean relative humidity was lower in recent harvests and the old/recent cut edge than in the south facing uncut forest area (R^2 = 0.890, $p < 0.001$) (Figure 16). Mean canopy cover was also lower in recent cuts and old/recent cut edges in comparison to the north facing uncut forest, old cut, and the edge between them (uncut/old cut edge) (R^2 = 0.870, $p <$

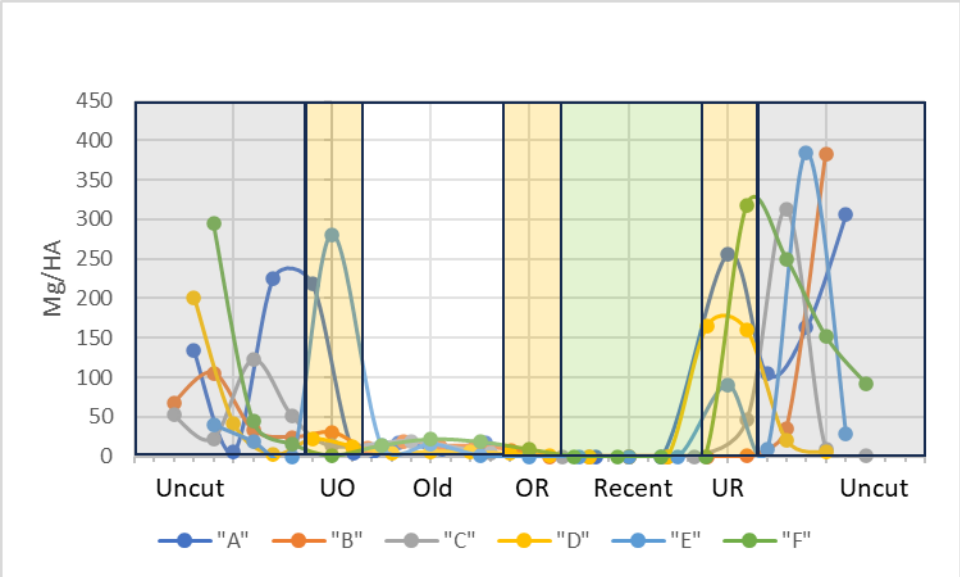


Figure 11. Carbon Storage Across Transects

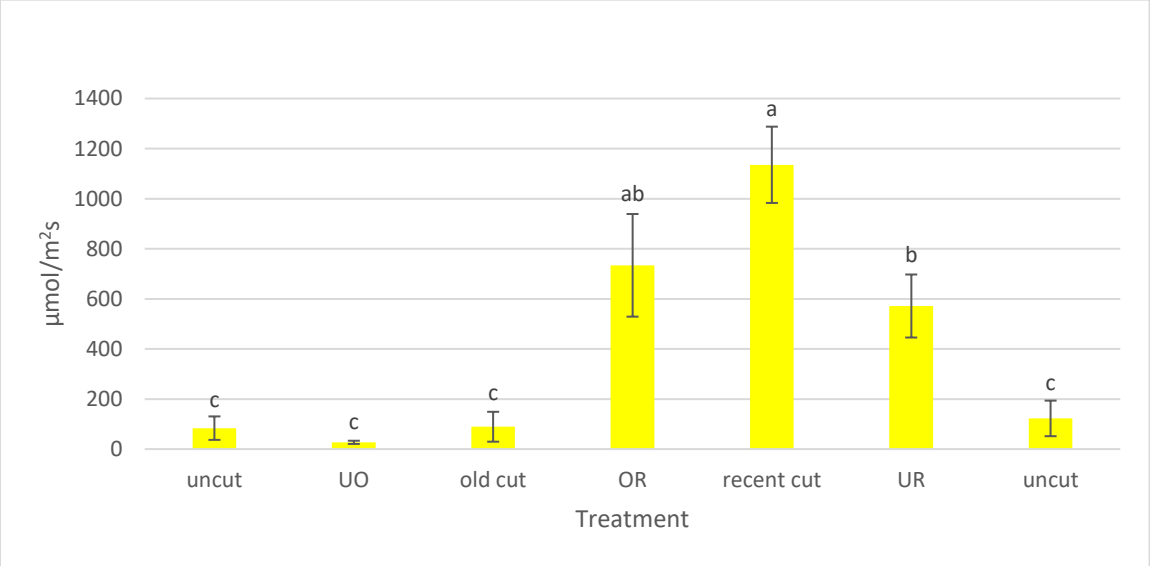


Figure 12. Mean Photosynthetically Active Radiation by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

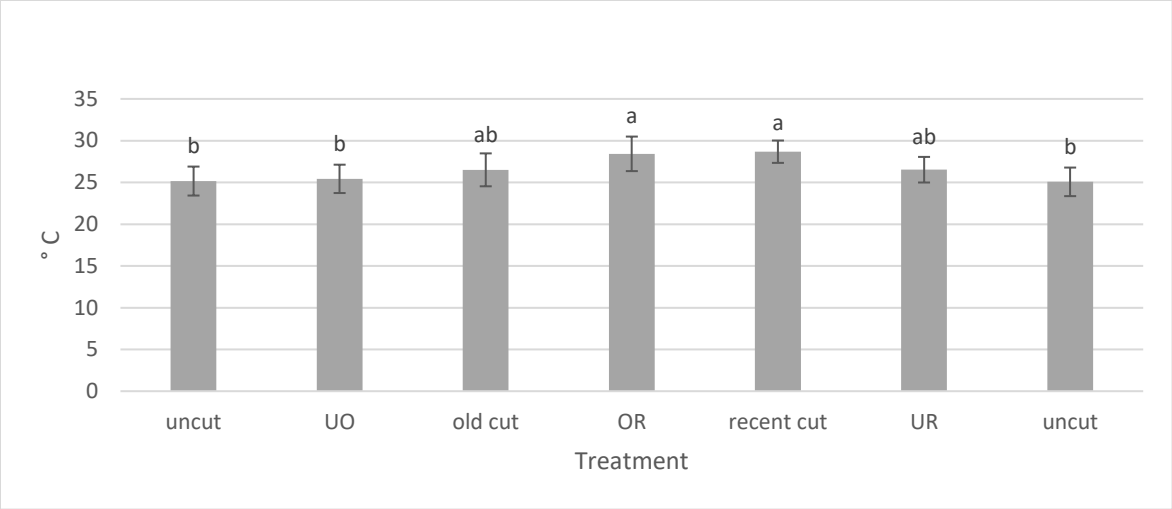


Figure 13. Mean Air Temperature by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.



Figure 14. Mean Soil Temperature by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

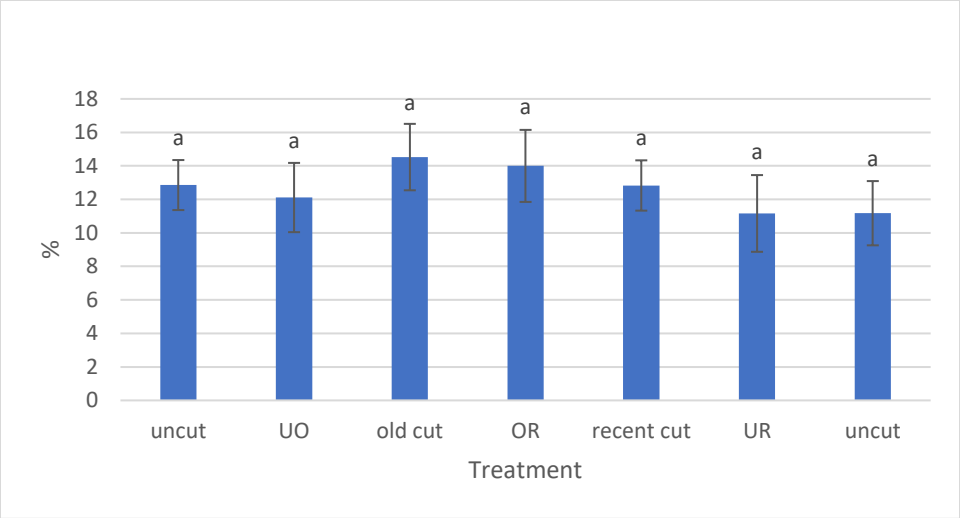


Figure 15. Mean Soil Moisture by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

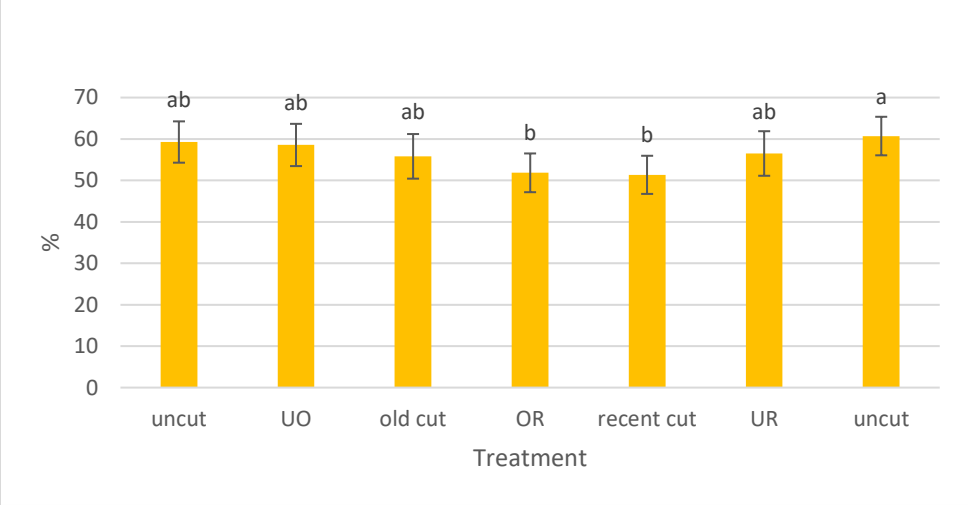


Figure 16. Mean Relative Humidity by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

0.001) (Figure 17). Mean decomposition across treatments was not significant (p = 0.560) (Figure 18). BA across treatments differed (R^2 = 0.566, p = 0.003), with recent harvests and the old/recent cut edges having significantly less BA than south facing uncut forest and the uncut/recent cut edge, which is also south facing (Figure 19). This is similar to C storage, in which old cuts and recent cuts, as well as the old/recent cut edge demonstrated less stored C than the south facing uncut forest area, and the edge between it and the recent cut (uncut/recent cut edge) (R^2 = 0.594, p = 0.001) (Figure 20).

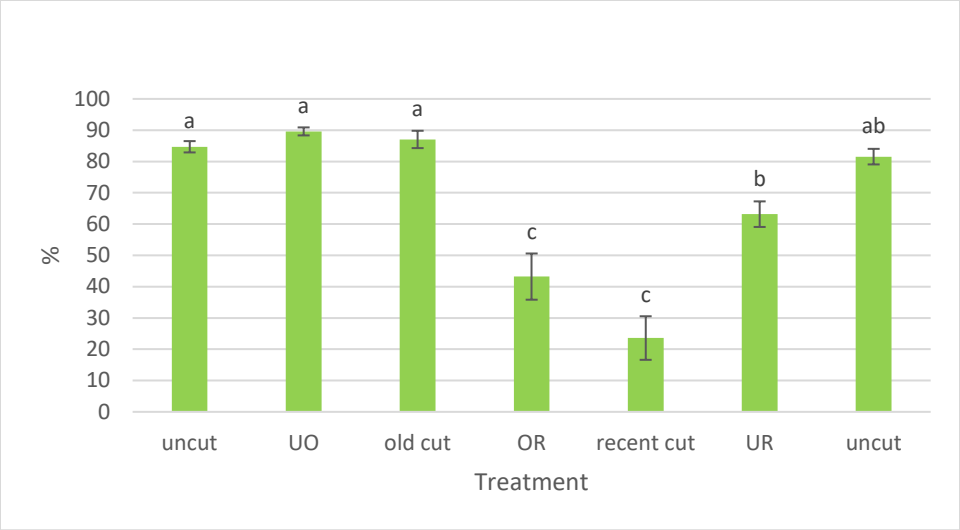


Figure 17. Mean Canopy Cover by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

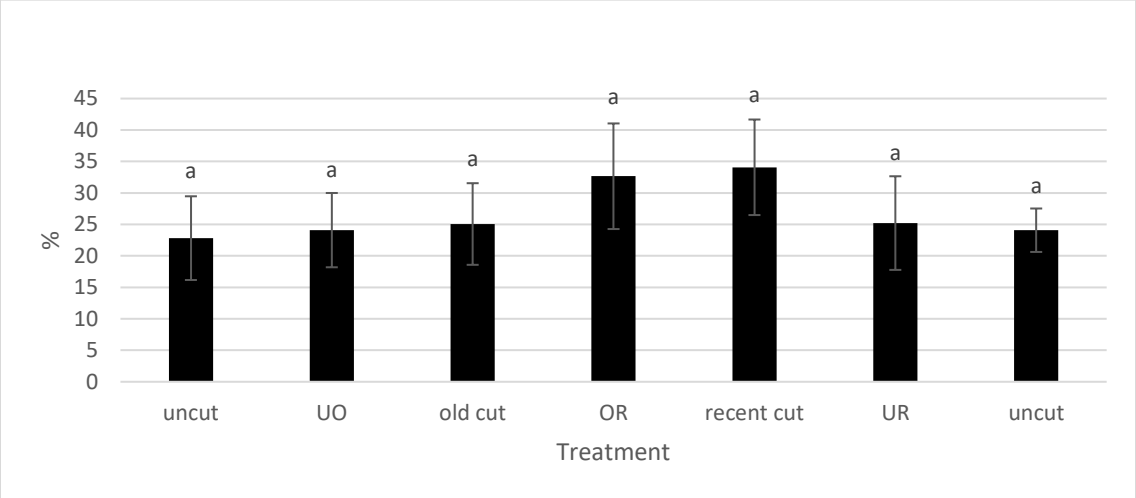


Figure 18. Mean Decomposition by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

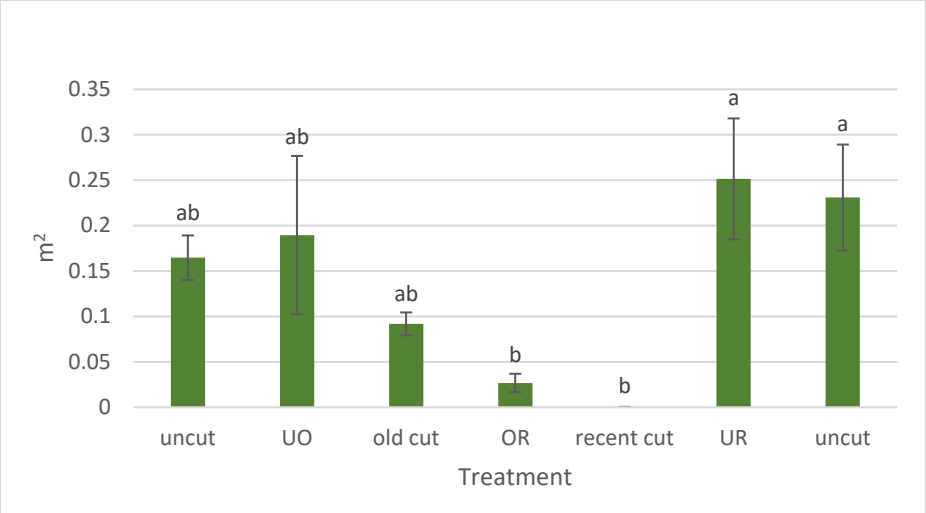


Figure 19. Mean Basal Area by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

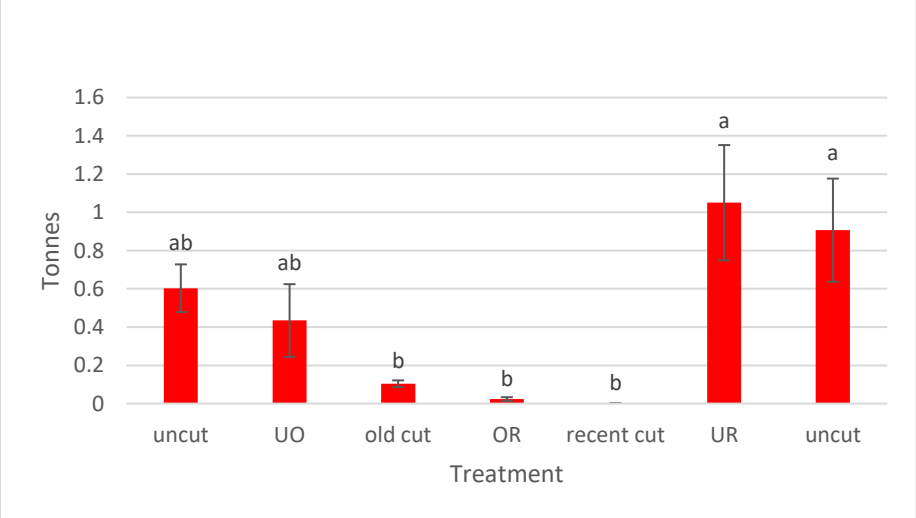


Figure 20. Mean Carbon Storage by Treatment.

UO, OR, and UR are the uncut/old cut edge, old/recent cut edge, and uncut/recent cut edge, respectively. Means with the same letters are not significantly different at the alpha = 0.05 level. Error bars represent one standard error.

Chapter 6: Discussion

The hypothesis that microclimate variables can be used to show the depth of edge effects is partially supported by the research in this study. PAR, in particular, can be readily visually assessed and the depth of edge effects on this variable can be determined. This study found that PAR can be altered up to 15 m away from a physical edge in any direction. Other variables such as soil temperature and air temperature had minor differences, making them difficult to visually assess, but increased temperatures appear to extend for up to 20 m into uncut forest areas extending away from a physical edge. In this study, relative humidity had too much variation to make well informed predictions about the depth of edge effects, as it was possible to determine in some transects but not in others. This is perhaps due to natural gaps in the canopy that altered fine-scale microclimates even within the uncut forest. Where it was possible to see the impacts of edge effects on relative humidity, the depth of these effects were seen for up to 15 m into the uncut forests. Canopy cover had too much variation to accurately determine a depth of edge effect. However, one interesting observation was that canopy cover was more uniform in the old cuts than other transect segments. The lack of ability to see the depth of edge effect in canopy cover may be explained better by stand development stage, as described by Oliver (1980). Using Oliver's (1980) stand development stages, the old cut could be classified as stem exclusion, thus resulting in a dense canopy layer. However, the uncut areas have experienced natural mortality, thus entering them into the understory re-initiation phase and rendering a less dense canopy layer when compared to the old cuts due to the vertical stratification in canopy cover. Once again, there was too much variability across transect segments to make assumptions about the impacts edges have on soil moisture. However, variability in soil moisture may be related to species composition in the nearby vicinity of soil moisture measurements (Snell et al., 2016). Furthermore, MacLean (2017) found that the depth of edge effects on several variables in Transition Hardwood-White Pine-Hemlock forests fell

within 30 m. Although the alteration of certain variables such as PAR or air temperature in uncut forests appears evident in our study, it is possible that many gaps are on the borderline of being too small to adequately display differences.

The second hypothesis was that carbon dynamics along edges would differ from carbon dynamics within the uncut portion of the forest. This hypothesis was partially supported, as the uncut/recent cut edge had the highest amount of stored C. However, neither the uncut/old cut edge nor the old/recent cut edge experienced the same nominal levels of stored C. This may be explained by aspect, as uncut/recent cut edges were typically south facing, while uncut/old cut and old/recent cut edges were typically north facing. Additionally, south facing uncut forests had higher C storage values than the north facing uncut forests. This indicates that the south facing uncut/recent cut edge may have received more PAR than the north facing uncut/old cut edge. This is a factor that was not considered in this study but is worth investigating further for carbon sequestration and storage potential when considering harvesting techniques. Although canopy cover was the only microclimate variable that was statistically significant for predicting C storage in our models, the incorporation of other factors not evaluated in this study such as aspect, elevation, underlying bedrock composition (Reed & Kaye, 2020) or other long-term microclimate data over individual points along a transect may yield additional information.

The hypothesis that differences in BA across treatments could be explained by microclimate conditions, primarily light, was not directly supported by this study. In study sites, PAR was found to be highly variable due to other conditions such as natural blow downs or trail systems that allowed for large variations within treatment sections. This may have been mitigated if PAR measurements were taken at a variety of heights and stratified. However, canopy cover was a significant factor in predicting BA; additionally, canopy cover and PAR are correlated, indicating that PAR may have been significant if it were not for physical constraints present within study sites. Additionally, longer transect lengths which would have allowed for more data points to

determine better averages and identify outliers may have allowed PAR to be a more useful measurement for predicting BA, as expected.

Interestingly, although there is nominally higher BA on the edges of the uncut forests (uncut/old cut edge and uncut/recent cut edge) when compared to the adjacent uncut forests, the same was not true of C storage. Only one edge, the uncut/recent cut edge, had higher BA and C storage values. This could be due to the size of the stems located along these edges, or the hardness of the edge, as uncut/recent cut edges were typically harder edges with little undergrowth while uncut/old cut edges were softer and scattered with small bole saplings. Many studies often neglect small trees and saplings (Brown, 2002) due to the nonlinear relationship of the allometric biomass equations. Therefore, 10- three cm saplings of a given species do not contain as much biomass as one 30 cm tree. In turn, this means that the 10 saplings do not have as much C storage as the individual tree, and thus it is often assumed that the smaller trees and saplings can be negated. However, according to Brown (2002), this depends on the successional stage, as a study by Schroeder et al. (1997) determined that trees less than 10 cm in diameter could make up anywhere from 10-75% of the total carbon storage of the stand, depending on successional stage. This was witnessed in our study as well, where old cuts were almost entirely composed of trees less than 10 cm (data not shown), and yet had a noticeable contribution towards carbon storage.

The hypothesis that decomposition on forest edges will be different than in the uncut forest due to differences in microclimate conditions, primarily soil moisture, was not supported by this study. This is because decomposition was not found to have statistically significant differences across any treatment. However, there does appear to be a trend in decomposition, with overall greater nominal amounts occurring in recent cut treatment segments. Furthermore, although canopy cover did not account for a large percentage of predictability in decomposition, the relationship is present. The ability to see trends but not statistical significance across

treatments, as well as the discovery of a microclimate variable responsible for some influence on decomposition would suggest that decomposition is likely influenced by some other variables not explored in this study, such as soil pH (Hayakawa et al., 2014). Although we failed to reject the null hypothesis regarding the relationship between decomposition and soil moisture, previous studies have found significant relationships between species composition and soil moisture percentages (Snell et al., 2016), suggesting that species composition rather than location along the transect may be responsible for differences in decomposition. Other studies have also found high variability in decomposition in open areas, and significance has varied depending on depth of burial (Sparrow et al., 1992). These are all factors which may be contributing to the high variability and lack of significance, or it may be possible that filter papers were not left in the field for a long enough period. Decomposition study times vary from one month in tropical forests to nearly two years in temperate forests (Hayakawa et al., 2014). A recent study found that decomposition within the organic layer is not impacted by forest edges (Schedlbauer & Miller, 2022), meaning that it is possible that the inclusion of additional variables or longer incubation times may not change the decomposition results, simply due to the soil horizon in which they were installed.

Although caution must be exercised when interpreting differences in trends rather than statistical differences, differences in C storage on north and south facing edges warrant further investigation. Although the uncut/recent cut edge could not have responded quickly enough to be of higher nominal value due to increased PAR from the recent cut, it is possible that the apparent increase along this edge is due to increased PAR from southerly angles when the old cut was completed. Therefore, we recommend that future studies on C storage on sites utilizing the irregular shelterwood reproduction method should evaluate pre- and post- harvest conditions of microclimate variables, particularly PAR, at stratified heights along the canopy to document changes. Additionally, the same types of studies should be conducted on other

silvicultural treatments, as this study clearly documents that even small patch cuts result in large variations among microclimate variables. Future studies, in combination with the documentation outlined in this study, may aid modification of existing practices or development of new silvicultural practices that would maximize C storage and minimize C losses. Additionally, differences in BA and C within the same areas indicate that BA cannot truly be used a measure of C storage within a stand, so future management practices should focus on actively managing C rather than BA as an approximation of C, as estimates will vary depending on stand structure. The results of this study also indicate that directionality of skid trails and aspect of cuts will have implications for C storage that need to be taken into consideration when creating harvesting plans.

Although above-ground C storage responses are seen in the old cuts, they are not nearly as great as in the uncut forest sections. However, the irregular shelterwood reproduction method may be able to simulate an old growth forest, with variable sized gaps used to simulate the natural death of large overstory trees or patches of trees. The advantage to this simulation is that different sized gaps could be utilized to optimize growing conditions for desired species. Additionally, in true old growth forests, as trees begin to decline, the tree would eventually become a source of C rather than a sink. Under forest management techniques designed for C storage, older trees could be removed and utilized for wood production prior to their decay where the stored C could be captured as a secondary product, rather than letting them decline and become a source of C. Then, regeneration would occur, and although response times will lag, this would limit losses of C whenever harvests are to occur. This process could be managed similarly to mean annual increment (MAI) or periodic annual increment (PAI) in which a particular tree, or stand, is evaluated for removal based upon its potential to sequester and store C. In this way, trees would be harvested at intervals that are species dependent to maximize C storage and minimize C losses due to decomposition of standing wood. However,

coarse woody debris has other valuable functions and continues to store previously sequestered carbon (Harmon & Hua, 1991).

Chapter 7: Conclusion

In conclusion, we found some evidence to indicate that microclimate variables can be used to show the depth of edge effects on a subtropical forest ecosystem. Although there are great differences in microclimate variables across transect segments, and depth of edge effects on PAR appear to extend 15 m into the uncut forests, some segments may not be of adequate length to adequately create entirely interior or clearcut conditions. This is in sync with other studies such as the one by MacLean (2017) that found depth of edge effects to extend up to 30 m away from a physical edge, while many gaps in the current study were on the order of 30 m in length. Therefore, longer transect lengths would likely help determine the depth of edge effects for several additional microclimate variables.

Although C dynamics and BA did differ across microsites, PAR was not found to be related to the changes in conditions. Instead, the only variable sampled that explained differences in C and BA was canopy cover. Given the correlation between canopy cover and PAR, it may be that canopy cover is ultimately acting as a proxy for PAR, and future studies should consider measuring canopy cover and PAR at multiple heights to effectively determine differences across transect segments. Furthermore, nominal differences in BA and C appear to be influenced by edge aspect, with south facing edges having higher nominal values than their north facing counterpart. Additionally, we believe that decomposition was more closely related to variables not investigated by this study, such as soil pH, which warrants further investigation to ultimately understand the C dynamics occurring across microsites. However, the magnitude of differences in microclimate variables and carbon observed across small distances suggest that small scale changes in silvicultural practices related to factors such as gap sizes, shapes, and orientation, could have a greater than expected impact on net carbon sequestration and storage when implemented at larger scales.

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Vita

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