

**Identifying and Assessing Metrics of Ecosystem Recovery in Eastern
Hardwood Forests**

**A Thesis Presented for the
Master of Science
Degree
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ABSTRACT

The establishment of a metric for ecosystem recovery, utilizing ecosystem functions as a basis for measurement, would improve our ability to evaluate the success of ecosystem recovery practices. This project sought to examine several ecosystem functions for the potential to serve as a metric for recovery of surface mined and clearcut sites. The southern Appalachian region provided an ideal space for such an endeavor due to extensive timber and coal mining industries and the rich biodiversity of the region. Sampling was done on 10th acre research plots equally distributed between two site types (surface mined and clearcut) and 5 age classes measured from the time since last disturbance (0-5 years, 6-10 years, 11-15 years, 16-29 years, and 30 plus years) in order to evaluate change over time in the selected functions. Each age class had three sites, in addition to two control sites which were defined as having been minimally disturbed for 50 or more years prior to the study. Infiltration rate, soil density, root biomass, flying and non-flying insect biomass, decomposition rate, canopy cover, tree species composition, basal area, tree species richness, and aboveground tree biomass were all assessed for trends across age classes and differences between disturbance types. Of these ecosystem functions, infiltration rate and root biomass at 18cm belowground were positively responsive to changes over time on surface mined sites, and soil density demonstrated some reduction as well. Aboveground tree biomass showed significant increases on both surface mined and clearcut sites approximately 15-20 years post-disturbance, along with canopy cover which showed positive growth up to 15 years post-disturbance. Further investigation into aboveground tree biomass, basal area, and canopy cover as potential metrics for ecosystem recovery is recommended, as they each show promise as a metric of ecosystem recovery.

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CHAPTER I
INTRODUCTION

The forests of the Appalachia are a significant ecological resource, even on a global scale (Riitters et al., 2000), largely due to the large quantities of natural resources nestled within the region, including, but not limited to, fertile agricultural space, timber harvesting, and coal mining (Hinkle et al., 1993). However, exploitation and use of these resources, especially in the case of coal mining, has led to overall loss of forest interior (Wickham et al., 2007) and forest cover (Drummond & Loveland, 2010) in the region.

Prior to 1977, and the establishment of the Surface Mining Control and Reclamation Act (SMCRA), any reclamation that took place on surface mines was concerned with replacing soil on the disturbed site, with little thought given to any further revegetation or recovery, though occasionally conifers or hardwoods would be planted (Plass 2000), if anything at all. However, the lax or non-existent laws concerning reclamation led to other negative environmental effects, such as erosion and acid drainage (Dunlap & Lyon, 1985). The establishment of SMCRA in 1977 introduced a major change to the management of surface mine reclamation, forcing mining companies to stabilize slopes and revegetate bare ground or else face fines or other financial consequences (Skousen & Zipper, 2014). However, many sites reclaimed under SMCRA are left with extremely compacted soil in an attempt to avoid the aforementioned issues with erosion and acid drainage (Angel et al., 2005), which has been shown to negatively impact the revegetation and overall recovery of these surface mined sites to a functional and productive state (Zipper et al., 2011a). In response to this, the Forestry Reclamation Approach (FRA) was developed and emphasizes a reduction in soil compaction and planting of native ecologically compatible herbaceous and tree species (Burger et al., 2005; Zipper et al., 2011b; Angel et al., 2005).

Unfortunately, though FRA methods have proven effective in the efforts to restore surface mined sites to their original structure and function, recent studies suggest that the majority of mine sites reclaimed under SMCRA in the Appalachian region are failing to reach those goals of site recovery (Ross et al., 2021; Thomas et al., 2023). Additionally, there is evidence to indicate that mining companies are failing to fulfill the financial obligations enacted by SMCRA (Simonton & Surber, 2017) and in some cases even going bankrupt to avoid these costs altogether (Macey & Salovaara, 2019).

With this in mind, the initial goal of this project was to test methods that surface mining companies and regulatory agencies might use to gauge and monitor the progress of a post-reclamation surface mining site as it recovers, both for the sake of the ecosystem, and potentially for accountability purposes as well. Ideally, these methods should be quick, cheap, and effective, so as to make them attractive for the aforementioned companies and agencies to make use of. The ideal end state of the land would obviously vary by site, context, and ownership, but the recovery goal is often returning the site to a state similar in structure and function to its original or surrounding forest ecosystem, for a number of reasons, including land use for timber harvesting.

Disturbance types were heavily considered in the early stages of the project. As mentioned above, the initial design dealt only with surface mined sites, and that remained

a critical central feature of the project. However, early on came the consideration that testing these factors on more than one type of disturbance would create more room for comparisons and conclusions from results. Thus, clearcut harvest sites were added to the design both to serve as a point of comparison between surface mined sites and a set of undisturbed control sites.

Each element of ecosystem function selected served as a proxy for one or more physical or biological processes that play an important role facilitating structure and function in an ecosystem. For instance, decomposition rate served as a measure of carbon cycling, or soil density and infiltration rate serving as physical measures related to soil compaction and hydrologic flow. Other factors like aboveground biomass or insect biomass were chosen as functions that may be directly correlated to ecosystem structure and recovery and warranted testing as potential metrics.

Finally, in order to act as a metric of ecosystem recovery, some manner of change or variation must be observed. It was determined that a series of age classes would be established for each of the site types, in order to observe how each ecosystem function changes over time on both clearcut and surface mined sites, with replication where possible.

Taken all together, the final, overall, goal of this study was to determine if one or more of the chosen functions, detailed later in the manuscript, would demonstrate a clear, consistent, and significant variation or change across age classes, also detailed later, on either or both clearcut and surface-mined sites, and may therefore warrant further consideration as a metric for ecosystem recovery on disturbed eastern hardwood sites.

To that end, the following hypotheses were tested:

1. Dependent variables would show differences between age classes.
2. Dependent variables would not show variation by site type.
3. Dependent variables in the final age classes would not vary from dependent variables in the control groups.

The results of these tested hypotheses have been presented in this manuscript's later chapters as detailed in the following manner.

This first chapter has served to summarize and provide a brief explanation for each chapters' presence, in addition to laying the groundwork for the project as a whole. The second and third chapters of this manuscript are themselves standalone manuscripts and address in detail the process by which the goals of this project were carried out. Both chapters justify and contextualize their contents in detail. The second chapter examines the question of ecosystem recovery metrics through a silvicultural lens of reforestation and recovery time. That chapter exclusively uses the tree and tree species data for its

analysis and served as a test for tree regeneration as a metric for recovery on primary and secondary successional sites. The third chapter addresses the bulk of the project using and analyzing the other chosen ecosystem factors in a methodical approach. Each factor is put through the same steps of analysis and examined as a potential metric against a logical set of criteria. The fourth and final chapter will serve as a conclusion chapter, wherein the results, caveats, and challenges of the overall project will be addressed, as well as suggestions for future directions of this research.

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CHAPTER II

A version of this chapter was originally published by Ian Kennedy, Melody Mount, Wayne Clatterbuck, David Buckley, and Jennifer Franklin.

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The student was the primary author and writer of the paper, which received multiple edits and reviews by co-authors, as well as multiple steps of peer review to further refine the final manuscript.

Abstract

Rates and pathways of secondary succession were investigated and compared between clearcut and surface mined sites in east Tennessee using chrono sequence techniques. Plots were established within 5-year age classes ranging up to 30 years after the disturbances on sites with similar productivities. Clearcut sites were hypothesized to undergo vegetative succession more rapidly than surface mined sites due to the difference in intensity and impact of disturbance on the substrate. A control site for each type of disturbance was also evaluated as a metric for the expected pathway of succession, community structure, and species composition (forest type). These control sites were selected for their relative lack of human disturbance and proximity to disturbed areas. Preliminary results suggest that clearcut sites are progressing differently than their expected oak-hickory forest type at a more rapid successional rate than surface mined sites as hypothesized. If an oak-hickory species composition is to be maintained after these stand initiation disturbances, silvicultural practices to encourage these species are recommended.

Introduction

Surface mining is an intense and severe form of disturbance with profound effects on vegetation, soil, and hydrology (Angel and others 2005). The result is often a bare site with heavily compacted, rocky substrate, and little-to-no topsoil or seed bank. Strict regulations, implemented under the Surface Mine Control and Reclamation Act (SMCRA), include the requirement that sites must be revegetated following reclamation. As part of the rules under SMCRA, the mine soils on site were generally heavily compacted in an attempt to reduce problems with erosion and acid drainage, amongst other issues, but can negatively impact natural revegetation on the site (Angel and others 2005). Additionally, in the effort to avoid noncompliance, many companies plant fast growing vegetative cover which may not necessarily be native and can inhibit reforestation and recovery (Zipper and others 2011). This does not mean that succession

does not and cannot occur, rather that it is often greatly delayed (Zipper and others 2011). Many sites reclaimed since 2010 have incorporated the Forestry Reclamation Approach (FRA), which calls for reduced compaction and the planting of native tree seedlings (Burger and others 2017). As such, the revegetation of surface mined sites presents a unique opportunity for study as the reduced vegetation growth due to compacted soil, and the introduction of nonnative vegetation provides both a rare example of comparison between two different stages of secondary succession and can provide insights useful to both surface mine restoration, and the process of succession itself (Wieggleb and Felinks 2001).

The mountainous regions of northeastern Tennessee provide numerous locations for monitoring and evaluating vegetative succession on surface mined and clearcut sites. Additionally, the compositional trajectory of these heavily disturbed sites, post-disturbance, could provide insights not only into the rate of forest recovery on surface mined and clearcut sites but also how the developing forests compare to the oak-hickory forest type common to the area.

The intent of this study was to compare vegetative growth and species composition between surface mined, clearcut, and control sites to determine how quickly and in what direction vegetative succession was occurring. Due to the intensity and severity of such disturbances, surface mined sites were hypothesized to lag behind clearcut sites in regeneration. In addition, because clearcut sites were expected to eventually develop toward the oak-hickory stands native to the region, the anticipated growth lag and poor site conditions, such as highly compacted soil, suggested that surface mined sites were unlikely to show signs of oak or hickory growth within the scope of the study.

Materials and Methods

In order to examine the change in clearcut and surface-mined sites over time, five age classes were established based on time since last disturbance; 0-5, 6-10, 11-15, 16-29, and 30+ years. These were labeled as age classes 1 through 5, respectively, for analysis. The fourth age class covers a greater time period than prior age classes under the assumption that by that time, the canopy should be closed. Temporal changes within the site will be on a smaller scale due to the stability provided by a closed canopy microclimate (De Frenne and others 2021). Each age class was allotted a minimum of three sites for replication. Two sites were also selected as control sites (labeled as age class 6) which had not been disturbed in 50+ years. This created a total of 32 sites, with one extra surface-mined site in the fourth age class. Sites were selected using historical images available via Google Earth Pro (version 7.3) and were based on a series of criteria inherent in their disturbance type, age class, and other factors such as aspect, elevation, distance from other sites, and accessibility.

All sites selected had a northern or flat aspect and a similar elevation, to ensure similar access to light and other climate and weather effects. Within age classes, sites that

were geographically disparate from one another were also considered ideal to capture a more detailed image of development across a wider geographic range. All sites were located on the Cumberland Plateau region of northeastern Tennessee. Sites were often clustered in certain areas that had landowner permission to access, and care was taken to avoid duplicating a given disturbance type and site age within each area. Elevation and geographic distance were considered secondary priorities and economic drivers of both timber and mining industries limited the availability of sites in some age classes.

Each site consisted of a single, circular, 0.10-acre plot, set randomly on the site location. In every 10th acre plot, every tree with a diameter at breast height, (d.b.h.) approximately 1.37 meters above the ground, >1 inch was measured and identified by species. Data were analyzed in completely randomized design, with disturbance type and age class as main effects. All analyses were conducted using SAS 9.4 (SAS 2013).

Statistical Analysis

Average basal area (BA) per acre was calculated across sites and each measured specimen within each age class using the following equation:

$$BA = d.b.h.^2 \times 0.005454 \quad (1)$$

Average BA for an age class was calculated using the sum of all basal areas for each site within a given age class, and then divided by the number of basal areas in each age class. Average BA did not meet the assumptions of normality and was modified with a square root transformation prior to analysis. Analysis of BA for each age class and disturbance type was conducted using PROC GLM, which is a two-way factorial ANOVA function (SAS 2013). Differences between disturbance types within an age class were determined with Duncan post-hoc tests. Average d.b.h. and trees per acre were similarly analyzed.

The number of species was tallied and averaged for each age class and disturbance type, including controls. However, species richness is a categorical data type, thus it was necessary to conduct two non-parametric Kruskal-Wallis tests, which were carried out manually. One test included both disturbance types with controls, and one only tested age classes with no consideration for disturbance type. Mean ranks of disturbance types or age classes were separated with a Dunn's post-hoc test.

Additionally, for the final age class of mine, clearcut, and for control sites, the contribution of each species to total basal area was calculated.

Results

Average BA (Figure 1.1) showed significant interaction between main effects, age class and disturbance type ($P < 0.0001$). When split by disturbance type, age class proved significant for surface-mined sites ($P < 0.0001$), and for clearcut sites ($P = 0.0003$). On surface-mined sites, post-hoc testing showed that age classes 1 and 2 were not

significantly different from each other, but together were significantly lower than age class 3. This, in turn, was significantly lower than age class 4, which was significantly lower age classes 5 and the control. Age class 5 and the controls did not differ significantly from each other. For clearcut sites alone, post-hoc testing indicated that age class 1 was significantly lower than the controls, but neither were significantly different from the other age classes on their own.

Additional post-hoc testing was performed comparing average basal area on clearcut and surface-mined sites by age class. Within each age class, both disturbance types were also compared to the control sites. In the first age class, clearcut and mined sites were not significantly different from one another, but both were significantly different from the control sites. Both site types were significantly different from one another in the second age class, and both clearcut and surface-mined sites were different from the control sites. Mine sites' basal areas were significantly lower than clearcut sites in the third age class, in addition to being significantly lower the control sites. However, clearcut sites in the third age class no longer showed significant difference in basal from control sites. In the fourth age class, clearcut sites did not differ significantly from mine sites, or from the controls, though basal areas on mine sites were still significantly lower than the controls. In the fifth age class, the control sites and mine sites were not significantly different from each other, but basal area on clearcut sites was significantly greater than both the mine sites and the controls.

Species richness (Table 1.1) showed a significance difference between disturbance types in the Kruskal-Wallis H test ($\chi^2 = 5.99$, $H = 6.23$). However, when tested across all age classes regardless of disturbance type, the lack of significant differences between age classes showed that the number of species did not change with site age ($\chi^2 = 11.07$, $H = 9.06$). Average d.b.h. and trees per acre on surface-mined sites differed significantly from controls, but they were not significantly different on clearcut sites.

Species composition results were varied. On clearcut sites, yellow-poplar (*Liriodendron tulipifera*) comprised the largest percentage of stems in every age class except the fifth, with the first three age classes having percentages well over 20 percent (60 percent, 52 percent, and 36 percent, respectively), and the fourth marginally lower at 19 percent. In the final age class, red maple (*Acer rubrum*) comprised the majority of trees at 39 percent. Oak (*Quercus* spp.) regeneration on clearcut sites was at a maximum 14 percent in the fourth age class, and overall made up a combined 5 percent of stems across all age classes. Oaks were not present at a significant count in the final clearcut age class. On control sites, 73 percent of the trees present were maple and beech (*Fagus grandifolia*) and 6 percent of trees were oaks. The majority of trees on surface-mined sites overall were black locust (*Robinia pseudoacacia*) (23 percent), which was the most populous species until the final age class where yellow-poplar was dominant (29 percent).

Basal area and species composition combined also yielded interesting results in the older age classes. On undisturbed sites (Figure 1.2c), oak species made up a combined 40 percent basal area, with another 34 percent composed of maple species. The remaining percentage consisted of various other native species, including yellow-poplar (10 percent). This was not the case in the final age classes for surface-mined and clearcut sites. Surface-mined sites (Figure 1.2a) had no oak regeneration and were dominated by yellow-poplar (64 percent), maple species (17 percent), and eastern white pine (*Pinus strobus*) (15 percent). Clearcut sites (Figure 1.2b) were primarily yellow-poplar (29 percent) and red maple (25 percent) but did contain oak regeneration (22 percent). Basal area and species composition combined also yielded interesting results in the older age classes. On undisturbed sites (Figure 1.2c), oak species made up a combined 40 percent basal area, with another 34 percent composed of maple species. The remaining percentage consisted of various other native species, including yellow-poplar (10 percent). This was not the case in the final age classes for surface mined and clearcut sites. Surface mined sites (Figure 1.2a) had no oak regeneration and were dominated by yellow-poplar (64 percent), maple species (17 percent), and eastern white pine (*Pinus strobus*) (15 percent). Clearcut sites (Figure 1.2b) were primarily yellow-poplar (29 percent) and red maple (25 percent) but did contain oak regeneration (22 percent).

Discussion

In the first three age classes, succession proceeded as hypothesized, with clearcut sites recovering faster than surface mined sites (Figure 1.1). However, in the fourth age class, while not yet comparable to the control sites, surface mined sites were not significantly different from the clearcut sites. By the final age class, surface mined sites showed no variation in basal area from the controls, unlike clearcut sites, which were lower on average. This directly contrasts with our expected outcomes, as it was anticipated that basal area on surface mined sites would continue to lag behind clearcut sites even into the fifth and final age class.

There are some additional factors that may have contributed to the differences in basal area. In the third and fourth age, mine site classes experienced significant variation in basal area from each other, as well as the first two age classes and the final age class. This suggests that, while younger age classes are, as predicted, limited by their site conditions, sites in the third age and fourth age class may have some unknown advantage or differing conditions from the younger sites. It is known that two sites within the third age class were treated using the Forestry Reclamation Approach (FRA) (Burger and others 2017). As such, due to the age of the sites in the fourth age class, a preponderance of fast-growing species such as pine and black locust could help explain the variations observed in basal area.

Additionally, in the final age class, surface mined sites statistically show no significant variation from the control sites, and the same is true for clearcut sites. While those sites were at least 30 years removed from their last disturbance, there was no upward limit to their age. Thus, several of these older mine sites were likely last

disturbed prior to the enactment of SMCRA in 1977. Many of these surface mined sites prior to this point were left uncompacted, and occasionally even had their topsoil replaced with the previously removed spoil. As such, the success and trajectory of these sites may not be comparable to the eventual trajectory of the younger mining sites, specifically those that have been reclaimed under SMCRA.

The number of species tended to increase with age class, and species composition provided an interesting perspective, namely the lack of oak regeneration in pure percentage of stems on both clearcut and mine sites. The species composition by basal area provides additional insights (Figure 1.2a-c). While oak species are present on older clearcut sites and control sites, they do not dominate on clearcut sites, and are heavily rivaled on control sites by maples and to a minor degree, yellow-poplar, which dominates the clearcut sites. The advanced age of the older clearcut sites may be the reason. Control sites had not been disturbed in 50+ years, and these clearcut sites were only required to be 30 years removed from the last disturbance. However, even on the control sites, the expected populations of hickory are entirely absent, as they are on clearcut sites as well. This supports the hypothesis put forth by Nowacki and Abrams (2008) regarding rapid changes in species richness and stand composition, which they postulate is a result of fire suppression over the course of the last century especially.

Older mine sites lack oaks entirely and are dominated by yellow-poplar, eastern white pine, and maples. The presence of eastern white pine is explained by differing policies of revegetation on older mine sites, as pines were commonly planted as a treatment for reclamation during that time. The dominance of yellow-poplar and maple could be due to early successional site conditions, which also could explain their large presence on older clearcut sites.

It is worth noting that there is potential evidence of highly limited regeneration of hickory species, and questionable regeneration of oaks, even in the apparent presence of larger reproductively capable adults on both clearcut and surface mined sites. Neither site type seems to be experiencing vegetative succession towards the expected oak-hickory forest type. The lack of hickory species on control sites is also worth noting. Both genera are intermediate in shade tolerance, occupy an intermediate successional stage, require a seed source to establish prior to the disturbance, and grow slowly as seedlings, often succumbing to faster growing vegetation. Both oak and hickory would not be prominent during these stages of succession unless their progeny were present prior to the disturbance, especially considering the substrate is removed on surface mine sites.

A larger inventory of both surface mined and clearcut sites may provide a more comprehensive analysis, though finding enough sites that meet the criteria to perform such an analysis would likely be challenging. Further study is recommended into the restoration and reforestation of surface mined sites with the understanding that the growth of vegetation alone is not always a reliable indicator of the progress of restoration (Avera and others 2015). Additionally, the limited oak regeneration and lack of hickory

regeneration is of concern, and future silvicultural studies and implementation of silvicultural practices based around these species is recommended.

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APPENDIX

Table 1.1: Average d.b.h., trees per acre, species richness, and standard error by disturbance type and age class

Disturbance type	Age class	d.b.h.		Trees per acre		Species	
		Average	SE	Average	SE	Average	SE
		<i>inches</i>		<i>n</i>		<i>n</i>	
Mine	1 (0-5)	0.9	0.9	23	23	0	0
	2 (6-10)	1.6	1.0	40	21	2	1
	3 (11-15)	2.9	0.3	417	148	9	1
	4 (16-29)	4.5	0.4	453	136	8	1
	5 (30+)	7.7	1.9	377	110	7	3
Clearcut	1 (0-5)	4.1	1.5	470	430	5	2
	2 (6-10)	3.7	0.8	630	223	9	2
	3 (11-15)	3.5	0.6	1247	475	10	1
	4 (16-29)	4.9	0.7	627	208	8	0
	5 (30+)	4.7	0.1	363	47	8	2
Control	6 (N/A)	8.9	3.8	255	115	8	1

d.b.h. is diameter at breast height (4.5ft. aboveground); SE is standard error

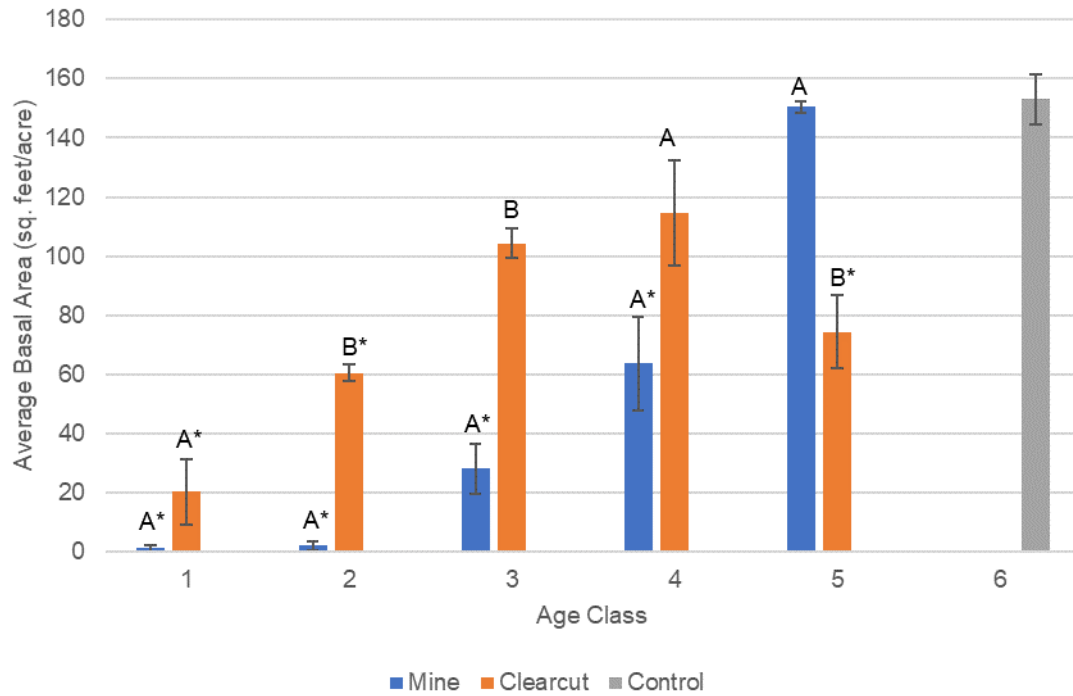
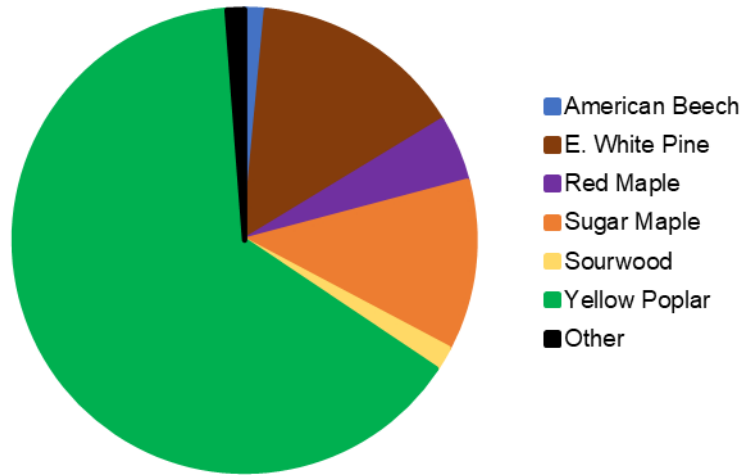
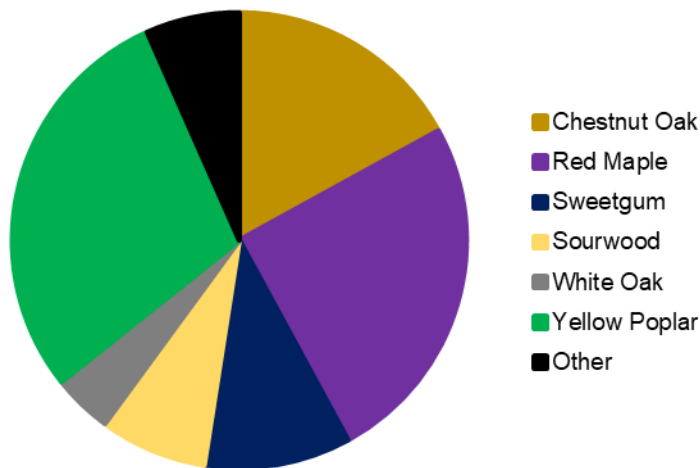


Figure 1.1: Average basal area by age class and disturbance type. Bars indicate standard error. Different letters indicate statistical differences between disturbance types at $P \leq 0.05$. Asterisk indicates significant difference from control at $P \leq 0.05$.

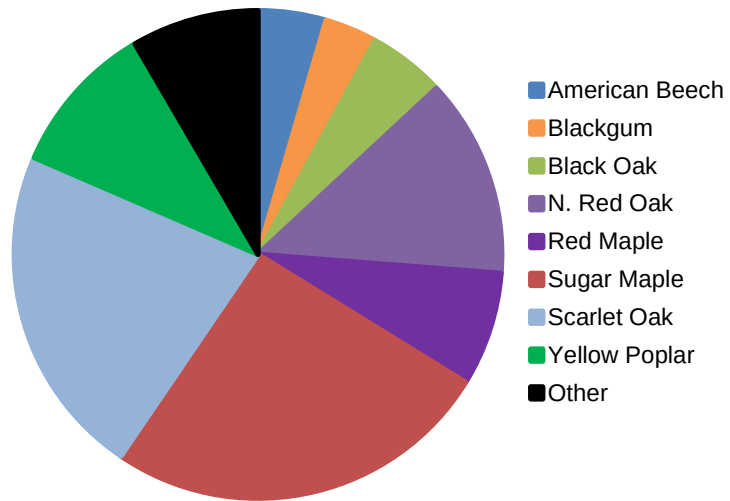


(a) 30+ year old surface mined sites



(b) 30+ year old clearcut sites

Figure 1.2: Species composition by basal area on (a) ≥ 30 -year-old surface-mined sites, (b) ≥ 30 -year-old clearcut sites, (c) control sites. Predominant species were American beech (*Fagus grandifolia*), black oak (*Quercus velutina*), blackgum (*Nyssa sylvatica*), chestnut oak (*Quercus montana*), eastern white pine (*Pinus strobus*), northern red oak (*Quercus rubra*), red maple (*Acer rubrum*), scarlet oak (*Quercus coccinea*), sourwood (*Oxydendrum arboreum*), sugar maple (*Acer saccharum*), sweetgum (*Liquidambar styraciflua*), white oak (*Quercus alba*), and yellow-poplar (*Liriodendron tulipifera*).



(c) Control sites

Figure 1.2 (continued)

CHAPTER III

Abstract

Recovery on surface mine sites is not a straightforward or simple process. Therefore, it is important to determine a metric for assessing the recovery of ecosystem structure and function on heavily disturbed forest sites. We examined 7 factors of ecosystem structure and function: overstory regeneration, canopy cover, insect biomass, infiltration rate, soil density, root density, and decomposition rate. Each chosen variable was hypothesized to be an indicator of recovery of said ecosystem structure and function, with a strong relationship to time since the last major disturbance. We selected clearcut harvest and surface mined sites and formed 5 age classes at 0-5, 6-10, 11-15, 16-29, and 30+ years according to time since last disturbance, with 3 sites in each age class for replication purposes. Additional control sites were added for comparison, with each control having experienced a minimum of human disturbance within the last 50 years. Data was collected between June and September of 2022. Overstory was measured on each site using a 0.04-hectare plot, and remaining variables were sampled on 3 sub-plots within each plot. Decomposition samples experienced a relatively high loss rate due to wildlife activities. Results show that aboveground biomass, canopy cover, and root biomass at 18cm may be useful as metrics for ecosystem recovery on surface mined sites, while only aboveground biomass shows diagnostic potential on clearcut sites. Such metrics would see great value for determining the success of recovery efforts and the impact of forest management activities.

Introduction

Surface mining for coal in the Appalachian region is a long-standing practice (Hinkle et al., 1993; Plass, 2000). Prior to the Surface Mining Control and Reclamation Act (SMCRA) in 1977, very little reclamation was required by law on these surface mined sites, and what was required usually only included the replacement of the removed topsoil, and may include some replanting of trees, but this was not universal (Dunlap & Lyon, 1985; Skousen & Zipper, 2014). After the establishment and enforcement of SMCRA, surface mined sites are required to undergo reclamation. Soil was often compacted in an effort to prevent erosion. In areas where topsoil is not available, this leaves behind bare mineral soil to which amendments are applied and vegetation is established as part of the required reclamation, but many sites reclaimed under SMCRA are still dominated by herbaceous cover species and early successional trees (Chaney et al. 1995). In response, the Forestry Reclamation Approach was established which focuses on reducing soil compaction and ensuring the establishment of natural and compatible herbaceous and woody vegetation (Burger et al., 2005; Zipper et al., 2011b). Surprisingly, unreclaimed surface mines, those which were abandoned before the implementation and enforcement of SMCRA, have been observed to recover more completely on occasion than those reclaimed under SMCRA (Skousen et al., 2006)

The establishment of a singular scale of measure, a metric, or series of metrics, for evaluating a disturbed ecosystem's recovery of function would be beneficial for both mining companies, which are bound by legal bond to restore ecosystem function to their

mine sites post-operations (Skousen & Zipper 2014), and regulatory agencies which must monitor these sites as they recover and ensure mining companies remain accountable for the recovery process (Skousen & Zipper, 2014). To this end, individual elements of an ecosystem most sensitive to changes due to disturbance should be evaluated first (UNSD, 2021), and analysis of these factors over time allows for observation of trends that may be compared against undisturbed ecosystems of a similar type. Additionally, these metrics should be easily replicable with minimal cost and training, to make their use as easy and affordable to various relevant parties as possible.

This study examined several elements that served as representatives of ecosystem functions for potential use as metrics for ecosystem recovery. Kremen (2005) distinguishes ecosystem functions as elements of an ecosystem that occur with or without human involvement. The variables of this study are often referred to as ‘ecosystem functions’, or simply ‘functions’, and represent the selected ecosystem functions that are common specifically to forested ecosystems native to the southern Appalachian region. As of this study, the most common or popular methods of evaluating ecosystem recovery on surface mined sites heavily feature soil compaction, soil chemical composition or native revegetation and forest regrowth as measures of ecosystem potential for recovery (Zipper et al., 2011a; Simmons et al., 2008; Franklin et al. 2012)

Ecosystem functions selected for testing in this study were chosen based on a review of the literature. Soil compaction is a considerable barrier to root growth (Panayiotopoulos et al., 1994), is common on surface mined sites, and features strongly as an advised element to address when considering reclamation and recovery of surface mined forest ecosystems (Burger et al., 2005; Zipper et al., 2011b). Measuring soil bulk density, referred to hereon as ‘soil density’, allowed for an estimate of compaction without the problems encountered when measuring penetration resistance on very rocky minesoils. .

Similarly, soil compaction is known to have a negative impact on the ability of water, and rainfall runoff in particular, to infiltrate mine soils (Negley & Eshelman, 2006). As such, infiltration rate of water into soil was chosen as a potential metric of forest ecosystem recovery, along with soil density. As biological processes slowly alleviate soil compaction over time, and it was expected that soil density would decrease, and infiltration rate would increase as time since disturbance increases, as has been observed in other cases (Reynolds & Reddy, 2012).

Insects are crucial to many ecosystem functions, including pollination, decomposition, and as a food source for other animals (Dangles & Casas, 2019; Hamaekers, 2021). They serve as a strong foundational point for many ecosystems and are known to have varying responses to disturbances in their habitats (Cobb et al., 2007; Dodd et al., 2012). If insect biomass demonstrated a consistent and significant response to increasing time since reclamation, then there existed potential for insect biomass as a metric of forest ecosystem recovery.

Zipper et al. (2011a) found a positive correlation between site age since reclamation and nitrogen and phosphorous accumulation in the soil, both of which are important to plant nutrition and are generally beneficial to ecosystem function overall (Haering et al., 2004). However, measuring for these chemicals can be time consuming and costly, and requires specialized equipment and or training. That said, the process of decomposition of organic matter in soil greatly depends on the presence of phosphorous and heavily involves the fixation of nitrogen into a bioavailable state (Attiwell & Adams, 1993). Decomposition rate tends to be much less costly and time consuming to measure and provides an estimate of soil biological activity and nutrient cycling, an important function of forest ecosystems.

A closed canopy tends to create a more stable microclimate (De Frenne et al., 2021), which is important for stability and succession in a forest ecosystem. It was therefore presumed that there may be a relationship between percent canopy cover and ecosystem recovery.

Finally, aboveground biomass was also assessed as a potential mechanism of ecosystem recovery. FRA methods placed great emphasis on planting compatible herbaceous and woody tree species as part of the reclamation process (Zipper et al., 2011b), and establishment of rapid growth herbaceous ground cover has been linked to reduced tree growth on surface mined sites (Franklin et al., 2012). It therefore followed that surface mined sites capable of supporting a significant or at least increasing aboveground biomass, must have had the necessary ecosystem functions in place to do so. If there existed a positive relationship between aboveground biomass and time since reclamation, then aboveground biomass might also serve as a metric for forest ecosystem recovery.

Clearcut sites were chosen for use as comparison to surface mined sites, as the process of clearcutting a site does not require the removal of topsoil and the associated seed bank (Simmons et al., 2008). Clearcutting could therefore be considered a lesser disturbance than surface-mined sites, making them useful for comparison as a more advanced form secondary succession. Taken together, this enabled a potential metric of ecosystem recovery to be evaluated under both severe and moderate disturbances and could include the possibility that such a metric might only be useful for one disturbance type, or only useful as a metric to a certain point in the recovery process.

So, in order to identify a potential metric of ecosystem recovery following a moderate to severe disturbance, it was the intent of this study to examine how the aforementioned ecosystem functions (soil density, infiltration rate, insect biomass, decomposition rate, canopy cover, and aboveground biomass) change relative to time since reclamation or disturbance on surface mined and clearcut sites.

Therefore, it was hypothesized that one or more of the measured functions would not show significant variability between surface-mined and clearcut sites. Regardless of disturbance type, for any one or more of the tested factors to be a suitable candidate as a

metric, it should also show a statistically significant and predictable change between differing age classes. Finally, it was predicted that the final age classes on both clearcut and surface mined sites would not vary significantly from the control sites, which have not been disturbed for 50 or more years, with any given factor. This was under the assumption that sites of a sufficient age should, ideally, have recovered enough of their functions as to be indistinguishable from sites that have not experienced major disturbances for an extended period of time. The assessment of control sites established “goal values” for the measured functions. If the final age classes do not differ significantly from those values, then the sites and functions themselves have reached what could be considered an undisturbed state.

Materials and Methods

Sites were chosen and established according to Kennedy et al. (2023), with five age classes (0-5, 6-10, 11-15, 16-29, and 30 plus), consisting of three sites per age class per disturbance type, and two reference sites with more than 50 years since the last disturbance, and all with a north, northeast, northwest, or flat aspect. On each site, one 0.04-hectare plot was established at a random location (Figure A1).

Within each plot (Figure 2.1) were placed three subplots halfway between the center and edge of the plot, each spaced 120° from one another and labeled A, B, and C. Plot A was usually placed to the south and the other subplots established clockwise from there. These subplots allowed for analysis of variation at the microsite level for the tested ecosystem functions, and each function, aside from aboveground biomass, was measured at each subplot.

Infiltration rate was measured using the single ring method (Lili et al., 2011), and a known volume of water equal to 444 milliliters (mL). Vegetation was clipped in an area of soil approximately 30 cm in diameter, and a small amount of surface soil was removed, if necessary, to create a level surface for the infiltration ring. Time taken for water to fully drain was recorded in seconds, and if infiltration was not complete within 30 minutes (1800 seconds), then the process was aborted and recorded as 1800 seconds. Two infiltration tests were performed at each subplot, the first with the soil at its existing moisture content, and the second with the soil saturated from the previous test. Only the second test was used for analysis to control variation in soil moisture.

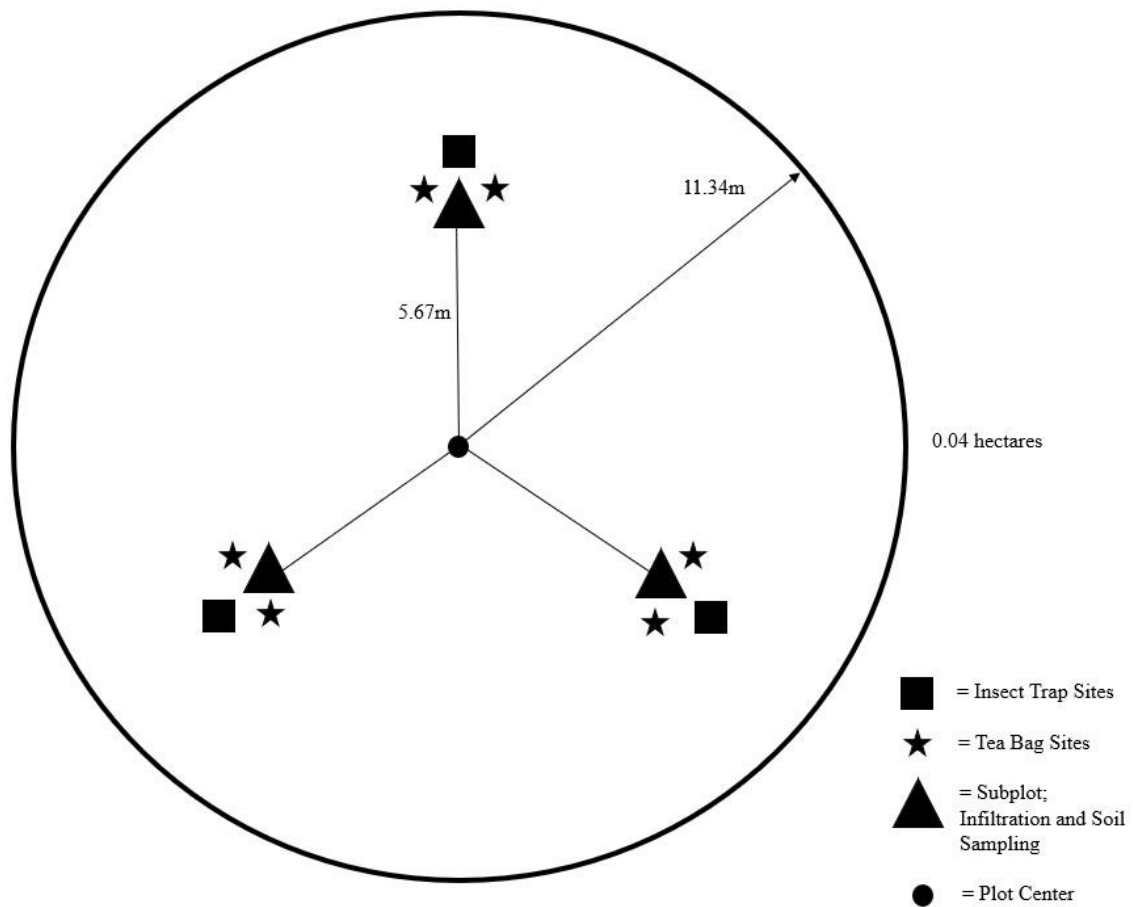


Figure 2.1: Diagram of the plot layout used for this study.

The infiltration rate was calculated using two equations. The first,

$$W = V/A \quad (1)$$

where W= the height of water within the ring, V= the known volume of water used for the test (444mL), and A=the inside area of the ring. The second equation,

$$I=W/t \quad (2)$$

gives the infiltration rate, I, using the water height, W, divided by the time taken for the water to drain, t, and converted into centimeters per hour (cm/hr).

After the infiltration test was complete, soil samples were collected from the soil saturated from the infiltration tests. Samples were taken using a 5.1cm inside-diameter PVC tube sharpened on the edge, marked with lines at 6.0cm and 18.0cm respectively. The tube was hammered into the ground to the first depth, and the soil sample placed in a plastic bag and labeled. In the same spot, the second soil sample was collected, with the tube hammered to the second depth line, and the sample, again, placed in a plastic bag and labeled. All soil samples were returned to the lab, where they were stored at 1-4°C until they were processed. This meant that each subplot had two soil samples associated.

Each soil sample had roots and rocks removed from them. Rocks were removed and their volumes were measured using water displacement in a graduated cylinder, and recorded for soil density calculation. The roots were washed and divided into diameter classes of 0-2mm, 2-10mm, and >10mm, and oven dried at 50°C along with the soil samples. Dry mass of roots and soil samples was recorded.

To calculate soil density, D, the dry mass of the soil, M, was divided by the difference between the known volume of the tube, v_t , and the measured volume of the rocks in the sample, v_r , to give the density of the soil in grams per milliliter (g/mL).

$$D = M/(v_t - v_r) \quad (3)$$

Once soil samples were obtained, the remaining hole was partially filled back in to allow for the placement of a simple conventional pitfall trap (Greenslade, 1964; Montgomery et al., 2021), meant to capture ground-based insects.

One pitfall trap was placed per subplot and covered to discourage interference by weather and wildlife, and prevent capture of small vertebrates. Traps consisted of one 237ml clear plastic cup, filled halfway (approximately 120ml) with propylene glycol. Traps were covered with a square white coroplast board approximately 6-8 inches on a side and secured with nails through the corners to hold them approximately 1cm above ground level (Figure A2). These traps were left for twenty-eight days, then their contents were retrieved and stored in test tubes at 1-4°C until they were processed. These tubes were then drained, and the specimens stored in a 95% ethanol solution to halt further decomposition and for later processing. Samples were drained through a sieve (Schwan et

al. 1993), and sorted into flying, a non-flying, and non-insect classes and mass was recorded. Non-insects included arachnids, centipedes, snails, and other arthropods. These specimens were excluded from further analysis as the original intent was only to study insect biomass.

To measure decomposition rate, a pair of tea bags containing green or rooibos tea were placed approximately 8cm deep and 20 cm apart following a slightly modified methodology of the Tea Bag Index test (Keuskamp et al., 2013). These tea bags were left buried for 90 days, after which they were retrieved and dried in an oven at 50°C for a minimum of 48 hours. Once dried, the tea was removed from the bag, and roots or mycelium that may have grown into the tea bag were extracted as completely as possible. The mass of the dried tea leaves was collected and these masses were then used to calculate the decomposition rate, k , as per Keuskamp et al. (2013).

Canopy cover was collected using a phone app called CanopyCapture (Patel, 2018). Percentage cover was recorded three times per subplot.

Aboveground tree biomass was included in the analysis as a measure of successional regrowth on disturbed sites. Tree biomass in kilograms was calculated from DBH data collected from Kennedy et al. (2023) using biomass equations outlined in Chojnacky et al. (2014). Measurements in inches were converted to centimeters prior to calculation, and any constants for species that were not specifically outlined in Chojnacky et al. (2014) utilized the closest taxonomical species available.

Statistical Analysis

All data were analyzed using R Programming (Fox, 2019; Kassambara, 2023; Mangiafico 2023; Post team, 2022; R Core Team, 2022; Signorell, 2023). Each potential indicator was tested for normal distribution using Shapiro-Wilk, and non-normal data was transformed using the transformTukey function in R package, rcompanion (Mangiafico, 2023), in order to meet assumptions of normality. Data were then modeled using a two-way ANOVA against disturbance type (site type) and age class. Preliminary analysis showed that higher elevation sites tended to have steeper slopes, and these were more common on surface mine sites than clearcut harvest sites, therefore, elevation was included for all models as a covariate.

In the case of a significant interaction between site type and age class, the data were analyzed separately for each site type and modeled with a one-way ANOVA. Variables with a significant variation were analyzed with a Duncan post hoc test. The exception to this was canopy cover analysis which was analyzed with a Kruskal-Wallis test due to lack of normal distribution of means, with a Dunn's test used for post-hoc testing. Where relevant, all analysis was done with an alpha level of 0.05, p-values and means reported in text have been rounded (see Appendix B).

Results

Infiltration rate (Figure 2.2), when analyzed with main effects, site type and age class, showed significant variation between site types ($p=0.006$). When mine sites and clearcut sites were analyzed separately with each being compared to control sites (as age class 6), infiltration rate on mine sites differed significantly between age classes ($p=0.001$), but this was not the case on clearcut sites ($p=0.310$). Infiltration rates on mine sites were lowest in age classes 1 and 2 (~ 0.5 to 0.6cm/hr). This was significantly lower than the fourth (3.8cm/hr) and fifth age classes (2.6cm/hr). The third age class was intermediate of these points, not significantly greater than the first to ages, but significantly less than the fifth age class. Only the first age class was significantly lower than the control sites (2.67cm/hr).

Soil density at the first layer (Figure 2.3), 0-6cm deep, showed a significant interaction between site type and age class ($p=0.01$). On mine sites, age class differences were significant ($p=0.035$), but not on clearcut sites ($p=0.314$). In post hoc testing of mine sites, the fifth age class, which averaged a soil density of 0.56g/cm^3 , was significantly lower than the first three age classes which averaged between 1.1g/cm^3 and 0.95g/cm^3 .

Soil density at the second layer (6-18cm deep) was not significantly different according to site type ($p=0.62$) or age class ($p=0.54$).

Root mass at the first layer (Figure 2.4), 0-6cm, demonstrated significant variation in both age class ($p<0.001$) and site type ($p=0.01$), and while it did not have a significant interaction between the main effects ($p=0.364$), patterns within the charted results led to a closer examination. On mine sites, age class was significantly variable ($p=0.001$), while on clearcut sites it was very much not significant ($p=0.673$).

On mine sites, post hoc testing indicated that root mass at 0-6cm on surface mined sites in the first and second age classes was much lower than the third, fourth, and fifth age classes, with the greatest difference existing between the first age class (0.0185g/cm) and the third age class (0.0916g/cm). The third, fourth, and fifth age classes were all similar to each other, and to the control sites. Root mass at 0-6cm on control sites (0.101g/cm) was significantly greater only to first age class mine sites.

Root mass at the second layer (6-18cm) was significant by the interaction between site type and age class ($p=0.023$). Root mass on mine sites by age class proved rather significant ($p<0.001$), but not so on clearcut sites ($p=0.735$).

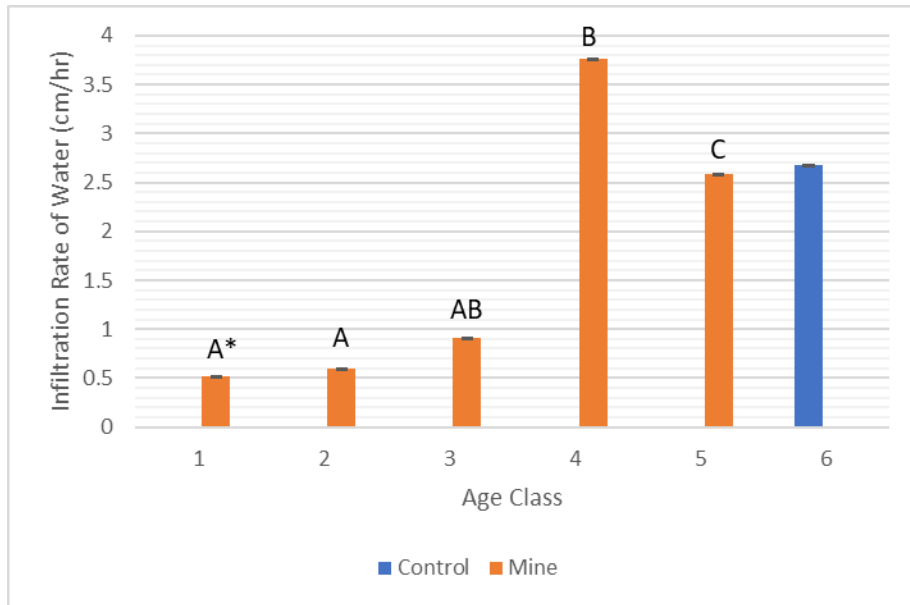


Figure 2.2: Average infiltration rate of water on surface mined sites by age class and site type. Bars indicate standard error. Different letters indicate statistical differences between disturbance types at $P \leq 0.05$. Asterisk indicates significant difference from control at $P \leq 0.05$.

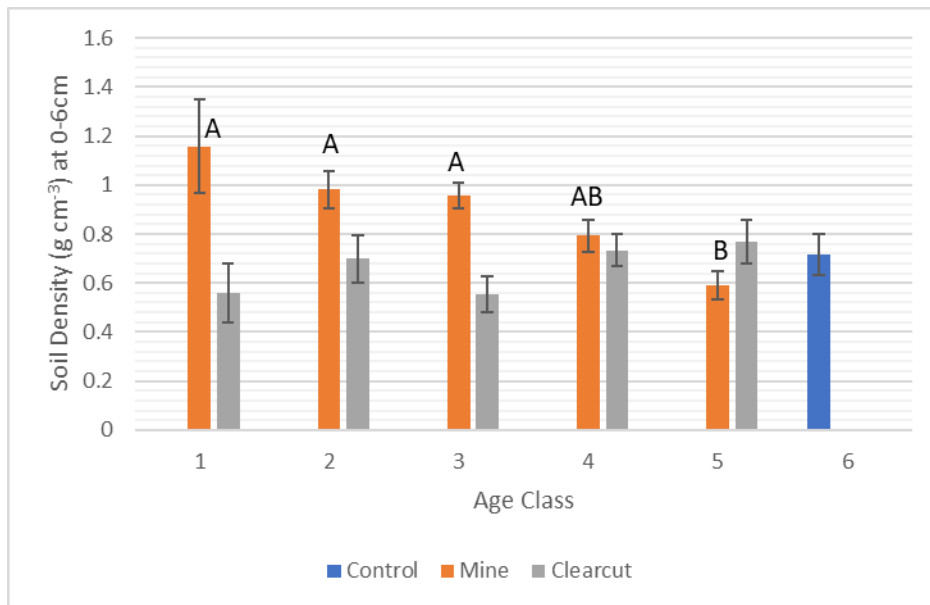


Figure 2.3: Average soil density on surface mined and clearcut sites at 0-6cm by age class and site type. Bars indicate standard error. Different letters indicate statistical differences between disturbance types at $P \leq 0.05$.

Second layer root mass on mine sites (Figure 2.5) showed significant differences between age classes in post hoc testing. Average root weight increased significantly as age class increased, spanning from 0.0062g/cm in the first age class, up to 0.1742g/cm in the fifth age class. There is a significant increase from the fourth age class, which averaged 0.0634g/cm, to the fifth age class. This is possibly due to two of the three sites in the fifth age class undergoing reclamation prior to the enactment of SMCRA, and as such receiving differing treatment from other mine sites. The difference between this age class and others is noticeable with some of the other tested functions as well.

Insect mass (excluding flying insects), varied significantly by site type ($p=0.001$), but not by age class ($p=0.214$). Without any significant interaction between main effects ($p=0.076$), and no significant variance by age class, post hoc testing examined specific differences between site types, rather than age classes.

According to post hoc testing, by site type, insect mass was significantly higher on clearcut sites (3.32g) versus mine sites (1.73g), with control sites settling between the two (2.06g), and not being significantly different from either of them.

Total insect mass (including flying and non-flying insects) showed a significant interaction between the main effects ($p=0.02$), therefore the data were split out by site type and analyzed by age class. Despite this, age class did not prove significant on either mine ($p=0.058$) or clearcut sites ($p=0.116$). Therefore, post hoc testing again examined differences between site types rather than age classes.

From post hoc testing, total insect mass was significantly greater on clearcut sites than mine sites, with 6.70g on average on clearcuts versus 4.36g on average on mine sites. As with the previous insect mass, neither clearcut nor mine sites significantly differ from the controls, though the controls averaged slightly lower than both at 4.21g.

Decomposition (Figure 2.6) was not significantly different by age class ($p=0.674$) nor was there an interaction between site type and age class ($p=0.285$), only site type proved significantly different ($p=0.013$). Post hoc testing by site type indicated that mine sites ($k=0.0172$) tend to have a higher rate of decomposition than clearcut sites ($k=0.0105$). However, these results have likely been heavily negatively impacted by sample loss. As with insect mass, many of the planted tea bags were either disturbed by wildlife, or else unable to be recovered, especially in the first and second age classes, and this was particularly true of the clearcut sites. It is therefore uncertain how representative these results may be.

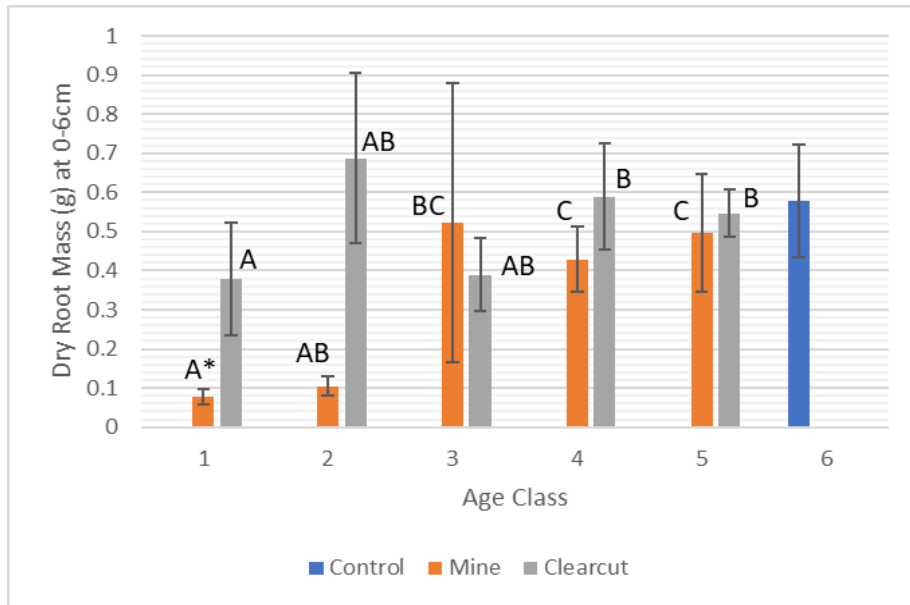


Figure 2.4: Average dry root mass on surface mined and clearcut sites at 0-6cm by age class and site type. Bars indicate standard error. Different letters indicate statistical differences between disturbance types at $P \leq 0.05$. Asterisk indicates significant difference from control at $P \leq 0.05$.

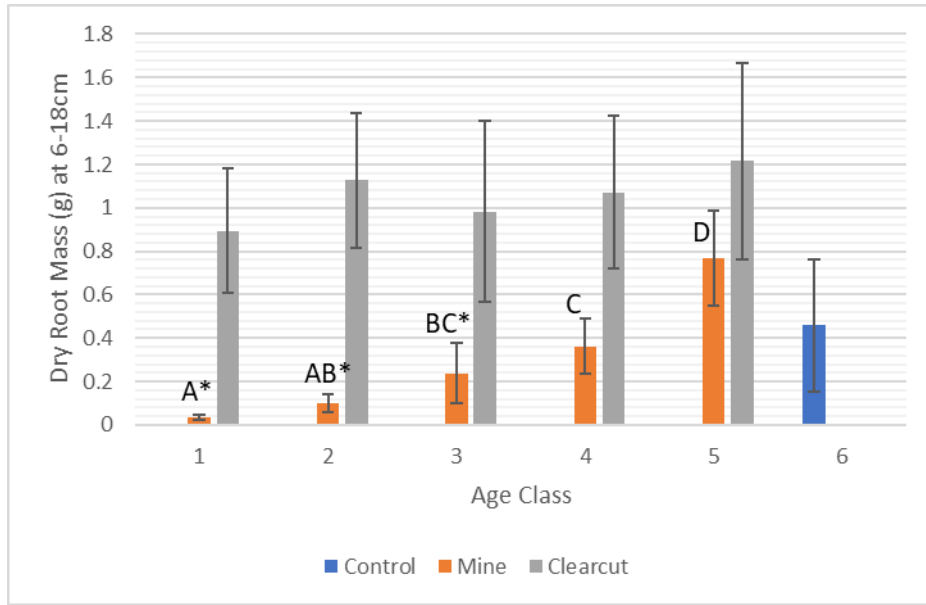


Figure 2.5: Average dry root mass on surface mined and clearcut sites at 6-18cm by age class and site type. Bars indicate standard error. Different letters indicate statistical differences between disturbance types at $P \leq 0.05$. Asterisk indicates significant difference from control at $P \leq 0.05$.

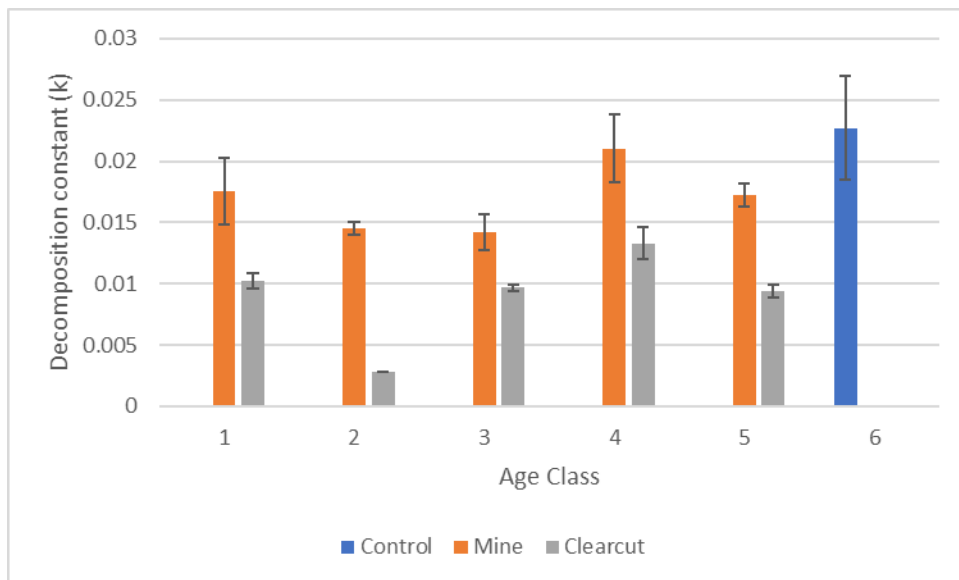


Figure 2.6: Average decomposition constant (k) on surface mined and clearcut sites by age class and site type. Bars indicate standard error.

Canopy cover (Figure 2.7) underwent two Kruskal-Wallis tests, split out by site type. Age class proved significant on both mine sites ($\chi^2=107.68$, $p < 0.001$) and clearcut sites ($\chi^2= 19.818$, $p=0.001$). Post hoc testing on both site types using Dunn's test demonstrated that clearcut sites seem to have a head start on canopy closure over mine sites. The first age class on clearcut sites averaged a 49% closed canopy and was only significantly different from the fourth age class, which had 96% canopy closure. In contrast, mine sites start with an average of 9% and improve over the course of the second age class until the third, where canopy closure is 83% on average, and slowly increases to 89% by the final age class.

Aboveground biomass (Figure 2.8) varied significantly in the interaction between site type and age class ($p<0.001$). Because of this, aboveground biomass was split out by site type, and both surface mined sites ($p<0.001$) and clearcut sites ($p<0.001$) proved significant by age class.

As with canopy cover, the youngest clearcut sites had more aboveground biomass than mine sites did, averaging 1583kg/hectare, compared to the 126kg/hectare that the first age class of mine sites averaged. Aboveground biomass on clearcut sites increase until around the third age class (6885kg/hectare) and proceeds to decrease steadily until the fifth age class (2771kg/hectare). In contrast, aboveground biomass on mine sites appears to increase quickly from 155kg/hectare in the second age class on average to 2127kg/hectare on average in the third. The aboveground biomass continues to increase well into the fifth age class.

Discussion

Clearcut sites showed no significant variation by age class for any of the tested factors save for aboveground biomass and canopy cover. On surface mined sites, infiltration rate, soil density at 0-6cm, root mass at both 0-6cm and 6-18cm, aboveground biomass, and canopy cover all demonstrated significant variation by age class. All factors listed showed a direct, positive correlation with age class, save soil density, which was inversely related.

Infiltration rate on surface mined sites, while showing a positive relationship with age class, did not achieve statistical significance until at least 11 years post disturbance. Reynolds and Reddy (2012) performed a similar study infiltration rate and soil density of surface mined sites in Wyoming at two different age classes, though all sites were reclaimed post-SMCRA, and the study used a double-ring method with multiple replicates rather than the single ring method used in this study. That said, the findings agree with the trend of infiltration rate increasing as age class increases, however, the measured rate of infiltration by Reynolds and Reddy (2012) tends to be higher than those found in this study. For example, in the final age class of 20-25 years post reclamation Reynolds and Reddy (2012) measured infiltration rate at 58.23mm/hr on their first site and 74.70mm/hr on their second. By comparison, the average infiltration in the fourth age class, which ranged from 16-29 years post reclamation, was approximately (converted

from cm/hr) 37mm/hr. Clark and Zipper (2016) performed a study of infiltration rate on a surface mine site in eastern Virginia that had been reclaimed in the early 2000s. Their findings also measured an infiltration rate that was higher on average than what was observed on mine sites of a comparable age class (average of 16.5cm/hr versus 0.09cm/hr). It was noted that differences in infiltration rates between studies likely have a great deal to do with differences in soil construction (Clark & Zipper, 2016; Guebert & Gardner, 2001), and has also been observed that differences in measurement techniques can have an impact on measured infiltration rates (Reynolds et al., 2000). Additionally, later age classes displayed no differences between themselves and control sites, which matches with the results obtained by Reynolds and Reddy (2012).

Soil density at 0-6cm on surface mined sites tended to decrease with age class, but this was not statistically significant until the fifth age class, thirty or more years post-disturbance. However, in contrast to the elevated infiltration rates that were observed in this study relative to others, aside from those found in the first age class, soil density at 0-6cm (or a comparable soil depth) seems lower overall. Soil density at a comparable depth on older mine sites seems to be around 1.02 to 1.40 g/cm³ on average (Reynolds & Reddy, 2012; Shrestha et al., 2005; Shrestha & Lal, 2008), compared to the average soil density of mine sites in this study in the final two age classes, which was 0.793 g/cm³ and 0.591 g/cm³ respectively. Differences in management practices is a possible explanation, but sites used by Reynolds and Reddy (2012) and Shrestha et al. (2005) were all reclaimed under SMCRA. Shrestha and Lal (2008) worked on a 28-year-old mine site that had been reclaimed before SMCRA and their average soil density at a comparable depth (0-5cm) was still greater than 1g/cm³. That said, a key element of FRA reclamation approaches involves forgoing the use of heavy equipment and instead loosely grading the topsoil to limit compaction (Burger et al. 2005), and as it is unknown precisely what reclamation practices were used on the majority of the examined surface mine sites, this could account for the comparatively reduced soil compaction. This would not however, explain the gap in average soil densities between the pre-SMCRA sites in the final age class of this study and the sites used by Shrestha and Lal (2008). Another possibility relates to differences in soil series and composition, which has been observed to result in differences of soil density (Shrestha & Lal, 2011). Soil series and composition was not well-recorded in this study so it remains uncertain as to the cause of the comparatively reduced soil density of the investigated mine sites, especially considering the comparatively lower infiltration rates.

Soil density at 6-18cm did not vary by age class or site type and was thus deemed unsuitable for further analysis. However, particularly on surface mined sites, average soil density seemed to decrease at increased soil depths, which is a pattern also noted by Shrestha and Lal (2008).

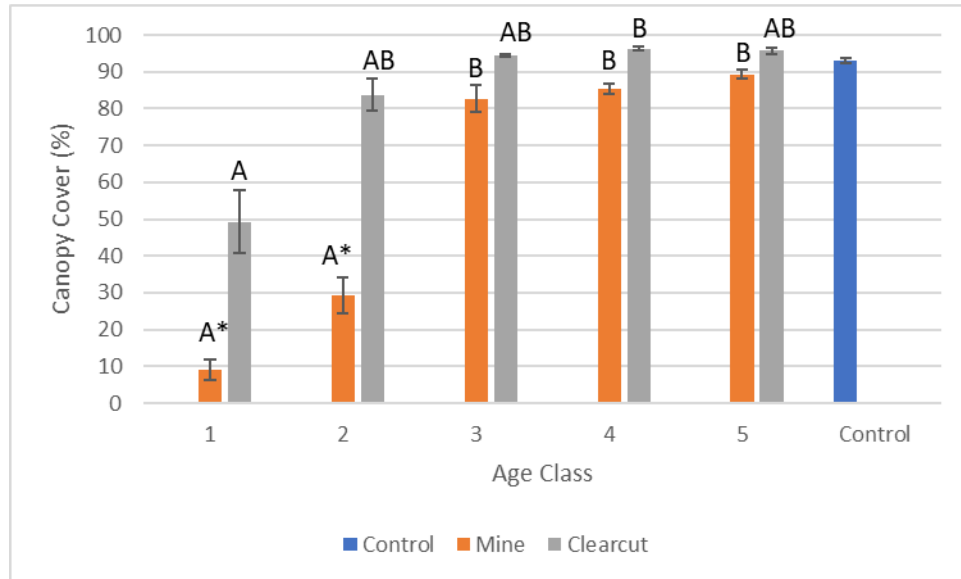


Figure 2.7: Average canopy cover on surface mined and clearcut sites by age class and site type. Bars indicate standard error. Different letters indicate statistical differences between disturbance types at $P \leq 0.05$. Asterisk indicates significant difference from control at $P \leq 0.05$.

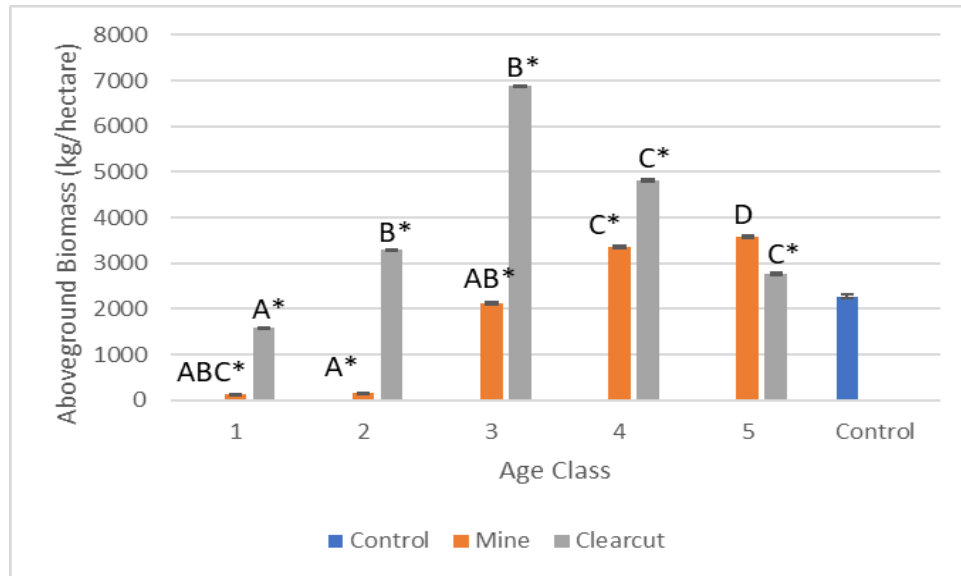


Figure 2.8: Average aboveground biomass on surface mined and clearcut sites by age class and site type. Bars indicate standard error. Different letters indicate statistical differences between disturbance types at $P \leq 0.05$. Asterisk indicates significant difference from control at $P \leq 0.05$.

Similar to infiltration rate, root mass at 0-6cm on surface mined sites showed little change until 11 to 16 years post-disturbance but did not appear to improve significantly beyond that point. This is somewhat in line with results observed on a similar study which used a 40-year chronosequence on surface mined sites in North Dakota, where root biomass showed no change over time (Bohrer et al., 2017).

However, root mass at 6-18cm on surface mined sites demonstrated the clearest visual correlation with age class, which contrasts heavily with Bohrer et al. (2017). Statistically, and visually, the deeper root mass appears to demonstrate a slow, but steady growth from initial disturbance which becomes significant around 10-15 years post-disturbance, before spiking suddenly in the final age class. This enormous difference between the fourth and fifth age classes could be attributed to a difference in reclamation practices post-operations on mine sites in the fifth age class, most of which were reclaimed pre-SMCRA, and as such did not undergo the same level of soil compaction which is known to limit root growth (Panayiotopoulos et al., 1994).

Neither decomposition rate nor insect mass showed significant variability by age class on either surface mined or clearcut sites, but both varied significantly according to site type. Decomposition rate has a consistently higher constant, k , value on surface mined sites as compared to clearcut sites, which was unexpected. It was anticipated that, given the disparity in disturbance level between surface mining and clearcutting, decomposition rate on clearcut sites would be higher, but this proved to be untrue. Additionally, unlike other factors, the higher rate of decomposition on surface mined sites is consistent across age classes and cannot be explained merely by the final surface mined age class, which has shown a trend of higher productivity throughout the study. It was presumed at the start of the study that there may be a relationship between decomposition rate and age class due to the positive correlation between phosphorous and nitrogen and site age noted by Zipper et al., (2011a), which are two soil chemicals heavily involved in soil function (Haering et al., 2004), and decomposition (Attiwill & Adams, 1993). While this does not seem to be the case, neither does it explain the disparity in decomposition rate between surface mined and clearcut sites. A possible explanation could be increased decomposition rates because there is a dearth of organic resources to work from in mine soils especially initially, which was observed by Littlfield et al. (2013). This runs counter to the findings of Stahl et al., (2003) that noted an abundance of organic carbon in surface mined soils in Wyoming, and a significantly reduced microbial biomass relative to undisturbed sites. This led them to conclude that decomposition rates in reclaimed mine soils are likely to be lowered, which was not supported by the findings of this study. However, this analysis would greatly benefit from repeated study or closer examination, due to the high rate of sample loss that undoubtedly influenced results.

Insect mass for both non-flying insects and insects overall were significantly more abundant on clearcut sites over surface mined sites, which was an expected outcome. The preservation of the soil on clearcut sites (Simmons et al., 2008) likely lends itself to better habitation than the mine soils more commonly found on surface mined sites, especially younger ones. With regards to the lack of relationship to age class, multiple studies have

examined the response of insect species to disturbances, and the results tend to be dependent on the family of insects in question, which was not accounted for in this study (Cobb et al., 2007; Dodd et al., 2012). Additionally, the number of insect samples lost over the course of the study may warrant repeated investigation to verify conclusions.

On surface mined sites, canopy cover developed until the end of the third age class, approximately fifteen years post-disturbance, up to 83%, and did not change significantly after that point. This is likely around the time the canopy closed on these sites, and any changes after that point, aside from another disturbance, are unlikely to be significant, which limits the time period in which canopy cover may be useable as a metric for recovery. Skousen et al. (2006) observed similar canopy cover values (approximately 70%), if a little lower, on mine sites in West Virginia between 19- and 23-years post-reclamation. Canopy cover on clearcut sites proved much less informative, as the canopy closed within the first 10 years post-disturbance and is unlikely to be very diagnostic of recovery progress as a result.

Aboveground biomass on surface mined sites did not demonstrate significant change until the third age class, approximately 10-15 years post-reclamation. After that point, it appears to change rapidly until the final age class, which was not significantly different from the control sites. This contrasts somewhat with Sena et al. (2021) who observed statistically significant increases in aboveground biomass on several surface mined sites in Kentucky over a 19-year chronosequence. However, the overall trend of increasing aboveground biomass relative to age class is still compatible with their findings.

Changes over time in aboveground biomass on clearcut sites were significant within the first decade post-disturbance and proceeded to rapidly grow over the next 20 years. Growth plateaued briefly around 10-15 and 20-30 years post disturbance, but overall maintained a progressive upward trend. This is in line with the succession and cycling of shade-intolerant to shade-tolerant species described by Boring et al. (2014) which consolidated the results of numerous studies of the same clearcut watershed across 30 years to synthesize and discuss the successional forest dynamics of the area. Essentially, shade-intolerant species would quickly populate the newly freed space created by clearcutting and remain dominant until the shade tolerant species came up, which briefly increases the collective biomass of the stand. Eventually, the shade-intolerant species are outcompeted which leads to another decrease in biomass, the entire arc of which can be observed in Figure 2.8.

That said, the final age class did significantly vary from the control sites, which implies that the 30+ year old clearcut sites are not yet, or no longer are, comparable to the controls which have remained undisturbed for 50 or more years. It is therefore uncertain whether the positive trend of aboveground biomass on clearcut sites would continue beyond 30+ years of age. This seems likely given that aboveground biomass on control sites is significantly higher on average than the average in the last age class on clearcut

sites. Regardless, this would appear to make aboveground biomass an ecosystem function well worth further investigation for value as a metric for ecosystem recovery.

All of the factors, save for soil density at 6-18cm, demonstrated significant variation between surface mined and clearcut sites. As such, change in ecosystem service factors over time may not be comparable between surface mined and clearcut sites, and by proxy, other sites subjected to severe and moderate disturbances. This suggests that potential metrics of ecosystem recovery may be disturbance specific. This idea is further supported by the results, given that many of the significant changes by age class that took place on surface mined sites, did not do so on clearcut sites.

Conclusion

Of the ecosystem functions tested, aboveground biomass appears to be the best candidate for further investigation as an ecosystem recovery metric on both surface mined and clearcut sites in eastern hardwood forests, though the results are unlikely to be comparable between site types. This implies that metrics for ecosystem recovery may be specific to the type of disturbance and may also be highly dependent on the severity of the disturbance. Canopy cover on surface mined sites is also worth consideration as a potential metric, though only up to a certain point as it is only useable as a measure before the canopy actually closes. Given that this appears to take anywhere from 15 to 20 years post-disturbance on surface mined sites, which is approximately the time aboveground biomass seems to require to be useful, a combined measurement may be necessary for a complete evaluation. Root biomass at 18cm may also warrant further analysis specifically on surface mined sites. However, all three of these suggested metrics are measures of reforestation and plant regrowth which have been implied to be an incomplete set of indicators for restoration of ecosystem functions that existed prior to disturbance (Avera et al., 2015). As such, measures of soil structure and function, such as infiltration rate and soil density, particularly in the upper soil horizons, should also be considered for further investigation as metrics, in tandem with the aforementioned measures of reforestation.

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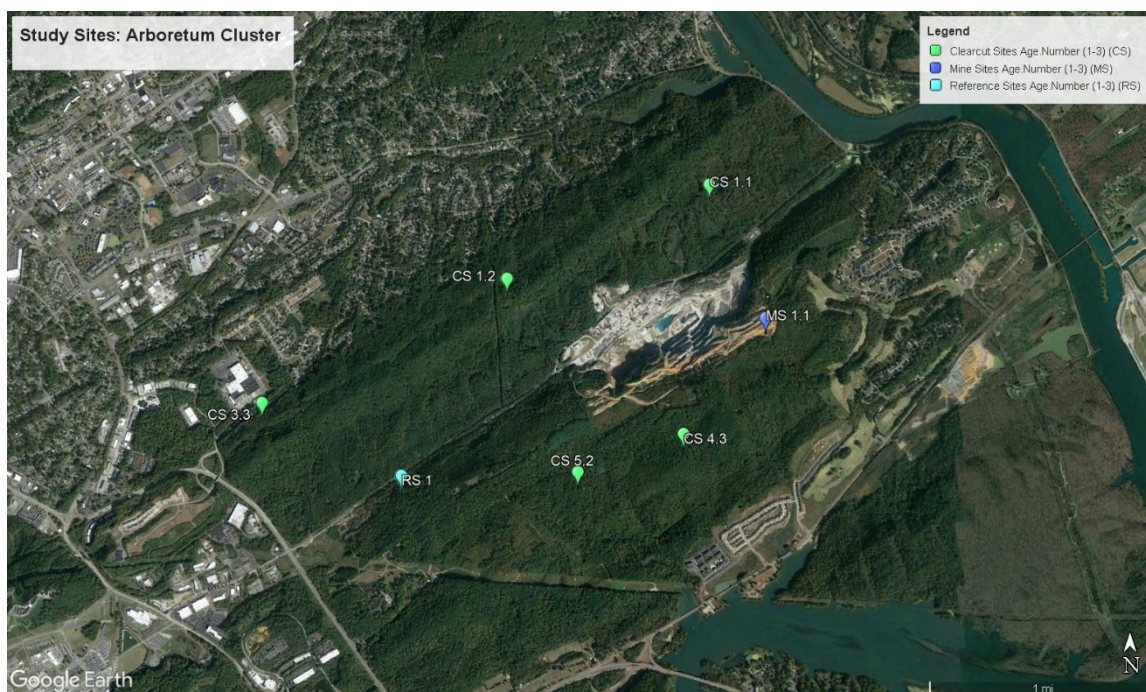
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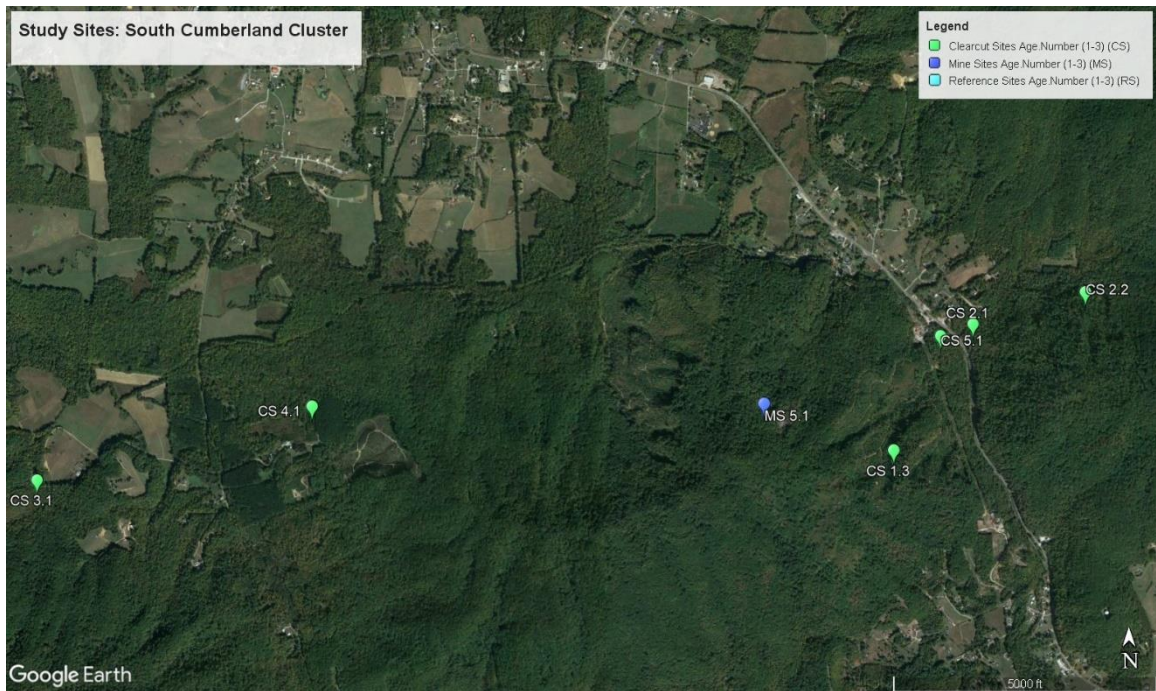
APPENDICES

Appendix A



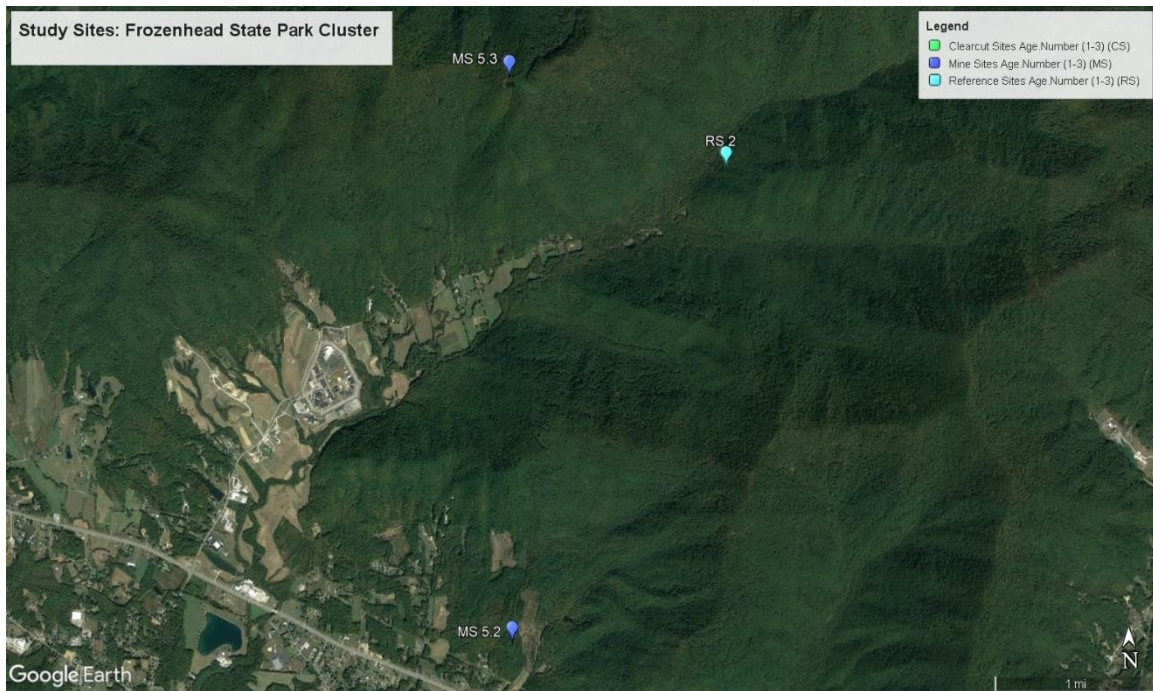
(a) Study sites located at the University of Tennessee Arboretum near Oak Ridge, TN (Google Earth Pro, 2022a).

Figure A1: Maps generated by Google Earth displaying the clusters of locations of sites used in this study labeled by site type, age class, and site number consisting of (a) UT Arboretum Cluster, (b) South Cumberland Cluster, (c) Frozenhead State Park Cluster, (d) Windrock Park Cluster, (e) Zeb Mountain Cluster, and (f) Nature Conservancy Cluster. MS indicates a surface mine site, CS indicates a clearcut site, and RS indicates a reference or control site. Sites are numbered by Age Class.Site Number (e. g. MS 3.2 means that site is a surface mine site in the second age class and is the second of these sites in this age class)



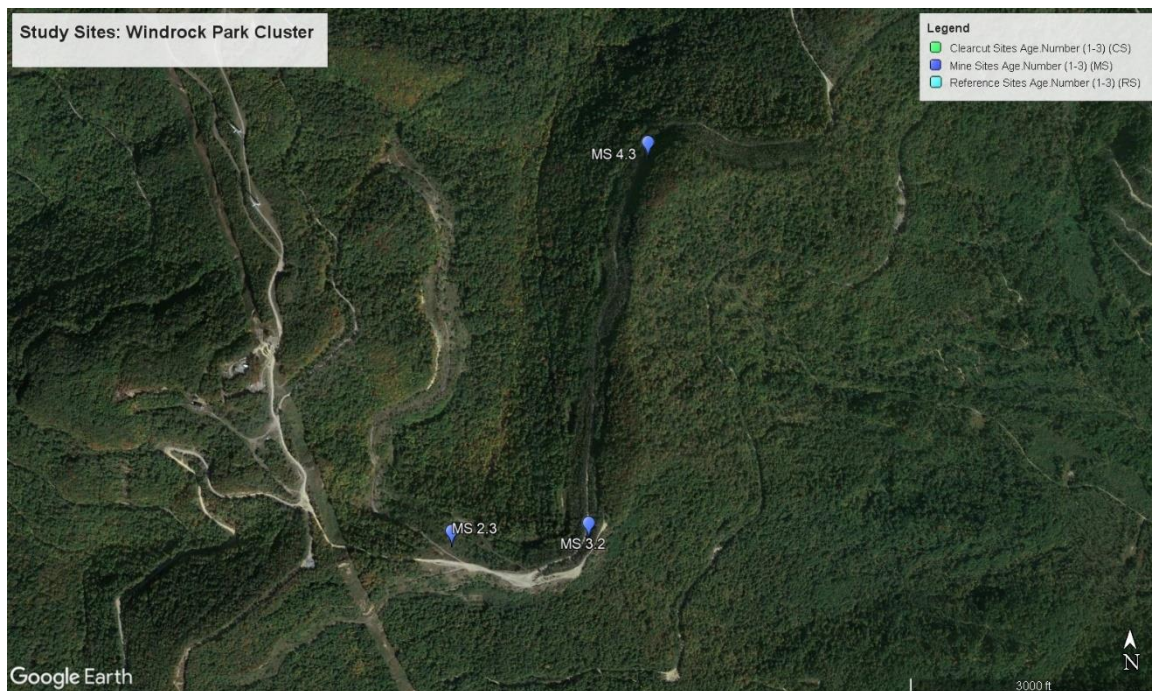
(b) Study sites located in the South Cumberland region, near Joyner and Coalfield, TN (Google Earth Pro, 2022b).

Figure A1 (continued)



(c) Study sites located within and around Frozenhead State Park, near Wartburg, TN (Google Earth Pro 2022c).

Figure A1 (continued)



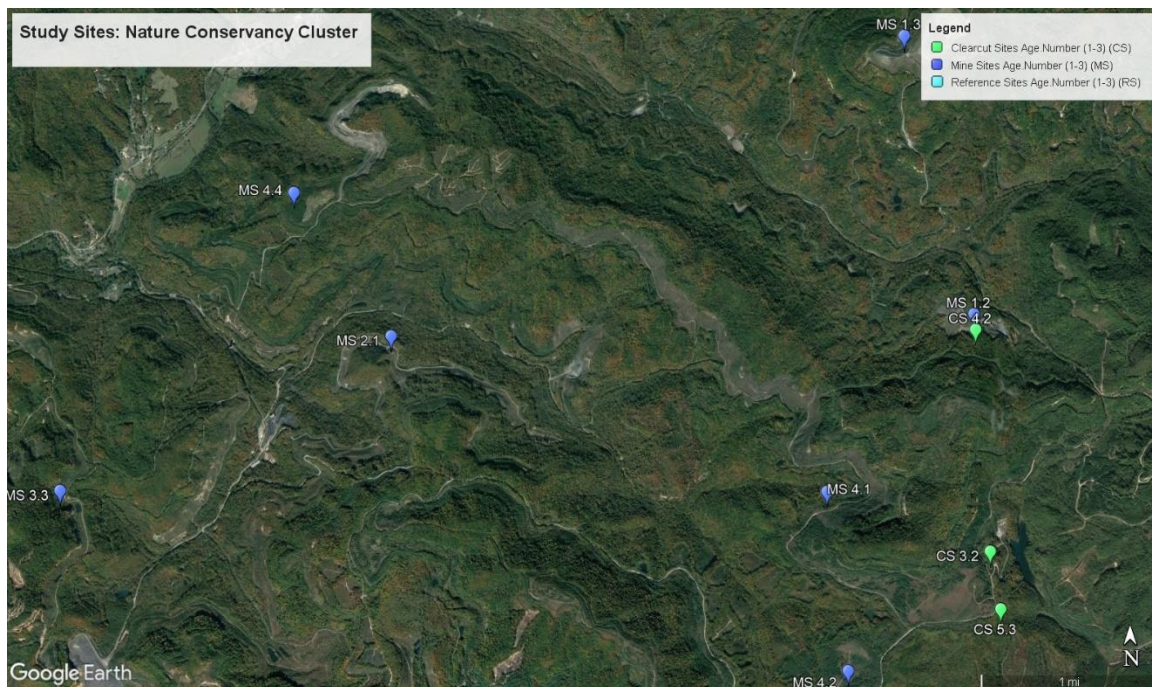
(d) Study sites located within Windrock Park, near Windrock, Oliver Springs, TN
(Google Earth Pro 2022d)

Figure A1 (continued)



(e) Study sites located on Zeb Mountain, near Elk Valley, TN (Google Earth Pro 2022e)

Figure A1 (continued)



(f) Study sites located on land owned by The Nature Conservancy, located near Clairfield, TN (Google Earth Pro 2022f)

Figure A1 (continued)



Figure A2: Images of installed simple pitfall trap components. Images sourced by author.

Table A1: Averages of potential ecosystem function metrics by site type and age class

Site Type & Age Class	Infiltration Rate (cm/hr)	Density 1 (g/cm ³)	Density 2 (g/cm ³)	Root Dry Weight 1 (g)/Diameter (cm)	Root Dry Weight 2 (g)/Diameter (cm)	Insect Mass (g)	Total Insect Mass (g)	Decomposition Rate (k)	Canopy Cover (avg)	Aboveground Biomass (kg/hectare)
Mine						1.7342	4.3556	0.0172		
1	0.0001	1.1570	0.7782	0.0135	0.0062				9.1111	126.2260
2	0.0002	0.9813	0.5696	0.0185	0.0171				29.3333	155.4721
3	0.0003	0.9566	0.5944	0.0916	0.0496				82.6667	2127.5491
4	0.0010	0.7926	0.6708	0.0753	0.0634				85.4815	3356.5318
5	0.0007	0.5914	0.5555	0.0872	0.1742				89.2593	3573.3156
Clearcut						3.3119	6.6968	0.0105		
1	0.0019	0.5601	0.5760	0.0665	0.1708				49.2963	1582.7270
2	0.0006	0.6986	0.5930	0.1204	0.1447				83.7778	3291.2379
3	0.0008	0.5515	0.6306	0.0684	0.2181				94.5417	6884.6962
4	0.0008	0.7326	0.5120	0.1033	0.2285				96.2778	4812.0469
5	0.0056	0.7671	0.5131	0.0958	0.1321				95.6667	2770.3958
Control										
	0.0007	0.7177	0.5955	0.1012	0.1181	2.0622	4.2088	0.0227	93.0556	2272.9337

Table A2: Standard errors of potential ecosystem function metrics by site type and age class

Site Type & Age Class	Infiltration Rate (cm/hr)	Density 1 (g/cm ³)	Density 2 (g/cm ³)	Root Dry Weight (g)/Diameter 1 (cm)	Root Dry Weight (g)/Diameter 2 (cm)	Insect Mass (g)	Flying Insect Mass (g)	Decomposition Rate (k)	Canopy Cover	Aboveground Biomass (kg/hectare)
Mine						0.3680	0.7940	0.0025		
1	0.0088	0.1909	0.1004	0.0036	0.0019				4.7710	13.5067
2	0.0076	0.0754	0.0542	0.0043	0.0072				8.0863	21.5263
3	0.0097	0.0522	0.0590	0.0627	0.0230				6.6328	19.2072
4	0.0545	0.0659	0.0397	0.0148	0.0225				2.0672	18.8005
5	0.0158	0.0585	0.0378	0.0265	0.0332				2.0780	29.4022
Clearcut						0.4632	0.8037	0.0012		
1	0.1087	0.1210	0.0732	0.0252	0.0545				11.0367	18.1324
2	0.0274	0.0950	0.0526	0.0381	0.0559				7.8846	21.3152
3	0.0252	0.0732	0.0392	0.0163	0.0691				0.5345	20.4372
4	0.0304	0.0657	0.0858	0.0237	0.0742				0.6009	23.7177
5	0.2558	0.0880	0.0600	0.0107	0.0482				1.9255	25.5518
Control										
6	0.0404	0.0829	0.0716	0.0253	0.0291	0.8488	1.8608	0.0104	1.4472	42.7785

Appendix B

Infiltration Rate (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	0.02752	0.013762	5.436	0.00616 **
Age.Class	4	0.04041	0.010102	3.990	0.00536 **
Elevation.ft.	1	0.00827	0.008265	3.265	0.07463 .
Site.Type:Age.Class	4	0.02576	0.006439	2.543	0.04611 *
Residuals	78	0.19746	0.002532		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

9 observations deleted due to missingness

Infiltration Rate (Mine)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	0.05271	0.010541	5.746	0.000682 ***
Elevation.ft.	11	0.02465	0.002241	1.221	0.313214
Residuals	32	0.05871	0.001835		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

5 observations deleted due to missingness

Infiltration Rate Mine Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test				
95% family-wise confidence level				
\$Age.Class				
	diff	lwr.ci	upr.ci	pval
2-1	0.013728574	-0.030239866	0.05769701	0.52930
3-1	0.040316434	-0.002911505	0.08354437	0.06692 .
4-1	0.079265995	0.033698063	0.12483393	0.00092 ***
5-1	0.086399986	0.040093155	0.13270682	0.00041 ***
6-1	0.061948586	0.012093318	0.11180385	0.01565 *
3-2	0.026587860	-0.017380579	0.07055630	0.22702
4-2	0.065537422	0.017866667	0.11320818	0.00782 **
5-2	0.072671412	0.023957244	0.12138558	0.00400 **
6-2	0.048220013	-0.002797328	0.09923735	0.06345 .
4-3	0.038949561	-0.004278377	0.08217750	0.07641 .
5-3	0.046083552	0.001491644	0.09067546	0.04300 *
6-3	0.021632152	-0.024351142	0.06761545	0.34512

5-4	0.007133991	-0.033994718	0.04826270	0.72617
6-4	-0.017317409	-0.063300703	0.02866589	0.44864
6-5	-0.024451400	-0.072781704	0.02387891	0.31535

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Infiltration Rate (Clearcut)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	0.02035	0.004070	1.237	0.310
Elevation.ft.	1	0.00446	0.004461	1.356	0.251
Residuals	40	0.13161	0.003290		

4 observations deleted due to missingness

Density 1 (first layer) (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	0.000624	3.122e-04	4.715	0.0118 *
Age.Class	4	0.000266	6.640e-05	1.003	0.4117
Elevation.ft.	1	0.000000	2.900e-07	0.004	0.9472
Site.Type:Age.Class	4	0.000943	2.358e-04	3.561	0.0103 *
Residuals	74	0.004900	6.621e-05		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

12 observations deleted due to missingness

Density 1 (Mine)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	0.0008663	1.733e-04	2.660	0.0348 *
Elevation.ft.	1	0.0000179	1.794e-05	0.275	0.6024
Residuals	44	0.0028662	6.514e-05		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2 observations deleted due to missingness

Density 1 Mine Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test
95% family-wise confidence level
\$Age.Class

	diff	lwr.ci	upr.ci	pval
2-1	-0.0016709319	-0.009574763	0.006232900	0.6721
3-1	-0.0020995116	-0.010652150	0.006453127	0.6284
4-1	-0.0067082755	-0.014766923	0.001350372	0.1026
5-1	-0.0119789098	-0.020899112	-0.003058707	0.0084 **
6-1	-0.0072753499	-0.017567330	0.003016631	0.1664
3-2	-0.0004285797	-0.008332411	0.007475252	0.9135
4-2	-0.0050373436	-0.012580062	0.002505375	0.1887
5-2	-0.0103079779	-0.018818398	-0.001797557	0.0176 *
6-2	-0.0056044180	-0.015452248	0.004243412	0.2645
4-3	-0.0046087639	-0.012033121	0.002815593	0.2175
5-3	-0.0098793982	-0.018458483	-0.001300313	0.0242 *
6-3	-0.0051758383	-0.014927347	0.004575670	0.2958
5-4	-0.0052706343	-0.012813353	0.002272084	0.1692
6-4	-0.0005670744	-0.009225288	0.008091139	0.8956
6-5	0.0047035599	-0.004369154	0.013776274	0.3018

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Density 1 (Clearcut)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	0.0004004	8.008e-05	1.239	0.314
Elevation.ft.	1	0.0000063	6.280e-06	0.097	0.757
Residuals	33	0.0021336	6.465e-05		

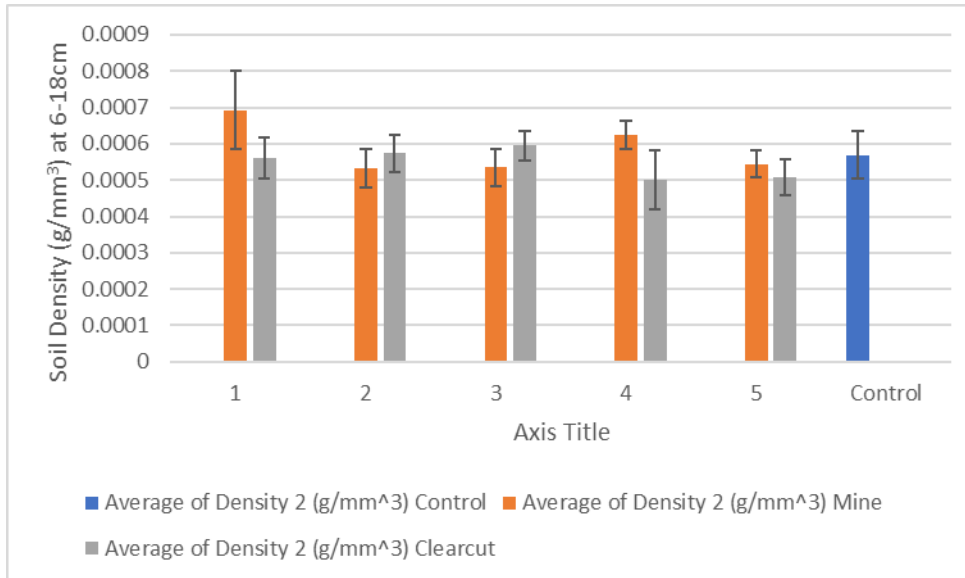
11 observations deleted due to missingness

Density 2 (second layer) (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	2.900e-08	1.451e-08	0.482	0.6197
Age.Class	4	9.340e-08	2.336e-08	0.775	0.5447
Elevation.ft.	1	8.690e-08	8.686e-08	2.883	0.0938 .
Site.Type:Age.Class	4	1.265e-07	3.162e-08	1.050	0.3877
Residuals	73	2.199e-06	3.012e-08		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

13 observations deleted due to missingness



Root 1 (root mass first layer) (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	0.2282	0.11410	4.845	0.010262 *
Age.Class	4	0.5253	0.13133	5.577	0.000507 ***
Elevation.ft.	1	0.0185	0.01848	0.785	0.378256
Site.Type:Age.Class	4	0.1032	0.02581	1.096	0.364242
Residuals	82	1.9311	0.02355		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

6 observations deleted due to missingness

Root 1 (Mine)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	0.5362	0.10724	4.534	0.00102 **
Site.Type	1	0.2173	0.21729	9.186	0.00322 **
Elevation.ft.	1	0.0185	0.01848	0.781	0.37919
Residuals	86	2.0343	0.02366		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

5 observations deleted due to missingness

Root 1 Mine Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test
95% family-wise confidence level

\$Age.Class					
	diff	lwr.ci	upr.ci	pval	
2-1	0.05644594	-0.046958100	0.1598500	0.28088	
3-1	0.11769371	0.008884938	0.2265025	0.03391	*
4-1	0.18128680	0.074541723	0.2880319	0.00078	***
5-1	0.19220682	0.073316631	0.3110970	0.00128	**
6-1	0.21351616	0.050374355	0.3766580	0.00942	**
3-2	0.06124778	-0.043623058	0.1661186	0.24885	
4-2	0.12484086	0.019874949	0.2298068	0.01962	*
5-2	0.13576089	0.018036521	0.2534852	0.02332	*
6-2	0.15707022	-0.004415740	0.3185562	0.05683	.
4-3	0.06359309	-0.036158971	0.1633451	0.20846	
5-3	0.07451311	-0.039458191	0.1884844	0.20147	
6-3	0.09582244	-0.061984200	0.2536291	0.23819	
5-4	0.01092002	-0.092441801	0.1142818	0.83415	
6-4	0.03222935	-0.116702368	0.1811611	0.67342	
6-5	0.02130933	-0.126381171	0.1689998	0.77494	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Root 1 (Clearcut)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	0.1157	0.02313	0.801	0.5556
Elevation.ft.	1	0.0987	0.09871	3.417	0.0718
Residuals	41	1.1845	0.02889		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3 observations deleted due to missingness

Root 2 (root mass second layer) (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	1.345	0.6727	13.696	7.38e-06 ***
Age.Class	4	0.983	0.2457	5.003	0.00117 **
Elevation.ft.	1	0.033	0.0329	0.669	0.41577
Site.Type:Age.Class	4	0.591	0.1478	3.008	0.02277 *
Residuals	82	4.027	0.0491		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

5 observations deleted due to missingness

Root 2 (Mine)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	1.6501	0.3300	11.559	3.26e-07 ***
Elevation.ft.	1	0.0146	0.0146	0.511	0.478
Residuals	45	1.2848	0.0286		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2 observations deleted due to missingnes

Root 2 Mine Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test				
95% family-wise confidence level				
\$Age.Class				
	diff	lwr.ci	upr.ci	pval
2-1	0.09742561	-0.063003910	0.2578551	0.22765
3-1	0.22472864	0.044367039	0.4050902	0.01513 *
4-1	0.27915023	0.116250718	0.4420498	0.00092 ***
5-1	0.51661009	0.335525658	0.6976945	1.7e-07 ***
6-1	0.44320124	0.244105954	0.6422965	2.3e-05 ***
3-2	0.12730303	-0.044203336	0.2988094	0.14190
4-2	0.18172463	0.023908223	0.3395410	0.02443 *
5-2	0.41918448	0.241108241	0.5972607	9.1e-06 ***
6-2	0.34577563	0.151073470	0.5404778	0.00061 ***
4-3	0.05442159	-0.107433994	0.2162772	0.50174
5-3	0.29188145	0.105710570	0.4780523	0.00232 **
6-3	0.21847260	0.019358780	0.4175864	0.03182 *
5-4	0.23745985	0.079643451	0.3952763	0.00362 **
6-4	0.16405101	-0.006110193	0.3342122	0.05844 .
6-5	-0.07340885	-0.252774501	0.1059568	0.41411

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Root 2 (Clearcut)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	0.1857	0.03714	0.554	0.735
Elevation.ft.	1	0.1156	0.11556	1.723	0.197
Residuals	41	2.7503	0.06708		

3 observations deleted due to missingness

Total Insect Mass (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	2.874	1.4369	7.176	0.001681 **
Age.Class	4	1.321	0.3303	1.650	0.174696
Elevation.ft.	1	1.392	1.3924	6.954	0.010804 *
Slope....	1	3.074	3.0736	15.350	0.000245 ***
Site.Type:Age.Class	4	2.552	0.6379	3.186	0.019890 *
Residuals	56	11.213	0.2002		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

31 observations deleted due to missingness

Total Insect Mass (Clearcut)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	2.814	0.5629	2.388	0.05844 .
Elevation.ft.	1	0.702	0.7019	2.978	0.09350 .
Slope....	1	2.936	2.9357	12.454	0.00122 **
Residuals	34	8.014	0.2357		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

12 observations deleted due to missingness

Total Insect Mass (Clearcut)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	2.246	0.4492	1.995	0.116
Elevation.ft.	1	0.034	0.0345	0.153	0.699
Slope....	1	0.088	0.0881	0.391	0.538
Residuals	24	5.404	0.2252		

19 observations deleted due to missingness

Total Insect Mass Overall Site Type Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test					
95% family-wise confidence level					
\$Site.Type					
	diff	lwr.ci	upr.ci	pval	
Mine-Control	0.03625511	-0.39085549	0.4633657	0.86559	
Clearcut-Control	0.44967724	-0.00939902	0.9087535	0.05485 .	
Clearcut-Mine	0.41342213	0.18653556	0.6403087	0.00058 ***	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Non-Flying) Insect Mass (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	1.790	0.8951	8.258	0.00072 ***
Age.Class	4	0.652	0.1629	1.503	0.21370
Elevation.ft.	1	0.742	0.7419	6.844	0.01141 *
Slope....	1	1.206	1.2065	11.130	0.00151 **
Site.Type:Age.Class	4	0.971	0.2428	2.240	0.07623 .
Residuals	56	6.070	0.1084		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

30 observations deleted due to missingness

Insect Mass Overall Site Type Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test				
95% family-wise confidence level				
\$Site.Type				
	diff	lwr.ci	upr.ci	pval
Mine-Control	-0.05719265	-0.37144811	0.2570628	0.71680
Clearcut-Control	0.27833448	-0.04277427	0.5994432	0.08799 .
Clearcut-Mine	0.33552714	0.15992635	0.5111279	0.00025 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				

Decomposition Rate (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	0.0830	0.04148	4.700	0.0131 *
Age.Class	4	0.0207	0.00518	0.586	0.6739
Elevation.ft.	1	0.0014	0.00138	0.156	0.6942
Slope....	1	0.0275	0.02752	3.118	0.0831 .
Site.Type:Age.Class	4	0.0456	0.01139	1.291	0.2851
Residuals	54	0.4766	0.00883		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
32 observations deleted due to missingness					

Decomposition Rate Site Type Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test				
95% family-wise confidence level				
\$Site.Type				
	diff	lwr.ci	upr.ci	pval
Mine-Control	-0.01419450	-0.09798932	0.06960032	0.7355
Clearcut-Control	-0.08253607	-0.17139355	0.00632141	0.0685 .
Clearcut-Mine	-0.06834157	-0.11663265	-0.02005049	0.0064 **

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				

Canopy Cover Kruskal Wallis Test (Mine)

Kruskal-Wallis rank sum test	
data: Canopy.Cover by Age.Class	
Kruskal-Wallis chi-squared = 107.68, df = 5, p-value < 2.2e-16	

Canopy Cover Kruskal Wallis Post Hoc Dunn Test (Mine)

Dunn's test of multiple comparisons using rank sums : holm		
	mean.rank.diff	pval
2-1	16.222222	0.8889
3-1	77.240741	1.7e-09 ***
4-1	70.870370	4.3e-08 ***
5-1	86.333333	1.0e-11 ***
6-1	103.305556	2.5e-13 ***
3-2	61.018519	3.6e-06 ***
4-2	54.648148	4.5e-05 ***
5-2	70.111111	5.7e-08 ***
6-2	87.083333	1.3e-09 ***
4-3	-6.370370	0.9001
5-3	9.092593	0.9001
6-3	26.064815	0.3167
5-4	15.462963	0.8889
6-4	32.435185	0.1117
6-5	16.972222	0.8889

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1		

Canopy Cover Kruskal Wallis Test (Clearcut)

Kruskal-Wallis rank sum test

data: Canopy.Cover by Age.Class
Kruskal-Wallis chi-squared = 19.818, df = 5, p-value = 0.001352

Canopy Cover Kruskal Wallist Post Hoc Dunn's Test (Clearcut)

Dunn's test of multiple comparisons using rank sums : holm		
	mean.rank.diff	pval
2-1	14.240741	0.97970
3-1	18.569444	0.61884
4-1	43.083333	0.00098 ***
5-1	38.000000	0.07496 .
6-1	11.000000	1.00000
3-2	4.328704	1.00000
4-2	28.842593	0.09001 .
5-2	23.759259	0.65314
6-2	-3.240741	1.00000
4-3	24.513889	0.29233
5-3	19.430556	0.97970
6-3	-7.569444	1.00000
5-4	-5.083333	1.00000
6-4	-32.083333	0.08615 .
6-5	-27.000000	0.61884

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1		

Aboveground Biomass (Overall)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site.Type	2	157	78.63	31.536	4.06e-14 ***
Age.Class	4	499	124.84	50.071	< 2e-16 ***
Elevation.ft.	1	12	11.93	4.783	0.028904 *
Slope....	1	23	22.76	9.130	0.002561 **
Site.Type:Age.Class	4	50	12.56	5.037	0.000495 ***
Residuals	1377	3433	2.49		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
88 observations deleted due to missingness					

Aboveground Biomass (Mine)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	229.7	45.94	15.326	5.53e-14 ***

Elevation.ft.	1	1.0	0.98	0.328	0.567
Slope....	1	4.2	4.22	1.407	0.236
Residuals	477	1429.8	3.00		

Signif. codes:	0	****	0.001	***	0.01
				*	0.05
				.	0.1
				'	'
					1
1 observation deleted due to missingness					

Aboveground Biomass Mine Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test					
95% family-wise confidence level					
\$Age.Class					
	diff	lwr.ci	upr.ci	pval	
2-1	-0.4732966	-2.20492901	1.2583359	0.59820	
3-1	-0.1061858	-1.42778550	1.2154138	0.87462	
4-1	0.8293126	-0.48125572	2.1398809	0.21433	
5-1	1.6499026	0.20814797	3.0916572	0.02388	*
6-1	1.4900742	0.04474021	2.9354083	0.04313	*
3-2	0.3671107	-0.70313581	1.4373573	0.50063	
4-2	1.3026092	0.15293956	2.4522788	0.02539	*
5-2	2.1231991	0.90414324	3.3422550	0.00033	***
6-2	1.9633708	0.70110001	3.2256416	0.00161	**
4-3	0.9354984	0.51751938	1.3534775	7.0e-06	***
5-3	1.7560884	1.26314952	2.2490273	1.1e-11	***
6-3	1.5962601	0.97615149	2.2163687	1.2e-07	***
5-4	0.8205900	0.39073380	1.2504461	0.00013	***
6-4	0.6607616	0.11692708	1.2045962	0.01736	*
6-5	-0.1598283	-0.73764984	0.4179932	0.58703	

Signif. codes:	0	****	0.001	***	0.01
				*	0.05
				.	0.1
				'	'
					1

Aboveground Biomass (Clearcut)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Age.Class	5	409.1	81.83	33.525	< 2e-16 ***
Elevation.ft.	1	20.5	20.49	8.394	0.00384 **
Residuals	1035	2526.2	2.44		

Signif. codes:	0	****	0.001	***	0.01
				*	0.05
				.	0.1
				'	'
					1

Aboveground Biomass Clearcut Post Hoc (Duncan)

Posthoc multiple comparisons of means : Duncan's new multiple range test						
95% family-wise confidence level						
\$Age.Class						
	diff	lwr.ci	upr.ci	pval		
2-1	0.80882401	0.4657045	1.1519435	4.2e-06	***	
3-1	0.87808216	0.5589986	1.1971658	2.5e-08	***	
4-1	1.79511341	1.4132006	2.1770262	< 2e-16	***	
5-1	1.72292685	1.2974391	2.1484146	< 2e-16	***	
6-1	2.31651744	1.7438738	2.8891611	< 2e-16	***	
3-2	0.06925816	-0.2069182	0.3454345	0.6228		
4-2	0.98628940	0.6389467	1.3336321	3.7e-09	***	
5-2	0.91410284	0.5239826	1.3042231	2.2e-06	***	
6-2	1.50769343	0.9628586	2.0525282	5.0e-09	***	
4-3	0.91703124	0.6267869	1.2072755	1.6e-10	***	
5-3	0.84484468	0.5110511	1.1786383	8.0e-07	***	
6-3	1.43843527	0.9360110	1.9408595	2.8e-09	***	
5-4	-0.07218656	-0.4423527	0.2979796	0.7020		
6-4	0.52140403	0.0327683	1.0100398	0.0365	*	
6-5	0.59359059	0.0422916	1.1448896	0.0344	*	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

CHAPTER IV

CONCLUSION

In spite of somewhat interesting and informative results, this project had many facets that warrant further or repeated examination. The investigation of decomposition rate and insect biomass carried with them a very high rate of sample loss. Much of this was due to wildlife interference, or else samples simply going missing on site. While decomposition rate and insect mass both returned inconclusive results, effectively eliminating them as potential metrics in the eyes of this study, it is entirely possible, even likely, that this sample loss contributed heavily to this outcome.

Site selection was a major challenge as well. The given criteria of a north facing slope, with three sites per age class of both site types, balanced with accessibility and land use permissions meant that, while the process was selective, it was difficult to find sites that met each criterion perfectly, if at all.

Age classes were organized in 5-year increments, with the exception of the fourth age class, which spanned approximately 15 years, and the fifth and final age class which was open ended by design. This left room for development and changes to take place within those spans that may not have been detected or understood, especially in the case of the last two age classes. The most grievous example was the sites in the final age classes whose last disturbance was prior to the SMCRA legislation in 1977 which saw a massive shift in reclamation policy and post-operations management. Having an open-ended final age class, while providing freedom of selection for older age classes, also brought a level of uncertainty to many results which made analysis challenging. This was the case to a lesser degree with the fourth age class as well due to its size.

A series of repeat or alternate study or two with a capped upper age limit, and that fourth age class split out, is recommended as it may reveal more information regarding that is presently unnoticed or uncertain. Additionally, taking into account sample loss and site scarcity in design would be greatly beneficial to any future studies regarding ecosystem restoration metrics in eastern hardwood sites.

Future analysis may also benefit from a change in ecosystem type. Ecosystem level variances in precipitation, elevation, biodiversity, and temperature all play a role in ecosystem functions. An investigation into metrics of ecosystem recovery in a differing ecosystem would likely prove worthwhile.

With all of this in mind, this study concluded that average basal area, soil density at 0-6cm depth, infiltration rate, root mass at 6-18cm depth, canopy cover, and aboveground biomass were the ecosystem functions most capable of serving as metrics of ecosystem recovery. Special attention was given to average basal area, canopy cover, and aboveground biomass as these potential metrics displayed correlation to site age on both surface mined and clearcut sites, demonstrating their potential for recovery assessment across more than one disturbance type.

VITA

Ian Kennedy started as an undergraduate at the University of Georgia, where he attended for two years, before transferring to Kennesaw State University to pursue a B.S. in Biology with a concentration in Ecology. He worked as an undergraduate researcher in an ecology lab studying montane longleaf pine regeneration and cataloguing tree and herb species at Sheffield WMA in Dallas, Georgia. After graduating in 2021, he accepted a paid summer internship with the Atlanta Botanical Gardens working to grow and maintain pitcher plants in addition to several other endangered plant species, before starting his Master's degree in Forestry in spring of 2022.