

USING BEFORE-AFTER-CONTROL-IMPACT-PAIRS TO MONITOR THE EFFECT OF LONGWALL MINING ON MATURE FOREST STANDS IN SOUTHEASTERN OHIO

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ABSTRACT.—Longwall mining involves complete removal of coal from underground seams which results in varying degrees of surface subsidence. In Belmont County, OH, The Ohio Valley Coal Co. is planning to mine the Pittsburgh No. 8 coal seam that lies 300 - 600 feet below the surface of an old growth forest, Dysart Woods. The mining, and associated subsidence, is opposed by several groups on the grounds that it may harm the old growth forest. This study was designed to investigate the potential impacts of longwall mining and other environmental stresses by intensively monitoring two forest ecosystems before, during and after mining. One stand (test stand) is in an area that was undermined at a depth of 400 - 500 feet below the surface during the winter of 2001-2002. The other is in an area that was not undermined. Otherwise the two stands are relatively similar. Several standards were used to indicate the health and vigor of the trees and stands, including tree growth rates, vigor ratings, and mortality rates.

The two sites represent maturing stands of 5 acres or larger that possessed many of the attributes of old-growth forests. They both contained a mixture of species that are best described as “mesophytic hardwoods” including oaks, yellow-poplar, white ash, black cherry and a component of shade tolerant species such as American beech and sugar maple. The general approach was to collect pre-mining data for both stands from 1999 through most of 2001. The test site was mined under in late 2001, and then data were collected during all of 2002 to provide post-mining data. The ecological performance (tree growth, vigor, and mortality) was measured to determine if any divergence occurred between the two sites.

The trees responded to the drought in 1999 with a generally reduced radial growth at both sites. In fact the two sites behaved in a similar manner over the course of the study except for the unusually high rate of growth for the test stand in 2001. But the tree response was not associated with mining, since the growth, vigor and mortality of trees at the test site did not change appreciably relative to the control site in 2002, the post-mining year.

Introduction

Coal removal by the longwall method is a type of deep mining process that extracts all the coal in a particular geologic layer (seam) resulting in subsidence at the surface and fracturing of rock layers above the mine. Concerns have been expressed by several groups that longwall mining could result in damage to forests, because of the hydrologic alterations caused by subsidence. Of particular concern is Dysart Woods, an old growth remnant of mesophytic hardwoods in Belmont County, OH.

This study is designed to investigate the potential impacts of longwall mining on forests by intensively monitoring two forest ecosystems before, during and after mining. The methodology we used can be described as before-after-control-impact-pairs (BACIP). This approach is one of several similar methods termed “quasi-experiments” described by Zenner (2003) as being appropriate for elucidating ecological patterns and processes. In preparation for this study, two maturing hardwood stands with an oak component and other site and stand characteristics that were similar to old growth remnant forests in southeastern Ohio were located. One stand (test stand) is in an area that was mined under at a depth of 400- 500 feet below the surface during the winter of 2001-2002. The other is in an area that was not mined under. Although the slope aspects of the two stands were somewhat different, the stands

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were relatively similar in most other ways. The purpose of the control stand was to help quantify the effects of variables unrelated to longwall mining (weather, etc.) and to provide a baseline for comparison with the test stand. Several standards were used to indicate the health and vigor of the trees and stands. These include: tree mortality, density and type of regeneration, tree growth rate, vigor ratings of trees, etc.

Dysart Woods is a remnant old-growth stand that probably originated as part of an extensive forest that once covered vast areas of North America prior to European colonization (McCarthy 1995). Dysart Woods' two stands total approximately 30 acres. Both stands contain an old-growth cohort of oaks (mostly white oak, *Quercus alba*) and yellow-poplar (*Liriodendron tulipifera*). These old-growth trees are reportedly over 300 years of age, approaching the limit of their life expectancy as indicated by the rate of tree mortality, determined to be approximately 3.0% per year in 2003. Shade tolerant hardwoods such as sugar maple and American beech (*Fagus grandifolia*) are gradually replacing the old-growth oaks. A thorough ecological inventory of Dysart Woods was conducted in the fall of 1997 and the results are provided by Hicks and Holt (1999).

Our ecological inventory revealed that the forests displayed reverse J-shaped diameter distributions, typical of all-age, old-growth forests. However, the diameter distribution of the old-growth oak cohort was bell-shaped, typical of even-age stands. The successional replacement of the overstory is well under way at Dysart Woods where a mortality rate of approximately 3.0% per year was observed for large old-growth trees. Nearly all trees in mid-story and understory canopy positions are shade tolerant species such as sugar maple and American beech. Downs and Abrams (1991) concluded that such replacement of old-growth stands with shade tolerant species is inevitable. In fact, they observed a stage of this transition in maturing second-growth oak stands as well. Franklin et.al. (1987) emphasized that tree death and replacement is part of the normal ecological process of stand development.

The old growth stands at Dysart Woods may have originated after a major disturbance such as forest fire. Many authors agree that indigenous people probably used fire extensively to clear land (MacCleery 1992) and the dominance of oaks in many areas of the central hardwood region implies the involvement of fire as a disturbance (Abrams 1992). It is also generally documented that, in the absence of recurrent fire, remnant old-growth oak-hickory stands are becoming rare, regardless of efforts to preserve them, due to the successional replacement of oaks by shade tolerant species (Fralish et al. 1991).

In a comparison of old-growth and second-growth oak forests in Missouri, Shifley et.al. (1995) found that apart from the presence of more large trees (>17 in. dbh), the two types of forest shared many common attributes. Likewise, after comparing the composition and structure of a second-growth and an old-growth forest in Pennsylvania, Downs and Abrams (1991) concluded that they represent "early vs. late stages of oak replacement."

Since old-growth stands are relatively rare, small in extent and subject to changes, it is important to examine the factors that might accelerate these changes. Manion (1981) proposes a so-called "mortality spiral" that represents what occurs when trees are placed under external stress. Stress initiates a chain reaction that may involve attack by secondary organisms (insects and diseases), and ultimately results in death of the tree. Waring (1987) noted that stress results in re-allocation of photosynthates. Repeated drought stress results in trees with relatively larger root systems, sacrificing aboveground growth to favor root growth. Waring also observed that stem growth often shows the impact of stress more quickly than other indicators, stating: "Stem growth only occurs once the resource demands for foliage and root growth have been accommodated." The extension that can be drawn from Waring's conclusion is: if longwall mining initiates stress in trees, this stress will be detectable as a reduced rate of annual radial growth of the affected trees.

The USDA Forest Service, Forest Health Protection program periodically reports forest health conditions in the United States. In a report covering the Northeastern Area (USDA 1993), they list

general forest stressors as “fire, weather and air pollution.” Decline and mortality of trees could potentially be an effect of longwall mining. The USDA Forest service has published a series of Forest Health Monitoring Fact Sheets and they list the following as “indicators” of forest health:

1. Tree Crown Condition Indicator – diameter, live crown ratio, density, dieback, foliage transparency, crown vigor.
2. Tree Growth Indicator – radial growth measured at dbh (diameter breast height).
3. Tree Mortality Indicator – unusually high rates of mortality, often with a spatial pattern.
4. Tree Damage Indicator – presence of fungal fruiting bodies, wounds, cracks, broken or dead roots, etc.
5. Tree Regeneration Indicator – failure of, or abnormal, regeneration compared to expected levels.

Methods

Because of the difficulty and expense of monitoring ecosystem response using replicated experimental designs, we selected the BACIP method, using trees as the experimental unit instead of sites. Osenberg et al (1994) indicate that this method is applicable for comparing impacts of an environmental change, but care must be given to the site selection and the parameters chosen for comparison. Underwood (1994) recommends multiple control locations to improve the power of such experiments, but Stewart-Oaten and Murdoch (1986) indicate that the proper choice of a control site and replication through time will enable BACIP designs to provide reliable results. The primary criteria used for site selection in this study were: Sites should have the proper status regarding mining activity and possess the appropriate species and forest conditions so as to be analogous to old-growth forests. The test site was selected from an area in Belmont County to the west of the village of Centerville, OH and the control site was approximately 15,000 feet away, in an area not planned for mining. Data were collected at both sites beginning in May of 1999. The mining passed by the test site in May, 2001 and went under the site between November and December of 2001, thus data were collected for three growing seasons prior to and one season post mining. The two sites were deemed appropriate since they had the proper species mix, soil and site characteristics, as well as characteristics of old growth. The difference in aspect of the two sites was not manifested in substantial differences in species composition and site quality.

Approach

The general approach of the BACIP design is to establish a baseline by measuring the control and test stands during the pre-mining interval to insure that tree in the two stands responded in similar ways. The ecological performance of the two stands is observed during and after mining to determine if any divergence occurs between the test and control sites after mining.

Initial Ecological Inventory. The stands were sampled using point sampling to obtain an estimate of basal area. Fixed area plots of 0.1-acre were used to obtain most data on trees (2 in. dbh and up), and 6-ft.-radius plots (2 per overstory plot) were measured to obtain regeneration information. A 100% sample of all larger trees (>16 in. dbh) was conducted over the entire stands. Sixteen 0.1-acre overstory plots at the test site and 15 plots at the control site were installed, which is the approximate number to estimate the average basal area to an accuracy of 10% of the true mean. Sample points were located systematically through the area using a sampling grid, beginning from a random starting point. At the center of each sample location, a permanent stake was placed with a label to identify its location. The basal area at this point was estimated using a 10-BAF (basal area factor) prism. The Society of American Forester's cover type (Eyre 1980) was determined based on the stand composition in the area around the sampling point. The slope position aspect and slope inclination were determined at the sampling points. All trees (>2 in. dbh) within a 0.1-acre circular plot around the center point were measured and numbered starting from a north compass bearing and proceeding clockwise until a complete circle has been turned. Each tree's number was painted at dbh. The species, dbh to the nearest 0.1 in., total height to the nearest foot, crown class, vigor class and expected longevity (a subjective judgement) was recorded for each tree. A paint mark was placed at the position where dbh

was measured in order to assure that the same location is used in each re-measurement. Trees in the plots were re-measured at the end of the growing season each year.

Two 6-ft.-radius sample plots, one at plot center and another 18 ft. from center on a random azimuth were established. All woody vegetation was counted by species, and tallied by height classes (<6", 6"-4', >4'). An estimate of total ground cover in percent was also recorded.

In addition to the trees sampled in the 0.1-acre plots, all the large trees (including standing dead) in the stand (>16 in. dbh) were measured and located on a map. These trees were numbered and labeled using a tag attached to the base of the tree. Data recorded for these trees was the same as collected for the trees in the fixed-area plots, including an estimate of the years since death for standing dead trees. These trees in the "large tree" sample were measured for dbh, total height and vigor class each year at the end of the growing season.

From the population of larger trees, a sub-sample of approximately 10 trees was selected from each of 5 species (two per species) in each stand (test and control) for intensive study ($N_{\text{tot}} = 20$). The 5 species were: white oak, northern red oak (*Quercus rubra*), yellow-poplar, sugar maple, and white ash (*Fraxinus americana*). Criteria for selecting the intensively sampled trees were size and age (generally larger and older trees were given preference), vigor and appearance (only healthy appearing trees were selected), and proximal competition. Only trees in the dominant and codominant crown class were used, excluding trees at the edge of large canopy gaps or in open-grown situations. In the spring of 1999, two increment cores were extracted from each of the intensively studied trees—the first at a random azimuth and the second 90 degrees clockwise from the first. One core extended to the center of the tree for age determination and both were averaged to construct a skeleton plot of average radial growth over the past 20 years. These trees were equipped with band dendrometers that permitted continuous measurement of growth in circumference. In this way, it was possible to accurately track the radial growth of the trees over time. This precise measurement provided a quality check on the annual measurements of the large trees, which was done using a steel diameter tape. The two banded trees of each species at each site have been monitored biweekly throughout the growing season and monthly during the dormant season for the duration of the study.

Subsequent Inventories. The permanent plot centers have been revisited each year at the end of the growing season for both test and control stands, including three growing seasons in the pre-mining period and one in the post-mining period. All trees in the sample plots were measured for the same characteristics as in the initial sampling, including any mortality that occurred. Regeneration samples were taken in the beginning of the study, but not at the end. It was felt that impacts unrelated to longwall mining (white-tailed deer, droughts, periodic seed crops, shading, etc.) were much more influential on seedling densities than other attributes we were studying, therefore these data were unlikely to yield meaningful results. Regarding the large tree samples for each stand, all trees that were larger than 16 inches dbh in 1999 were measured at the end of each growing season for dbh, total height, vigor rating and expected longevity.

Using the approach indicated above, it was possible to track the radial growth, height growth, vigor and mortality of the population of trees at both sites. The permanent plots allowed for the documentation of the performance of trees in all canopy strata while the large tree sample keyed on the largest and oldest cohort of trees in the stand. This is especially important when relating the present results to old growth forests. The BACIP approach with a test/control pairing and pre-and post-mining data provided an opportunity to calibrate the performance of trees at the two sites before mining and to observe their responses to environmental variations that are unrelated to mining, e.g. the 1999 summer drought. The focus was, therefore, to examine the data for a departure in the growth/vigor/mortality that may occur in the post-mining period for trees at the test site, compared to those at the control site.

Preliminary Analysis

Data from the initial inventory were entered from field data sheets to a spread sheet program where averages for dbh, height, crown class, vigor rating, number of trees per acre, etc. were calculated by stand and by species. Other variables computed by stand and species are: regeneration densities, importance values and measures of species diversity. The utility of these computations was to establish whether or not the test and control sites were relatively similar. Using average basal areas per acre, average dbh, number of trees per acre and site index, the relative stocking of the stands was determined. Differences in stocking that may exist could help explain differences in diameter growth rates between the two stands. Diameter distributions of the two stands were plotted to see if they conform to the reverse J-shaped form expected for old-growth stands. Data on tree densities by species and number of different species were used to compute the Shannon-Weiner H' , a measure of species diversity.

Annual measurements of basal area increment (BAI) and vigor change for both the 0.1 acre fixed-area plots and the large tree sample (dbh ≥ 16 in) were tabulated and compared. For both sets of sample data, we used analysis of variance (PROC GLM, SAS Institute 2001) to determine if there were significant differences between the means of test and control stands. The following effects were evaluated: site, year, species, and site * year. For six of the more abundant species (white oak, northern red oak, sugar maple, yellow-poplar, American beech, and white ash), we also evaluated the site * year * species interaction for annual BAI and vigor change.

Diameter growth changes (at breast height) for the 10 intensively measured trees (two each for white oak, northern red oak, yellow-poplar, sugar maple, and white ash) were analyzed using linear regression. To compare growth between species, sites, and years, we fit a least squares line ($y = mx + b$, where y = circumference at day_x, m = slope of the line, and b = intercept) to a portion of the growth curve for each sample tree for the period May 1-September 1 of each year. We then evaluated the significance of the following effects: species, site, year, as well as interactions (site*year, species*site*year) on the slope, m , using PROC GLM (SAS Institute 2001). Finally, we used Duncan's Multiple Range Test to identify significantly different mean values.

Growth ring analysis provided a recent growth history of trees in both stands. If trees in the two stands were initially growing at similar rates, but differed after mining, it would suggest that mining could be responsible for the difference. Thus, the comparisons include both pre- and post-mining comparisons on the same trees as well as treatment-control comparisons between trees in the test and control stands.

Results

Comparison of Initial Site Conditions

The ecological inventory that was conducted in the spring of 1999 revealed that the two stands were relatively similar. Based on data from the 0.1-acre plots, the average dbh for all trees down to 2 inches was 7.2 for the control and 8.4 for the test stand. The control and test stands were both approximately 7 acres in size. There were 175 trees exceeding 16 inches in dbh in the control stand and 222 in the test stand. Thus the density of large trees (> 16 inches dbh) was 24.2 trees per acre in the control stand and 32.2 large trees per acre in the test stand. Table 1 summarizes much of the point/plot data collected at the two sites. As can be seen, the predominant cover type in the control stand was type 60 (beech-sugar maple) while 97% of the plots in the test stand fell in type 27 (sugar maple). The basal area stocking in the two stands was virtually identical with 84 square feet/acre in the control stand and 85 in the test stand. Stem density, seedling density and species diversity was similar for the two stands (table 1). The slope inclination was similar between the two stands, although more plots occurred on lower slope positions at the control site compared to the test site. Both stands were situated along the side slope of a ridge but in the case of the control site, the aspect generally faced southwest whereas the aspect at the test site generally was inclined toward the northeast. The soils, although not identical, were similar, being dominated by Lowell-Westmoreland silt loams. Site quality, expressed as site index (50-year base) of northern red oak trees was estimated from age and height data of 6 trees at the control site and 5 from the test site. The estimated site index at the control site was 76 ft. and it was 71 ft. at the test site, which did not constitute a statistically significant difference.

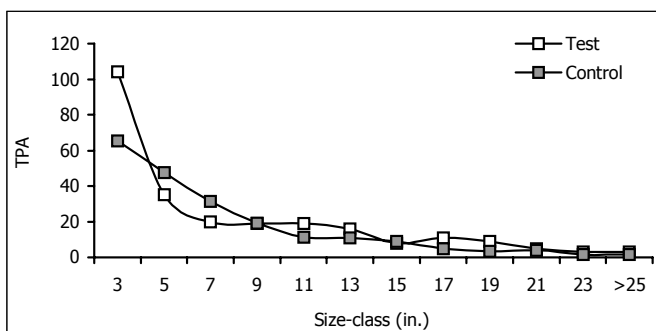


Figure 1.—Size-class distribution for trees ≥ 2 in dbh from 0.1 ac permanent plots, Control and Test sites.

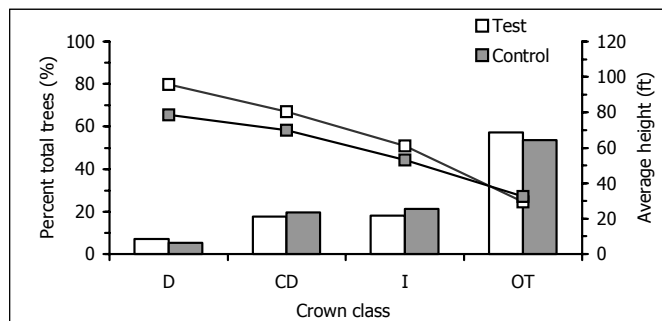


Figure 2.—Percent trees and average height (ft) by crown class from 0.1 ac. permanent plots, Control and Test sites.

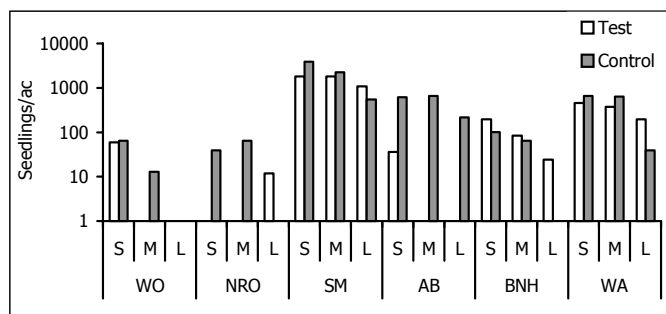


Figure 3.—Tree seedling/sprout size-class distribution for more abundant species from 0.1 ac permanent plots, Test and Control sites. Small = $<6''$ tall, Medium = $6''$ - $4'$ tall, Large = $>4'$ tall. Species codes: WO = white oak, NRP = northern red oak, SM = sugar maple, AB = American beech, BNH = bitternut hickory, WA = white ash. Note that the y-axis is $\log_{10}$ scale.

The diameter distribution of trees at both the control and test sites conformed to a reverse J-shaped curve that is typical of, but not unique to, mature second-growth and old growth forests (fig 1). The canopy structure of the two stands was very similar as well. In Figure 2 it can be seen that trees in the dominant crown class were fewer in numbers in the control stand as compared to those in the test stand, but had a greater average height (averaging 79 ft. in the control and 96 ft. in the test stand).

The initial regeneration density was fairly abundant at both sites (12,000 seedlings/acre in the control stand and 7,500 in the test stand). Most of the regeneration was shade tolerant species such as sugar maple and American beech. Oak regeneration was found at both sites, but in relatively small numbers, and only smaller-sized seedlings (fig. 3).

Tree species importance values represent a useful means for comparing forest ecosystems. As indicated in Table 2, sugar maple was the dominant species in both stands (being very dominant in the test stand). At the control site, American beech was well represented, followed by yellow-poplar and red

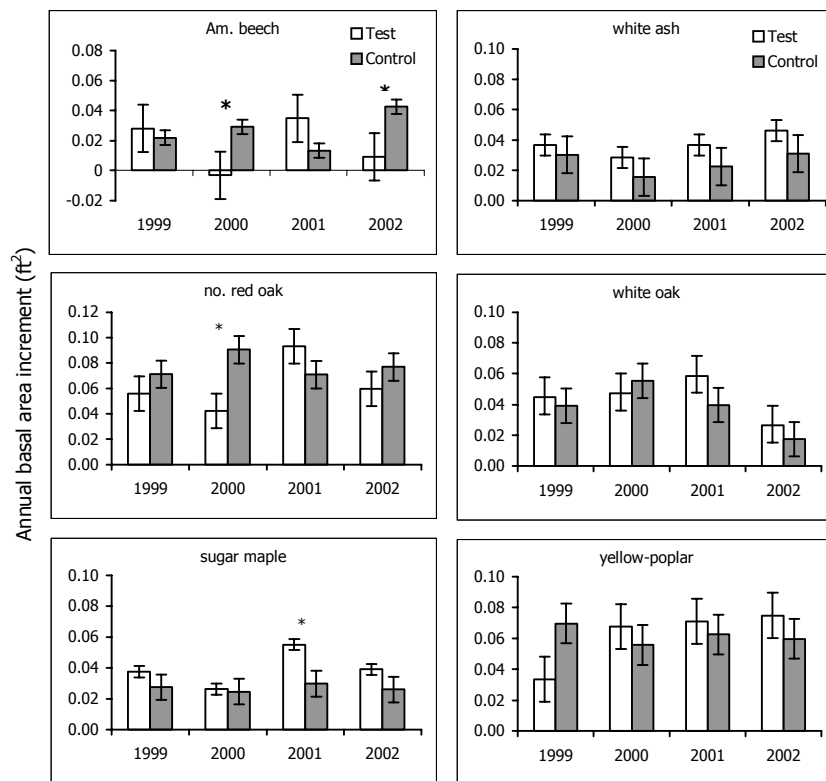


Figure 4.—Mean basal area increment (ft²), 1999-2002, for six tree species (dbh $\geq$ 16 in. dbh) for Test and Control sites. Means within years that are significantly different ($\alpha = 0.05$) are indicated by an asterisk.

and white oaks, while at the test site, the importance values fell off dramatically after sugar maple, with red oak ranked in the top 5 species, as well as shagbark hickory, slippery elm and white ash.

The test and control sites were comparable to the other old growth stands in Belmont County (Hicks and Holt 1999; Lafer and Wistendahl 1970). For example, the same species were represented in the overstory of Dysart Woods as in the test and control stands, with the exception of black cherry at the test site and bigtooth aspen and chestnut oak at the control site. In the test and control stands, as well as in other old growth stands, sugar maple had the highest importance value of any species. Dysart Woods had a larger average diameter, somewhat higher basal area and a greater proportion of white oak in the canopy than the test and control stands. But in spite of these differences, the test and control stands were comparable to each other and to nearby old growth remnants.

Ecosystem Changes (1999-2002)

As stated previously, radial growth is considered a good indicator of tree response to environmental stress. Since the underground mining activity occurred beneath the test site in the late winter of 2001, the growing season of 2002 was the first opportunity to look for mining-induced stress. We used the basal area increment (BAI) of the population of large trees (>16 inches dbh) to see if an effect of mining could be detected. We separated them by species. Six species contained sufficient trees to make statistically viable comparisons. Summary results of ANOVA for BAI and vigor class change are given in Tables 3 and 4.

In Table 5 the least-squares comparisons that were made between the main effects site (test and control) and years show that 4 comparisons were significant at the 5 percent level. These include the test vs. control in 2001, the test 1999 vs. the test 2001, the test 2000 vs. the test 2001 and the test 2001 vs. the test 2002. The test vs. control in 2002 (the post-mining year) was not significant. On

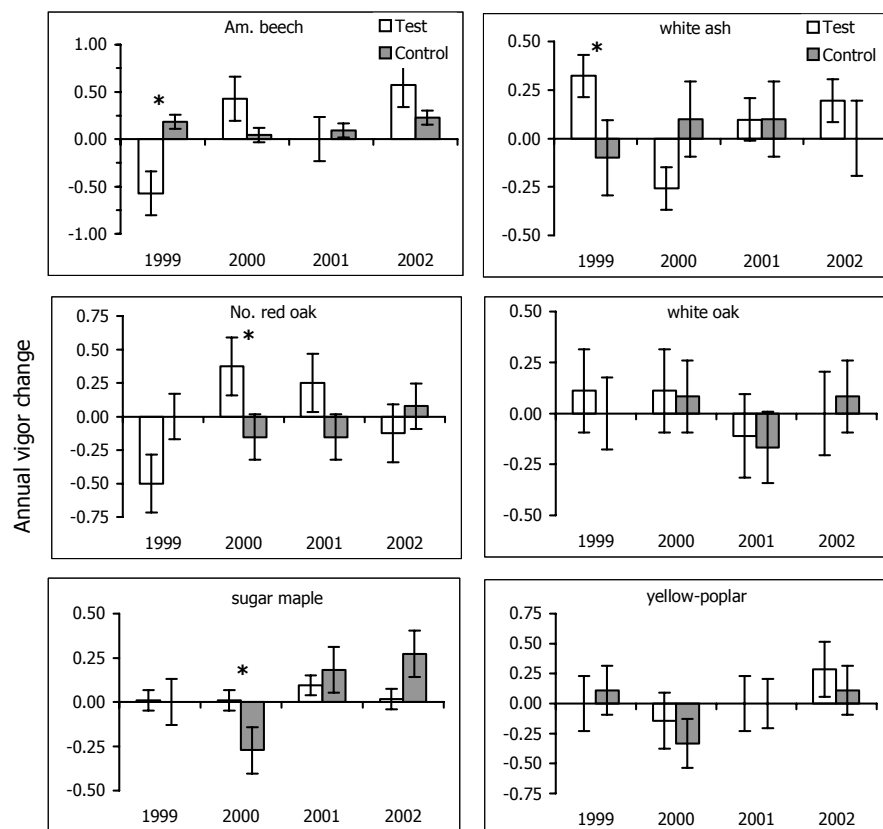


Figure 5.—Mean vigor change, 1999-2002, for six tree species (dbh ≥ 16 in.) for Test and Control sites. Vigor rating 1 = healthy crown with few dead branches, 7 = tree dead. A positive vigor change indicates a decline in vigor. Means within years that are significantly different ($\alpha = 0.05$) are indicated by an asterisk.

closer inspection, the reason for all these significant differences appears to be due to the fact that the BAI of the trees at the test site was unusually high in 2001 (the year immediately preceding the undermining of that site). In Table 5, it can be seen that the average BAI for large trees at the test and control sites was approximately 0.04 ft² per year, except in 2001 for the test site, when it was almost 0.06 ft². Since 2001 was a pre-mining year, this would not constitute an effect of mining. The significant interaction that was detected between site, species and year is somewhat more complex in its interpretation. In Figure 4 it can be seen that American beech, the most abundant species in the large tree population at the control site, had somewhat erratic growth, being very high in 2000 and 2002, and low in 2001. Sugar maple, the most abundant species at the test site showed a spike in growth in 2001 at that site. The rapid growth of this species at the test site in 2001 also partially explains the significantly higher overall increment of large trees at the test site in 2001.

Regarding average vigor ratings for trees in the large-tree sample, no significant differences occurred after mining, either with regard to site or year (fig. 5, table 6). There were a few instances in years prior to mining that the difference in average vigor rating of trees of some species was found to be significantly different at one site compared to the other. This was the case for red oak and sugar maple in 2000 (pre-mining). In both cases, the test site trees showed a significant positive difference (reduction in vigor) compared to those at the control site. This was also the case for white ash in 1999 (pre-mining), but the reverse was true for American beech in 1999 (pre-mining), where the trees at the test site actually were rated lower (increase in vigor), compared to those at the control site. The pre-mining vigor changes at the two sites probably represent random fluctuations, or the effect of observers, since vigor rating is a subjective value. Since there were no significant changes in vigor at either site in

Table 1.- Summary data for 0.1 acre sample plots, Control and Test Sites.

Parameter	Control	Test
SAF Cover Type (% total)		
Type 27	20	93
Type 28	7	0
Type 52	13	7
Type 53	13	0
Type 59	13	0
Type 60	33	0
Basal area (0.1 ac. plots, ft ² /ac.)	84.00 ± 7.5	84.95 ± 9.4
Basal area (BAF - 10)	115	95
Stem density (TPA)	210	255
Seedling density (stems/ac.)	12,119	7486
Species diversity (<i>H'</i> , Shannon-Weiner)	2.38	1.86
Species evenness (<i>E</i>)	0.781	0.701
Species richness (trees, ≥ 2 in. DBH)	21	14
Slope percent (% average)	36.6	26.1
Slope position (% total)		
ridge	0	18.8
upper slope	0	18.8
lower slope	86.7	62.5
bottom/hollow	13.3	0
Aspect class (% total)		
North	0	43.8
Northeast	0	25
East	0	18.8
Southeast	6.7	0
South	6.7	12.5
Southwest	33.3	0
West	40	0
Northwest	13.3	0

Table 2.- Species importance values (IV) for all trees ≥ 2 in. dbh. IV = (RBA/ac+RF+RA)/3.

Species	Test	Control
white oak	5.4	13.4
no.red oak	6.0	8.3
black oak	2.8	0.5
scarlet oak	--	1.2
chestnut oak	--	1.1
sugar maple	50.6	22.6
red maple	--	5.1
Am. beech	3.3	19.8
shagbark hickory	7.6	1.0
black cherry	2.2	3.8
yellow poplar	1.0	7.2
white ash	7.5	0.5
bigtooth aspen	--	4.3
black walnut	0.6	0.6
black gum	1.1	3.4
dogwood	--	2
e. hophornbeam	--	2.8
slippery elm	7.5	1.0
hackberry	1.9	--
bird cherry	1.9	--
pignut hickory	--	0.5
musclewood	--	0.6
mockernut hickory	--	0.5
Am. elm	1.2	
Totals	100.0	100.0

the post-mining period, this can be interpreted to indicate that there was no detectable effect of mining on tree vigor rating to date. Another way of looking at vigor ratings is to observe what proportion of the species increased, decreased or remained unchanged in vigor. Regarding the six species that were compared in prior analyses as to their vigor ratings, at the test site in 2002 one species (17%) remained unchanged in 2002 compared to 2001, one species (17%) improved in vigor and the remaining four species (66%) declined in vigor. Species at the control site were similar, with one species (17%) showing no change and five species (83%) showing a decline in vigor rating for 2002. These declines in vigor could be related to natural phenomena, such as the drought of 1999.

Tree mortality is another measure of health (Elliott and Swank 1994). The annual mortality rate estimated for old growth forests often ranges from 1% to 2% per year. The mortality rates observed in our large tree sample were below 1% at both sites (table 7). The average annual mortality rate for the test site was 0.77%, whereas the rate for the control site averaged 0.41% per year. Interestingly, about 70% of the mortality at the test site occurred in 1999 after the severe summer drought of that year and only one tree died at the test site in 2002, following mining.

Data from the 0.1-acre fixed-area plots provided useful information, especially regarding trees in the lower canopy positions (understory). Results from our fixed-area plots for radial and basal area growth of understory trees is summarized in Table 8. Sugar maple, a very shade tolerant species, dominated the understory of both sites, and because of low numbers of other species, sugar maple appears to be the only species that provides a legitimate comparison between the understory response of the two sites. Basal area growth of understory sugar maples at both sites was extremely slow, owing to the limited resources in the understory and the small size of the trees. At the control site, the average annual growth per understory sugar maple was 0.0015 square feet over the four years whereas understory sugar maples at the test site averaged 0.004 square feet per tree per year. In 2002, the post-mining year,

Table 3.- Analysis of annual basal area increment for trees ≥ 16 in. dbh, 1999-2002, by site and by species.

Factor	df	SS	MS	F	p
Site	1	0.0002	0.0002	0.12	0.726
Year	3	0.0067	0.0023	1.50	0.213
Species	5	0.1528	0.0306	20.40	<0.001
Site x Year	3	0.0162	0.0054	3.61	0.013
Site x Year x Species	35	0.0791	0.0023	1.51	0.030

Table 4.- Analysis of annual vigor change for trees ≥ 16 in. dbh, 1999-2002, by site and by species.

Factor	df	SS	MS	F	p
Site	1	0.1167	0.11666	0.31	0.577
Year	3	2.6072	0.86905	2.32	0.074
Species	5	1.2250	0.24499	0.65	0.659
Site x Year	3	1.7860	0.59532	1.59	0.190
Site x Year x Species	35	20.1076	0.57450	1.53	0.025

Table 5.- Least squares means of annual basal area increment (ft^2) for site x year interaction for trees ≥ 16 in. dbh, and p-values for least square means comparison for site x year interaction. The first letter indicates C=Control or T=Test, and the final four digits indicates year. Values less than 0.05 indicate that basal area increment values are significantly different ($\alpha=0.05$)

Site	BAI (ft^2)	C-1999	C-2000	C-2001	C-2002	T-1999	T-2000	T-2001
		0.043	0.045	0.040	0.042	0.039	0.035	0.058
C-2000	0.045	0.754						
C-2001	0.040	0.554	0.365					
C-2002	0.042	0.863	0.627	0.675				
T-1999	0.039	0.548	0.374	0.956	0.655			
T-2000	0.035	0.195	0.113	0.452	0.255	0.516		
T-2001	0.058	0.022	0.045	0.005	0.014	0.007	0.001	
T-2002	0.043	0.914	0.691	0.662	0.959	0.646	0.268	0.025

Table 6.- Least squares means of annual vigor change for site x year interaction for trees ≥ 16 in. dbh.

Year	Control	Test
1999	0.03	-0.10
2000	-0.09	0.09
2001	0.01	0.06
2002	0.13	0.16

understory sugar maples at the test site grew at a rate of 0.005 square feet per tree, while understory sugar maples at the control site also exceeded their four-year average and grew at a rate of 0.004 square feet.

With regard to vigor rating for the understory trees, the results are also displayed in Table 8. Here it can be seen that in 2002, the post-mining year, 67% of the species at the control site showed declining vigor (a higher number for vigor rating) while only 43% of the species at the test site showed declining vigor. Sugar maple, the most abundant species, did show a greater increase in vigor rating (a larger decline in vigor) at the test site than at the control after mining. However, understory trees are not

Table 7.- Annual mortality for all trees, by sample unit, site, and year.

Sampling unit	1999	2000	2001	2002	Average %
<i>0.1 acre plots</i>					
Test (N ₁₉₉₉ = 272)	2	1	2	2	0.64
Control (N ₁₉₉₉ = 327)	0	15*	3	8**	1.99
<i>Large tree sample (dbh ≥ 16 in)</i>					
Test (N ₁₉₉₉ = 226)	5	1	0	1	0.77
Control (N ₁₉₉₉ = 183)	0	2	1	0	0.41

*12 of these were overtopped trees (primarily maples, dogwood, and hophornbeam).

**6 of these were overtopped trees (primarily maples, dogwood, and hophornbeam).

Table 8.- Mean basal area increment (ft²), and mean vigor change for more abundant understory (overtopped) tree species in 0.1 ac. fixed area plots, Test and Control sites.

	Species	N	Basal area increment (ft ²)				Vigor change			
			1999	2000	2001	2002	1999	2000	2001	2002
Control	white oak	11	-0.004	0.005	-0.001	0.000	-0.1	0.1	0.0	0.0
	northern red oak	6	0.000	0.003	0.001	0.002	0.0	0.1	0.0	0.1
	scarlet oak	4	-0.001	0.003	0.001	0.000	0.0	0.1	0.0	0.0
	sugar maple	69	-0.001	0.004	-0.001	0.004	0.0	0.1	0.0	0.1
	red maple	11	0.008	0.003	0.000	0.005	0.5	0.0	0.0	0.1
	Am. Beech	35	0.000	0.004	0.001	0.001	0.0	0.1	0.1	0.0
	black cherry	4	0.004	-0.003	-0.003	0.000	0.1	-0.1	-0.1	0.0
	yellow-poplar	5	-0.006	-0.001	0.001	0.009	-0.2	0.0	0.0	0.2
	blackgum	6	0.000	0.000	-0.005	0.001	0.0	0.0	-0.1	0.0
	dogwood	6	-0.004	0.001	0.010	0.002	-0.1	0.0	1.0	0.1
	hophornbeam	9	0.000	0.004	0.001	0.009	0.0	0.1	0.0	0.4
Test	sugar maple	144	0.002	0.006	0.003	0.005	-0.3	0.3	0.0	0.7
	shag. Hickory	7	-0.005	0.009	0.002	0.002	0.2	-0.7	0.3	1.0
	hackberry	4	-0.002	0.005	-0.003	-0.001	-0.3	1.0	0.0	0.0

good subjects for assessing mining-related impacts since they are exposed to competition from overtopping trees, which probably overwhelms other potential impacts.

Mortality of trees in the 0.1-acre plots (including understory trees) is presented in Table 7. Note that trees at the control site showed a higher rate of mortality than those at the test site (1.99% compared to 0.64%). In 2002 the mortality rate for trees in the 0.1-acre plots at the control site was above the 4-year average at 2.4%, while the mortality rate at the test site was just above its 4-year average at 0.73%. These results seem to corroborate the results from the large tree sample, that being that no detectable effect of mining on tree health was apparent.

Regarding seasonal diameter growth for the intensively monitored trees, a plotting of cumulative growth for each sample tree over the term of the study was prepared. These are shown in Figure 6. When slope values for the four growing seasons were compared, the effects of species and year were highly significant ($p < 0.0001$), as was the interaction of species-site-year ($p = 0.033$). The significance of year as an effect can be attributed to annual variations in climatic conditions (fig.7). For example, using Ohio weather data, precipitation during the 1999 growing season (May-September) totaled 13.5 cm; totals for 2000 and 2001 were 20.0 and 20.1 cm, respectively. The Palmer Drought Severity Index (PDSI) during the 1999 growing season averaged -2.5, a value that is slightly above the threshold for severe drought (-3.0). In contrast, PDSI for the 2000 and 2001 growing seasons averaged 0.76, slightly above normal.

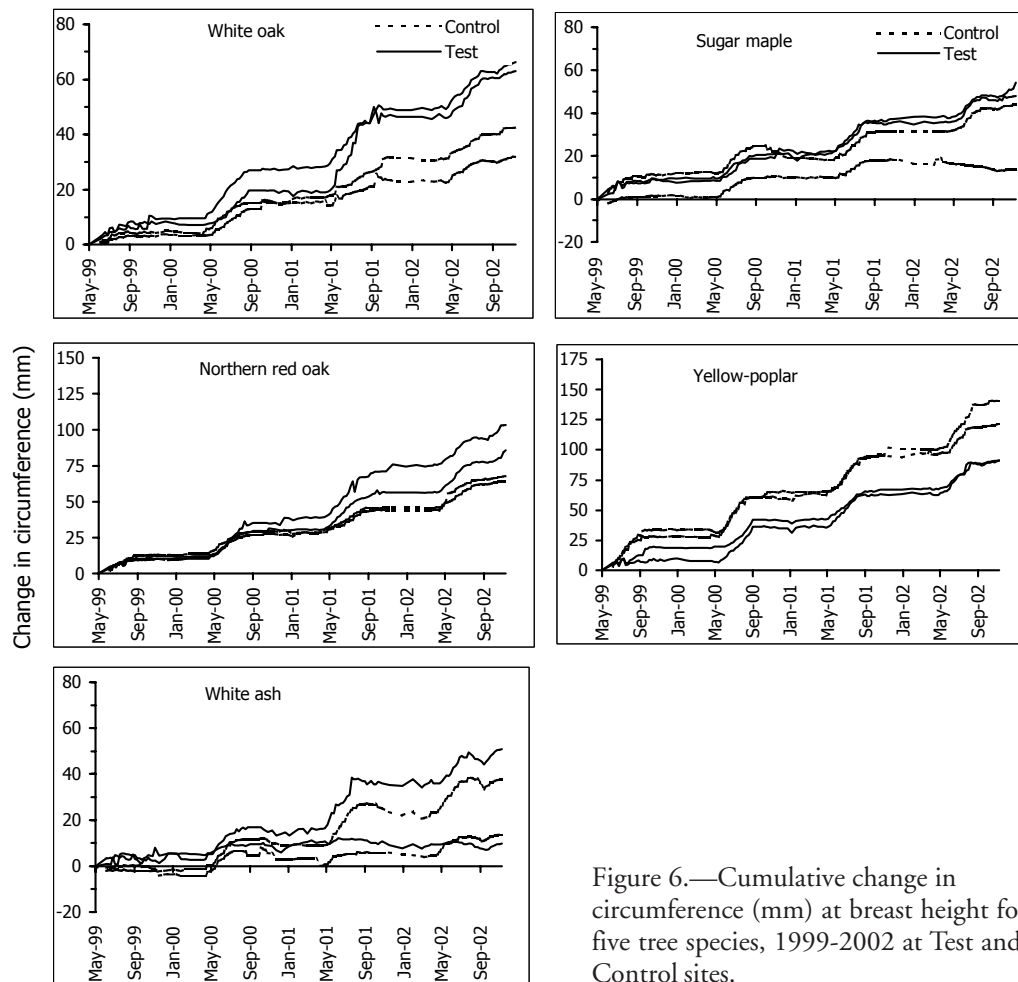


Figure 6.—Cumulative change in circumference (mm) at breast height for five tree species, 1999-2002 at Test and Control sites.

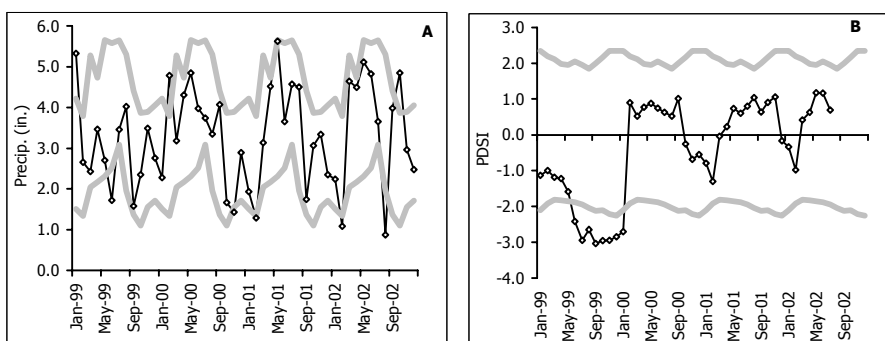


Figure 7.—Monthly precipitation (A) and Palmer Drought Severity Index (B), 1999-2002, Climate District 12, Ohio. Gray lines indicate + 1 Stdev. From 100 year mean.

The significant effect of species on rate of radial growth was also expected. The five species examined in this study represent a spectrum of adaptation ranging from species typically associated with mesic habitats (sugar maple and yellow-poplar), a drought tolerant species generally associated with more xeric sites (white oak), as well as two species with wider amplitude (northern red oak and white ash) (Burns and Honkala 1990). Life history strategies of the species present another gradient, ranging from fast growing and opportunistic species such as yellow-poplar and northern red oak to more conservative species such as white oak and sugar maple (Bormann and Likens 1979, Burns and Honkala 1990). The combination of habitat preference and life history strategies resulted in distinct growth responses for the five species over the four sample years. These growth differences are reflected in slopes of mean growing season growth trend, following the order, from greatest to smallest: yellow-poplar > northern red oak > white oak, sugar maple, and white ash.

Over the four-year period, the effects of site and the interaction of site and year yielded no statistically significant differences ($p > 0.05$). The absence of a site effect, in part, corroborates the initial selection of study site locations. The fact that the interaction of site and year was non-significant suggests that mining under the test site during the winter of 2001 did not result in detectable significant changes in overall growth trends when compared to the previous years. These findings are similar to those obtained by Runkle (1993) from a single-point-in-time study.

Conclusions

This study used a BACIP design to investigate the impact of longwall mining on a mature forest ecosystem. Because tree growth is a function of the environment they are exposed to, an effort was made to study the growth processes that could be affected by mining.

Two sites were selected that supported mature forests with a species composition similar to nearby old-growth forests. The radial growth of trees in the dominant canopy was used as a primary measure of the trees' response to changes brought about by mining. The study was conducted over a period of four growing seasons, three prior to mining under the test site and one after mining.

The trees responded to the drought in 1999 by showing a generally reduced radial growth at both sites. Tree responses did not appear to be associated with mining, since the growth, vigor and mortality of trees at the test site did not change appreciably relative to the control site in 2002, the post-mining year. Based on the results of this well documented and controlled study, longwall mining under the conditions tested had no discernable effect on the health of the forest or trees above the mine after one year. The BACIP design is a practical approach for studies of this type and continuation of the monitoring for several post-mining years will provide a more definitive answer regarding the impact of longwall mining on maturing forests.

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