COMPARISON OF SOIL PRODUCTIVITY IN A COMMERCIAL PINE PLANTATION VERSUS AN OLD-GROWTH PINE FOREST

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Abstract

Commercial pine plantations differ from old-growth pine forests in terms of species richness and understory productivity. This study compares two communities: a pine plantation and a pine forest at the University of Michigan Biological Station (UMBS). We examined species richness, depth of organic matter (OM), total bulk density, moisture content, pH and conductivity by soil horizon (A and E), as well as light availability to undergrowth. Lab analyses involved total macronutrient composition and carbon content of the soil horizons. Initial description of a deeper A soil horizon in the old-growth forest suggests greater detritus decomposition and nutrient bioavailability to in the undergrowth community. Our findings indicate that: 1) the richness and diversity of tree seedling and sapling species in the old-growth forest is greater than the pine plantation; 2) phosphorous and nitrogen macronutrient levels are higher in the old-growth forest than the pine plantation; 3) the measured pH is higher in the old-growth indicating lower soil acidity; 4) the OM horizon of the pine plantation is deeper than the old-growth forest and; 5) and E horizon soil in the old-growth has higher carbon content than the pine plantation. Our results present possibilities for further experiments comparing effects on soil productivity by herbaceous species, mono- and polyculture systems, and effects of secondary successional species on unproductive soils. Forestry management implications for the pine plantation would be to leave branch trimmings while harvesting trees to promote understory restoration as found in the old-growth, which had significantly more productivity and diversity.

1. Introduction

Soil productivity is the ability of soil to provide water and nutrients to plants (US Forest Service, 2015). Crucial macronutrients found in soil include nitrogen, potassium, and phosphorus. These nutrients have been found to be more important in the understory community for species richness and biomass than intraspecific competition between those understory species (Crutsinger, 2013). Macronutrients are cycled into the soil as dead plants become organic matter (OM). Forest harvesting removes OM, consequently removing nutrients, and possibly leading to a lower soil productivity (Mack, 2014). Acidity is also a known variable of productivity. Both sites consist of pine forests, which have naturally more acidic soils from pine needle decomposition (Nevel et al., 2014).

Decomposition of detritus makes necessary carbon available from the soil to understory growth. A carbon to nitrogen ratio of 10:1 is ideal for decay. During decomposition, nitrogen can be a limiting factor. When there is excess carbon, the soil can be robbed of nitrogen (Washington State University, 2015). Pine needles have a C:N ratio ranging from 60:1 to 110:1, meaning pine forest soil can be nutrient deprived and therefore decompose more slowly (Bielecki et al., 2006). The high density of trees as well as the lack of OM decomposition could cause the plantation to have higher levels of nitrogen robbing. We focused on soil ecology and distribution of tree seedlings and saplings in a commercial pine plantation versus an old-growth pine forest.

The study site is broadly defined as the property of the University of Michigan Biological Station (UMBS). The station was founded in 1909 after gifting to the University by local landowners. The property has been a center for undergraduate field courses since its conception and was established as part of the Man and Biosphere Programme in 1979. UMBS has been noted as the oldest research station of its kind, consistently producing unique projects and data (Heinen and Vande Kopple, 2003). The station consists of roughly 11,000 acres of land, ranging from wetlands, stream systems, prairies, to native forests (Heinen, 2015). This property is effective for research of successional communities due to a property-wide cut and burn at the turn of the century (Heinen and Vande Kopple, 2003).

The first site of data collection is a commercial red pine (*Pinus resinosa*) plantation, situated on Riggsville Road (Pellston, MI) on the UMBS property (45°33'07.3"N 84°44'54.1"W).

This plantation is similar to many Northern Michigan locales planted by the Civilian Conservation Corps in the 1930s, and the State of Michigan in the 1950s to replace abandoned farmland (Bielecki et al., 2006). Ecologically, the site is a young forest with early successional plants along with the red pines (Bielecki et al., 2006). The red pines are planted in rows with about 1.5 m between trees and 3 m between rows. The red pines are harvested using the bole-only technique, which takes away only the trunk and branches for processing. This method removes branches and subsequent OM that would decompose in the forest ecosystem and increase productivity (FPANS, 2015).

The old-growth forest that was analyzed in this study is located on Douglas Lake Road in Pellston, MI (45°34'22.8"N 84°44'26.9"W). This area, like most of the property owned by UMBS, was cut and burned during the nineteenth and early twentieth centuries and has since transitioned into a second-growth conifer forest (Heinen and Vande Kopple, 2003; Gates, 1985). The forest is noticeably different from the pine plantation in known species of trees and also understory growth.

Our variables measured tree species diversity in the undergrowth, soil properties, and nutrient content. For the comparison of the plantation and old-growth forest, we propose that: 1) there will be a greater abundance and diversity of tree seedling and sapling species in the old-growth forest; 2) there will be a greater abundance of macronutrients that include phosphorus, nitrogen, and potassium in the A and E horizons of the old-growth forest; 3) there will be a less acidic pH in the A and E soil horizons of the old-growth forest; 4) the depth of OM will be less in the old-growth forest versus the plantation due to pine duff decomposition; and 5) there will be a greater abundance of carbon in the A and E soil horizons of the old-growth forest versus the plantation (Lebron et al., 2012).

2. Materials and Methods

Equipment used in the study included 100 and 50 m transect tapes, 1 m^2 quadrats, marking flags, a diameter at breast height (DBH) tape measure in cm, a soil core sampler, whirl packs, a lux meter and a soil auger. We collected undergrowth data from the plantation and old-growth forest. For both sites, we set up 80 m transects east to west with three 50 m transects that intersected at

0, 40, and 80 m running north to south. For each of these 50 m transects, we counted the total number of individuals and species of different tree seedlings found in alternating $1m^2$ plots. We measured the depth of the OM for each 1 m^2 plot. We also recorded number of individual tree saplings within 2 m of each 50 m transect. For general comparison, trees with a DBH greater than 4 cm were averaged across one of the 50 meter transects.

Soil samples were collected for multi-variable measurements. One soil core of roughly 200 mL was collected and sifted from each site and kept field-moist to calculate bulk density. A and E soil horizons were sampled at ten different locations along the perimeter of the transect grid with a soil auger. The horizons were separated to test for macronutrients (nitrate, phosphate, ammonium) and carbon content. About 60 g of each horizon was kept field-moist for moisture, pH, and conductivity measurements. Each soil core was sifted through a 2 mm sieve after field collection.

To calculate moisture and bulk density, each sample was dried in an oven for 24 hours at 60°C. bulk density was determined by dividing the mass of dried soil (g) by the volume of moist soil (ml). To calculate the moisture content of the soil, we used a formula for calculating soil moisture: $\frac{g\ H_20}{g\ wet\ soil} = \frac{m_{wet}-m_{dry}}{m_{wet}}$, where $\boldsymbol{m}$ = mass of our 200 mL soil with variability of wet and dry. One sample from both the A and E horizons were divided into .2 g to test for phosphate concentration, 5 g to test for nitrate and ammonium concentrations, and 1 g was oven dried and ball-milled in a Spex Sampleprep 80000 Mixer/Mill for one minute to test for percent carbon. The milled samples were then weighed to roughly 20 µg for the E horizon samples and 5 µg for the A horizon samples, "crimped", and analyzed for percent carbon. A Fisher-Scientific AP110 pH meter was used to measure the pH of the A and E horizons from both sites. The pH test was prepared by mixing 20 g of each soil horizon with 20 mL of deionized water for 20 minutes. A similar solution of 1:1 deionized water and soil from each horizon sample was used to measure conductivity with a YSI Model # 30-50FT meter. Sites were in relatively close proximity, which allowed us to regard climate as a constant variable. The amount of sunlight was measured with a lux meter and calculated as a mean value of availability.

The Shannon-Weiner Index was used to test species richness between the two sites. The formula used to calculate this is $H =- \Sigma[(p_i) * ln(p_i)]$, where: $\mathbf{p}_i$ = proportion of total sample represented by species *i* (Shannon-Wiener Diversity Index, 2015). To test for significant difference in depth of OM, macronutrients, and carbon content between the sites, we performed an independent samples t-test.

3. Results

When comparing the tree species in the understory, the plantation consisted of red maple (*Acer rubrum*) seedlings and white pine (*Pinus strobus*) seedlings. The dominant herbaceous species in the plantation consisted of bracken fern (*Pteridium pubescens*), American wintergreen *(Gaultheria procumbens)*, and shadbush serviceberry (*Amelanchier sp.*). The tree species found in the old-growth forest include white birch (*Betula papyrifera*), white pine (*Pinus strobus*), and beech (*Fagus grandifolia*). Herbaceous plant species in the old-growth forest included American wintergreen *(Gaultheria procumbens)*, lowbush blueberry (*Vaccinium angustifolium*), bracken fern (*Pteridium pubescens*), and several species of lilies and orchids.

By using the Shannon-Weiner Index, we found the plantation to have an index of 0.9552 and the old-growth forest to have an index of 1.4700 (Table 1.). The values of the index usually range from 1.5 to 3.5 with higher values indicating greater species richness. This index indicates that the old-growth forest has more richness of species. Since we only used understory tree seedling in the calculation, the values are on the lower range of the index. We calculated effective number of species (ENS) using values of species richness from the above index. The plantation has an ENS of 2.5991 and the old-growth forest has an ENS of 4.2492, which means that the old-growth had over 1.6 times more richness of species.

Lab analyses resulted in many significant differences between soil properties given in Table 1. below. The mean nitrate level in the combined A and E horizons in the plantation is 18.195 ug N/L and the mean nitrate level in the old-growth is 23.6842 ug N/L (Table 1.). An independent samples t-test of nitrate levels had a p-value of 0.051, therefore significant at the 0.05 alpha level. The mean phosphate level in the combined A and E horizons in the plantation is 42.5850 ug P/L and the level for the old-growth forest is 53.9300 ug P/L (Table 1.). An independent samples t-test of phosphate levels had a p-value of 0.004, therefore significant at the 0.01 alpha level.

Table 1. Summary of data from pine plantation and old-growth forest comparing species richness, soil properties, and environmental conditions

	Plantation	**Old-Growth**
Average Pine DBH	25.41 cm	31.92 cm
Mean OM Depth	4.20 cm	3.25 cm
Bulk Density	0.915 g/mL	0.648 g/mL
Moisture Content	Horizon A: 0.249 g H_20/ g wet soil Horizon E: 0.078 g H_20/ g wet soil Mean: 0.1635 g H_20/ g wet soil	Horizon A: 0.364 g H_20/ g wet soil Horizon E: 0.105 g H_20/ g wet soil Mean: 0.2345 g H_20/ g wet soil
pH	Horizon A: 3.65 Horizon E: 3.72 Mean: 3.685	Horizon A: 3.74 Horizon E: 3.89 Mean: 3.815
Conductivity	Horizon A: 32.3 uS/cm Horizon E: 19 uS/cm Mean: 25.65 uS/cm	Horizon A: 29.1 uS/cm Horizon E: 25.6 uS/cm Mean: 27.35 uS/cm
Light Availability (in Luxes)	1033 lx	885 lx
Total Number Species Found in Undergrowth	7 species	8 species
Total Number of Individuals Found in Undergrowth	282	197
Shannon-Weiner Index	0.9552	1.4700
Effective Number of Species	2.5991 species	4.2492 species
Mean Nitrate Levels (A + E Horizons)	18.1895 ug N/L	23.6842 ug N/L
Mean Phosphate Levels (A + E Horizons)	42.5850 ug P/L	58.9300 ug P/L
Mean Ammonium Levels (A + E Horizons)	306.8947 ug N/L	543.5789 ug N/L
Mean Carbon Content (A + E Horizons)	Horizons A+E: 0.0897 % Horizon E: 0.0138 %	Horizons A+E: 0.1555 % Horizon E: 0.0315 %

The mean ammonium levels in the combined A and E horizons in the plantation is 306.8947 ug N/L and the level for the old-growth is 543.5789 ug N/L (Table 1.). An independent samples t-test of ammonium levels had a p-value of 0.000, therefore significant at the 0.001 alpha level. When testing for conductivity, which suggests ions including potassium, calcium, and magnesium, the A horizon of the plantation had a higher measurement, but the E horizon of the old-growth had higher conductivity (Table 1.). There were no sizeable differences in pH between the sites (Table 1.), but both are quite acidic. These were direct readings that may be a result of pine duff acidity in both soil types.

The mean OM depth is 4.20 cm for the pine plantation and 3.25 cm for the old-growth forest (Table 1.). An independent samples t-test of OM depth had a p-value of 0.000, therefore significant at the 0.001 alpha level. The mean carbon content of soil is 0.0897 % for the plantation and 0.1555 % for the old-growth forest (Table 1.). An independent samples t-test for carbon content in the A and E horizons had a p-value of .193, which is not significant at the 0.05 alpha level. An independent samples t-test of carbon content in the E horizons had a p-value of 0.015, therefore significant at the .05 alpha level.

4. Discussion and Conclusion

Species richness in plant communities is important. All plants fulfill a similar niche requiring water, soil nutrients, sunlight, and carbon dioxide, but when a plant dies, another must take its place. Heterogeneity of niches and abiotic environments ensure that either an individual of the same species or a different species could fill an open niche (Grubbs, 1977). The number of unique species found at each site is very close, with 7 species at the plantation and 8 at the old-growth. After calculating the distribution of the species with the Shannon-Weiner Index, the effective number of species is almost double in the old-growth (Jost, 2015). This supports our hypothesis that the old-growth would have greater species diversity. This diversity in the old-growth could be attributed to the more favorable soil conditions, such as OM and macronutrient content, moisture, and bulk density.

The deeper horizon of OM in the plantation supports our hypothesis that pine duff decomposition is slower in the plantation compared to the old-growth forest. This is possibly a result of lower decomposition rates of fallen debris and lack of fallen debris that is characteristic of monoculture forests (Heinen, 2015). The lower decomposition rates of monoculture forests can be compared to tropical polyculture forests with more species richness and faster nutrient cycling, which result in less OM and a deeper A horizon (Lebron et al., 2012). In a study of soil nitrate cycling between a mature coniferous forest and a ten year old conifer plantation, it was found that the mature coniferous forest had a 2-3 times higher gross mineralization rate than the ten year old conifer plantation (Davidson et al., 1992). This is consistent with our results because the old-growth forest we studied had a smaller horizon of pine duff (OM), which is indicative of higher decomposition rates.

Bulk density is the weight of soil in a given volume. It is important to measure because higher bulk density suggests sandier soil with high nutrient leaching from the A horizon. Bulk density tends to increase with sand compaction as well as with depth, and when above 1.6 g/mL, root growth can be restricted. The plantation's soil had a much higher bulk density, indicating sandier soil, which is consistent with the lower nutrient and moisture content that our results confirm (Brown, 2015).

We found that the old-growth forest had moister soil. The moisture content of the old-growth is 0.2345 g H_20/ g wet soil versus 0.1635 g H_20/ g wet soil for the plantation (Table 1.). Higher moisture content in the old-growth soil positively correlates to our finding of higher concentrations of macronutrients in the old-growth. Higher moisture levels increases the rate of OM decomposition which releases more macronutrients like N, P, and S (Certified Crop Advisor Study Resources-Northeast Region, 2010).

Our lower sunlight reading of 885 lx in the old-growth forest versus 1033 lx in the plantation can be attributed to the lower density of canopy cover in pine plantations that are planted evenly and spaced out (Table 1.). The high density of trees may also indicate that the plantation has reached or overreached carrying capacity, limiting further growth in the community.

Our second hypothesis stated that there will be a greater abundance of macronutrients (phosphorus, nitrogen, and potassium) in the A and E horizons of the old-growth forest. The results on macronutrient deposits in both forests showed little significance for separate soil horizons, therefore we predicted that because of soil moisture and leaching, a statistical test of variables in the A and E horizons combined would yield more powerful comparisons.

The Law of the Minimum states that yield of plant growth is proportional to amount of most limiting nutrient (Barak, 1999). Nitrogen, potassium, and phosphorus are considered primary nutrients because they are most likely to be limiting. The old-growth has a higher content of all these primary nutrients than the plantation. The main input of macronutrients is always the decomposition of organic matter (Barak, 1999). In the plantation, the trees are removed and not left to decay, leading to nutrient deficiencies.

Nitrogen can be taken up as nitrate (anion) or ammonium (cation). The plant preference for which nitrogen compound used is species and pH dependant. Soils were found to be generally acidic with a pH of 3.685 at the plantation and a pH of 3.815 at the old-growth (Table 1.). This indicates that ammonium would be prefered over nitrate by plants (Barak, 1999). The amount of ammonium found cycling in the soil is much higher than nitrate, supporting plants preference of ammonium. The biological functions of nitrogen include protein substituents, RNA/DNA base pairs, and hormones. The source of nitrogen is mainly from the decomposition of organic matter, but also from atmospheric fixation and rainfall. Phosphorus is another macronutrient that we tested for. Its main biological function is to make up ATP (Barak, 1999). The old-growth had a higher amount of phosphorous with an average of 58.9300 ug P/L compared to the plantation's average of 42.5850 ug P/L (Table 1.). When testing for conductivity, we were testing for potassium and other micronutrient cation content. The plantation had a higher A horizon conductivity and the E horizon of the old-growth had a higher conductivity than the plantation. The means were 25.65 uS/cm for the plantation and 27.35 uS/cm for the old-growth (Table 1.). Conductivity was analyzed as a universal measurement of ion abundance in soil. Potassium is usually not leached from the A horizon like other nutrients, which could explain why the A horizons tend to have higher conductivity. It is considered the "universal cation" of biological systems as a macronutrient (Barak, 1999). Calcium, another nutrient indicated by conductivity, is a secondary nutrient that acts as a structural element in the cell walls of roots and shoots. Unlike Potassium, it can be removed by leaching (Barak, 1999). Fertilizers are often added to plantations to correct for limiting macronutrients or low cycling of secondary nutrients (Barak, 1999). We are not certain whether or not fertilizers were added to the plantation, but if they were, this could be the explanation for the similar conductivity readings between the two sites.

Our pH measurements led us to accept our third hypothesis that there would be a less acidic pH in the old-growth. Although the acidity is slightly lower in the old-growth, the difference was proven to be statistically insignificant. This reading of a lower pH in both the A and E horizons of the plantation is attributed to the less diverse OM decomposing. Strictly pine needle OM has a much higher acidity in plant compounds over other species (Heinen, 2015). This variable may not be a reliable source for soil productivity because both the plantation and old-growth forests have a pH far below the normal range of 6.5 for soils (Barak, 1999).

Our results indicate a significant difference in carbon content between only the E horizons of study sites. The carbon content in the E horizon of the old-growth site was found to be significantly higher than the E horizon of the plantation. The difference in the E horizon carbon content is supported by the finding that soil carbon stocks decline by 13% when land is converted from a native forest to a plantation (Guo and Gifford, 2002). The difference in carbon content only found in the E horizon could be the result of carbon leaching from the A horizon to the E horizon. Another possibility for the insignificance may be the rapid growth of understory in the old-growth, which sequesters a large amount of carbon. In conclusion, the variables measured have provided compelling support for our hypotheses and have affirmed the greater productivity of a polyculture pine forest dominated by natural processes versus a commercially planted pine forest.

There were various processes that could have been sources of error. The area in the plantation that was sampled included a trail where vehicle disturbance was evident. In contrast, the old-growth sampling site was in an enclosed area of forest with minimal human disturbance. The trail through the plantation may have skewed data to include less richness than otherwise found in adjacent 1 m^2 plots off the trail. This also factored into OM depth calculations. It should be noted that an OM depth in the old-growth forest was not taken due to human error and this single data point was not used in our calculation. Plant misidentification also affected our analysis of species diversity. Some species like black cherry (*Prunus serotina*) and shadbush serviceberry (*Amelanchier sp.*) looked similar in appearance, especially at earlier stages of development.

For future studies, it would be interesting to see if herbaceous plant diversity would also relate to soil nutrient content. Another related experiment would be soil testing in a monoculture and polyculture to compare differences in nutrient cycling. Current forestry management implications from our results would be to leave branch trimmings to decompose in the plantation. This would stimulate more decomposition of detritus and increase soil productivity to restore the understory such as in the old-growth. For an agroecological experiment, the results found above could be applied to agricultural soil plots. Nutrient cycling of the polyculture old-growth in this study could be translated into a seed mix of secondary successional plants to be sprayed over unproductive agriculture plots to promote biomass growth and reestablish fertile and arable soils for future growing in cycles from agriculture to succession in soils.

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