Soil properties associated with frost pocket valleys and upland macroclimates on Martha’s Vineyard

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ABSTRACT

The frost pocket valleys on Martha’s Vineyard are characterized by scrub oak thickets with few tree oaks, while their associated upland macroclimate sites have many mature tree oak stands with some scrub oaks in the understory. This noticeable difference in vegetation structure is the driving force behind my study. I sought to understand if there were any differences in soil properties between the two study sites that could provide insight as to why there are fewer tree oaks growing in the frost pocket valleys. I performed many nutrient analyses (extractable ammonium and nitrate as well as total soil and leaf CHN) and looked at various soil hydraulic properties (field capacity and soil texture) in order to gain a better understanding of these two sites. Nutrient analysis did not provide any explanations for the difference in vegetation structure; however, I did see a significant difference between the soil textures of the two sites. The frost pocket soils were much sandier and coarser which has a variety of implications, one of which is that the trees in the frost pocket valleys have the potential to be drought stressed during dry periods when the soils may not be able to hold as much water.

Key words: frost pocket, upland macroclimate, soil properties, nutrients, texture, vegetation structure

INTRODUCTION

The scrub oak thickets on Martha’s Vineyard are uncommon throughout the northeastern United States and are of particular conservation interest (Motzkin et al. 2002). Scrub oaks are an early successional species and are to some extent maintained by early fall and late spring frosts. These frosts often damage more susceptible competing tree oak species (Swain and Kearsley 2001). There is a stark difference in vegetation structure between frost pocket microclimate sites and their corresponding upland macroclimate sites. Both sites have scrub oak in the understory, however, the frost pockets are dominated by the scrub oak with only a few tree oaks scattered throughout, while the upland macroclimate areas have mature tree oak stands and less scrub oak in the understory (Figure 1).

The frost pocket valleys have coarse soils which can be attributed to past glaciofluvial processes. While some have ascribed the origin of the valleys on Martha’s Vineyard to a large volume water that poured over the outwash plains due to forward motion of the Wisconsin ice
being balanced by melting (Woodsworth and Wigglesworth 1934), the morphology of the valleys argue against the possibility that the valleys were formed by runoff (Uchupi and Oldale 1994). Uchupi and Oldale (1994) suggest that the frost pocket valleys on Martha’s Vineyard were either eroded by groundwater seeps at the distal ends of outwash plain wedges or along the foreset surfaces of sandy deltas on a lake behind the glacial front. These proglacial lakes were formed during periodic readvances of the glacier and where characterized by high hydrostatic heads which forced the water table to rise. Due to the elevated water table and high pressure, groundwater was pushed through the permeable outwash sands, which formed groundwater seeps downslope. When the proglacial lakes drained, the water table dropped below the level of the valley floors which caused stream flow to terminate (Uchupi and Oldale 1994).

I am interested in the soil properties of these frost pocket microclimates and seek to understand any differences between the valley and upland sites. There have been studies on leaf phenology in microclimates (Aizen and Patterson 1995) as well as temperature and historical disturbances effects on vegetation (Motzkin et al. 2002); however, there are not many studies that have looked at soil properties. My main questions are 1) are the soil properties different between the uplands and valleys of the frost pockets and 2) if so, are the differences in soil properties the driving force behind the differences in vegetation structure in frost pocket valleys and the upland macroclimates?

**Study Sites**

I collected my field samples at four different sites on Martha’s Vineyard. Deep Bottom and Quampeche Bottom have an upland and valley site, while Pohoganut Bottom has two upland sites and two valley sites (Figure 2); each upland is paired with a valley. The valleys are eroded into the late Wisconsin outwash plain and are suggested to be formed by groundwater sapping (Uchupi and Oldale 1994).

**METHODS**

At each site I sampled every two meters along a transect, collecting 13 cores per site for a total of 104 cores. Three cores from each site were left undisturbed for field capacity and textural analysis. Each core was taken to a depth of 15 cm and I measured the length of each core in order to calculate the volume of each core for a bulk density measurement. I collected tree oak and scrub oak leaves at each site, from three different areas. 80 soil samples (10 from
each site) and 48 leaf samples (6 from each site, 3 scrub oak and 3 tree oak) were ground and analyzed for carbon and nitrogen.

**Nutrients**

In lab, I homogenized the soil cores that were not left undisturbed (10 at each site) and weighed a subsample (10 g) of each for a soil moisture value. The sub samples were dried at 50 °C for 48 hours and weighed again. I determined an initial pH value for all samples at each site by creating a slurry of 5 g of soil and 25 mL of deionized water and taking measurements with a pH/conductivity meter (Accumet Model 20, Fischer Scientific). I did initial and final KCl extractions in order to obtain values for extractable ammonium and nitrate as well as mineralization and nitrification rates. I performed initial extractions 13 November and final extractions 1 December for an incubation period of 18 days. I extracted 15 g of soil with 100 mL of KCl and all samples were placed on a shaker table for 1 hour. The samples settled for 24 hours and I then filtered them into scintillation vials using 25 mm GF/F swinnex filters. Nitrate concentrations were determined using the Lachat method 31-107-04-1-c (Diamond 2008) and ammonium concentrations were determined using a modification of the method from Strickland and Parsons (1972) based on the phenol-hypochloric method from Solarazano (1969). The final units of ammonium and nitrate pools as well as mineralization and nitrification rates (g/m² and g/m²/yr, respectively) were determined using the average bulk density value at each site.

**Soil Hydraulic Properties**

I determined field capacity of the undisturbed cores by lining each core with a Scotch-Brite pad and placing them in a tub of water to fully saturate. Once saturated, the cores were moved to a dry tub to drain and capped to prevent evaporation. I weighed the drained cores, dried the cores at 60 °C for 72 hours, and reweighed the cores for a final dry weight. I calculated field capacity for each core using the following equation:

\[
\frac{g \text{ water}}{g \text{ soil}} \times \frac{cm^3 \text{ water}}{g \text{ water}} \times \frac{g \text{ soil}}{cm^3 \text{ water}} = \text{field capacity (cm}^3 \text{ water/cm}^3 \text{ soil)}
\]

I determined soil texture using the hydrometer method. I weighed out 40 g of soil (3 samples per site) and added 250 mL of dionized water and 100 mL of a sodium-hexametaphosphate (HMP) solution (50 g/L), which disperses the soil particles so that they do not aggregate to one another. All samples were placed on a shaker table overnight. I then
transferred the suspension to a sedimentation cylinder and brought the volume to 1 L with deionized water. I thoroughly mixed the suspension and took readings on a hydrometer after 30 seconds, 1 minute, 3 minutes, 30 minutes, 1 hour, 1.5 hours, 2 hours, and 24 hours. I calibrated the hydrometer using 100 mL of the HMP solution and 900 mL of deionized water. I determined \( X \), the mean particle diameter (\( \mu m \)) in suspension at time, \( t \), using the following equation:

\[
X = \theta t^{-1/2}
\]

\[
\theta = (18\eta h' / [g(\rho_s - \rho_1)])^{1/2}
\]

\[
h' = -0.164R + 16.3
\]

\( \theta \) = sedimentation parameter, \( \mu m \) min\(^{1/2} \)
\( h' \) = effective hydrometer depth, cm
\( \eta \) = fluid viscosity in poise, g/cm/s (0.01 poise)
\( g \) = gravitational constant, cm/s\(^2 \) (981 cm/s\(^2 \))
\( \rho_s \) = soil particle density, g/cm\(^3 \) (2.3 g/cm\(^3 \))
\( \rho_1 \) = solution density, g/cm\(^3 \) (1.0 g/cm\(^3 \))

I used the following equations to correct for density and viscosity variations for the HMP solution:

\[
\rho_1 = \rho^* (1 + 0.630 C_s)
\]

\[
\eta = \eta^*(1 + 4.25C_s)
\]

\( C_s \) = concentration of HMP, g/mL (0.05 g/mL)

I determined clay fractions by calculating the mean particle diameter in suspension at various times using the following equation:

\[ P_{2\mu m} = m \ln(2/X_{24}) + P_{24} \]

\( X_{24} \) = mean particle diameter in suspension at 24 hr
\( P_{24} \) = summation percentage at 24 hr
\( m = (P_{1.5} - P_{24})/\ln(X_{1.5}/X_{24}) \) = slope of the summation percentage curve between \( X \) at 1.5 hr and at 24 hr
\( X_{1.5} \) = mean particle diameter in suspension at 1.5 hr
\( P_{1.5} \) = summation percentage at 1.5 hr

I computed sand fractions (\( P_{50\mu m} \)) using the same procedure as for \( P_{2\mu m} \); however, the 30 second and 1 minute hydrometer readings were used rather than the 1.5 hour and 24 hour readings, respectively. I subtracted the computed \( P_{50\mu m} \) value from 100 to obtain the sand percentage at both study sites. Gravel fractions for both sites were taken out of the sand fractions while the silt
fractions were determined as the percent remaining after summing the gravel, sand, and clay fractions.

**Statistical Analysis**

I used SPSS 20.0 (IBM Corporation) to run all of my statistical analyses. Data were analyzed using independent t-tests in order to compare means between the two types of study sites.

**RESULTS**

The average pH of the soil varied slightly between sites (Figure 3); however, there was no statistical significance ($t = -0.557$, $df = 78$, $p = 0.579$).

**Nutrients**

Nutrient analyses of soil composites from each site did not show any differences between the frost pockets and the upland macroclimates (Figure 4). The frost pockets had an average of 37.06 g C/m$^2$ while the upland macroclimate sites had an average of 37.74 g C/m$^2$ ($t = -0.199$, $df = 78$, $p = 0.842$). For total nitrogen values, the frost pocket sites averaged 1.58 g N/m$^2$ while the upland macroclimate sites averaged 1.31 g N/m$^2$ ($t = 1.079$, $df = 78$, $p = 0.284$). Extractable nitrogen in the soils also showed no statistical differences (Figure 5) with an ammonium pool of roughly 0.10 g N/m$^2$ for both sites ($t = -1.105$, $df = 78$, $p = 0.312$) and a nitrate pool of zero. The nitrate pool was zero for both the initial and final extractions; therefore, there was no nitrification occurring in the soils. There was, however, an increase in ammonium over the 18 day incubation period leading to mineralization rates of 2.86 g N/m$^2$/yr in the frost pocket sites and 4.21 g N/m$^2$/yr in the upland macroclimate sites (Figure 6). There was no statistical difference between the reported mineralization rates at the two sites ($t = -1.491$, $df = 78$, $p = 0.187$).

There was no statistical difference in the total carbon content of scrub oak leaves between the two sites ($t = 1.704$, $df = 6$, $p = 0.139$) nor was there any difference in the carbon content of the tree oak leaves ($t = -0.857$, $df = 6$, $p = 0.424$) (Figure 7a). Total nitrogen content of both scrub oak and tree oak leaves also proved to be insignificant ($t = 1.300$, $df = 6$, $p = 0.241$, $t = -0.184$, $df = 6$, $p = 0.860$, respectively) (Figure 7b). The frost pocket sites did show a significant difference between the scrub oak and tree oak carbon ($t = 3.772$, $df = 6$, $p = 0.009$) (Figure 7a); however, the upland macroclimate sites had no difference between the scrub oak and tree oak carbon content ($t = 0.175$, $df = 6$, $p = 0.867$). There were no statistical differences between the
scrub oak and tree oak nitrogen content in the frost pockets (t = 0.491, df = 6, p = 0.641) or the upland macroclimates (t = -1.307, df = 6, p = 0.239) (Figure 7b).

**Soil Hydraulic Properties**

Field capacity of frost pocket soils and upland macroclimate soils showed no significant differences (t = 0.158, df = 22, p = 0.876); frost pocket soils were able to hold an average of 0.37 cm³ water/cm³ soil while upland macroclimate soils were able to hold an average of 0.36 cm³ water/cm³ soil (Figure 8). Since there was no difference in field capacity between the two sites, it would be expected that there would also be no difference in the texture of the soil between the frost pockets and the upland macroclimates. However, the frost pocket soils were significantly sandier than the upland macroclimate soils (t = 3.549, df = 22, p = 0.002) and also had more gravel (t = 5.814, df = 22, p <0.001), although the gravel made of the smallest portion of the textural analysis (Figure 9). The upland macroclimates had a significantly higher silt content than the frost pockets (t = -3.365, df = 20, p = 0.003); however, there was no difference in the clay content of the soils between the two sites (t = -0.318, df = 20, p = 0.754).

**DISCUSSION**

Although there were no differences in pH between the frost pocket valleys and the upland macroclimates (Figure 3), the results I obtained are within the range found by other studies on the Vineyard. Neill and colleagues (2007) studied soil characteristics of various land cover categories on Martha’s Vineyard, two of which included scrub oak and tree oak. The organic soil had a pH value of 3.9 at both sites while pH values for mineral soil were reported as 4.4 and 4.5, respectively. The soils I used for pH were a homogenized mixture of organic and mineral soil and the average pH value for both the frost pocket valleys and the upland macroclimates was 4.2, which is within the range reported above.

**Nutrients**

The total carbon and nitrogen analysis of the soils did not reveal any differences between the frost pocket valleys and the upland macroclimates. There was much more carbon present in the soil than there was nitrogen (Figure 4) which is what I would expect, since nitrogen is the limiting factor for the scrub oaks and tree oaks growing in these systems. Most of the total carbon and nitrogen analysis for the scrub oak and tree oak leaves show no statistical difference; however, the scrub oak leaves in the frost pocket sites had significantly more carbon than the tree
oak leaves in the frost pocket sites. Although there was only about a two percent difference between the two types of leaves (Figure 7a), the analysis suggests that the scrub oak leaves are slightly more resilient to decomposition since they have more carbon. When considering the carbon and nitrogen analysis for the soils and leaves, it would appear that there is no difference in nutrient availability between the two sites. Therefore, it is unlikely that nutrient availability is contributing the stark difference in vegetation structure.

There was no nitrate pool at either site (Figure 5). However, nitrate is easily leached out of soils, so this is not a surprising result. A study done on Martha’s Vineyard also showed no nitrate pools in representative sites of the frost pocket valleys and the upland macroclimates (Neill et al. 2007). Since there was no nitrate pool at either site there is no way to obtain or compare rates of nitrification. There was an ammonium pool present at both sites; yet, the lack of difference between the two sites is just another indication that nutrient availability is not what is causing the drastic difference in vegetation structure.

The average mineralization rates I obtained from initial and final KCl extractions were slightly lower in the frost pocket sites than in the macroclimate sites (Figure 6). Although there was no statistical significance between the two sites, it is possible that the leaf litter in the frost pocket sites isn’t as easy to decompose. The frost pocket valleys are dominated by scrub oaks and which suggests that the majority of the leaf litter is composed of scrub oak leaves, rather than tree oak leaves. As stated above, the scrub oak leaves in the frost pocket have a greater carbon content than the tree oak leaves, which makes them harder to decompose. Therefore, even though I did not see a statistical difference in mineralization rates, the higher carbon content of the scrub oak leaves could be one explanation for why there are lower mineralization rates in the frost pocket valleys.

**Soil Hydraulic Properties**

Field capacity, or a freely drained soil’s ability to hold water, did not differ between the two sites although all but one of the frost pocket sites had a lower field capacity than the upland macroclimates (Figure 8). It is unusual that I did not see a difference in field capacity given that there was such a large difference in the sand percentage between the two sites (Figure 9); however, the coarser soils in the frost pocket valleys have various implications for why vegetation structure between the frost pocket valleys and the upland macroclimates is drastically different. It is possible that, due to the coarser soil texture, the frost pocket valleys could
experience a drought effect during dry spells throughout the growing season. When looking at the relationship between the growth rate of oak trees in the frost pocket valleys and the upland macroclimates and precipitation (data collected and worked up by Jamie Harrison), it is clear that there is a stronger relationship between tree growth and rainfall in the frost pocket valleys (Figure 10). Although there is a lot of variability, the fact that the tree oaks in the frost pockets grow more quickly when there is more rain suggests that they are more likely to become drought prone. While it is possible that a drought effect in the frost pockets could be simply due to the large fluctuations in temperature, it is likely that the coarser soils add to drought sensitivity. During prolonged dry spells the soils in the frost pocket valleys could lose water faster, which would add even greater stress on the tree oaks. This is just one possible explanation and is a very interesting link between the two projects.

A lot of work would need to be done, moving forward, to determine if there is any sort of drought effect on the tree oaks in the frost pocket valleys. In order to gain a better understanding of how tree growth, precipitation, and soil texture are linked it would be essential to continue studying these sites. One possible option would be to take measurements like photosynthetic capacity or carbon dioxide exchange over a leaf’s surface during the growing season to see if these tree oaks are indeed water stressed. It would also be beneficial to study other leaf properties such as cuticle thickness and stomatal density. All of these measurements would allow for a better understanding of how tree growth is affected in these frost pocket valleys and why we see such stark differences in vegetation structure between the two study sites.

CONCLUSIONS

I did not see any differences in nutrient availability between the frost pocket valleys and the upland macroclimates, which goes against my original hypothesis; however, I can confidently say that difference in nutrient availability is not the driving force behind the very clear difference in vegetation structure between the two study sites. While there was no difference in field capacity between the two study sites there was a significant difference in the soil texture, which is due to how the valleys were formed and has various implications. In order to better understand the difference in vegetation structure between the frost pocket valleys and the upland macroclimates more extensive research needs to be done.
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LITERATURE CITED
FIGURES

Figure 1. Bird’s eye view of the Deep Bottom frost pocket and its corresponding upland macroclimate.

Figure 2. Map of study sites on Martha’s Vineyard. Each black dot represents a paired upland macroclimate and a frost pocket valley.

Figure 3. Mean pH ± SE of soil at frost pocket sites and upland macroclimate sites

Figure 4. Mean carbon and nitrogen content (g/m²) of soil at frost pocket sites and upland macroclimate sites

Figure 5. Mean ammonium and nitrate pools (g N/m²) ± SE of soil at frost pocket sites and upland macroclimate sites, nitrate values are zero

Figure 6. Mean mineralization rates (g N/m²/yr) ± SE for frost pocket and upland macroclimate soils incubated for 18 days

Figure 7. Mean carbon content (a) and nitrogen content (b) of leaves (%) ± SE for scrub oak and tree oak leaves at frost pocket sites and upland macroclimate sites

Figure 8. Mean field capacity of soils (cm³ water/cm³ soil) ± SE for frost pocket sites and upland macroclimate sites

Figure 9. Summation percentage of gravel, sand, silt, and clay ± SE for frost pocket and upland macroclimate soils

Figure 10. Relationship between tree oak growth rate (cm²/tree/yr) and adjusted precipitation (mm) for tree oaks in frost pocket and upland macroclimate sites
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Figure 6. Mean mineralization rates (g N/m$^2$/yr) ± SE for frost pocket and upland macroclimate soils incubated for 18 days.
Figure 7. Mean carbon content (a) and nitrogen content (b) of leaves (%) ± SE for scrub oak and tree oak leaves at frost pocket sites and upland macroclimate sites.
Figure 8. Mean field capacity of soils (cm$^3$ water/cm$^3$ soil) ± SE for frost pocket sites and upland macroclimate sites
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