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# LAND USE CHANGE IN THE NORTHEAST UNITED STATES: RETAINING FOREST STRUCTURE AND ITS SOIL HYDRAULIC PROPERTIES THROUGH SILVOPASTURE

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LAND USE CHANGE IN THE NORTHEAST UNITED STATES: RETAINING FOREST
STRUCTURE AND ITS SOIL HYDRAULIC PROPERTIES THROUGH SILVOPASTURE


BY


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THESIS


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This thesis has been examined and approved in partial fulfillment of the requirements for the degree of Natural Resources by:

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Original approval signatures are on file with the University of New Hampshire Graduate School.

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**Contents**

**List of Tables**

**List of Figures**

**ABSTRACT**

LAND USE CHANGE IN THE NORTHEAST UNITED STATES: RETAINING FOREST

STRUCTURE AND ITS SOIL HYDRAULIC PROPERTIES THROUGH SILVOPASTURE

By

Anthony Stewart

University of New Hampshire, September 2017


Growing demand for locally produced agriculture in the Northeast US could result in significant land use change from forests to open pasture and other agricultural uses. This conversion may reduce the soil hydrologic flow due to tree removal and increased soil compaction, leading to increasing surface runoff and erosion. Silvopasture—an agroforestry system that integrates trees with livestock—offers a potentially more sustainable alternative to conversion to open pasture, and has recently gained interest with local land owners and farmers in the region. The retention of trees within pastures may help maintain critical hydrologic functions of forest soils by promoting higher infiltration rates and hydraulic conductivity, and thereby avoiding degradation of forest hydrologic functions. We assessed the impacts of forest-to-pasture vs. forest-to-silvopasture conversion on soil hydraulic properties at two study sites, an unreplicated treatment site at the UNH Organic Dairy Research Farm (ODRF) in Lee, NH and a replicated treatment site at the North Branch Farm (NBF) in Saranac, NY. Specifically, we measured unsaturated hydraulic conductivity ($K(h)$) at the soil surface and saturated hydraulic conductivity ($K(sat)$) at 15 cm and 30 cm depths under three land uses: intact forest, open pasture, and silvopasture. Differences between land uses were observed in $K(sat)$ results at both sites. At the ODRF, the $K(sat)$ at 15cm depth was highest in intact forest, intermediate in

silvopasture, and lowest in open pasture. However, at the 30 cm depth there were no distinct differences. The NBF site exhibited a different pattern, where the 15 cm K(sat) in silvopasture and open pasture were similar and both lower than the intact forest, but at the 30 cm depth, silvopasture K(sat) was higher than open pasture and comparable to the slightly higher intact forest. The reduced soil hydraulic conductivity under open pasture may have consequences for increasing surface runoff and soil erosion in response to high intensity rainfall. Soil hydraulic properties in silvopasture, although variable, have some potential to function as an intermediate between higher levels in the intact forest and lower levels in the open pasture which would partially maintain ecosystem and hydrologic services.

**Introduction**

Extreme alterations of ecosystem structure and function often occur via land use change. For the Northeastern U.S, land use change is not a foreign concept. Early European settlement facilitated the extensive forest removal for early 18th and 19th century North American agriculture (Foster et al., 2008). Currently, almost all the past farmland is now covered by secondary forest and urbanized areas largely due to the movement of agricultural production to the Midwest (Foster et al., 2008; Nowak and Greenfield, 2012). However, continued increasing populations growth northeastern states, increasing awareness of climate impacts from large scale agriculture, and increasing desire for improving local economies have driven demand for more locally produced food in the Northeastern U.S (Donahue et al., 2014; Timmons et al., 2008; Martinez et al., 2010). To meet estimated demand in 2050 for a higher population and more local consumption, regional farmers will potentially double their current agricultural production capacity (Donahue et al., 2014). Open pasture for dairy and beef production is a fundamental and financially important sector of Northeastern agriculture and presently comprises approximately 50% of Northeastern U.S farms (USDA NASS, 2014). With growing pressure to increase local grass fed cattle production, farmers in the region will primarily look to increase forage production via open pasture, a land use supported by regional glacial till soils with their high mineral content, steep terrain, and shallow depth (Donahue et al., 2014). The expansion of open pasture will likely remove forest cover due to its accessibility as a prominent landscape feature already on Northeastern U.S farm property. For example, 65% of New Hampshire farm area is covered by unmanaged forest or woodlands (Nowak and Greenfield, 2012; USDA NASS 2014). However, this cover is slowly declining due to conversion from forest to agricultural and urban land uses (Donahue et al., 2014).

The process of forest clearing and conversion to agriculture has been shown to significantly alter ecosystem services especially hydrologic services such as streamflow and groundwater storage (Foley et al., 2005; Neary et al., 2009). Unmanaged and intact forests maintain critical hydrologic functions including evapotranspiration, soil infiltration, and hydrologic flow through soils. Fluctuations in these functions via land use conversion can significantly affect the quantity of streamflow and groundwater storage. In particular, replacement of forests with pasture can induces substantial reductions in surface and subsurface hydraulic conductivity, which represents the soil's capacity to transport water. Unmanaged forests maintain higher soil hydraulic conductivity than other agricultural land uses due to less compact soils, deeper and more extensive root systems, and greater abundance of soil macrofauna that facilitate macropore formation (Beven and Germann, 1982; Neary, 2009). In contrast, forest-to-pasture conversion followed by grazing and trampling by livestock can cause soil compaction, resulting in higher soil bulk densities, lower soil infiltration, and lower soil hydraulic conductivity (Lal, 1996; Drewry, 2006, Greenwood and McKenzie, 2001, Zimmerman et al., 2006; Zimmermann et al., 2010). Under heavy precipitation events that exceed soil infiltration capacity and soil hydraulic conductivity, precipitation can be converted to overland flow, reducing inputs into the soil and deeper groundwater storage (Zimmermann et al., 2006; Ghimire et al., 2013; Simonit and Perrings, 2013).

Silvopasture, a type of agroforestry that intentionally integrates livestock, forage grass, and trees on the same unit of land, offers an alternative to open pasture that is potentially less degrading on hydrologic services through the role trees in maintaining more favorable soil hydraulic properties. Additionally, silvopastures can contribute to the production of multiple goods and services on the same landscape—beyond just forage and cattle production, including

2

timber, fuelwood, recreational benefits, diverse nontimber forest products (e.g., maple syrup, tree fruits and mast, and mushrooms), increased carbon storage, microclimate regulation, soil erosion control, and wildlife habitat (Chedzoy and Smallidge, 2011; Karki and Goodman, 2014). The array of potential benefits has facilitated interest in silvopasture land use worldwide (Orefice et al, 2017). This extensive geographic range of adaptation has also produced a wide variety of silvopastures with different forage grasses, trees, and grazing animals. For example, in South America, agroforestry land uses are sometimes derived from the natural forest but interest has also been expressed for planting exotic tree species such as *Eucalyptus spp.* for dual management of grazing and high quality timber (Cubbage et al., 2012; Frey et al., 2012). Establishment of silvopasture by planting overstory trees has also been observed in New Zealand to help enhance and diversify income with dual management (Knowles, 1991; Cubbage et al., 2012). In the United States, silvopasture has been implemented primarily in the Southeastern and Northwestern regions, utilizing a variety of tree species and understory forages (Fike et al., 2004; Sharrow et al., 2009; Arbuckle et al., 2009; Feldhake et al., 2010; Orefice et al., 2017). However, silvopasture in the Northeastern region of the U.S has been scarcely documented until recently (Orefice et al., 2017). Silvopasture may be more favorable for pasture than agriculture in the Northeastern U.S because soils are relatively rocky and shallow, and it combines two important sectors of the local economy: timber and pasture production (Foster et al., 2008). Furthermore, regional extension programs have stressed diversification of agricultural landscapes to increase ecosystem resilience and mitigate financial risks for farmers in the face of changing climates and economies. (Chedzoy and Smallidge, 2011; Frey et al., 2012). Still, the application of current silvopasture research may be limited regionally and there is a lack of silvopasture study in the

Northeastern U.S. More research into silvopasture implementation in this region would provide insight into a potentially viable agricultural land use.

Research in the Northeast has thus far shown farmer interest in silvopasture as a diversified land use practice that also provides greater protection against soil compaction and nutrient losses compared to open pasture (Orefice et al., 2016; Orefice et al., 2017). However, there is still limited knowledge about the potential impacts of silvopasture on hydrologic services compared to forest and open pasture. As previously noted, forest-to-open pasture conversion can severely degrade soil hydraulic properties, and alters hydrologic services of groundwater storage and streamflow (Bruijnzeel, 2004; Zimmermann et al., 2006; Drewery, 2006, Zimmermann et al., 2010). An investigation by de Aguiar et al., (2010) demonstrated that silvopasture using native forest trees in Brazil had a higher soil hydraulic conductivity than intensively cropped fields and other agroforestry practices, leading to a reduction in soil erosion. Conversely, a study by Sharrow (2007) showed that silvopasture using young, row-planted pine trees maintained a similar soil hydraulic conductivity as open pasture. Yet, when assessing the impact of trees on hydraulic properties, finer spatial scales may become important, as soil in closer proximity to a tree has been shown to maintain a higher hydraulic conductivity (Ilstedt et al., 2016). A spatial relationship has been shown in various landscapes that include trees but rarely in agroforestry settings and especially with more intensive grazing (Benegas et al., 2014). Moreover, the site-specific conditions, land use change mechanism, overstory tree composition, and understory forage composition differ considerably within each silvopasture across the world, and the potential silvopasture use in the Northeastern U.S will continue to add to the land use diversity.

Despite growing interest in expanding silvopasture practices among farmers in the Northeast, there is also a noted lack of consistent supporting information from other practitioners

and professionals (Orefice et al., 2017). Indeed, for new farmers, access to information regarding silvopasture has been a stated barrier to the practice's adoption (Arbuckle et al., 2009). While recent work has addressed forage grass species viability and changes to some soil physical and chemical properties in the Northeast, there remains a lack of information regarding effects of forest conversion to pasture vs. silvopasture, especially given evidence from other regions that these land use practices can drastically differ in their soil hydrology (Sharrow, 2009; Neary, 2009; Orefice et al., 2016). The growing interest in expanding agriculture in the Northeastern U.S presents an opportunity to study silvopasture and determine its potential intermediate soil hydraulic property characteristics. The notion of intermediate properties is based on the hybrid structure of silvopasture, combining trees from a thinned forest and forage grazing from a pasture. If indeed silvopasture is an intermediary system, then soil hydraulic properties would reflect intermediate quantities within the range between the higher intact forest and lower open pasture.

The objective of this investigation is to assess the soil hydraulic properties of surface unsaturated hydraulic conductivity (K(h)), a parameter measuring the rate of water entering the soil, and subsurface saturated hydraulic conductivity (K(sat)), a parameter measuring within soil water movement rates. These measurements are taken within unmanaged and intact forest, thinned silvopasture, and open pasture systems to assess the hypothesis that silvopasture soil K(h) and K(sat) are intermediate between higher forest soils and lower open pasture soils. The assessment will take place at two locations: one immediately after conversion from forest to silvopasture and open pasture and another location where conversion from forest to silvopasture and open pasture took place four years prior. With these two locations, this study will test the hypothesis that soil hydraulic properties are highest in an intact forest, lowest in an open pasture,

and intermediate in a silvopasture. Additionally, this study will evaluate the effects of different land uses and land use duration on soil hydraulic conductivity and the potential implications for the broader hydrologic cycle components and water resources.

**Methods**

*Site Characteristics*

Field measurements were conducted at two locations: The University of New Hampshire's Organic Dairy Farm (ODRF), also known as the Burley-Demeritt Farm, located in Durham, New Hampshire (43.09 North, -70.99 West), and the North Branch Farm (NBF) in the Northern Adirondacks region near Saranac New York (44.59 North, -73.89 West). At ODRF, the mean annual precipitation is 1219 mm. Soil classification primarily consists of Hollis-Charlton fine sandy loam with smaller portions of Charlton fine sandy loam and Leicester-Ridgebury very stony fine sandy loams on mild slopes throughout the site. Original forest composition at the ODRF contains 70-80 years old mixed species, primarily of eastern hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*), red oak (*Quercus rubra*), white oak (*Quercus alba*), shagbark hickory (*Carya ovata*), red maple (*Acer rubrum*), black birch (*Betula lenta*), yellow birch (*Betula alleghaniensis*), and smaller portions of other Northeastern deciduous species. Understory vegetation presence is very sparse and the only notable vegetation present were ferns (*Polypodiales spp.*).

At the NBF, mean annual precipitation is 953 mm. The soil classification at the site predominantly consists of Monadnock fine sandy loam with a smaller presence of Colton gravelly loamy coarse sand on more moderate slopes and more cobble present than the ODRF. The original forest composition consists of a northern hardwoods mixed forest approximately 50-60 years old with presence of mostly red maple (*Acer rubrum*), paper birch (*Betula papyrifera*), white ash (*Fraxinus americana*), black cherry (*Prunus serotina*), aspen (*Populus spp.*), American elm (*Ulmus Americana*), apple (*Malus spp.*), and American basswood (*Tilia americana*).

*Experimental Design*

Due to logistical constraints and differences in silvopasture implemented by the two landowners, the experimental design differed slightly between study sites. At the ODRF, treatments consisted of unmanaged forest (reference), forest conversion to open pasture, and forest conversion to silvopasture, implemented in the Fall and Winter of 2014. Each treatment was established as an unreplicated 1-hectare (2.5 acre), 50 x 200 m plot adjacent and parallel to each other. Whole tree harvest was used to remove 100% of trees from the open pasture and approximately 50% of the basal area in the silvopasture to create approximately 50% canopy coverage. Post-treatment basal area in the silvopasture was 20 $m^2ha^{-1}$ reduced from approximately 50 $m^2ha^{-1}$. Remaining trees consisted of mostly white pine (10 $m^2$ $ha^{-1}$), eastern hemlock (5.7 $m^2$ $ha^{-1}$), red oak (2.2 $m^2$ $ha^{-1}$), and small portions (<0.5 $m^2$ $ha^{-1}$) of other deciduous species. Orchard grass (*Dactylis glomerata)* was seeded for forage immediately after treatment application and again in Spring 2016. Immediately following the seeding, 10 dairy cows grazed sections of the silvopasture and open pasture simultaneously in approximate sections of 15x100 m. Each week cattle grazed the length of the treatment plots, section by section to cover the entire area, except for fenced-off areas containing permanently equipment. Hay bales were laid out evenly across both treatment plots to evenly distribute cattle presence due to lack of early forage vegetation.

The intact forest reference plot featured a notable landscape depression on the southeast corner much lower than the other two treatments and contained a higher presence of gleyed soils, indicating minimal soil water drainage for this section. Gleyed soil was not observed in other areas of the intact forest treatment plot or other the treatments and therefore, this area was avoided in the sampling scheme. For the remaining area, a blocked-randomized sampling scheme

was used to account for the variation in topography. The blocking included five distinct terraces on the landscape, identified across the treatment plots. Within each block, random sample points were selected with the number of sample points corresponding to the area of each block. Additionally, a 5 m buffer zone was used in each treatment to avoid the effects of the nearby treatment plots. In total, there were 15 sample points per treatment plot for hydraulic sampling and 10 for soil core sampling.

At the NBF, similar treatments (i.e., thinned forest for woodlot, silvopasture, and open pasture) had already been applied at the NBF site for earlier silvopasture studies in July 2012 (Orefice, 2016). Intact forest reference plots were established at the site location in the 2016 summer to match the experimental design of the ODRF. The thinned forest for woodlot treatment was used to compare bulk density between land uses, as it had a similar bulk density to the pre-treatment intact forest but was not included in comparisons for hydraulic measurements. Each treatment was replicated three times on 1/3 ha (3/4 ac) plots, randomized within three blocks, comprising a total area of 2.7 ha that was protected by fencing around the perimeter. Thinning for conversion to silvopasture reduced basal area to 37% from 19 $m^2ha^{-1}$ to 7 $m^2ha^{-1}$ (Orefice et al., 2016). Remaining species in the silvopasture plots included primarily black cherry (*Prunus serotine*) and red maple (*Acer rubrum*). Tree removal consisted of species of white ash (*Fraxinus americana*) and American elm (*Ulmus americana*). Multiple forage grass species were established in 2014 in both the silvopasture and open pasture plots (Orefice et al., 2016). However, at the time of this study, Orchardgrass was the dominant species. Beef cattle grazed silvopasture and open pasture forage grasses down to a height 5 cm beginning in August 2013. Grazing duration was dependent upon the time for livestock to reduce forage height but consisted of two sessions annually of 1.5-2 days per treatment plot in June and August.

9

Sampling was organized with a blocking scheme to account for slope with three blocks located within each treatment plot constituting an upper, middle, and lower slope block. Each block represents 1/3 of the sampling area after a 5m buffer zone has been established along the treatment plot border. Within each block, 2 sample locations were established for soil hydraulic properties totaling six sampling points per treatment plot and 54 for the entire area.

*Samples and Measurements.*

Soil hydraulic measurements consisted of saturated hydraulic conductivity (K(sat)) and unsaturated hydraulic conductivity (K(h)). A compact constant head permeameter or Amoozemeter (K(sat) Inc. Raleigh, NC; Amoozegar, 1989) was used to measure K(sat) at 15 cm and 30 cm depths in the field. At each sample point, a hand auger was used to dig two, 2.5 cm radius (r) holes, one for each depth on opposite sides of the sample point separated by 1 m to prevent interference between auger holes. The auger holes were also positioned perpendicular to any slope present to avoid possible effects of microtopography. The Amoozemeter K(sat) measurement process consisted of establishing a constant hydraulic pressure head within the auger hole so that the water height (H) in auger hole with radius (r) is constant. When the ratio $H/r \geq 5$, water outflow rates can be measured in intervals until soil saturation and a steady state flow is achieved.

$$1. \quad K(sat) \ = \ \frac{Q\left\{\sin^{-1}\frac{H}{r} - \sqrt{(\frac{r}{H})^2 + 1}\frac{r}{H}\right\}}{2\pi H^2}$$

K(sat) is then calculated using the steady state flow rate and the Glover solution according to equation (1), Q is the steady state water percolation rate into soil, H is the constant water depth in the auger hole, and r is the auger hole radius (Amoozegar, 1989).

Additionally, a Minidisk Tension Infiltrometer (MDI) (Decagon Devices, Inc.) was used

to measure unsaturated hydraulic conductivity (K(h)) at the soil surface four times per sample location. The device allows water to infiltrate the soil surface under a constant tension simulating rainfall inputs but not ponded infiltration.

$$2.\ I = C_1 t + C_2 \sqrt{t}$$

$$3.\ K = \frac{C1}{A}$$

The unsaturated flow rate is derived from equation (2) from Zhang (1997), where $I$ is the cumulative infiltration, $C_2$ is related to soil sorptivity, $C_1$ is related to unsaturated hydraulic conductivity, and $t$ is the time duration (s). The $C_1$ parameter is therefore used to calculate unsaturated hydraulic conductivity (K(h)) with equation (3). $C_1$ is the slope of the curve generated by plotting measurements of cumulative water flow into the soil versus the square root of time.

$$4.\ A = \frac{11.65(n^{0.1}-1)e^{[2.92(n-1.9)\alpha h_o]}}{(\alpha r_o)^{0.91}}$$

The value $A$ is calculated from van Genuchten model parameters $n$ and $\alpha$ for a retention curve under specified soil texture class, $r_o$ for disk radius, and $h_o$ for the suction setting shown in equation 4 (Zhang 1997). A value table is provided by Decagon Devices Inc. which contains estimates of the value $A$ for specific soil texture classes, suction setting, and instrument dimensions. A 2 cm suction setting was used for all field measurements.

At the ODRF, A slide hammer soil corer was used to extract soil samples at depths of 0-15 cm and 15-30 cm. Soil cores were taken after hydraulic measurements at the same sample locations and depths. After sampling, soil cores were dried for 24 hrs at 105 $^o$C. A 2 mm sieve was used to remove rocks and debris and then a dry soil weight was taken and divided by the volume of the soil corer cylinder to calculate bulk density. Remaining soil samples were used in a hydrometer texture analysis based on Stokes Law to determine the percentage of sand, silt, and

clay. A 30 g sample of soil was mixed into 100 ml of 5% sodium hexametaphosphate and then shaken on a reciprocal shaker for 24hrs. Distilled water was then added to the soil solution up to 1L in a larger glass cylinder and then thoroughly mixed by inversion to disperse all particles. Readings were taken with a hydrometer as the soil settled at 45 s and 2 hr intervals. The percent composition of clay and silt corresponded to the 2 hr and the 45 s readings, respectively. The percent composition of sand was equal to 100% minus the clay and silt percentages.

For the NBF, soil bulk density was measured by Orefice et al. (2016) in July of 2012 (pre-treatment) and in July 2014 (post-treatment), two years after forest conversion. Soil cores were taken in the top 10 cm of the soil in the center of the treatment plots. For the forest treatment, samples were measured in July 2012 as an intact forest and then again in July 2014 as a thinned woodlot. There was no change in bulk density over this treatment and therefore the values are shown to represent an intact forest.

*Statistical Analysis*

Due to the lack of replication in the ODRF, statistical analysis incorporated pseudoreplication by utilizing the blocking scheme as experimental units (n = 5) to test for differences among treatments. Land use treatment and blocks within plots were used as the fixed effects. At the NBF, treatment effects were assessed using a mixed effects model with land use treatment and plots as the fixed effects. Location of each sample point was used as the random effect for both sites. The differences between the means of each land use within a depth class was then further assessed using a Tukey-Kramer post hoc HSD test. For the silvopasture treatments, we were especially interested in exploring the influence of distance from the tree center on soil hydraulic properties. Thus, for every hydraulic measurement in silvopasture

treatments, the distance to the nearest tree was recorded then measurements were sorted into 'near' and 'far' categories based on distances above or below the median distance to the nearest tree. The 'near' category represents hydraulic measurements below the median distance to the nearest tree and the 'far' category represents the hydraulic measurements above the median. Due to this examination only occurring in the silvopasture, the significance test uses individual points of data within each category to compare the means. A pooled t-test will be used to test for significant differences between means for the two tree distance categories, 'near' and 'far'. The p-values generated from each test were assessed with a significance alpha value of 0.05. All statistical tests were performed in JMP®, Version 13. SAS Institute Inc., Cary, NC. At both sites, comparisons included differences in bulk density, texture, K(h), and K(sat) between the three land uses, intact forest, silvopasture, and open pasture at their respective depth classes. However, at the NBF site bulk density data were collected for only the 0-10cm depth and were compared within this depth. Data were log-transformed to conform to normal distributions for statistical tests. However, for interpretation ease, mean and standard error values are reported as untransformed.

## Results

*UNH Organic Dairy Farm*

Bulk density at the 15 cm depth showed a trend of higher values in the open pasture compared to the intact forest and silvopasture, but these differences were not significant (Table 1). At the 30 cm depth, differences between land uses were more muted and not significant. Soil texture composition was also similar across almost all depths and sites, with the exception of silt, which was significantly higher in the forest compared to the open pasture but not silvopasture at 30 cm. For all treatments, soil texture composition constituted a classification as a sandy loam texture.

*Table 1. Soil physical properties of bulk density and soil texture composition. Soil texture was not measured in the NBF. Bulk density measurements in the NBF were published by Orefice et al., 2014 and were taken at the top 10cm of soil. The asterisk denotes this value is measured in the thinned forest for woodlot treatment at the NBF. Different letters denote significant differences across land uses (rows) for each measurement according to a post-hoc Tukey HSD test.*

| Site | Depth | Measurement | Forest | Silvopasture | Open Pasture |
|------|-------|-------------|--------|--------------|--------------|
| ODRF | 15cm | Bulk Density (g cm$^{-3}$) | 0.54$^a$ | 0.54$^a$ | 0.65$^a$ |
|      |       | Sand (%) | 57.20$^a$ | 61.83$^a$ | 64.83$^a$ |
|      |       | Silt (%) | 27.27$^a$ | 24.70$^a$ | 21.70$^a$ |
|      |       | Clay (%) | 15.53$^a$ | 13.47$^a$ | 13.47$^a$ |
|      | 30cm | Bulk Density (g cm$^{-3}$) | 0.79$^a$ | 0.78$^a$ | 0.83$^a$ |
|      |       | Sand (%) | 62.67$^a$ | 70.87$^a$ | 71.00$^a$ |
|      |       | Silt (%) | 20.80$^b$ | 16.63$^{ab}$ | 14.23$^a$ |
|      |       | Clay (%) | 16.53$^a$ | 12.50$^a$ | 14.77$^a$ |
| NBF | 10cm | Bulk Density (g cm$^{-3}$) | 0.93$^{b*}$ | 1.01$^{ab}$ | 1.05$^a$ |

For hydraulic properties, surface K(h) did not differ between treatments (Figure 1). Further, surface K(h) was also notably lower than the measured subsurface rates at the 15 cm depth but were a similar magnitude at the 30 cm depth. At 15 cm, intact forest K(sat) mean was

much higher than the other land uses, approximately twice as high as silvopasture and six times higher than open pasture (Figure 1). However, significant differences were only detected between forest and pasture at this depth. At 30 cm depth, the overall magnitude of K(sat) was much lower, with open pasture having slightly lower values than forest and silvopasture, but no significant differences were observed (Figure 1). There was a sharp decrease in K(sat) for the intact forest, approximately five times lower than the corresponding 15 cm depth.



*Figure 1. Soil hydraulic properties measured at the ODRF for three depths in each land use. Boxes represent the range between the 25th and 75th quartiles or the inter-quartile range. Black lines in the boxes represent the median and black triangles represent the mean. Whiskers represent 1.5 times the interquartile range and outliers are shown as circles outside of this range. Different letters denote significant differences across land uses (rows) for each measurement according to a post-hoc Tukey HSD test.*

*North Branch Farm*

Bulk density for the NBF post-treatment was significantly greater in the open pasture and silvopasture compared to pre-treatment levels, with the largest values measured in the open pasture and no significant change observed in the thinned forest for woodlot. Overall, post-

treatment bulk density ranged highest (1.05 g cm$^{-3}$) in the open pasture, intermediate (1.01 g cm$^{-3}$) in the silvopasture, and lowest (0.93 g cm$^{-3}$) in the woodlot (Table 1.). Although bulk density in the open pasture was significantly higher than the woodlot, bulk density under silvopasture was not significantly different from the other two treatments.

For hydraulic properties measured in all treatments and the reference forest in 2016, surface K(h) varied among land uses, with silvopasture having the highest K(h) compared to both pasture and woodlot, although differences were not statistically significant (Figure 2). For K(sat), a pattern similar to the ODRF emerged where intact forest K(sat) was highest at both the 15 cm and 30 cm depths (Figure 2). At the 15 cm depths, intact forest was approximately three times higher than both silvopasture and open pasture, which were similar to each other. At the 30 cm depth, intact forest again was the highest, although it was not significantly greater than either silvopasture or open pasture. However, despite lack of significance at this depth (ANOVA p = 0.0979), silvopasture K(h) was intermediate between the (higher) woodlot and the (lower) open pasture (Figure 2).
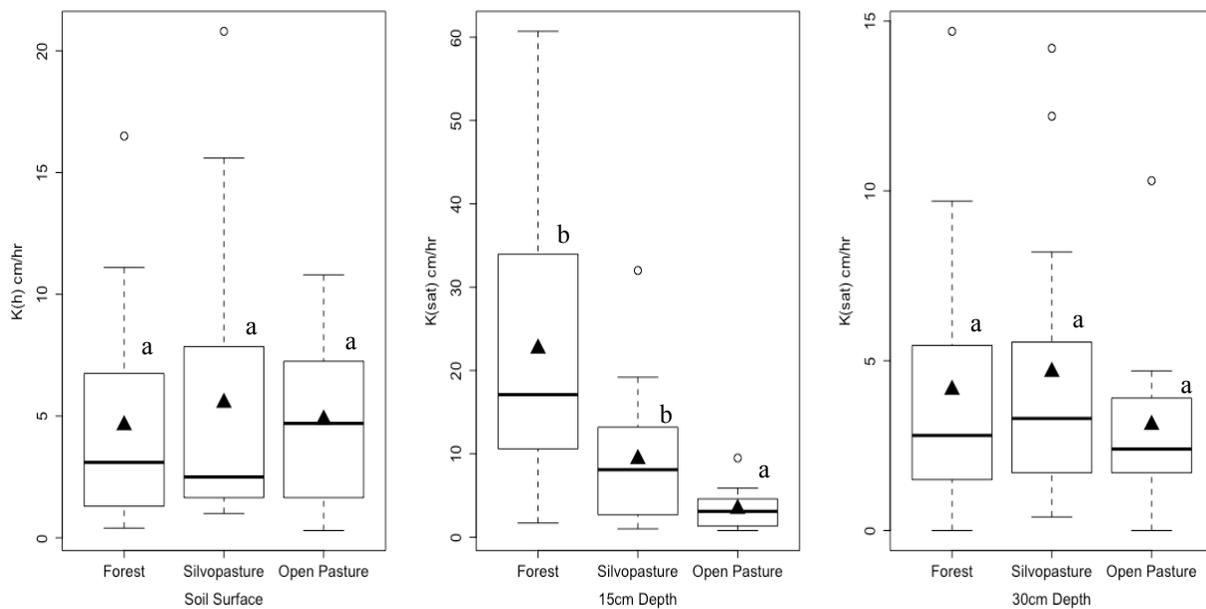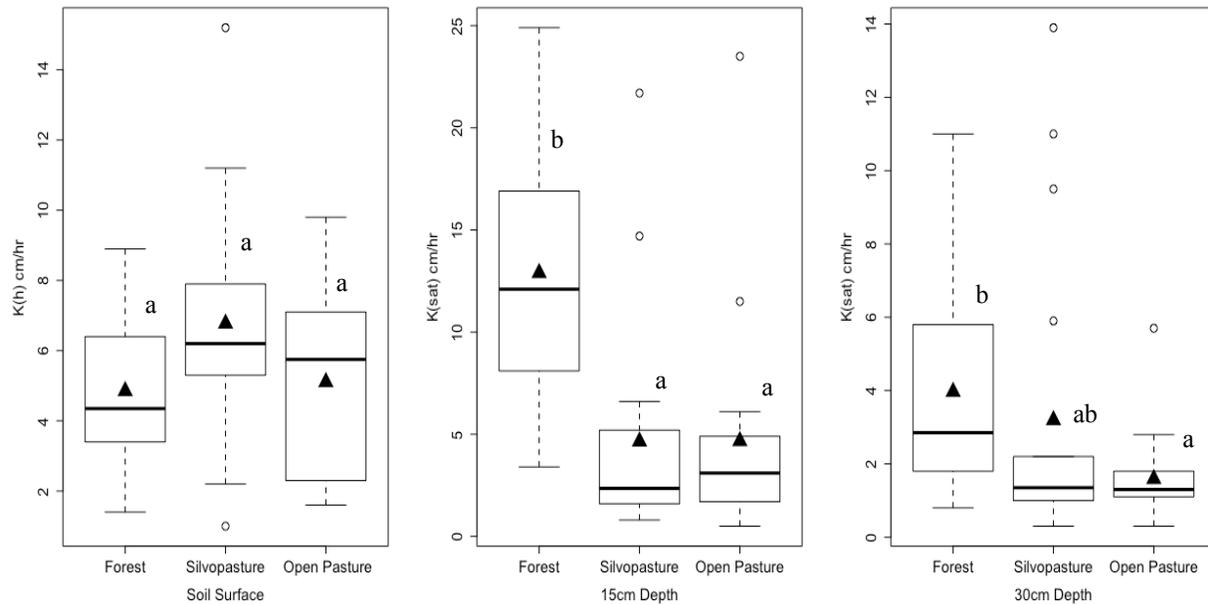
*Figure 2. Soil hydraulic properties measured at the NBF for three depths in each land use. Boxes represent the range between the 25th and 75th quartiles or the inter-quartile range. Black lines in the boxes represent the median and black triangles represent the mean. Whiskers represent 1.5 times the interquartile range and outliers are shown as circles outside of this range. Different letters denote significant differences across land uses (rows) for each measurement according to a post-hoc Tukey HSD test.*

*Hydraulic properties in proximity to individual trees*

An interesting pattern emerged for hydraulic properties in relation to distance from trees in the silvopasture. For this analysis, 3.1 m was the median distance each measurement point was from the closest individual tree, which are treated as pseudoreplicates within the larger silvopasture treatment. At the ODRF, K(sat) at 15 cm was significantly lower at 'far' compared to 'near' sample locations (Figure 4). For K(h), although measurements in the near categories were slightly higher than in the far category, this difference was not significant. No similar relationship found in the lower 30 cm depth.

17

*Figure 3. Soil hydraulic properties measured under tree proximity categories in silvopasture at the ODRF. The Near category contains measurements below the median distance from a tree and the Far category contains measurements above the median distance from a tree. Boxes represent the range between the 25th and 75th quartiles or the inter-quartile range. Black lines in the boxes represent the median and black triangles represent the mean. Whiskers represent 1.5 times the interquartile range and outliers are shown as circles outside of this range*

Similar to the ODRF site, tree proximity in the NBF showed a pattern of positive limited influence on near surface K(sat) in silvopasture (Figure 4), although no significant differences were detected. At 15 cm depth, untransformed mean K(sat) was almost twice at 'near' vs 'far' locations; however, differences were not significant in the log-transformed pooled t-test. The other variables, K(h) and K(sat) at 30 cm, showed relatively lower magnitude of difference between near and far categories compared to K(sat) at 15 cm. Both untransformed means exhibited a trend of slightly higher values near trees compared to far from trees.
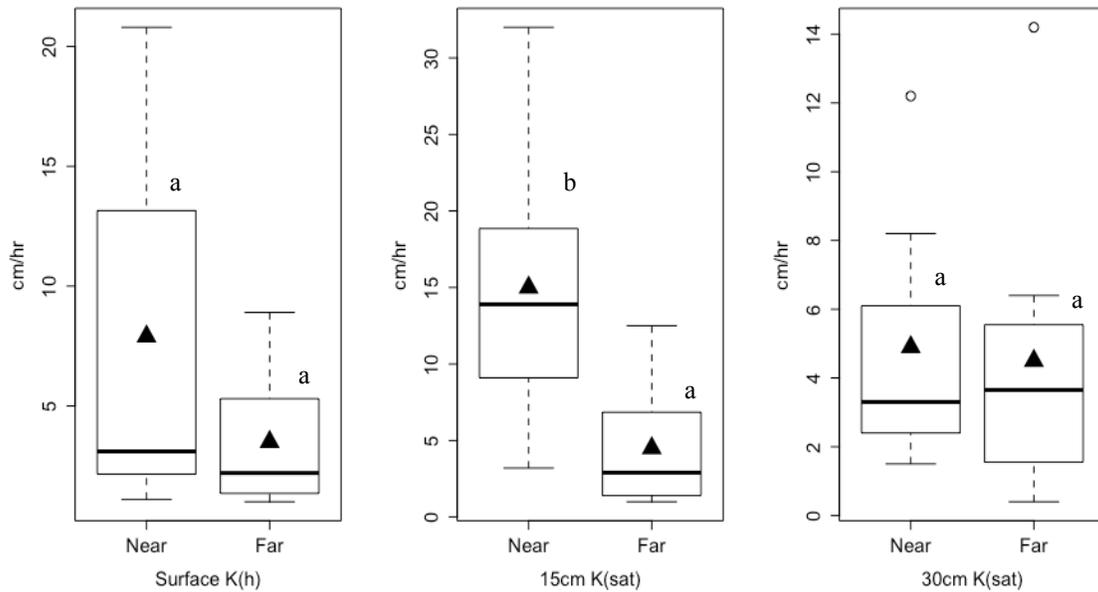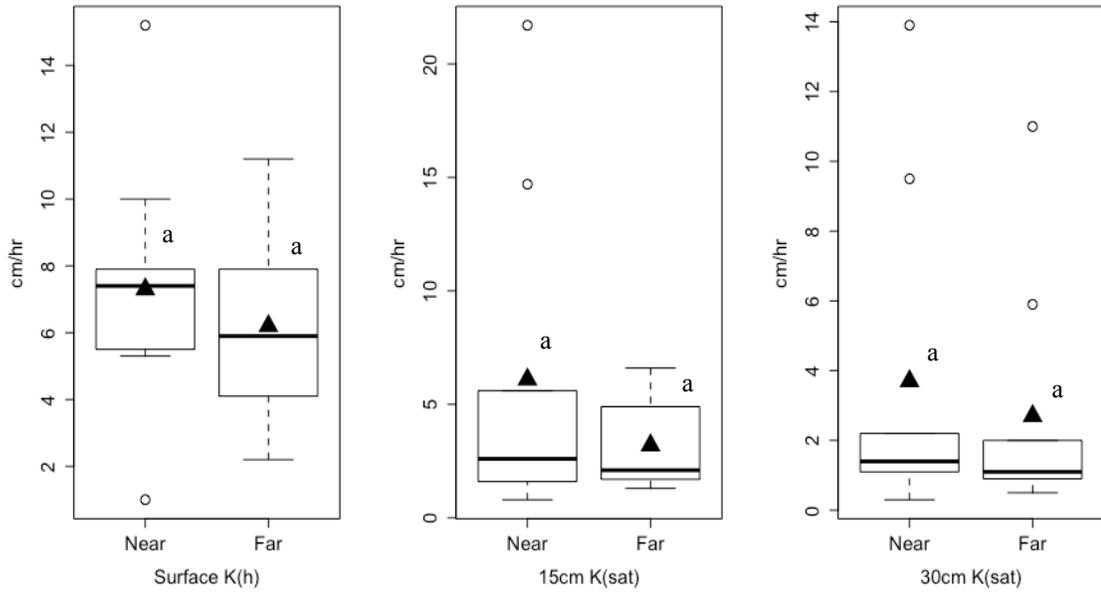
*Figure 4. Soil hydraulic properties measured under tree proximity categories in silvopasture at the NBF. The 'near' category contains measurements below the median distance from a tree and the 'far' category contains measurements above the median distance from a tree. Boxes represent the range between the 25th and 75th quartiles or the inter-quartile range. Black lines in the boxes represent the median and black triangles represent the mean. Whiskers represent 1.5 times the interquartile range and outliers are shown as circles outside of this range*

**Discussion**

In this study, the hypothesis that silvopasture maintains intermediate soil hydraulic properties between the lower open pasture and higher intact forest, had varied supported between the two sites. At the ODRF, silvopasture 15 cm K(sat) was similar to the higher intact forest and significantly higher than the open pasture. However, it is important to note the ODRF site lacks replication for the treatments and limits support for the hypothesis and application outside of this area. Although limited, the implemented treatments the ODRF give insight into the initial impacts on soil hydraulic properties during the conversion process. In the NBF where replication was included, support was also shown at the 30 cm K(sat) where silvopasture was similar to both the higher intact forest and lower open pasture, both of which were dissimilar from each other. Conversion from intact forest to open pasture appears to be more consistent in reducing subsurface soil K(sat). However,, land use conversion to silvopasture exhibited differing effects on K(h) and K(sat), which varied with time since land use conversion, individual tree proximity, and land use history. The variation of soil hydraulic properties with these factors can have consequences for other components in the larger watershed water cycle and for water resources.

*Impact of land use change on soil hydraulic properties at the ODRF*

An impact of land use conversion was observed at the ODRF open pasture and silvopasture during the summer after conversion, where K(sat) at 15 cm depth was significantly reduced compared to the intact forest. This observation was most likely due to the heavy machinery used to remove trees which has been shown to compact soils and significantly increase bulk density in forest removal for logging (Greacen and Sands, 1980; Lal, 1996). Another observation in the silvopasture is that the remaining trees may have mitigated

compaction by altering the path of the heavy machinery, and avoiding compaction in some areas around trees. Additionally, grazing in the silvopasture and open pasture may have further contributed to the abrupt K(sat) reduction. Zimmermann et al. (2010) attributed the significant decline in soil K(sat) within one year after land use conversion from intact forest to a grazed open pasture to initial cattle grazing. Trampling by cattle was a more significant soil compaction factor when considering their conversion process used slash-and-burn tree removal, which does not use heavy machinery and is less compacting on soil. However, due to the lack of repeated cattle grazing over the summer season at the ODRF, heavy machinery was likely the primary mechanism for reduction of hydraulic properties at this site. For silvopasture, although the impact was also immediate, the decrease in K(sat) was not as severe. The remaining forest structure appears to partially mitigate near surface K(sat) reduction from the recent land use conversion process. Significant differences in K(sat) were not observed for the surface or the 30 cm depth. Effects on deeper depths were possibly not observed because upper soil layers were capable of absorbing the compaction; however; with continued land use pressures over longer time scales, deeper soil layers may also experience reductions in K(sat). The lack of difference in K(h) between land uses at the soil surface may indicate the presence of a hydrophobic layer from organic matter and leaf litter decomposition that formed prior to the recent land use conversion . For example, other studies have found that pine needles, bark, roots, and other organic matter decomposition can contribute to a hydrophobic soil surface (Rumpel et al., 1998; Passialis and Voulgaridis, 1999). Over time, the surface hydrophobicity and associated impacts on K(sat) would likely diminish as forage grasses establish and develop extensive shallow root systems and as pine needle litter becomes less prominent.

*Impact of land use change on soil hydraulic properties at the NBF*

At the NBF, four years after conversion and treatment establishment, the effects of land use on hydraulic properties were more pronounced at a deeper depth. The variation was more muted among land uses at the 15 cm depth in the NBF, where silvopasture and open pasture were similar. However, at the 30 cm depth in the NBF, K(sat) differences in land use varied more and silvopasture was more intermediate between open pasture and forest. The effect in deeper soil depths of the NBF open pasture suggest that continued land use and compaction from cattle grazing begins to affect the deeper soil K(sat) and may forecast changes to the deeper soil K(sat) in the ODRF. This notion has been observed in some previous studies but the effect on land use change from forest to agriculture has been predominantly documented for depths in the 0-30 cm range and find K(sat) is similar across land uses at lower depths (Lal, 1996; Zimmermann et al., 2006; Scheffler et al., 2011). However, Salemi et al., (2013) reported a trend of more reduced subsurface K(sat) under land use conversion, where open pasture K(sat) in depths below 30 cm were significantly lower than K(sat) in forest and eucalyptus plantations. Furthermore, Ghimire et al., (2013) observed K(sat) at lower depths down to 50 cm in both a natural forest and disturbed forest was consistently higher than in open pasture. The trend is similar to shallower depths but differences are less pronounced. Landscapes with trees appear to maintain a higher hydraulic conductivity throughout deeper soil depths and the removal of trees and with conversion to open pasture can reduce soil hydraulic conductivity significantly.

*Retaining trees mitigates land use conversion effects on soil hydrology*

The observations in both silvopasture sites indicated the positive influence of individual trees on subsurface soil hydrology. The most significant indication was the difference between

near and far 15 cm K(sat) in the ODRF but there was an indication across all measurements in the silvopasture that hydraulic conductivity was higher near trees. Broadly, forest trees have been shown to exhibit higher soil hydraulic properties than agricultural land uses (Bruijnzeel, 2004; Neary et al., 2009; Ilstedt et al., 2013). Niemeyer et al., (2014) further documented a positive relationship between Leaf Area Index (LAI) and soil surface K(sat). The relationship continues to extend to a finer scale where individual trees have also been shown to have positive effects on soil infiltration and other hydraulic properties. Soil closer to trees has been shown to have more preferential flow paths and increased infiltrability compared to open areas Tobella et al., 2014; Benegas et al., 2014). These effects have direct implications for water resources as soil near trees can more easily percolate to groundwater storage instead of evaporating. Ilstedt et al. (2014) showed that near individual trees, up to 15% of annual rainfall can accumulate as groundwater drainage compared to approximately 1.3% at further distances in open spaces.

For the current study, the soil hydraulic conductivity relationship with tree proximity appears to be the strongest with the 15 cm K(sat) and roots could play roles in mitigating reductions in K(sat). It was mentioned earlier in the treatment implementation for this study, that trees left after thinning are avoided by heavy machinery and compaction near trees is avoided, helping maintain a higher soil hydraulic conductivity. Remaining tree roots can also increase the soil's bearing capacity, reducing possible compaction impact from heavy machinery and grazing (Greacen and Sands, 1980). Furthermore, trees in the silvopasture will have less competition and more resources available after thinning, and consequently, their root systems can expand after release from thinning which may increase the production of more channels for soil water flow (Greacen and Sands, 1980; Schroth, 1995). Near individual trees, root abundance is higher possibly further contributing to higher soil K(sat) by providing channels and pathways for water

23

through the soil (Jones et al., 2011; Benegas et al., 2014; Tobella et al., 2014; Ilstedt et al., 2014).

Further research with a distinct focus on the spatial relationship with trees should elucidate a

finer scale understanding of the proximity relationship between trees and soil hydraulic

properties.

An important consideration for designing silvopastures for optimum positive impacts on

water resources is the tradeoff between positive impacts of trees on soil hydraulic properties via

reduced compaction and evaporation and potentially negative impacts on water supply via

transpiration. With a finer understanding of the spatial relationship between soil and trees,

further support can be given to the concept of an optimum tree cover in regards to hydrologic

services where groundwater recharge can be maximized due to positive effects of trees on soil

hydraulic conductivity, while minimizing water losses due to transpiration by removing some

trees for partial canopy coverage (Ilstedt et al., 2014). An example of a hydrologically optimum

tree cover is documented in Ilstedt et al., (2014) where model simulations with several

ecohydrological measurements produced optimum tree densities ranging from 5 to 30 trees ha$^{-1}$

depending on soil water use by trees. However, many factors such as climate, rainfall regime,

and soil type can affect this optimal quantity but others such as tree size, age, and species can be

controlled or accounted for in landscape design by a knowledgeable land manager or farmer.

Farmers and land managers should also account for additional spatial relationships between trees

and forage grasses where light availability through the overstory can be a significant limiting

factor, with too little light restricting forage production and too much light reducing soil moisture

(Brudvig and Asbjornsen, 2008). This concept of an optimum forest cover would be very

applicable in the favorable landscape of the Northeastern U.S where silvopasture is derived from

a mixed species forest. Moreover, the concept could be more useful considering future water

resources with the increasing chances of intense drought periods (Kunkel et al., 2013). This current study has shown some evidence for positive influences by trees in silvopasture despite compaction impacts which would be suitable for determining an optimal landscape tree density. However, there are still numerous factors that need to be considered before implementing an optimal tree density suitable for farmer needs and grazing in the Northeastern U.S.

*Site comparison: NBF and ODRF*

Land use conversion in the Northeastern U.S for grazing animals will likely consist of either open pasture or silvopasture derived from an intact forest due to its widespread coverage in the region. For silvopasture adoption, there will likely be variation amongst farmers who will structure silvopastures based on their specific needs and the NBF and ODRF represent possible forms of New England silvopasture. However, the differences in hydraulic properties between silvopasture and open pasture varied for both the NBF and ODRF and is apparent at different depths. The differences between the sites measured soil hydraulic conductivity properties can be attributed to overall forest age, forest structure, and land use history.

An initial observation between sites is that the magnitude of K(sat) in the reference forest was lower at the NBF than the ODRF. This observation may be due to forest age, where the ODRF contained trees with ages ranging from 80-100 years old whereas the NBF forest contained trees that were approximately 50-60 years old. Older and more developed forests have been shown to have high soil K(sat) which appears to increase with age (Greenwood and Buttle, 2014). A silvopasture that retains trees from an older forest may retain more developed root systems which span a wider area, which in turn, would provide more soil channels and preferential flow paths for soil water flow and higher K(sat). Furthermore, cumulative organic

matter additions from litterfall breakdown over a longer period in more mature forests can lower soil bulk density and mitigate compaction impact (Greacen and Sands, 1980). However, the range of tree ages is also indicative of the land use history of each site prominent factor in soil characteristics. At the NBF, open pasture was prominent until the 1960s before beginning again in 2012 (Orefice et al., 2016). Although reforestation has occurred in the NBF over the last 50-60 years, legacy effects from the previous pasture can persist throughout long periods of time. Greenwood and Buttle, (2014) observed that recovery of hydraulic properties in the near surface soil after pasture in secondary forests could take 40 years or longer to return to undisturbed forest levels. At the NBF, soil water hydraulic channel formation could still be ongoing as the forest ages and develops and this may explain the observation of higher K(sat) in the reference forest and silvopasture in the ODRF compared to the NBF.

The notions of land use history and forest age may also explain how the older ODRF exhibited a significant difference between 'near' and 'far' 15cm K(sat) whereas the NBF did not. Reduced K(sat) across the landscape coupled with a younger forest may limit significant effects by individual trees on nearby soil K(sat) when silvopasture and open pasture are established. However, as the trees age and develop in the NBF silvopasture, the development of tree roots and organic matter accumulation could contribute towards increasing or mitigating decline of K(sat) in the nearby surrounding soil. However, this hypothetical relationship with tree age and K(sat) in nearby soil requires more research.

*Implications for watershed hydrologic services*

In the larger watershed hydrologic cycle, reduction of K(sat) can significantly affect the partitioning of water. Primarily, it increases the risk for saturation-excess overland flow during

high intensity rainfall events where water inputs exceed the K(sat) rate (Bruijnzeel, 2004; Zimmermann et al., 2006; Neary, 2009; Germer et al., 2010). Projections for the Northeastern U.S region predict increases in total annual precipitation via short duration but high intensity storms (Kunkel et al, 2013). An example of this phenomenon did occur at the ODRF on July 23$^{rd}$ 2016 which produced 4.74 cm of rainfall in one hour, exceeding the maximum soil hydraulic rate, 3.6cm hr$^{-1}$ in the 15 cm K(sat), measured in the open pasture. This observation and the regional trend indicates detrimental impacts on the soil surface via from overland flow. The subsequent surface erosion can remove soil and nutrients from the upper horizon, degrading soil (Bruijzneel, 2004; Zimmermann et al., 2006; de Aguiar et al., 2010). Water quality in streams is also a concern with overland flow coming from open pastures and potentially carrying nutrients and erosion sediment across landscapes to streams (de Aguiar et al., 2010).

Additionally, reduced soil hydraulic conductivity and overland flow diverts water from entering groundwater storage, a crucial water resource. For example, groundwater constitutes 60% of freshwater resources in New Hampshire (New Hampshire Department of Environmental Services, 2008). There is also the risk of forming a shallow perched water table, restricting vertical water flow into groundwater sources that reside at deeper depths (Salemi et al., 2009). Though, the soil hydraulic conductivity measured in this study indicates lateral water flow movement, hydraulic properties can significantly vary across a landscape with changes in microtopography (Zimmermann and Elsenbeer, 2008). Therefore, impacts on subsurface water inputs should be heavily considered in land use conversions in the Northeastern U.S, especially considering the region relies on groundwater resources.

In regards to surface water, precipitation diverted from groundwater storage potentially converts to stream runoff faster facilitating high streamflow following precipitation events but baseflows are reduced due to the lack of inputs from groundwater (Bruijnzeel, 2004). This is problematic in areas that rely on surface water resources for consumption or ecological services, due to the reduction in flows during dry periods or seasons (Ogden et al., 2013). In the extensively forested Northeastern region, higher baseflows are prevalent in watersheds due to the high soil infiltration rates with short term high intensity flows mitigated by evapotranspiration. Although the Northeastern U.S region will experience more intense, high rainfall storms, water limitation can occur in during period between storms, consequently exacerbating a landscape scenario with limited soil hydraulic conductivity (Bruijnzeel, 2004; Kunkel et al., 2013). With prospective land use change to agriculture, the potential intermediate structure of silvopasture represents an optimal scenario for maintaining soil hydraulic conductivity near forest soil levels and continued regulation of stream flows.

## Conclusions

Increasing interest to expand agriculture in the Northeastern region of the United States will likely facilitate land use conversion of forest removal. Intact forest has been the dominant hydrologic cycle component in the Northeastern U.S. Replacement of forest with open pasture has been shown to severely reduce soil hydraulic conductivity, increasing the chances of saturation excess overland flow with other hydrologic consequences. However, silvopasture acts as an intermediate between intact forest and open pasture by combining their structures into a hybrid system. In the current study, silvopasture indicated partial evidence of intermediate soil hydraulic conductivity rates between the higher intact forest and the lower open pasture. However, the pattern was not consistent across all depths and both sites. There is some indication that retaining trees for silvopasture may maintain a higher soil hydraulic conductivity and support for a proximity relationship with individual trees is presented in other previous research.

As interest for this land use grows in the Northeastern U.S, the increase in accessible silvopasture at local farms helps address the limitation of available study sites and provide data for the growing practice adoption. Expansion also facilitates more opportunities to study alterations to additional ecohydrologic processes due to land use change and within-silvopasture ecological interactions. Continuing research can work towards optimizing the silvopasture system for the Northeastern U.S region utilizing the concept of optimal tree density to best regulate ecosystem services. Future research will formally characterize the silvopasture system in an ecological context and provide Northeastern U.S farmers with necessary information and advice for their natural resource and land management.

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