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Forest conversion to silvopasture and open pasture: effects on soil hydraulic properties

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Abstract Growing demand for local products in the northeastern U.S. may incentivize forest conversion to pasture, degrading critical soil hydrologic properties such as surface infiltration (K_h) and subsurface saturated hydraulic conductivity (K_{sat}). Silvopasture, combining tree cover and grazing, may mitigate these impacts by maintaining the positive effects of trees on soil hydraulic properties. We tested this hypothesis using an experimental field manipulation to compare effects of forest conversion to open pasture versus silvopasture on K_h and K_{sat} at the Organic Dairy Research Farm (ODRF) and North Branch Farm (NBF). Measurements of surface K_h and K_{sat} at two soil depths (15 cm and 30 cm) were taken 1 and 4 years after treatment establishment at ODRF and NBF, respectively. Data were analyzed using a mixed effects modeling framework. Results show 15 cm K_{sat} was significantly lower in pasture compared to forest across both sites. However, in contrast to our hypothesis, soil hydraulic properties in silvopasture did not differ from other treatments at either site. Notwithstanding, silvopasture 15 cm K_{sat} at ODRF (9.4 cm h^{-1}) was statistically similar to both the forest (22.6 cm h^{-1}) and pasture (3.4 cm h^{-1}) and exhibited a weak positive correlation with proximity to trees (R^2 = 0.219, P = 0.042). In conclusion, our study did not find strong evidence that recently established silvopastures mitigate negative hydrologic impacts of forest conversion. Future research should focus on a broader range of northeastern sites and include greater replication over longer time scales to better elucidate opportunities for silvopasture.

Keywords Agroforestry · Infiltration · Conductivity · Land use change · Pasture · Grazing

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Introduction

The landscape of the northeastern region of the U.S. is heavily forested and many of the region's farm lands contain a high proportion of tree cover (Foster et al. 2008; Nowak and Greenfield 2012). For example, in the northern tier of northeastern states (i.e., the six New England states and New York) the proportion of total farmland classified as "woodland" ranges from approximately 22% to over 60% (USDA NASS 2012). Hence, farms in this region have access to substantial areas of forested land and the ecosystem services they provide (Hale et al. 2014). At the same time, regional forest area has been declining since the 1980s (Olofsson et al. 2016), and projected trends in population growth combined with increasing demand for locally produced agricultural products may contribute to the expansion of agriculture in the region, particularly in the form of pasture and forages for livestock production (Chedzoy and Smallidge 2011; Donahue et al. 2014). These trends, in tandem with new policy initiatives aimed at incentivizing the conversion of forested farmlands into productive agricultural uses could impact the ecosystem services that forested lands provide to the region (Donahue et al. 2014).

Forests maintain important ecosystem services including hydrologic services such as high water quality and regulated water flows (Neary et al. 2009). Converting forests to agricultural land uses can alter these hydrologic processes (Beven and Germann 1982; Bruijnzeel 2004), particularly through impacts on soil water hydraulic properties, which play a critical role in regulating hydrologic flows (Lal 1996; Bruijnzeel 2004; Horel et al. 2015). For instance, conversion of forest to open pasture can lead to soil compaction and reduced soil hydraulic conductivity due to heavy machinery use, livestock trampling, replacement of deep-rooted trees with shallow-rooted grasses, and reduced abundance of soil macrofauna that facilitate macropore formation (Lal 1996; Greenwood and McKenzie 2001; Bruijnzeel 2004; Zimmermann et al. 2006, 2010). Tree removal can be especially detrimental to hydrologic functions since trees contribute to maintaining soil hydraulic conductivity through their extensive root systems (Kumar et al. 2010; Jose et al. 2019) and positive impacts of soil organic matter inputs from leaf litter and fine root turnover on soil structure and porosity (Neary et al. 2009). The spatial distribution of these soil properties has been shown in some systems to be strongly correlated to the proximity to individual trees (Benegas et al. 2014; Niemeyer et al. 2014; Ilstedt et al. 2016; Lunka and Patil 2016).

Silvopasture is an agroforestry system that intentionally integrates livestock, forages, and trees on the same unit of land (Jose and Dollinger 2019). Silvopasture systems are often considered as more sustainable and diversified alternatives to open pasture, due to their capacity to produce multiple goods (e.g., timber, fuelwood, and/or non-timber forest products such as maple syrup, tree fruits, and mast) and ecosystem services (e.g., carbon sequestration, microclimate regulation, soil erosion control, and wildlife habitat) (Chedzoy and Smallidge 2011; Jose and Dollinger 2019). Silvopasture has been implemented across the U.S., utilizing a variety of tree and forage combinations (Fike et al. 2004; Sharrow et al. 2009; Arbuckle et al. 2009; Feldhake et al. 2010); however, the ecology and management of silvopasture in the northeastern U.S. has only recently been explored (Orefice et al. 2017). Silvopasture presents a uniquely promising land use in this region because it combines two dominant sectors of the local economy—timber and livestock production, and can also be successfully established on the shallow and relatively rocky forested soils prevalent throughout the northeastern U.S. (Foster et al. 2008; Chedzoy and Smallidge 2011). Moreover, a recent study found strong interest among the region's farmers in converting forest to silvopasture as a diversified land use practice, and identified a perceived lack of information about the management and ecology of silvopasture as a major obstacle to its broad implementation (Orefice et al. 2017).

The trees integrated into silvopasture in the northeastern region of the U.S could play an important role in regulating soil hydrologic processes (Bruijnzeel 2004). While studies elsewhere have documented the effects of trees on soil hydraulic properties in silvopasture and other grazing land uses (Benegas et al. 2014; Lunka and Patil 2016; Ilstedt et al. 2016; Chandler et al. 2018), these relationships have not been extensively explored in the heterogeneous, mixed species forests of the northeastern U.S. (Chedzoy and Smallidge 2011; Orefice et al. 2017, 2019). To address this knowledge gap, we quantified the impacts of forest conversion to silvopasture and open pasture on two key soil properties related to hydrologic functioning: surface unsaturated hydraulic conductivity (K_h) and subsurface saturated hydraulic conductivity (K_{sat}). A second objective was to evaluate how soil hydraulic properties vary with distance from trees within a silvopasture. We hypothesized that (1) soil hydraulic conductivity rates following forest conversion to silvopasture would be greater than forest conversion to open pasture and more similar to forest, and (2) within silvopastures, variation in soil hydraulic properties across sampling locations would be spatially correlated with proximity to trees.

Methods

Study site: ODRF

The first of two study sites was the University of New Hampshire's Organic Dairy Research Farm (ODRF) in Durham, NH (43.09° N, − 70.99 W). This site has a 30-year (1981–2010) mean annual precipitation of 1220 mm and temperature of 8.2 °C (Arguez et al. 2012). Soils are classified as Hollis-Charlton fine sandy loam on mild slopes. The forest at ODRF consists of an 85-year old mixed species stand of eastern hemlock (*Tsuga canadensis* (L.) Carriére), white pine (*Pinus strobus* L.), red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), shagbark hickory (*Carya ovata* (Mill.) K. Koch), red maple (*Acer rubrum* L.), and black birch (*Betula lenta* L.). The study area was likely managed for grazing and pasture from the 1700s until the 1930s (Butterfield 2016), after which agricultural activities ceased and the area reverted back to forest (Foster et al. 2008). Three treatments, reference forest (hereafter 'forest'), open pasture, and silvopasture, were randomly assigned to three 1-hectare, 50 × 200 m rectangular plots, adjacent to each other along their 200 m edges. The open pasture and silvopasture were established during the fall and winter of 2015. Whole tree harvest with a skid steer was used to clear trees for the open pasture and to thin trees for the silvopasture, with remaining slash spread across the site using a FECON chipper in the spring of 2016. Silvopasture trees were thinned to 50% canopy coverage, reducing the basal area from 50 to 25 m^2 ha^{-1}. Retained silvopasture trees consisted of 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 of other broad-leaved deciduous species. Mean diameter of trees was 28.5 cm. Orchard grass (*Dactylis glomerata* L.) was seeded for forage immediately following treatment establishment and again in spring 2017 in both the open pasture and silvopasture plots. Following seeding, a herd of ten heifers was allowed to graze within 15 × 100 m fenced sections of the open pasture and silvopasture simultaneously for 1-week periods to assist in soil scarification. Weekly, heifers were moved sequentially in 15 × 100 m sections starting at one end of the treatment plots and moving across the entire 1-hectare treatment area. The grazing intensity was calculated as 1.42 head ha^{-1} day^{-1} $year^{-1}$. Hay bales were evenly distributed in the plots to compensate for low forage cover and to promote cattle movement within the entire fenced section. Each 1-ha plot was subdivided from east to west into five blocks to account for within-plot topographic variation and were considered pseudoreplicates for subsequent analyses. Soil hydraulic conductivity measurements (15 points) and soil core collection (10 points) were conducted in each of these blocks. In the silvopasture plot, distance to the nearest tree (m) was recorded for each soil hydraulic conductivity measurement location.

Study site: NBF

The second study site was the North Branch Farm (NBF) in Saranac, NY (44.59° N, − 73.89 W). The NBF site has a mean annual precipitation of 1056 mm and temperature of 6.7 °C for the 30 year climate normal (1981–2011, Arguez et al. 2012). The soils are predominantly classified as Monadnock fine sandy loam on moderate slopes. NBF was maintained for cattle grazing on open pasture up until the 1960 s, and following abandonment reverted to northern hardwood mixed forest until a recent farm conversion in 2012 (Orefice et al. 2019). Dominant tree species include black cherry (*Prunus serotina* Ehrh.), white ash (*Fraxinus americana* L.), red maple, apple (*Malus* spp.), sugar maple (*Acer saccharum* Marshall), paper birch (*Betula papyrifera* Marshall), aspen (*Populus* spp.), American elm (*Ulmus americana* L.), and American basswood (*Tilia americana* L.). The forest was converted to replicated silvopasture and open pasture treatments in July 2012 (see Orefice et al. 2019 for details). Each treatment was replicated three times on 1/3-hectare plots. Whole tree harvest was used to establish open pasture and thinning was used to establish silvopasture from forest conversion, reducing basal area by 63%, from 19 to 7 m^2 ha^{-1}. Silvopasture trees consisted of black cherry (2.6 m^2 ha^{-1}), red maple (1.3 m^2 ha^{-1}), and white ash (1.2 m^2 ha^{-1}). Mean tree diameter was 15.5 cm. Orchard grass was the dominant species at the time of this study and was originally seeded in 2012 in both the silvopasture and open pasture treatments. Twenty beef cattle including calves grazed silvopasture and open pasture forage grasses down to a height of 5 cm beginning in August 2013 for 1.5–3 days over 2–3 periods each summer for a mean of 2.96 cattle head ha^{-1} day^{-1} $year^{-1}$. Soil hydraulic measurements were conducted in situ during 2016 using a blocking scheme for slope, consisting of three equal size blocks (i.e., upper, middle, lower slope) within each treatment plot, and two sample locations within each block (six per plot). Similar to ODRF, distance to the nearest tree in the silvopasture plot was recorded for each soil hydraulic conductivity measurement. Additionally, soil cores were collected in the summer of 2017, whereby three cores at three depths (0–10 cm, 10–20 cm, 20–30 cm) were taken from each block within each treatment plot and across all replicated treatment plots and transported to the University of New Hampshire for further analysis.

Samples and measurements

Saturated hydraulic conductivity (K_{sat}) was measured using a compact constant head permeameter or Amoozemeter (K_{sat} Inc. Raleigh, NC; Amoozegar 1989; Reynolds 2013). At each sample location, we bored two, 2.5 cm radius holes to 15 cm and 30 cm depths. Under a constant hydraulic pressure, water outflow rates were measured in intervals until soil saturation and a steady state flow was achieved. K_{sat} was then calculated using the steady state flow rate and the Glover solution (Eq. 1):

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

where 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).

Unsaturated hydraulic conductivity (K_h) was calculated from the measured cumulative infiltration using a Minidisk Tension Infiltrometer (MDI) (Decagon Devices, Inc.) at the soil surface. Cumulative infiltration (*I*) is fit to Eq. (2) (Zhang 1997),

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

where 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 the slope of the curve generated by plotting measurements of *I* versus the square root of time and is used to calculate unsaturated hydraulic conductivity (K_h) with Eq. (3),

$$K_h = \frac{C_1}{A} \tag{3}$$

The value *A* is calculated from the relationship between van Genuchten parameters for a specific soil retention curve and the suction setting of the MDI (Zhang 1997). A 2 cm suction setting was used for all K_h measurements.

At ODRF, a slide hammer soil corer was used to extract soil samples at depths of 0–15 cm and 15–30 cm. At NBF, a gas-powered soil corer was used to collect soil cores in increments from 0 to 10 cm, 10–20 cm, and 20–30 cm. After sampling, soil cores were dried in an oven for 24 h at 105 °C. A 2 mm sieve was used to remove rocks and debris. The mass of dry soil for all samples was divided by the volume of the corresponding soil corer to calculate bulk density. Particle size analysis based on Stokes' Law was used to determine the percentage of sand, silt, and clay.

Statistical analysis

We used ANOVA within a mixed effects modeling framework to examine differences in soil physical and hydraulic properties among forest, open pasture, and silvopasture treatments, conducting separate statistical analyses for ODRF and NBF due to differences in land use history and forest species composition. Response variables at both farms were soil bulk density, texture, K_{sat}, and K_h, resulting in eight separate ANOVA models per farm for each measured variable. Due to the lack of replication at ODRF, the blocking scheme within each treatment was used as the pseudoreplicated experimental unit (n = 5) to test for differences among treatments and soil depths in soil physical and hydraulic properties, where land use treatment and soil depth were defined as a fixed effects and block was defined as a random effect in each ANOVA model. At NBF, which included replicated plots, land use treatment and soil depth were defined as the fixed effects and blocks nested within replicated plots as the random effect.

We used linear regression within a mixed modeling framework to assess changes in the soil hydraulic properties K_{sat} and K_h as a function of distance from tree within the silvopasture plots of ODRF and NBF. We ran separate models for each farm and for both the ODRF and NBF models distance from tree was identified as the fixed effect. The ODRF model specified block as the random effect while the NBF specified block nested within plot as the random effect structure. All data were log-transformed and residual plots checked to assure conformity to normal distributions for all statistical tests; however, figures, means, and error values are presented as untransformed for ease of visualization and interpretation. Treatment effects were considered significant at an alpha value of 0.05 and marginal at 0.10. Pairwise differences between the means of the independent variables (i.e., bulk density, texture, K_h, and K_{sat}) by treatment and soil depth classes were assessed using a Tukey–Kramer post hoc HSD test. All statistical tests were performed in R (R Core Team 2017).

Results

Physical properties

There were no significant differences in soil bulk density or texture between land use treatments at either ODRF or NBF (Table 1). Across both sites, depth was a significant factor for bulk density which increased with depth, but there was no significant interaction with depth and treatment. Soil texture composition (percent sand, silt, and clay) was also statistically similar between treatments at both sites but also varied with depth. At both sites, percent sand decreased and percent silt increased with depth, but percent clay did not vary with depth. In general, NBF soils were much sandier than ODRF soils with approximately 30% more sand content at NBF.

Table 1 Soil physical properties of bulk density and soil texture composition

Site	Depth	Measurement	Forest	Silvopasture	Open pasture
ODRF	0–15 cm	Bulk density (g cm^{-3})	0.54	0.54	0.65
		Sand (%)	57.20	61.83	64.83
		Silt (%)	27.27	24.70	21.70
		Clay (%)	15.53	13.47	13.47
	15–30 cm	Bulk density (g cm^{-3})	0.79	0.78	0.83
		Sand (%)	62.67	70.87	71.00
		Silt (%)	20.80	16.63	14.23
		Clay (%)	16.53	12.50	14.77
NBF	0–10 cm	Bulk density (g cm^{-3})	0.80	0.81	0.83
		Sand (%)	92.28	92.65	92.86
		Silt (%)	1.42	1.16	0.84
		Clay (%)	6.30	6.18	6.30
	10–20 cm	Bulk density (g cm^{-3})	0.95	0.97	1.14
		Sand (%)	91.81	91.97	92.53
		Silt (%)	0.92	0.82	0.68
		Clay (%)	7.28	7.22	6.79
	20–30 cm	Bulk density (g cm^{-3})	1.07	1.30	1.08
		Sand (%)	91.94	91.67	91.67
		Silt (%)	0.97	0.92	1.00
		Clay (%)	7.10	7.41	7.33

There were no significant differences between land use treatments and therefore no denotations

Hydraulic properties

At ODRF, we observed a significant treatment effect on K_{sat} at 15 cm (ANOVA: F = 11.778, $P = 0.007$), where the forest was significantly higher compared to the open pasture by nearly sevenfold ($P = 0.005$). K_{sat} at 15 cm was intermediate in the silvopasture relative to the forest and open pasture treatments; however, these differences were not significant ($P > 0.05$) (Fig. 1). There were no significant differences for surface K_h or for K_{sat} at 30 cm between treatments ($P > 0.05$, Fig. 1).

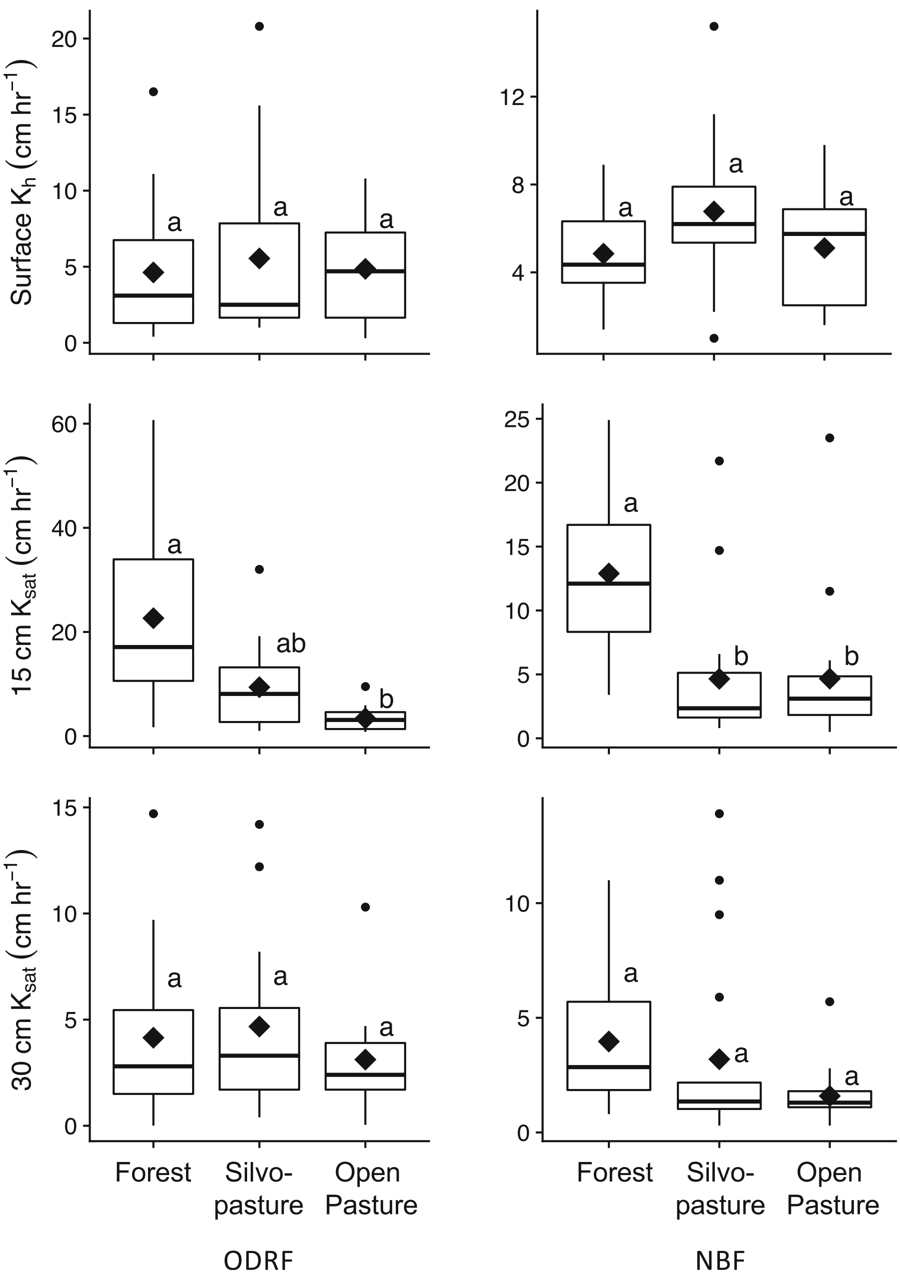

Fig. 1 Soil hydraulic properties measured at ODRF and NBF with boxes representing the 25th and 75th quartile range, horizontal lines in the boxes representing the median, diamonds represent the mean, whiskers represent 1.5 times the interquartile range, and outliers shown as circles. Different letters denote significant differences ($P < 0.05$)

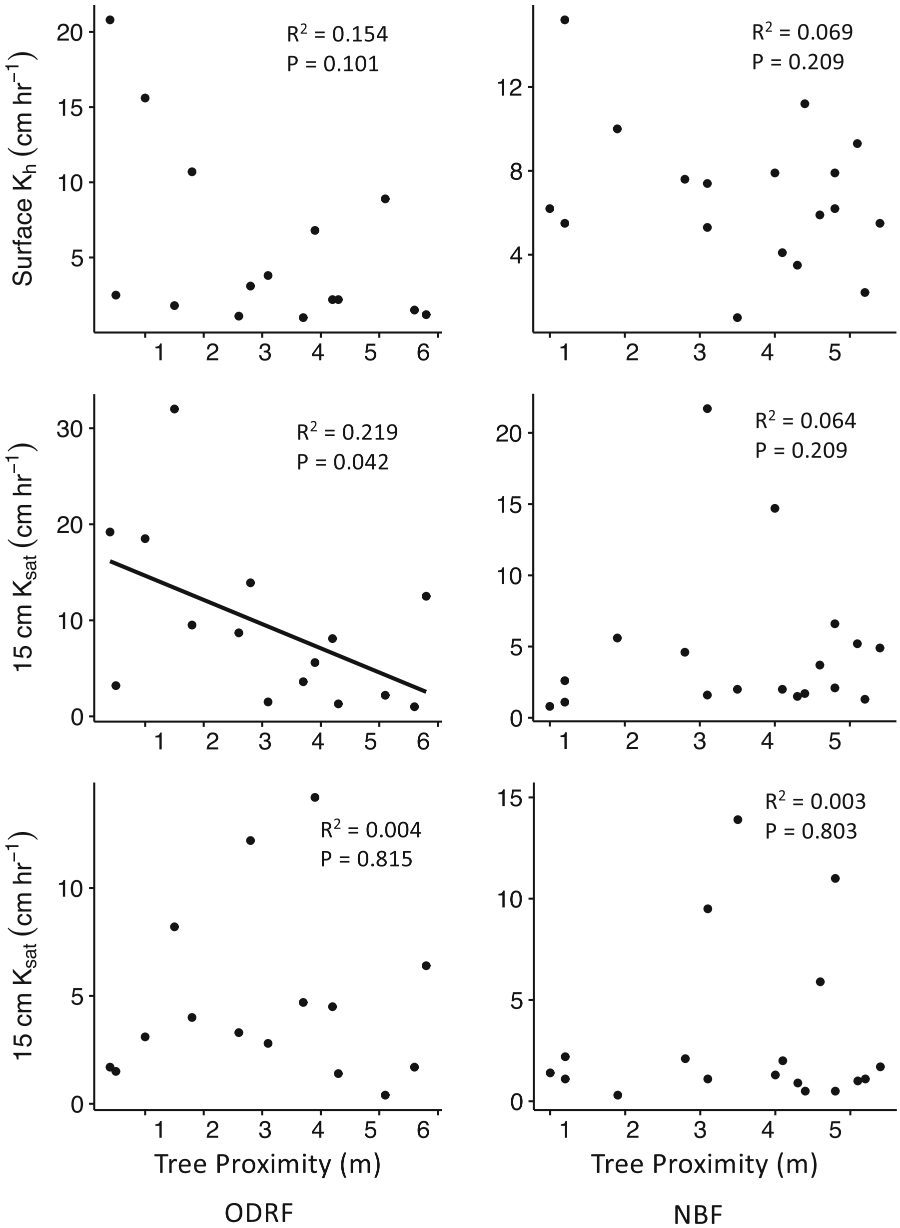

Fig. 2 Soil hydraulic properties as a function of distance to the nearest tree measured in the silvopasture treatments at ODRF and NBF

At NBF, K_{sat} at 15 cm also varied among treatments (ANOVA: F = 10.949, P = 0.001); however, in contrast to the ODRF, values in the forest were nearly threefold higher compared to both the silvopasture (P = 0.015) and open pasture (P = 0.017) treatments. There was no difference in K_{sat} at 15 cm between the silvopasture and open pasture treatment (Fig. 1). A marginal treatment effect was observed for K_{sat} at 30 cm (ANOVA: F = 3.510, P = 0.098), where values were higher for the forest compared to the open pasture (P = 0.090). There was no significant treatment effect for surface K_h (Fig. 2).

Spatial relationship between silvopasture trees and soil hydraulic properties

For silvopasture at ODRF, we observed a significant decrease in 15 cm K_{sat} over the distance of 0.5 m to 6 m from an individual tree (R^2 = 0.219, Slope = − 2.267, F = 4.838, P = 0.047) (Fig. 2). Soil nearest to individual tree stems had threefold higher 15 cm K_{sat} than soil at the furthest distance. However, there were no significant relationships with tree proximity for surface K_h or 30 cm K_{sat} in ODRF (Fig. 2) and no clear relationships with tree proximity for any measured variables in NBF silvopasture.

Discussion

Our study did not show strong evidence that newly converted silvopastures retain some of the hydrologic properties of forests. The strongest treatment effect we observed was for 15 cm K_{sat} which was at most sevenfold lower in the open pasture compared to the forest at both sites. Additionally, the lack of any strong patterns in 30 cm K_{sat} or K_h at both sites suggests that shallow soil horizons may be more sensitive to impacts of land use conversion. This result is consistent with other studies that have examined the effects of conversion of forest to open pasture (Lal 1996; Zimmermann et al. 2006, 2010, Scheffler et al. 2011, Horel et al. 2015). For example, Scheffler et al. (2011) observed that K_{sat} at 12.5 cm was significantly greater in a mixed tropical mature forest compared to an open pasture 25 years following conversion from the previous forest cover. Similarly, in their review documenting the effect forest conversion to open-pasture land use change on soil hydraulic properties, Horel et al. (2015) concluded that K_{sat} was often higher in original forest compared to open pasture, primarily due to the reduction in macropore abundance following the conversion from forest to open pasture.

Overall, we did not find support for our first hypothesis, as conversion of forest to silvopasture did not show significantly more positive soil hydraulic properties compared to open pasture across study sites or soil depths, although at one site (ODRF) silvopasture and forest 15 cm K_{sat} were similar. The lack of a clear differentiation between silvopasture and open pasture and a lack of indication from forest conversion to silvopasture to mitigate reduction of soil hydraulic conductivity deviates from the findings of previous research conducted in other regions. For example, de Aguiar et al. (2010) showed that soil hydraulic conductivity in a silvopasture was similar to that of a natural forest approximately 6 years post conversion and contributed to lower erosional water losses than open pastures. Likewise, Ilstedt et al. (2016) reported that pastures with trees exhibited higher groundwater recharge relative to open pastures, and that groundwater recharge was optimized at intermediate tree cover, reinforcing the idea that integrated tree-grass systems such as silvopasture can enhance hydrologic functions. Our results, especially at NBF, were more consistent with those reported by Sharrow (2007) and Lunka and Patil (2016) demonstrating that infiltration rates were lower in silvopasture compared to a forest and higher density tree clumps, respectively, and more similar to an open pasture. However, in both Sharrow (2007) and Lunka and Patil (2016), the forest and silvopasture were established by planting trees on an open pastures 12 and 22 years earlier, respectively which could explain their reduced K_{sat} compared to forests. By contrast, the age of our forests (85 years for ODRF and 50-years for NBF) and the forested land use prior to conversion to silvopasture would suggest that newly converted silvopastures would retain some of the soil hydraulic properties of the pre-treatment forest. The fact that they did not indicates that other physical and temporal factors may affect K_{sat} comparisons between treatments. Long-term monitoring over time since conversion at both NBF and ODRF silvopasture could show changes in K_{sat} consistent with trends in afforestation and forest development (Ilstedt et al. 2007; Greenwood and Buttle 2014).

Our findings at ODRF provided marginal support for our second hypothesis, that soil hydraulic properties within the silvopasture conversion would vary with distance from trees. The weak positive correlation between K_{sat} at 15 cm and distance to tree at ODRF is consistent with Benegas et al. (2014), which showed higher K_{sat} and more preferential flow paths near trees, due to more abundant tree roots providing subsurface macropores, as well as higher soil organic matter near trees enhancing soil water flow. Similarly, Kumar et al. (2010, 2012) observed higher water infiltration rates in agroforestry buffers compared to pasture, which was associated with greater root length density and improved soil structure and carbon content. Alternatively, given the short time since conversion at ODRF, it is also conceivable that machine operators avoided trees when implementing the thinning treatment, which may have reduced the degree of compaction near trees by heavy machinery that typically occurs during logging operations (Greacen and Sands 1980; Xu et al. 2002). Furthermore, we did not observe any significant relationships between tree proximity and soil hydraulic properties at NBF, suggesting that trees do not confer universal soil K_{sat} benefits in silvopastures.

Several factors may help explain the different patterns observed between the two study sites regarding the relationship between tree proximity and K_{sat} at 15 cm. Both Bezkorowajnyj et al. (1993) and Chandler et al. (2018) reported that grazing of livestock can mask the potential influence of trees on soil hydraulic properties. At NBF, grazing occurred over 4 years versus 1 year at ODRF and grazing intensity was greater at NBF (2.96 cattle head ha^{-1} day^{-1} $year^{-1}$) compared to ODRF (1.42 cattle head ha^{-1} day^{-1} $year^{-1}$), potentially increasing soil compaction and reducing K_{sat} compared to ODRF. The grazing history also varied between the two study sites, occurring more recently at NBF (the open pasture was abandoned 50 years ago), compared to ODRF (grazing was abandoned 80–90 years ago), affecting forest development and possibly preventing the recovery of soil hydraulic properties to pre-disturbance forest levels. Greenwood and Buttle (2014) estimated that 40–80 years of reforestation were required to fully restore soil Ksat in open pasture to levels typical of undisturbed forest. The larger tree size at ODRF (28.5 cm) compared to NBF (15.5 cm) also indicates this forest development difference in addition to the difference in basal area between sites, which was reduced by 63% at NBF compared to only 50% at ODRF. These differences may indicate a less pronounced impact of trees on soil hydraulic properties at NBF silvopasture and woody biomass coverage has been shown to be positively correlated with soil K_{sat} (Niemeyer et al. 2014). Consequently, the lack of a spatial correlation between soil hydraulic properties and tree proximity at NBF may, in part, reflect the combined effects of a lower recovery time, the younger age of the trees, and the lower tree density at this site.

While our current study provides new insights into the differences in soil hydraulic impacts from conversion of forest to silvopasture compared to conversion of forest to open pasture, it is important to note our study limitations. Treatments at the ODRF site lacked replication and were pseudoreplicated through blocking units, which limited our ability to make statistical inferences. The high variability of soil hydraulic conductivity measurements also created challenges for detecting differences between treatments and a more intensive sampling scheme within plots could help elucidate potential differences. Finally, differences in site conditions, land use history, and treatment implementation at the two study sites, as discussed above, also limited our ability to draw broader conclusions and speculation on silvopasture designs. To better evaluate how landscape characteristics and time factor into conversion of forest to silvopasture, impacts on soil hydrology, further research should include sites with a range of durations since conversion and forest species compositions, particularly in heterogeneous landscapes such as the northeastern U.S. Additionally, future studies should consider the spatial relationship between trees and soil physical properties to better understand how silvopastures can be designed to maximize the potential benefits of trees in these systems.

Conclusions

The lack of differences in soil hydraulic properties between forest conversions to silvopasture and open-pasture, especially at NBF, indicates that silvopasture does not universally mitigate the negative impacts of grazing on soil properties such as compaction. The similarity of 15 cm K_{sat} in the silvopasture to both the open pasture and forest, together with the weak correlation between 15 cm K_{sat} and tree proximity at ODRF, is suggestive of a potential ameliorative effect of silvopasture on the reduction of soil hydraulic properties following forest conversion; however, more long-term monitoring is needed to further elucidate these patterns. Factors including land use history, forest age, and grazing density, all of which differed between study sites, may have played a role in shaping the soil hydraulic properties of these newly created silvopastures. While this study presents mixed results and was based on a small number of sample sites with limited replication, it nevertheless provides important initial insights into how soil hydraulic properties might change given land use conversion from northeastern U.S forests to grazing land uses. As interest in adoption of silvopasture systems grows in the region, additional research on long-term experiments conducted at a diversity of sites will be critical to better evaluate the effects of conversion of forest to silvopasture on larger hydrologic processes, optimize potential silvopasture designs and management strategies, and provide further technical assistance to farmers looking to minimize impacts of land use conversion.

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References

Amoozegar A (1989) A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone. Soil Sci Soc Am J 53:1356–1361. https://doi.org/10.2136/sssaj1989.03615995005300050064x

Arbuckle JG, Valdivia C, Raedeke A et al (2009) Non-operator landowner interest in agroforestry practices in two Missouri watersheds. Agrofor Syst 75:73–82. https://doi.org/10.1007/s10457-008-9131-8

Arguez A, Durre I, Applequist S et al (2012) NOAA's 1981–2010 U.S. climate normals: an overview. Bull Am Meteorol Soc 93:1687–1697. https://doi.org/10.1175/BAMS-D-11-00197.1

Benegas L, Ilstedt U, Roupsard O et al (2014) Effects of trees on infiltrability and preferential flow in two contrasting agroecosystems in Central America. Agric Ecosyst Environ 183:185–196. https://doi.org/10.1016/j.agee.2013.10.027

Beven K, Germann P (1982) Macropores and water flow in soils. Water Resour Res 18:1311–1325. https://doi.org/10.1029/WR018i005p01311

Bezkorowajnyj PG, Gordon AM, McBride RA (1993) The effect of cattle foot traffic on soil compaction in a silvo-pastoral system. Agrofor Syst 21:1–10. https://doi.org/10.1007/BF00704922

Bruijnzeel LA (2004) Hydrological functions of tropical forests: not seeing the soil for the trees? Agric Ecosyst Environ 104:185–228. https://doi.org/10.1016/j.agee.2004.01.015

Butterfield M (2016) The Land in Our Hands-Burley-Demeritt Farm in Lee, NH: Its History. Lulu.com, Morrisville

Chandler KR, Stevens CJ, Binley A, Keith AM (2018) Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation. Geoderma 310:120–127. https://doi.org/10.1016/j.geoderma.2017.08.011

Chedzoy B, Smallidge P (2011) Silvopasturing in the Northeast an introduction to opportunities and strategies for integrating livestock in private woodlands. Cornell Coopertive Extension, New York

de Aguiar MI, Maia SMF, de Sá Xavier FA et al (2010) Sediment, nutrient and water losses by water erosion under agroforestry systems in the semi-arid region in northeastern Brazil. Agrofor Syst 79:277–289. https://doi.org/10.1007/s10457-010-9310-2

Donahue B, Burke J, Anderson M et al (2014) A new england food vision. http://www.foodsolutionsne.org/new-england-food-vision. Accessed 30 July 2019

Feldhake CM, Neel JPS, Belesky DP (2010) Establishment and production from thinned mature deciduous-forest silvopastures in Appalachia. Agrofor Syst 79:31–37. https://doi.org/10.1007/s10457-010-9289-8

Fike JH, Buergler AL, Burger JA, Kallenbach RL (2004) Considerations for establishing and managing silvopastures forage and grazinglands forage and grazinglands. Plant Manag Netw. https://doi.org/10.1094/FG-2004-1209-01-RV

Foster DR, Donahue B, Kittredge D et al (2008) New England's forest landscape ecological legacies and conservation patterns shaped by agrarian history. In: Redman CL, Foster DR (eds) Agrarian landscapes in transition: comparisons of long-term ecological and cultural change. Oxford University Press, New York, pp 44–88

Greacen E, Sands R (1980) Compaction of forest soils. A review. Aust J Soil Res 18:163. https://doi.org/10.1071/SR9800163

Greenwood WJ, Buttle JM (2014) Effects of reforestation on near-surface saturated hydraulic conductivity in a managed forest landscape, southern Ontario, Canada. Ecohydrology 7:45–55. https://doi.org/10.1002/eco.1320

Greenwood KL, McKenzie BM (2001) Grazing effects on soil physical properties and the consequences for pastures: a review. Aust J Exp Agric 41:1231–1250. https://doi.org/10.1071/EA00102

Hale I, Wollheim W, Smith R et al (2014) A scale-explicit framework for conceptualizing the environmental impacts of agricultural land use changes. Sustainability 6:8432–8451. https://doi.org/10.3390/su6128432

Horel Á, Tóth E, Gelybó G et al (2015) Effects of land use and management on soil hydraulic properties. Open Geosci 7:742–754. https://doi.org/10.1515/geo-2015-0053

Ilstedt U, Malmer A, Verbeeten E, Murdiyarso D (2007) The effect of afforestation on water infiltration in the tropics: a systematic review and meta-analysis. For Ecol Manag 251:45–51. https://doi.org/10.1016/j.foreco.2007.06.014

Ilstedt U, Bargués Tobella A, Bazié HR et al (2016) Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Sci Rep 6:21930. https://doi.org/10.1038/srep21930

Jose S, Dollinger J (2019) Silvopasture: a sustainable livestock production system. Agrofor Syst 93:1–9. https://doi.org/10.1007/s10457-019-00366-8

Jose S, Walter D, Mohan Kumar B (2019) Ecological considerations in sustainable silvopasture design and management. Agrofor Syst 93:317–331. https://doi.org/10.1007/s10457-016-0065-2

Kumar S, Udawatta RP, Anderson SH (2010) Root length density and carbon content of agroforestry and grass buffers under grazed pasture systems in a Hapludalf. Agrofor Syst 80:85–96. https://doi.org/10.1007/s10457-010-9312-0

Kumar S, Anderson SH, Udawatta RP, Kallenbach RL (2012) Water infiltration influenced by agroforestry and grass buffers for a grazed pasture system. Agrofor Syst 84:325–335. https://doi.org/10.1007/s10457-011-9474-4

Lal R (1996) Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. III. Runoff, soil erosion and nutrient loss. L Degrad Dev 7:99–119. https://doi.org/10.1002/(SICI)1099-145X(199606)7:2%3c99:AID-LDR220%3e3.0.CO;2-F

Lunka P, Patil SD (2016) Impact of tree planting configuration and grazing restriction on canopy interception and soil hydrological properties: implications for flood mitigation in silvopastoral systems. Hydrol Process 30:945–958. https://doi.org/10.1002/hyp.10630

Neary DG, Ice GG, Jackson CR (2009) Linkages between forest soils and water quality and quantity. For Ecol Manag 258:2269–2281. https://doi.org/10.1016/j.foreco.2009.05.027

Niemeyer RJ, Fremier AK, Heinse R et al (2014) Woody vegetation increases saturated hydraulic conductivity in dry tropical Nicaragua. Vadose Zo J. https://doi.org/10.2136/vzj2013.01.0025

Nowak DJ, Greenfield EJ (2012) Tree and impervious cover in the United States. Landsc Urban Plan 107:21–30. https://doi.org/10.1016/j.landurbplan.2012.04.005

Olofsson P, Holden CE, Bullock EL, Woodcock CE (2016) Time series analysis of satellite data reveals continuous deforestation of New England since the 1980s. Environ Res Lett 11:064002. https://doi.org/10.1088/1748-9326/11/6/064002

Orefice J, Carroll J, Conroy D, Ketner L (2017) Silvopasture practices and perspectives in the Northeastern United States. Agrofor Syst 91:149–160. https://doi.org/10.1007/s10457-016-9916-0

Orefice J, Smith RG, Carroll J et al (2019) Forage productivity and profitability in newly-established open pasture, silvopasture, and thinned forest production systems. Agrofor Syst 93:51–65. https://doi.org/10.1007/s10457-016-0052-7

R Core Team (2017) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Reynolds WD (2013) An assessment of borehole infiltration analyses for measuring field-saturated hydraulic conductivity in the vadose zone. Eng Geol 159:119–130. https://doi.org/10.1016/j.enggeo.2013.02.006

Scheffler R, Neill C, Krusche AV, Elsenbeer H (2011) Soil hydraulic response to land-use change associated with the recent soybean expansion at the Amazon agricultural frontier. Agric Ecosyst Environ 144:281–289. https://doi.org/10.1016/j.agee.2011.08.016

Sharrow SH (2007) Soil compaction by grazing livestock in silvopastures as evidenced by changes in soil physical properties. Agrofor Syst 71:215–223. https://doi.org/10.1007/s10457-007-9083-4

Sharrow SH, Brauer D, Clason TR, Garrett HEG (2009) Silvopastoral practices. In: Garrett HEG (ed) North American agroforestry: an integrated science and practice, 2nd edn. American Society of Agronomy, Madison, pp 105–131

USDA NASS (2012) Census of agriculture New Hampshire state and county data. https://www.nass.usda.gov/Publications/AgCensus/2012. Accessed 1 May 2017

Xu Y-J, Burger JA, Michael Aust W et al (2002) Changes in surface water table depth and soil physical properties after harvest and establishment of loblolly pine (*Pinus taeda* L.) in Atlantic coastal plain wetlands of South Carolina. Soil Tillage Res 63:109–121. https://doi.org/10.1016/S0167-1987(01)00226-4

Zhang R (1997) Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Sci Soc Am J 61:1024–1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x

Zimmermann B, Elsenbeer H, De Moraes JM (2006) The influence of land-use changes on soil hydraulic properties: implications for runoff generation. For Ecol Manag 222:29–38. https://doi.org/10.1016/j.foreco.2005.10.070

Zimmermann B, Papritz A, Elsenbeer H (2010) Asymmetric response to disturbance and recovery: changes of soil permeability under forest–pasture–forest transitions. Geoderma 159:209–215. https://doi.org/10.1016/j.geoderma.2010.07.013