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Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA

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SUMMARY

A full understanding of hydrologic response to human impact requires assessment of land-use impacts on key soil physical properties such as saturated hydraulic conductivity, bulk density, and moisture retention. Such properties have been shown to affect watershed hydrology by influencing pathways and transmission rates of precipitation to stream networks. Human land use has been shown to influence these soil physical properties as a result of erosion, compaction, and pore structure evolution. Our objective was to characterize soil physical properties under three land-use classes (forest, pasture, and managed lawn) in the southern Blue Ridge Mountains of southwestern North Carolina. A total of 90 points were sampled (30 in each land-use class) throughout a 983 km^2 study area. Saprolitic and alluvial soils were emphasized, and sites were selected that showed consistent land-use history over a period of at least 30 years. Particle size distribution, in situ saturated hydraulic conductivity (measured using an Amoozemeter compact constant head permeameter), bulk density, and volumetric moisture content at field capacity were measured at each point. Forest soils demonstrated markedly lower bulk densities and higher infiltration rates, and water holding capacities, than lawn and pasture soils. No soil property significantly differed between pasture and lawn. Mean values for each property were as follows (forest = F, lawn = L, pasture = P): saturated hydraulic conductivity (mm h^{-1}) – F = 63, L = 7, P = 8; bulk density (g cm^{-3}) – F = 0.8, L = 1.2, P = 1.2; volumetric moisture content (%) – F = 72%, L = 42%, P = 39%. Particle size distributions did not significantly differ among land-use classes or parent materials, and the differences between the hydraulic properties of forest vs. nonforest soils were attributed to compaction associated with land management practices. The magnitudes of differences between forest and nonforest infiltration rates suggest that widespread conversion of forest to other land uses in this region will be accompanied by decreased infiltration and increased overland flow, potentially significantly altering water budgets and leading to reduced baseflows and impaired water quality.

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Introduction

The inter-related soil traits of texture, saturated hydraulic conductivity, bulk density, and macroporosity influence hillslope and watershed hydrology (Farres, 1987; Rawls et al., 1993; Cerda, 1996). These characteristics determine the proportion of precipitation entering and retained in subsurface storage and the rates of transmission of water to stream networks, thus affecting both stormflow production and baseflow maintenance (Hewlett, 1961; Zimmermann et al., 2006; Tetzlaff et al., 2007). Land-use practices have been shown to be of key importance to soil hydrology, attributed to the effects of tillage, erosion, compaction, and pore structure evolution (Rasiah and Kay, 1995; Harden, 2006). Such disturbances, in some cases, outweigh genoform traits (e.g. those inherited from parent material, topographic setting, etc.) in determining soil water movement (Schwartz et al., 2003; Zhou et al., 2008).

Compared with soils impacted by human land use, soils underlying native vegetation (e.g., undisturbed forest) generally feature low bulk density and high saturated hydraulic conductivity, total porosity, and macroporosity, as a result of ample litter cover, organic inputs, root growth and decay, and abundant burrowing fauna (Lee and Foster, 1991). In contrast, soils exposed to human impact are often stripped of organic-rich upper horizons and compacted by heavy equipment or livestock, increasing bulk density and reducing infiltration rates (Celik, 2005; Li and Shao, 2006). In

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many cases, soils impacted by land-use change may demonstrate marked disparities from the original soil (Jiménez et al., 2006; Zhou et al., 2008). Replacement of natural vegetation with managed landcover is generally associated with decreased rooting networks and faunal activity, thereby reducing the potential for well-developed macropore networks (Reiners et al., 1994; Schwartz et al., 2003). The rooting systems of woody vegetation such as forest and shrubland demonstrate substantially greater depth, diameter, dispersion, and biomass than rooting systems of herbaceous plants or cultivated crops (Lee and Lauenroth, 1994; Jackson et al., 1996; Messing et al., 1997). Conversion of native vegetation to managed land is also commonly associated with decrease in litter accumulation and soil organic matter (Solomon et al., 2000; Richter and Markewitz, 2001), which significantly influences soil water retention characteristics and soil structure (Berglund et al., 1980; Buytaert et al., 2005; Harden, 2006). Studies investigating soil physical response to land-use change have heavily emphasized comparison of cultivated cropland soils vs. soils underlying native forest, shrubland, or grassland. However, current development pressures in many regions of suburban and exurban growth do not include conversion of native vegetation to cropland, and in fact are often associated with decline of cultivated land (Richter and Markewitz, 2001; Gragson and Bolstad, 2006). Land-use change in such settings is likely to involve conversion of native or secondary vegetation to pasture or managed turfgrass. As seen with cultivated soils, studies comparing soils under natural vegetation to pasture or lawn have also shown degradation of soil physical properties. A distinction is apparent between soils underlying woody vegetation, such as forest or shrubland, vs. herbaceous landcover, such as pasture or grassland, even under varied management practices and degrees of compaction (Jiménez et al., 2006).

Forest cover has been associated with lower bulk density and greater saturated hydraulic conductivity than pasture in different-climates and parent materials throughout the world (Reiners et al., 1994; Godsey and Elsenbeer, 2002; Jiménez et al., 2006; Li and Shao, 2006; Abbasi et al., 2007). Less is known regarding the physical response of soils to conversion of native vegetation to turfgrass. Residential development or the creation of golf courses, parks, ball fields, etc., typically involves topsoil removal and/or compaction associated with grading and sod-laying. It is probable that observed soil changes in response to land-use conversion to lawn grass are predominantly due to these initial disturbances (Wigmosta, 1991; Hamilton and Waddington, 1999). Furthermore, the nature of lawn grass and associated management do not encourage soil recovery post-disturbance. Lawn grass typically demonstrates shallow rooting depth, low organic matter accumulation, and is generally associated with lower faunal activity than pasture or forest (Pizl and Josens, 1995). The few studies addressing the physical properties of soils underlying lawn grass have shown exceptionally low infiltration rates and high bulk densities, (Hamilton and Waddington, 1999; Oliviera and Merwin, 2001). Comparison of soil physical properties across a land-use gradient in Baltimore that included forest, pasture, and managed lawn showed that soils underlying lawn grass demonstrated higher bulk density and lower porosity than forest or pasture soils (Pouyat et al., 2007).

Cumulatively, these changes in soil physical characteristics associated with conversion of native to managed vegetation reduce soil infiltration and storage capacities, possibly resulting in increased overland flow and reduced subsurface storage. Along with factors such as increased road density and impervious surface coverage, such soil changes are often important contributors to flashier hydrologic regimes, in which flood peaks are higher and baseflow recessions much faster. Decreased infiltration and increased Hortonian overland flow (surface runoff that occurs when rainfall intensity exceeds soil infiltration capacity), resulting from conversion of woody vegetation to human land use, has been demonstrated in many settings to be a direct consequence of altered soil hydrology (Bens et al., 2007; Zimmermann et al., 2006; Ilstedt et al., 2007; Leblanc et al., 2008). Booth et al. (2002) emphasized that the conversion of forests to lawns in urbanizing watersheds caused substantial hydrologic change often neglected with respect to the effects of impervious surface coverage. Given the increase in managed lawn associated with low- and medium-density urban growth occurring in many regions, it is of immediate importance to understand the effects of such land-use change on soil physical properties and the associated implications for watershed hydrology.

This research sought to determine the magnitudes of differences among soil physical properties under three land uses (forest, pasture, and managed lawn) and across two parent materials, alluvium (overbank fluvial sediment) and saprolite (heavily weathered bedrock), in the southern Blue Ridge Mountains of North Carolina. This region is currently experiencing pronounced growth. Cultivated land was avoided due to its declining presence in the study area, the pronounced cross-site inconsistency in management practices, and the temporal variation in properties through the cropping cycle. We attempted to avoid legacy effects from past land uses by limiting sites to those demonstrating consistency of land use for 30+ years. Particle size distribution, saturated hydraulic conductivity, bulk density, total porosity, and volumetric moisture content were determined for 90 surface soil samples from one geologic unit and associated with land-use class (forest, pasture, or lawn) and parent material (saprolite oralluvium). Five locations were selected for each landcover/parent material combination to represent regional variation and three points were sampled within each site to represent local variation.

Variability in soil physical properties due to differences in land use were expected to have resulted from two mechanisms: (1) direct compaction by heavy equipment and/or livestock associated with nonforest land uses, and (2) variation in macropore development, organic matter, and soil structure associated with different vegetation types and associated fauna Thus it was expected that nonforest land use (pasture and lawn) would be associated with increased bulk density and reduced saturated hydraulic conductivity, porosity, and volumetric moisture content, and that soils underlying managed lawn would demonstrate greater contrast to forest soils than would pasture soils. Understanding such differences is necessary for the development of a full understanding of how land-use change in this region is affecting watershed hydrologic processes, and is additionally necessary for providing data for use in regional hydrologic modeling to forecast hydrologic response to land-use change.

Study area

This research was conducted in Macon and Jackson counties in southwestern North Carolina (Fig. 1). These counties are located within the Tallulah Falls thrust sheet of the East Flank Blue Ridge lithotectonic belt (Robinson et al., 1992), a sub-unit of the Blue Ridge physiographic province. All bedrock types within the thrust sheet are crystalline, specifically consisting of intrusive igneous rocks and metasedimentary assemblages, metamorphosed 350–450 mya (Robinson et al., 1992; Wooten et al., 2003). A sub-area of Macon and Jackson counties underlain by a complex of biotite gneiss and amphibolite bedrock was emphasized in this study (Fig. 1). Macon and Jackson counties are characterized by moderate relief (540–1952 m), which is the product of bedrock weathering, fluvial erosion, and mass wasting during the period of tectonic stability since the early Cenozoic (Leigh and Webb, 2006). A saprolite mantle up to 30 m thick drapes the ridges and slopes throughout

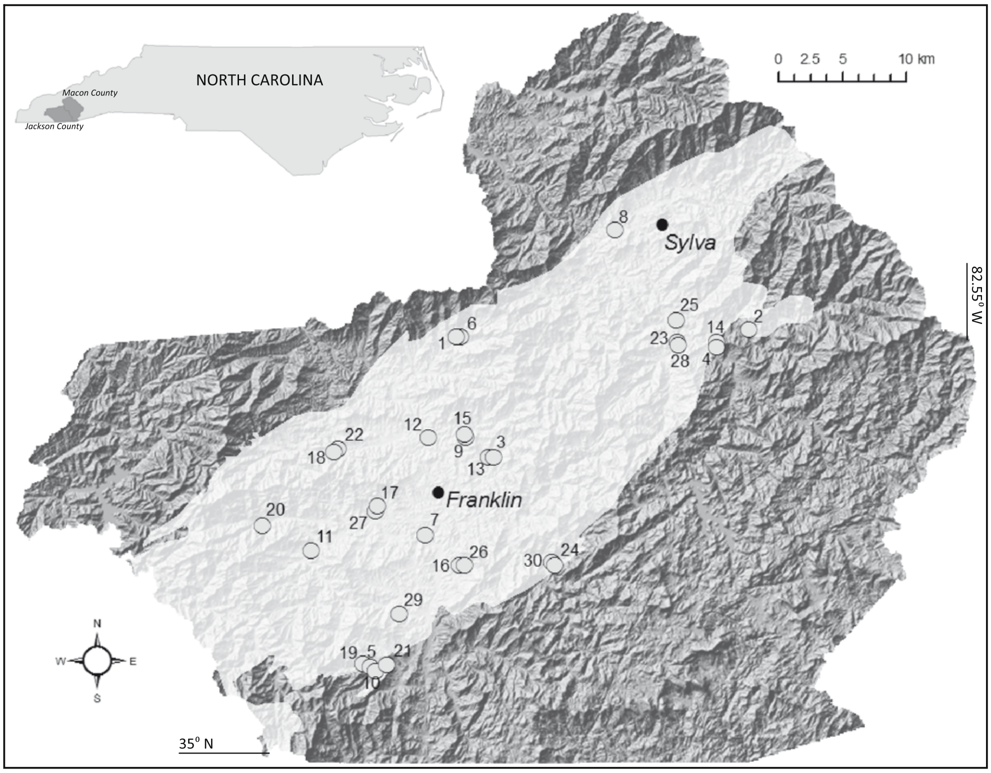

Fig. 1. Study area and soil sampling locations: Macon Co. and Jackson Co., NC. The white band across the counties represents a geologic zone of interlayered biotite gneiss and amphibolite (Robinson et al., 1992) – site selection was limited to this zone. Vertical exaggeration is 3×. Each mapped sampling location represents three sampling points, and location numbers correspond to the site characteristics in Table 2.

the study area, and substantial deposits of colluvium are present on benches, coves, and footslopes (Hewlett, 1961; Hadley and Goldsmith, 1963; Southworth et al., 2003).

Soil parent materials in the study area are saprolite (75.0% by area), colluvium (19.4%), alluvium (2.2%), and mixed colluvium/alluvium (1.3%), with the remaining 2.1% characterized by open water, earthen fill, and mining pits (Soil Survey Staff – NRCS, 2007). Most soils are classified as Udepts (60.8% by area) forming at high elevations and in younger colluvial and alluvial landforms. Udults commonly occur on saprolite backslopes of intermediate elevation and comprise 37.0% of the study area. Much smaller areas of Aqualfs, Udalfs, Aquepts, Psamments, and Udorthents are also present.

The 1971–2000 average annual temperature at the Coweeta Experiment Station (weather station elevation = 685.5 m), in the southern portion of the study area, is 12.7 °C, with average January and July temperatures of 2.7 °C and 22.1 °C, respectively (NCDC, 2003). The 30-year average annual precipitation is 183 cm, with a high monthly average of 20 cm occurring in March (NCDC, 2007).

In the absence of human disturbance, regional landcover would be nearly 100% forest (Yarnell, 1998; Delcourt and Delcourt, 2004). Present-day land use is predominantly forest, with nonforest landcover occurring primarily as pasture and low-density development (Table 1). Pronounced human impact has occurred since Euro-American settlement, with expansion of bottomland agriculture occurring since the early 19th century (Gragson and Bolstad, 2006). The region experienced intensive, widespread timber harvest and agriculture during the late 19th and early 20th century, followed by forest regrowth on mountain slopes (Davis, 2000). Agricultural land abandonment and vegetation regrowth have been common since the 1960s, accompanied by population growth and associated expansion of residential and low- to medium-density urban landcover (Wear and Bolstad, 1998; Gragson and Bolstad, 2006). The largest town in the study area is Franklin, with a 2006 population of 3618 (US Census Bureau, 2007).

Table 1
2001 Land Use - Macon Co. and Jackson Co., NC (Source: USGS, 2003).

Land use	% Area
Open water	0.6
Developed	5.9
Open	5.3
Low-intensity	0.5
Medium-intensity	0.1
High-intensity	0.0
Forest	85.6
Deciduous	80.8
Evergreen	3.1
Mixed	1.7
Shrub/scrub	1.4
Grassland/pasture	6.3
Cultivated cropland	0.1
Woody wetlands	0.1

Methods

Site selection

Ninety sites were identified for sampling, 30 within each of the three land-use classes of forest, lawn and pasture. All forest sites were under deciduous forest cover, pasture sites were open graminoid fields either grazed by livestock or maintained for hay production, and lawn sites were managed turfgrass, including lawns in homeowners' yards and municipal parks. All sites were within

Table 2
Site characteristics: land use, soil series, elevation, and aspect of soil sampling sites. Elevation, slope, and aspect values represent the range of the three sites at each location. Site numbers correspond to Fig. 1.

Alluvium sites[a]					Saprolite sites						
#	Name	Land use	Series	Elev. (m)	#	Name	Land use	Series	Elev. (m)	Slope (%)	Aspect (°)
1	Beasley Creek	Forest	Reddies	687–689	16	Chapel Hill	Forest	Evard–Cowee complex	668	21–26	170–178
2	Caney Fork	Forest	Rosman	673	17	Gibson Cove	Forest	Evard–Cowee complex	673–681	20–30	205–210
3	Rabbit Creek	Forest	Reddies	643–644	18	Olive Hill	Forest	Evard–Cowee complex	710–718	26–33	100–145
4	Tuckasegee River	Forest	Rosman	646–647	19	Shope Fork	Forest	Fannin	701–703	21–26	204–210
5	Weather Station	Forest	Reddies	687–688	20	Wayah Road	Forest	Evard–Cowee complex	749–787	33–34	214–245
6	Beasley Creek	Lawn	Reddies	691	21	Ledford Lane	Lawn	Evard-Cowee Complex	668–670	18–32	162–165
7	Fairgrounds	Lawn	Rosman	616	22	Olive Hill	Lawn	Evard–Cowee complex	701–703	17–21	111–135
8	Mark Watson Park	Lawn	Cullowhee	614–615	23	Speedwell Acres	Lawn	Evard-Cowee Complex	697–699	32–35	240
9	Watauga Hazard	Lawn	Reddies	619–620	24	Walnut Creek	Lawn	Evard–Cowee complex	661–664	21–28	140–180
10	Weather Station	Lawn	Reddies	686–687	25	WCU	Lawn	Cowee–Evard complex	674–679	20–24	178–182
11	Killian Farm	Pasture	Rosman	658	26	Chapel Hill	Pasture	Evard–Cowee complex	661–664	26–29	144–157
12	Rocky Branch	Pasture	Rosman	600	27	Gibson Cove	Pasture	Evard–Cowee complex	673–675	17–25	194–209
13	Rabbit Creek	Pasture	Reddies	643	28	Speedwell Acres	Pasture	Evard–Cowee complex	691–693	19–22	235–255
14	Tuckasegee River	Pasture	Rosman	648	29	Sunny Lane	Pasture	Evard–Cowee complex	668–670	17–32	183–200
15	Watauga Hazard	Pasture	Reddies	619	30	Walnut Creek	Pasture	Evard–Cowee complex	673–681	23–33	152–185

[a] For all alluvium sites: slope = 0–2%, aspect = n/a.

the "biotite gneiss and amphibolite" unit on the regional 1:250000-scale surficial bedrock map (Robinson et al., 1992), comprising a 983 km^2 area within Macon and Jackson Counties (Fig. 1). Site selection was limited to an elevation range of 600–800 m. Higher elevations were not included to avoid significant cross-site differences in temperature and precipitation associated with elevation. Digital Light Detection and Ranging (LiDAR) coverage of each county (0.305 m vertical resolution, 6.1 m pixel length) was obtained from the North Carolina Department of Transportation (NCDOT, 2007a,b). From the parent materials within the study area, only saprolite and alluvium were examined. Colluvium was excluded due to its characteristic textural heterogeneity. Sites were evenly distributed among saprolite and alluvium, resulting in 15 sites in each land-use class located within each parent material (Table 2). Alluvial sites were within Dystrudepts (Rosman, Reddies, and Cullowhee series), and saprolite sites were within Typic Hapludults (Cowee–Evard and Evard–Cowee series complexes and Fannin series; Table 3). Digital soil coverages of Macon and Jackson counties were obtained from the Soil Data Mart (USDA-NRCS, 2005, 2007). The parent material of each soil series in these counties was identified from the corresponding Offical Series Description (Soil Survey Staff - NRCS, 2007). The mapped series was verified by field profile descriptions. In a small number of cases, the designated map unit was determined to be incorrect and a different series was assigned based on profile description.

Alluvial sites were limited to flat, undissected portions of late-prehistoric or historic terraces, avoiding active floodplains or very old terrace surfaces. In order to avoid wide variability in insolation or textural and morphological differences associated with hillslope position, saprolite sites were limited to equivalent hillslope

Table 3
National cooperative soil survey official series descriptions (Soil Survey Staff, 2007).

Series	Taxonomic class	Typical texture	Official description
Alluvium			
Cullowhee	Coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Fluvaquentic Dystrudepts	Fine sandy loam	Somewhat poorly drained, moderately rapidly permeable soils on floodplains in the Southern Appalachian Mountains. They formed in recent alluvium that is loamy in the upper part and is moderately deep to sandy strata that contain more than 35 percent by volume rock fragments. They are very deep to bedrock. Slope ranges from 0% to 3%
Reddies	Coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Oxyaquic Dystrudepts	Fine sandy loam	Moderately well drained, moderately rapidly permeable soils on floodplains in the Blue Ridge. They formed in recent alluvium that is loamy in the upper part and is moderately deep to sandy strata containing more than 35 percent by volume gravel and/or cobbles. Slope ranges from 0% to 3%
Rosman	Coarse-loamy, mixed, superactive, mesic Fluventic Humic Dystrudepts	Loam	Very deep, well drained to moderately well drained, moderately rapidly permeable soils on floodplains in the Southern Appalachian Mountains. They formed in loamy alluvium. Slopes range from 0% to 3%
Saprolite			
Cowee	Fine-loamy, parasesquic, mesic Typic Hapludults	Gravelly sandy loam	Moderately deep, well drained, moderately permeable soils on ridges and side slopes of the Blue Ridge . They formed in residuum affected by soil creep in the upper part, and weathered from felsic to mafic, igneous and high-grade metamorphic rocks. Slope ranges from 2% to 95%
Evard	Fine-loamy, parasesquic, mesic Typic Hapludults	Sandy loam	Very deep, well drained, moderately permeable soils on ridges and side slopes of the Blue Ridge. They formed in residuum affected by soil creep in the upper part and weathered from felsic to mafic, igneous and high-grade metamorphic rocks. Slopes range from 2% to 95%
Fannin	Fine-loamy, paramicaceous, mesic Typic Hapludults	Loam	Very deep, well drained soils on gently sloping to very steep ridges and side slopes of the Blue Ridge. They formed in residuum that is affected by soil creep in the upper part, and is weathered from high-grade metamorphic rocks that are high in mica content such as mica gneiss and mica schist. Slopes are 6–95%

position (backslope, or the linear middle portion of a hillslope; Shaetzl and Anderson, 2005) of south-facing aspect (100–260°) and similar gradient (15–35%). LiDAR elevation data were used to determine the aspect and gradient, which were field-confirmed using a magnetic compass and clinometer.

ArcGIS 9.2 geographic information science (GIS) software was used to identify 30 locations meeting all site selection criteria (Fig. 1). These 30 sites were evenly distributed among parent materials and land uses, with five sites in each parent material/land-use combination (e.g., five alluvial forest sites, five saprolite forest sites, five alluvial lawn sites, etc., Table 2). At each site, three randomly-selected points at least 10 m apart were sampled and treated as independent, resulting in a total of 90 sampling points. The minimum distance of 10 m separating sampling points was determined following the design of similar studies (e.g. Jiménez et al., 2006), and from the results of previous studies demonstrating the absence of spatial autocorrelation of soil physical characteristics at distances greater than 1 m (Di et al., 1989; Lal, 1996; Webb et al., 2000; Zhou et al., 2008). Analysis of 1:62500-scale 1970s aerial photography and published land-use classifications from 1992 and 2001 (USGS, 2000, 2003) confirmed consistency of land use at each site over the past 30+ years.

Where possible, locations were identified where two land uses were adjacent within the same soil unit. Ten such pairs of locations were identified: three pairs each of adjacent forest/lawn and lawn/pasture locations and four pairs of adjacent forest/pasture locations. For the pair analyses, the three sites were grouped to represent each location.

Field data collection methods

At each sampling point, the organic matter was cleared from the mineral soil surface surrounding the sampling point, and three 25-cm deep, 5-cm radius boreholes were dug within 50 cm of the sampling point. A compact constant head permeameter (Amoozegar, 1989a) was used to measure the infiltration rate in each borehole. These values were converted to saturated hydraulic conductivities (K_{sat}) using the Glover Solution (Amoozegar, 1989b), and the geometric mean of the three K_{sat} values was used to represent each sampling point. A ring corer was used to extract two undisturbed 331.3 cm^3 core samples per point (from depths 0 to 7.5 cm and 7.5 to 15 cm) for laboratory analysis of bulk density, total porosity, volumetric moisture content, and saturated hydraulic conductivity (for comparison with field K_{sat}). Mineral soil bulk samples of 100 g were collected from the zones of 0 to 7.5 cm and 7.5 to 15 cm for particle size analysis.

Laboratory methods

A 50 g subsample of each bulk soil sample was crushed, passed through a 2 mm sieve, oven-dried, dispersed in sodium hexametaphosphate, and analyzed for particle size distribution

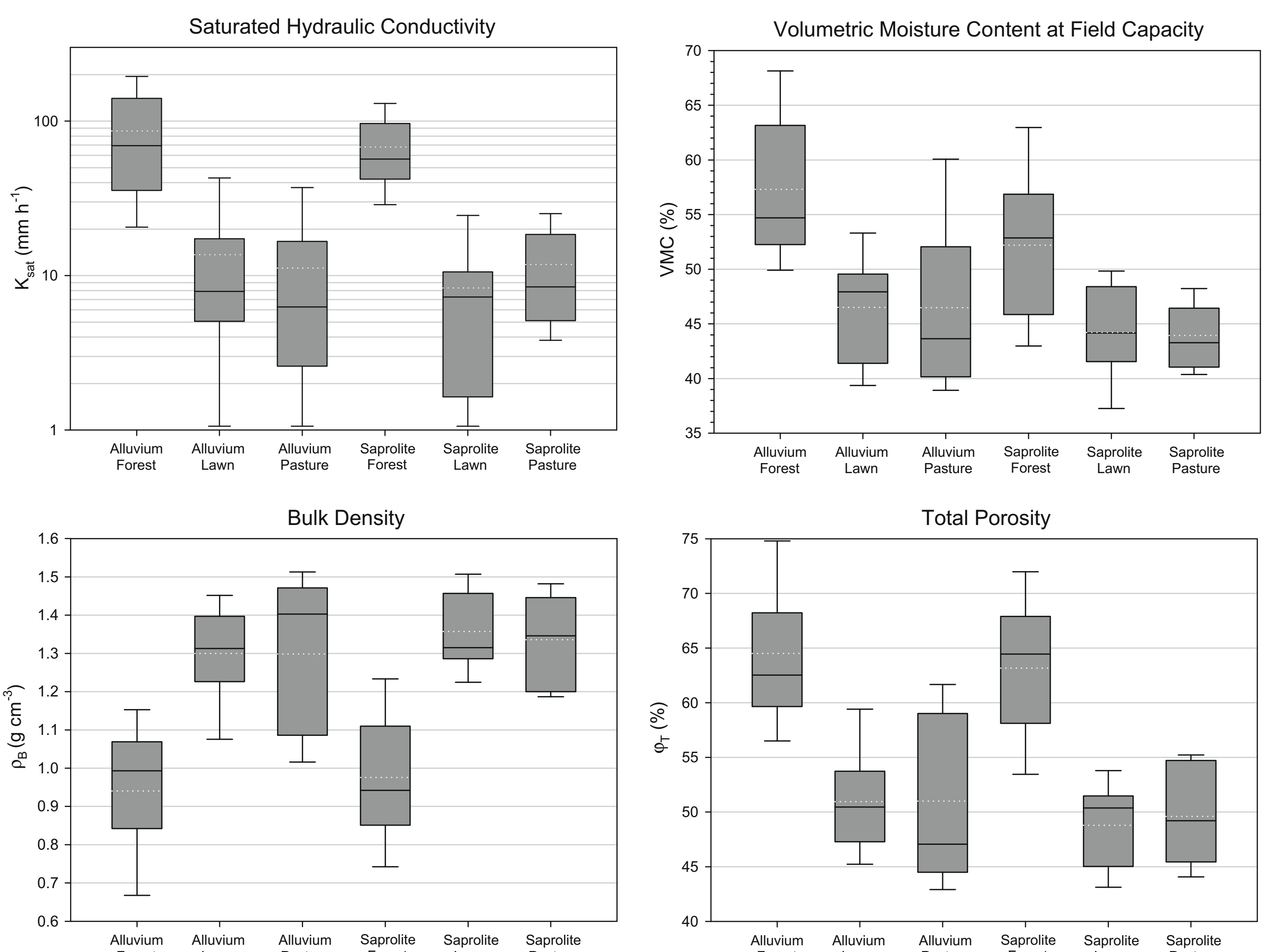

Fig. 2. Soil physical characteristics by parent material and land use. The boxes represent the inter-quartile range, with the black line across each box indicating the median value. The white dotted line represents the arithmetic mean, and the whiskers represent the 5th and 95th percentiles.

by hydrometer method (Gee and Bauder, 1986). Agro-Services International performed laboratory analyses of bulk density (ρ_B), gravitational moisture content (GMC), and saturated hydraulic conductivity ($K_{sat\text{-}L}$). Ring core samples of known volume were oven-dried and weighed to determine ρ_B (Blake and Hartge, 1986). Gravitational moisture content was determined by saturating the soil core for 24 h, following standard methods of soil wetting for determination of the initial drainage curve (Klute, 1986; Casas and Ninot, 2007; Andry et al., 2009). Cores were allowed to drain for 24 h, and gravitational moisture content at field capacity was determined by subtracting the drained core weight from the saturated weight. The gravitational moisture content (GMC) was converted to volumetric moisture capacity at field capacity (VMC_{fc}) by $VMC_{fc} = GMC/\rho_B$. $K_{sat\text{-}L}$ was determined using the constant head method (Klute and Dirksen, 1986). Total porosity (φ_T) was calculated from the ρ_B: $\varphi_T = 1 - \rho_B/\rho_P$, where ρ_P = particle density. Particle density was assumed to be 2.65 g cm^{-3} (Danielson and Sutherland, 1986; Li and Shao, 2006).

Statistical analyses

Two-way analysis of variance (ANOVA) was used to determine the relative roles of parent material and land-use class on soil hydrologic properties. One-way ANOVA was used to evaluate differences in soil physical characteristics as a function of land use and to test the variability among sites within a given land use. Normality was tested using the Kolmogorov–Smirnov test (Sheskin, 2007). Standard statistical transformations ($\log_{10}$, inverse, and square root) were used to achieve normal distributions where possible. In cases where such transforms failed to normalize a given parameter, the nonparametric ANOVA on Ranks test was used. Particle size data (as fractions summing to unity for each point) were arcsine-square root transformed prior to statistical analyses. *t*-Tests or nonparametric Mann–Whitney Rank Sum tests (Ott and Longnecker, 2001) were performed to test significance of difference between mean values of parameters for each parent material (alluvium vs. saprolite), and to test pairwise differences between the land-use classes of forest, lawn, and pasture. Paired *t*-tests or nonparametric Wilcoxon signed rank tests were used to compare means of the upper and lower cores. For all tests, a threshold of $p < 0.05$ was used to define statistical significance. All statistical analyses were performed using SigmaStat 3.5 and validated using SPSS 12.0.

Results

The physical characteristics of forest soils clearly and strongly differed from pasture and lawn soils in this study area. Forest soils demonstrated significantly lower ρ_B and higher φ_T, K_{sat}, and VMC_{fc} than soils in the other two land uses (Fig. 2). For no parameter did pasture and lawn soils significantly differ from each other. Soil texture was very similar among parent materials and land-use classes, removing the need for separate analyses for the two parent materials.

Particle size

The sand, silt, and clay percentages of the surface soil (average of 0–7.5 and 7.5–15 cm samples) ranged from 29% to 47%, 27% to 39%, and 26% to 32% among all 90 sites. The vast majority (83 of 90 sites) classified as sandy loam or loam, with the remainder falling into loamy sand, silt loam, and clay loam (Fig. 3). On average, the bottom core (7.5–15 cm) contained slightly less sand and silt than the upper core, and contained an average 2% more clay

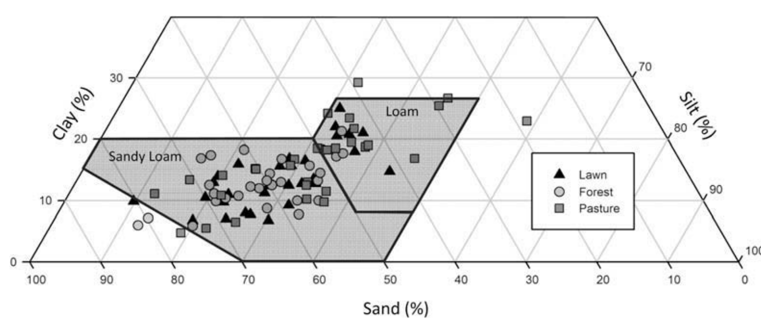

Fig. 3. Particle size distributions of forest, lawn, and pasture soils. Textural classes corresponding to particle size distributions observed in these soils are bounded by solid black lines (e.g., loam, clay loam).

Table 4
Hydraulic properties of upper (0–7.5 cm) and lower (7.5–15 cm) soil cores.

	0–7.5 cm[a] mean (sd)	7.5–15 cm[a] mean (sd)	Diff. of means[b]		
			t or *Z*[c]	*p*	Trans.
$K_{sat\text{-}L}$ (mm h^{-1})	42 (3)	20 (3)	6.59	<0.001	$\log_{10}$
ρb (g cm^{-3})	1.10 (0.25)	1.30 (0.23)	−12.47	<0.001	–
φ_T (%)[d]	57.5 (1.17)	50.2 (1.18)	12.83	<0.001	$\log_{10}$
VMC_{fc} (%)[d]	50.1 (1.15)	45.5 (1.19)	7.36	<0.001	$\log_{10}$
Sand[e] (%)	57.0 (11.8)	56.5 (13.2)	1.15[c]	0.251	asr
Silt[e] (%)	28.7 (8.2)	27.5 (8.4)	3.79[c]	<0.001	asr
Clay[e] (%)	14.4 (5.2)	16.1 (6.4)	−5.31[c]	<0.001	asr

t = paired *t*-test statistic; trans. = transformation used to achieve normal distribution; asr = arcsine–square root transformation; sd = standard deviation.
[a] *n* = 90.
[b] 178 degrees of freedom; symbols defined in Section "Laboratory methods".
[c] *Z* = Wilcoxon signed rank test statistic.
[d] Geometric mean/standard deviation.
[e] As percent of <2 mm mass.

Table 5
Soil physical characteristics by categories of parent material and land use.

	Depth (cm)	Parent material					Land use											
		Alluvium[a]	Saprolite[a]	Diff. of means[b]			Forest[c]	Lawn[c]	Pasture[c]	ANOVA[d]		Pairwise diff. of means[e]						
												Forest vs. lawn		Forest vs. Pasture		Lawn vs. Pasture		Trans.
		Mean (sd)	Mean (sd)	t or T[h]	p	Trans.	Mean (sd)	Mean (sd)	Mean (sd)	F or H[i]	p	t or T[h]	p	t or T[h]	P	t or T[h]	p	
K_{sat} (mm h^{-1})[f]	0–25	15[f](4)[f]	15[f](4)[f]	0.07	0.941	$\log_{10}$	63[f] (2)[f]	7[f] (3)[f]	8[f] (3)[f]	55.26	<0.001	9.43	<0.001	8.74	<0.001	0.69	0.493	$\log_{10}$
ρ_B (g cm^{-3})	0–7.5	1.09(0.25)	1.11 (0.3)	1941.5[h]	0.395	–	0.83(0.17)	1.23(0.14)	0.83(0.17)	63.42	0.001	0.00	0.001	0.00	0.001	0.29	0.771	–
	7.5–15	1.27(0.25)	1.33(0.2)	1921.5[h]	0.2)1921	–	1.08(0.21)	1.43(0.12)	1.39(0.17)	36.70[i]	0.001	58.5[h]	0.001	58.5[h]	0.001	958.5[h]	0.525	–
	Ave.	1.18(0.23)	1.22(0.2)	1930.5[h]	0.347	–	0.96(0.16)	1.33(0.12)	0.96(0.16)	60.99	0.001	9.71	0.001	9.40	0.001	0.30	0.765	–
φ_T (%)	0–7.5	59.0 (9.3)	57.8 (9.5)	−0.69	0.492	1/x	68.7 (6.5)	53.6 (5.4)	53.6 (5.4)	50.85[i]	0.001	873.0[h]	0.001	873.0[h]	0.001	873.0[h]	0.539	–
	7.5–15	51.9(9.2)	49.9 (7.9)	−0.95	0.344	1/x	59.1 (7.8)	46.2 (4.7)	46.2 (4.7)	(7.8)46	0.001	7.25	0.001	6.52	0.001	0.73	0.468	1/x
	Ave.	55.5 (8.8)	53.9 (8.3)	−0.87	0.388	1/x	63.8 (6.2)	49.9 (4.5)	50.3 (5.9)	48.78[i]	0.001	491.5[h]	0.001	923.5[h]	0.001	923.5[h]	0.906	–
VMC$_{fc}$ (%)	0–7.5	53.0 (8.4)	48.3 (5.7)	−2.99	0.00.4	1/x	56.2 (7.7)	48.5(5.1)	47.3 (6.2)	17.24	0.001	5.87	0.001	5.38	0.001	0.48	0.629	–
	7.5–15	47.2 (8.9)	45.3 (8.7)	−0.95	0.345	1/x	53.3 (9.5)	42.3 (5.0)	43.2 (6.5)	010.730	0.001	5.41	0.001	4.68	0.001	0.73	0.470	–
	Ave.	50.1 (8.2)	46.8 (6.3)	−2.00	0.050	1/x	54.8 (7.2)	45.4 (4.6)	45.2 (6.0)	24.64	0.001	6.13	0.001	6.03	0.001	0.09	0.925	–
Sand[g](%)	0–7.5	58(14)	56(9)	1932.0[h]	0.353	asr	61(9)	52(14)	52(14)	2.16	0.3062	1.03	0.306	2.01	0.051	1.08	0.285	asr
	7.5–15	57(16)	56(10)	1930.5[h]	0.347	asr	60(11)	58(11)	52(15)	1.33	0.1	0.43	0.669	1.55	0.128	1.16	0.250	asr
	Ave.	57(15)	56(9)	2145.5[h]	0.429	asr	60(10)	58(11)	52(15)	1.36	0.262	0.44	0.659	1.56	0.125	1.17	0.246	asr
Silt[g] (%)	0–7.5	29(10)	29(6)	1971.5[h]	0.542	asr	26(7)	28(7)	32(10)	3.36[i]	0.446	863.0[h]	0.446	893.0[h]	0.080	856.5[h]	0.243	asr
	7.5–15	28(11)	27(6)	2055.5[h]	0.952	asr	25(7)	26(7)	31 (10)	3.49[i]	0.174	939.0[h]	0.1178	881.5[h]	0.117	886.5[h]	0.099	asr
	Ave.	28(10)	28(6)	2087.5[h]	0.745	asr	26(7)	27(7)	31 (10)	5.84[i]	0.054	976.5[h]	0.353	926.5[h]	0.200	879.0[h]	0.118	asr
Clay[g] (%)	0–7.5	14(6)	15(5)	2206.0[h]	0.201	asr	13(4)	14(5)	16(6)	1.63	0.202	−0.74	0.462	−1.79	0.079	−1.05	0.299	asr
	7.5–15	15(7)	17(6)	1814.5[h]	0.060	asr	17(6)	16(6)	18(7)	0.28	0.761	−0.42	0.4	−0.73	0.467	−0.33	0.741	asr
	Ave.	15(6)	16(5)	1926.0[h]	0.315	asr	14(5)	15(6)	17(7)	3.97[i]	0.137	73.0[h]	0.823	873.0[h]	0.052	873.0[h]	0.143	asr

sd = standard deviation; trans. = statistical transformation used to achieve normal distribution; asr = arcsine–square root transformation; parameter symbols defined in text.
[a] $n = 45$.
[b] Eighty eight degrees of freedom.
[c] $n = 30$.
[d] Eighty nine degrees of freedom.
[e] Fifty eight degrees of freedom.
[f] Geometric mean/standard deviation;
[g] As percent of < 2 mm masss.
[h] Mann–Whitney rank sum test T-statistic.
[i] ANOVA on ranks test H-statistic.

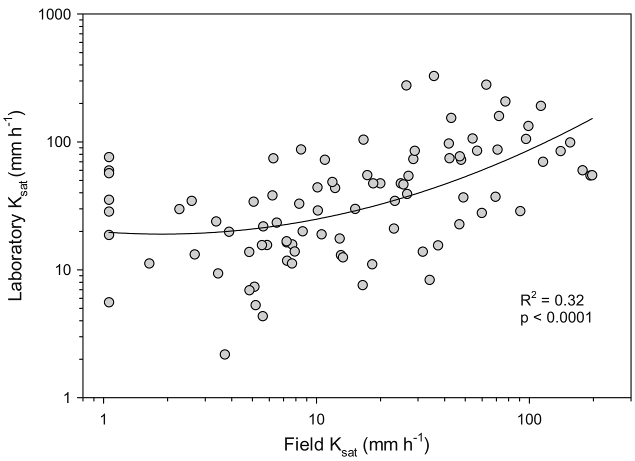

Fig. 4. Comparison of saturated hydraulic conductivity (K_{sat}) measurements by field and laboratory methods. Saturated hydraulic conductivity (K_{sat}) was measured by two methods: (1) in situ at each field sampling point using a compact constant head permeameter at a depth of 0–25 cm, and (2) by standard laboratory methods on 10 cm-diameter intact soil cores. The laboratory K_{sat} values presented here are the average of the two cores from each sampling point (0–7.5 cm and 7.5–15 cm). The R^2 and p-value reflect results from polynomial regression analysis performed on the $\log_{10}$-transformed variables ($y = 1.296–0.1215x + 0.2212x^2$).

(Table 4). Differences in silt and clay between the upper and lower cores were statistically significant, whereas differences in sand content were not. Differences in the sand, silt, and clay percentages among forest, lawn, and pasture soils were not significant, nor were textural differences among the parent materials (Table 5). The similarity of the particle size distributions among these samples allows comparison of the physical characteristics of ρ_B, φ_T, K_{sat}, and VMC_{fc} as a function of land use without concerns that systematic textural differences may be complicating the relationships.

Bulk density and porosity

The ρ_B of all soil sites ranged widely from 0.41 to 1.51 g cm^{-3} in the upper 7.5 cm and from 0.72 to 1.66 g cm^{-3} in the 7.5–15 cm depth. Overall, the mean ρ_B of the upper cores was significantly lower than the lower cores (1.10 vs. 1.30 g cm^{-3}, $T = 6349.0$, $p < 0.001$). The φ_T ranged from 42.9% to 84.5% in the upper core and 37.2% to 72.9% in the lower core. The mean φ_T values of the upper and lower cores were significantly different (58.4% vs. 50.9%, $t = 5.77$, $p < 0.001$). The ρ_B and φ_T of alluvial and saprolite soils were highly similar and did not significantly differ at either depth (ρ_B from 0 to 15 cm: 1.18 vs. 1.22 g cm^{-3}, $T = 1930.5$, $p = 0.347$; φ_T from 0 to 15 cm: 55.5 vs. 53.9%, $t = -0.87$, $p = 0.388$).

One-way ANOVA demonstrated that ρ_B and φ_T significantly differed among the land-use classes at both depths (Table 5), and pairwise comparisons indicate significant differences between forest soils and the other two land uses at both depths. The average ρ_B of the upper and lower cores in forest soils was 0.96 g cm^{-3}, 38% lower than lawn and pasture soils, which were essentially equal (1.33 and 1.32 g cm^{-3}. Correspondingly, the average φ_T of lawn and pasture soils did not significantly differ (49.9% vs. 50.3%; $T = 923.5$; $p = 0.906$), but the φ_T of forest soils was significantly higher than the lawn and pasture soils.

Saturated hydraulic conductivity

A paired t-test indicated that the mean saturated hydraulic conductivities determined by the in situ method (K_{sat}) and laboratory method ($K_{sat\text{-}L}$) were significantly different (mean = 33 vs. 55 mm h^{-1}; $t = 6.59$; $p < 0.001$). Because the field measurement represented the upper 25 cm, the average of the upper and lower core laboratory measurements was used for comparison with the field measurement (Fig. 4). The laboratory method indicated a larger range in conductivities than the field method (2.18–327.83 mm h^{-1} compared with 1.06–197.21 mm h^{-1}). The field K_{sat} values correlated more strongly with the ρ_B and VMC_{fc} than did the laboratory measurements ($r = -0.63$ vs. -0.67 with ρ_B, $r = 0.49$ vs. 0.59 for VMC_{fc}), despite the fact that $K_{sat\text{-}L}$, ρ_B, and VMC_{fc} were all measured from the same core sample. For this reason, field K_{sat} is emphasized in these results. The average $K_{sat\text{-}L}$ of the upper core was nearly twice as great as the lower core (75 vs. 35 mm h^{-1}; $t = 6.86$; $p < 0.001$).

Forest soils demonstrated far greater K_{sat} than lawn or pasture soils by both field and lab methods (Table 5). The average field K_{sat} of the forest soils was approximately seven times greater than the lawn and pasture soils, which were highly similar (forest = 77 mm h^{-1}, lawn = 11 mm h^{-1}, pasture = 12 mm h^{-1}). ANOVA results indicate significant difference in K_{sat} among the land uses, with pairwise results indicating that forest soils had significantly higher K_{sat} than lawn and pasture soils, which did not significantly differ (Table 5).

Volumetric moisture content

VMC_{fc} ranged from 37.7% to 74.0% in the upper core and from 32.6% to 87.8% in the lower core. The VMC_{fc} of the upper core

Table 6
Paired locations (adjacent locations with different land uses).

Location[a]	Parent material	K_{sat} (mm h^{-1})		ρ_B (g cm^{-3})		φ_T (%)		VMC_{fc} (%)	
		Forest	Lawn	Forest	Lawn	Forest	Lawn	Forest	Lawn
Beasley creek	Alluvium	78	13	1.06	1.31	60.0	50.6	54.2	46.7
Weather Station	Alluvium	96	32	0.79	1.11	70.3	58.1	60.2	52.2
Olive hill	Saprolite	66	8	0.98	1.32	63.2	50.2	51.7	44.6
		Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture
Rabbit creek	Alluvium	22	3	0.99	1.49	62.6	43.7	56.2	38.6
Tuckasegee River	Alluvium	69	22	0.97	1.44	63.3	45.6	52.2	42.9
Chapel hill	Saprolite	68	4	1.01	1.44	61.8	45.8	53.2	42.5
Gibson cove	Saprolite	41	9	1.19	1.41	55.1	46.7	44.8	40.6
		Lawn	Pasture	Lawn	Pasture	Lawn	Pasture	Lawn	Pasture
Watauga Hazard	Alluvium	8	4	1.38	1.37	48.1	48.2	40.0	41.8
Speedwell Acres	Saprolite	14	10	1.31	1.21	50.6	54.5	46.6	47.4
Walnut creek	Saprolite	7	22	1.48	1.36	44.1	48.6	42.1	43.5

K_{sat} values represent 0–25 cm depth; bulk density, porosity, and VMC values represent 0–15 cm depth.
[a] The value for each location represents the mean of three sites; symbols defined in Section "Laboratory methods".

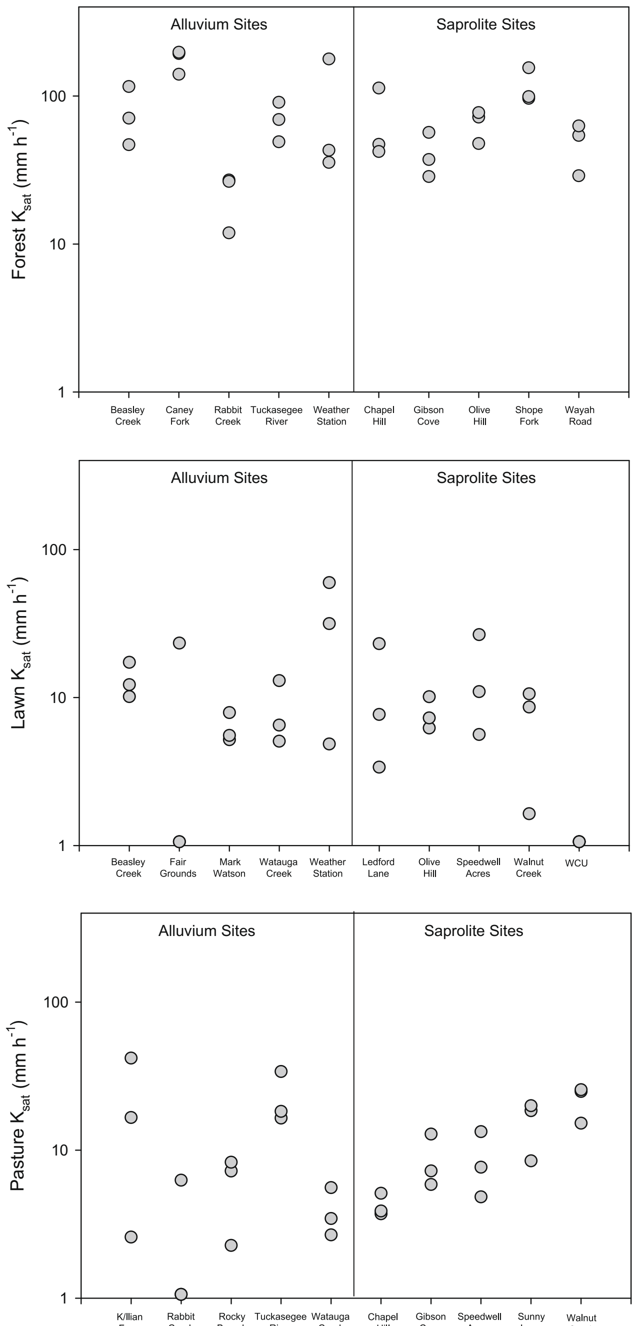

Fig. 5. Saturated hydraulic conductivity among sites. The field saturated hydraulic conductivities (K_{sat}) at the three sampling points at each location are shown, demonstrating the similar variability within a given locations to that seen among all locations within each land use and the similarity in K_{sat} between the parent materials (saprolite and alluvium).

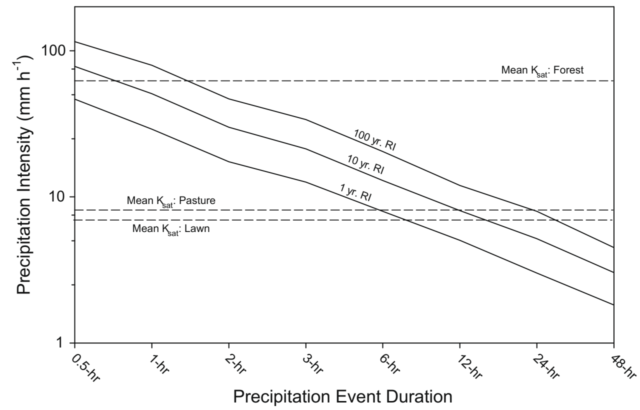

Fig. 6. Comparison of soil saturated hydraulic conductivities with precipitation intensities occurring in western North Carolina. The solid lines represent the recurrence intervals (RI) of storm events of given precipitation intensity and duration in Franklin, NC (re-created from Bonnin et al., 2004). The dashed lines represent the mean saturated hydraulic conductivity (K_{sat}) of soils underlying each land use ($n = 30$ sites per land use, mean = geometric). As K_{sat} represents the lower bound of the soil infiltration rate, the figure demonstrates the far greater likelihood of Hortonian overland flow in lawn and pasture soils, especially associated with sustained storm events, during which overland flow is of greatest concern to watershed hydrologic processes.

was significantly greater than that of the lower core (50.7% vs. 46.2%; $t = 7.36$; $p < 0.001$). As seen with the other variables, the VMC_{fc} of forest soils differed significantly from pasture and lawn soils, which again did not significantly differ from each other (Table 5). Forest soil VMC_{fc} was nearly 10% greater than pasture and lawn soils (54.8% vs. 45.4% and 45.2%).

Paired locations

Pair comparisons corroborate the results using all 90 sites (Table 6). In all forest/pasture and forest/lawn pairs, the forest soils demonstrated lower ρ_B and higher φ_T, K_{sat}, and VMC_{fc} than the nonforest soils. In no pair was the directionality of difference reversed. Differences within forest/nonforest pairs were of similar magnitude to those reported above, with the greatest contrasts between forest and pasture soils. There were very few pronounced within-pair differences for the lawn/pasture pairs, and there was no consistency in directionality of difference between lawn and pasture sites for any parameter.

Site variability of K_{sat}

As a correlate of the other physical parameters, field K_{sat} was used to evaluate the assumption of independence among the sampling points within each site. Within a given land use, the variability among sites was not drastically greater than seen among the three points within a given site (Fig. 5). ANOVA on ranks indicated that variability among lawn sites was not statistically significant ($H = 11.38$; $p = 0.251$). While forest and pasture sites did demonstrate statistically significant differences among sites (forest: $H = 19.065$; $p = 0.025$; pasture: $H = 19.146$; $p = 0.024$), in both land uses the exclusion of the site with the highest mean K_{sat} value resulted in a lack of statistically significant variability among the sites. However, ANOVA used to evaluate the difference in K_{sat} as a function of land use demonstrated that the differences among land use are still statistically significant when these sites are excluded. Thus, the treatment of all 90 sites as independent was deemed to be justifiable.

Discussion

The results of this study indicate a clear distinction between the hydraulic properties of forest vs. lawn and pasture soils. This is especially noteworthy given the similarity of textures among the soils included in this study. While it was hypothesized that lawn soils would show a greater distinction from forest soils than would pasture soils, both nonforest land uses exhibited remarkably similar soil physical characteristics. The differences observed in the K_{sat}, ρ_B, φ_T, and VMC_{fc} between forest and nonforest soils are interpreted to have resulted from a combination of land management and differences in macropore-forming biotic activity. Pasture sites have likely experienced compaction by livestock and/or heavy equipment, and lawn site preparation generally involves compaction or removal of topsoil. Forest soils typically demonstrate a far greater presence of woody roots and burrowing fauna, resulting in well-developed macropore networks (Messing et al., 1997). Such networks can have a profound impact on soil conductivities. Several studies have indicated a distinction between soils underlying woody vs. herbaceous vegetation, with shrubs and trees supporting much higher macroporosity and K_{sat} than even native, unmanaged grassland (Godsey and Elsenbeer, 2002; Jiménez et al., 2006; Li and Shao, 2006). The results of this study corroborate this distinction. While there are many examples of comparative studies between native vegetation and cultivated soils and between forest and pasture soils, far less information is available for turfgrass soils. There is a clear need for a more comprehensive understanding of the hydrologic effects of forest conversion to turfgrass, given the suburban and exurban development pressures facing many areas of the world.

The results of this study demonstrate pronounced magnitudes of difference between forest and nonforest soils, and the discussion that follows compares the magnitudes of difference for the individual parameters with differences between forest and nonforest soils in other studies.

Bulk density

In this study, nonforest soils had average ρ_B as much as 38% higher than forest soils. While a few studies have demonstrated only minor differences between the ρ_B of forest vs. pasture or grassland soils (e.g. Agnihotri and Yadav, 1995; Celik, 2005), a greater number of studies have indicated large differences under such landcovers. Over a range of 0–15 cm depth, Reiners et al. (1994) reported an average ρ_B of 0.69 g cm^{-3} under primary forest soils, in contrast to 0.80 g cm^{-3} under active pasture soils in the Costa Rican rainforest. Harden (2006) observed ρ_B of soils under grass cover five times greater than those under forest cover in the Ecuadorian parámo. Statistically significant differences of smaller magnitude have been observed in the Himalayan foothills of Pakistan (Abbasi et al., 2007) and within three of four studied soil series in Pennsylvania (Zhou et al., 2008). Livestock grazing has been shown to directly increase soil ρ_B in Argentina (Cisneros et al., 1999).

Fewer studies have investigated ρ_B differences between turfgrass and other land uses, but differences have been demonstrated in several regions. Pouyat et al. (2007) found ρ_B to be one of the most influential factors for statistically distinguishing forest vs. turfgrass landcover in the Baltimore metropolitan area, despite the minor difference in magnitude (average forest ρ_B = 1.1 g cm^{-3}, average park/golf course/residential/institutional turfrass = 1.2–1.3 g cm^{-3}). Zhou et al. (2008) found that woodland soils demonstrated lower ρ_B than urban soils in Pennsylvania.

Saturated hydraulic conductivity

On average, forest soils in this study area demonstrated K_{sat} values approximately seven times greater than pasture and lawn soils. Several other studies have shown similar magnitudes of difference between forest and pasture. Godsey and Elsenbeer (2002) and Zimmermann et al. (2006) found order of magnitude differences between the near-surface (0–12.5 cm) conductivities of forest and pasture soils in Brazil (250 vs. 15 mm h^{-1} and 206 vs. 26 mm h^{-1}, respectively). A similar magnitude of difference was demonstrated in Peru, where grazed pasture soils were characterized by an average K_{sat} of 41 mm h^{-1}, compared with 420 mm h^{-1} observed in forest soils (Allegre and Cassel, 1996). An even greater magnitude of difference was demonstrated in Colombia, where the average K_{sat} values of fine-textured forest and pasture soils were 143 vs. 2 mm h^{-1} and K_{sat} values of coarse-textured forest and pasture soils were 159 vs. 8 mm h^{-1} (Martínez and Zinck, 2004). The results of the Martínez and Zinck (2004) study are particularly noteworthy, as they indicate the land-use signature on soil K_{sat} is independent of soil texture. Significantly greater K_{sat} of forest vs. pasture soils has also been demonstrated in the Loess Plateau of China (Li and Shao, 2006) and in Nigeria (Ghuman et al., 1991), though not of as great a magnitude as demonstrated by the southern Blue Ridge soils or the aforementioned studies. A review of 14 afforestation studies in the tropics showed an average threefold increase in infiltration capacity compared with previous disturbed conditions (Ilstedt et al., 2007).

While pronounced differences in the hydraulic conductivities of forest vs. pasture soils have been shown throughout the world, several studies have shown a lack of significant difference between forest and pasture or grassland soils (e.g. Messing et al., 1997; Celik, 2005; Zhou et al., 2008). This discrepancy may be a result of complications of legacy effects of prior land use. The lack of difference could also be the result of the wide range of impacts characterizing a pasture or grassland site, e.g., whether or not the site has been exposed to livestock grazing or heavy equipment. Soil compaction by such mechanisms has been shown to reduce infiltration rates and conductivities (Agnihotri and Yadav, 1995; Allegre and Cassel, 1996).

While there is a large body of literature addressing differences in K_{sat} between forest and pasture sites, far fewer comparative values exist for forest and lawn sites. Zhou et al. (2008) reported a lack of significant difference between the conductivities of lawn and forest soils in Pennsylvania. The authors speculate the lack of statistical significance of differences may have resulted from pronounced temporal variability and from interactions between land use and other independent variables. Although few studies have compared lawn soils to native land uses directly, several studies have indicated very low conductivities of lawn soils, of similar magnitude to those seen in this study (Wigmosta, 1991; Hamilton and Waddington, 1999; Oliviera and Merwin, 2001).

Volumetric moisture content

Despite well-documented correlations between volumetric moisture content and other soil physical parameters, there is much less evidence for land-use dependence of volumetric moisture content than seen with K_{sat}, ρ_B, or φ_T. This study found consistent and significantly higher VMC_{fc} in forest than pasture and lawn soils, by a factor of nearly 20%. However, several studies have demonstrated no significant differences between the volumetric moisture content at field capacity of disturbed and undisturbed soils (e.g., Jusoff, 1989). Harden (2006) showed substantially greater volumetric moisture content of páramo grassland vs. forest soils in the Ecuadorian Andes. Páramo soils were shown to have VMC three times greater than the forest soils, despite the fact that the grassland soils demonstrated five times greater ρ_B. Soils in the Loess Plateau of China had equivalent gravitational water content at field capacity among shrubland, forest, and grass landcover (Li and Shao, 2006).

Implications for altered water budgets

The results of this study indicate pronounced reductions in K_{sat} with nonforest land use in the southern Blue Ridge Mountains. This region is currently experiencing development pressures associated primarily with exurban growth, and housing density is expected to increase dramatically in coming decades (Cho et al., 2003; Gragson and Bolstad, 2006). Land use in Macon and Jackson counties is predominantly forest (83% in 2001), and an increase in housing density will inevitably be associated with a decline in forest cover.

The results of this study indicate that significant changes in watershed land use from forest to turfgrass will be associated with major alterations to watershed water budgets. The decreased hydraulic conductivity will likely be associated with increased Hortonian overland flow. The rainfall intensity/duration/frequency (IDF) curves from Franklin, NC confirm this likely scenario (Fig. 6). With K_{sat} representing the lower bound of the soil infiltration rate, the IDF curves show that, while the mean K_{sat} of forest soils is high enough to accommodate all but very infrequent or short duration storm events, rainfall intensities commonly exceed the mean K_{sat} values of lawn and pasture soils. Storms of intensities exceeding the conductivities of lawn and pasture soils also commonly persist for significant durations.

Changes in the proportion of forest and nonforest land use within southern Blue Ridge watersheds will be associated with increased overland flow and decreased times of water transmission to stream networks. Such changes carry important implications for increased flood hazards, greater contaminant and nutrient transport to streams, surface erosion, and increased stream temperatures, as subsurface water temperatures are cooler than overland flow exposed to surface-heating. Correspondingly, increased overland flow is associated with reduced subsurface recharge and decreased baseflows, consequences of which include reduced water supply, increased concentration of contaminants in streams, and impaired instream aquatic habitat. This is a particular threat in the crystalline terrain of the southern Blue Ridge, where there is no significant bedrock aquifer supplying baseflow to streams – in this region, the soil and saprolite mantle is the predominant source of sustained streamflow (Hewlett, 1961; Velbel, 1985). Furthermore, as indicated by Harden (2006), decreases in the surface infiltration capacities of soils in mountainous terrain are particularly pronounced, because of the rapid rates of transmission of overland flow to stream systems in steep terrain.

Land-use impacts on soil hydrology have been shown to influence watershed processes in several studies. Harden (2006) showed that human activities in the Ecuadorian páramo have altered the timing and distribution of infiltration and runoff, specifically attributed to soil compaction. Increased overland flow was observed in King County, Washington, associated with turfgrass land use, attributed to topsoil removal and construction compaction (Wigmosta, 1991). Bens et al. (2007) determined that soils play a critical role for water retention and overland flow prevention for flood control in the German lowlands. It is clear from this and other studies that the flashier hydrologic regimes typically associated with increased impervious surface in human impacted areas are likely partially due to soil alteration associated with land-use change, and that there is a serious need to address such impacts when evaluating or predicting hydrologic response to land-use change. Unaddressed by this study are the potential downstream water chemistry effects of lawns and pastures. Given the increased occurrence of Hortonian overland flow, occasional transport of fertilizers, pesticides, and/or manure in surface runoff from lawns and pastures can be expected. Pickett et al. (2008) found equivalent soil lysimeter chemistry in differing cover types in urban Baltimore, but they did not investigate differences in soil hydraulic properties.

Conclusions

Soils in the southern Blue Ridge exhibit marked differences in physical characteristics under forest and nonforest land uses (pasture and lawn). Soil particle size distributions do not differ significantly among the parent materials or land uses, and soil hydraulic properties do not differ significantly between alluvium and saprolite soils. Among both parent materials, forest soils had significantly lower bulk density and higher saturated hydraulic conductivity and volumetric moisture content than pasture and lawn soils, which did not significantly differ from each other. The mean saturated hydraulic conductivity among forest sites was approximately seven times greater than in pasture and lawn soils. Nonforest soils had hydraulic conductivities lower than the rainfall intensities of common, long-duration storms in the region, and nonforest soils also had reduced water holding capacities. Accordingly, altered water budgets and increased Hortonian overland flow should be expected to accompany continued land-use change in the southern Blue Ridge. These results strongly support the concept that soil modification is a significant driver of the watershed hydrologic changes of increased floods and reduced baseflows observed with land-use change.

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