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Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation

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ABSTRACT

Forest planting is increasingly being incorporated into land management policies to mitigate diffuse pollution and localised flooding because forest soils are associated with enhanced hydraulic properties and lower surface runoff compared to soils under other vegetation types. Despite this, our understanding of the effects of different tree species and forest land use on soil hydraulic properties is limited. In this study we tested for the effects of two tree species, sycamore (*Acer pseudoplatanus*) and Scots pine (*Pinus sylvestris*), subject to contrasting land use systems, namely ungrazed forest and livestock grazed forest, on soil surface saturated hydraulic conductivity (K_{fs}) at a long term (23 year) experimental site in Scotland. Additionally these forest land use systems were compared to grazed pasture. K_{fs} was found to be significantly higher under ungrazed Scots pine forest (1239 mm hr^{-1}) than under ungrazed sycamore forest (379 mm hr^{-1}) and under both of these forest types than under pasture (32 mm hr^{-1}). However, this measure did not differ significantly between the sycamore and Scots pine grazed forest and pasture. It was inferred, from comparison of measured K_{fs} values with estimated maximum rainfall intensities for various return periods at the site, that surface runoff, as infiltration excess overland flow, would be generated in pasture and grazed forest by storms with a return period of at least 1 in 2 years, but that surface runoff is extremely rare in the ungrazed forests, regardless of tree species. We concluded that, although tree species with differing characteristics can create large differences in soil hydraulic properties, the influence of land use can mask the influence of trees. The choice of tree species may therefore be less important than forest land use for mitigating the effects of surface runoff.

1. Introduction

Forest soils are associated with higher rates of water infiltration (Agnese et al., 2011; Archer et al., 2013; Gonzalez-Sosa et al., 2010; Wood, 1977; Zimmermann et al., 2006) and lower surface runoff generation (Alaoui et al., 2011; Dev Sharma et al., 2013; Germer et al., 2010; Huang et al., 2003; Humann et al., 2011; Jordan et al., 2008) than soils under other vegetation types. Trees have consequently been identified as having a key role to play in the provision of the ecosystem services of water regulation and water purification, as defined by the Millennium Ecosystem Assessment (Alcamo et al., 2003). Strategic tree planting to mitigate flooding, prevent soil erosion and protect watercourses from diffuse pollution from agricultural land and urban environments is now incorporated into many policies and guidelines. In the UK, for example, the use of tree buffer zones and woodland has been recommended to reduce runoff and soil erosion (Environment, Food and Rural Affairs Committee, 2016; SEPA, 2016), and strategies for forest management to protect water quality have been set out (Scottish Executive, 2006; DEFRA, 2007).

Despite this, our understanding of how trees affect soil hydraulic properties is still extremely limited. One area of research that remains largely neglected is the variation in species' effects. Although roots, soil fauna and soil organic matter, all of which affect soil hydrology (Aubertin, 1971; Edwards and Bohlen, 1996; Eldridge, 1993; Lado et al., 2004; Schwärzel et al., 2012), have been shown to vary between tree species (Kalliokoski et al., 2008; Kasel et al., 2011; Neirynck et al., 2000; Reich et al., 2005; Scheu et al., 2003; Tang and Li, 2013; Trum et al., 2011), studies that compare soil hydraulic properties under different tree species are still very few (Table 1). In particular, contrasting differences in root characteristics, soil organic matter, and influence on earthworm populations, previously highlighted between broadleaved and conifer trees (Ovington, 1953; Reich et al., 2005; Trum et al., 2011; Withington et al., 2006), suggests a contrasting influence on soil hydraulic conductivity between these species types.

Forest land use can also have an impact on soil hydrology but this area of research has, like the effects of tree species on hydrology,

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Table 1
Published studies comparing soil hydraulic properties under different tree species.

Author(s) (year)	Location of study	Tree species and statistically significant difference
Bartens et al. (2008)	Greenhouse experiment	Red maple = black oak
Bens et al. (2007); Buczko et al. (2006); Wahl et al. (2003)	Kahlenberg, Germany	Scots pine = beech
Eldridge and Freudenberger (2005)	NSW, Australia	Eucalyptus = white cypress pine
Heiskanen and Mäkitalo (2002)	Finland	Scots pine > Norway spruce
Johnson-Maynard et al. (2002)	California, US	Scrub oak > Chamise > Coulter pine
Jost et al. (2012)	nr. Kreisbach, Austria	Spruce = beech
Mishra and Sharma (2010)	Uttar Pradesh, India	Mesquite/Forest red gum/Indian rosewood (significance not stated)
Sanou et al. (2010)	Burkina Faso, West Africa	Baobab = Néré

received little attention. With widespread land use conversion occurring over the last few decades, particularly in tropical regions (Godsey and Elsenbeer, 2002), researchers have focused on the hydrological consequences of converting forest to grazed pasture or arable land (Burch et al., 1987; Lorimer and Douglas, 1995; Wood, 1977; Zimmermann et al., 2010) and the effects of reforestation or afforestation (Hassler et al., 2011; Messing et al., 1997; Perkins et al., 2012; Zimmermann et al., 2006). Although these studies usually show much higher soil hydraulic conductivity under forest, the forests in these studies tend to be relatively undisturbed. More intensive forest land use may, however, diminish the benefits of reduced runoff attributed to tree cover. One such example is the grazing of livestock under trees. Livestock grazing in forest and on wooded pasture (silvopasture) has been a common practice for many centuries and is still widespread to this day (Sheldrick and Auclair, 2000). The Mediterranean dehesa, where livestock graze beneath scattered oak trees that provide wood, charcoal and cork, is one of the longest surviving and best known silvopastoral systems (Joffre et al., 1988). More recently, integrated systems of livestock grazing with pine trees, grown to produce high-grade timber, have been developed in countries such as New Zealand, Chile and the United States (Knowles, 1991; Sheldrick and Auclair, 2000). Livestock were initially introduced to control the understorey that develops under these highly pruned and thinned trees, but the practice has gradually extended to incorporate low-density planting of trees into existing pasture (Knowles, 1991). There is, however, some evidence to suggest that the trees in these systems may not enhance soil hydraulic properties. A study undertaken by Sharrow (2007), in an experimental agroforestry system planted with Douglas fir (*Pseudotsuga menziesii*) in the United States, found no significant tree effect when infiltration rates in silvopasture were compared with those measured in pasture while, in New Zealand, Yeates and Boag (1995) reported lower saturated hydraulic conductivity under radiata pine (*Pinus radiata*) silvopastures planted at various densities than under adjacent pasture (although they did not state statistical significance).

The objectives of this study were, therefore, to investigate the influence of both tree species and forest land use on soil surface hydraulic properties. Forest soils planted with a broadleaf species (sycamore) and a conifer species (Scots pine) were compared to test species effects, while both grazed forest (silvopasture) and ungrazed forest were compared with grazed pasture to separate the influence of the trees from the influence of the land use.

2. Materials and methods

2.1. Field site

The field site (Figs. 1 and 2a) used in this study is located at Glensaugh in Scotland (56° 54′ N, 02° 33′ E) and is owned and managed by the James Hutton Institute. Established in 1988, it originally formed part of the UK's National Network of Silvopastoral Experiments. These experimental sites (six in total) were created to investigate livestock productivity in an integrated sheep grazing and woodland pasture system (*i.e.* silvopasture) in the UK, with timber providing a potential alternative source of income. The tree species planted at this site, which was previously grazed pasture, included sycamore (*Acer pseudoplatanus*) and Scots pine (*Pinus sylvestris*). In addition to the silvopasture treatments, hereafter referred to as grazed forest, the grazed pasture and ungrazed forest treatments were set up as controls. All treatments were replicated three times in a randomised block design (see Fig. 1). There are distinct differences in the ground flora between treatments that is consistent across the three blocks. The pasture vegetation is dominated by grasses, primarily *Lolium perenne*, with *Holcus lanatus* and clover (*Trifolium repens*) also making up a significant proportion of the overall cover. *L. perenne* is also the dominant species in the Scots pine grazed forest plots, with significant proportions of *Agrostis capillaris* and *Poa trivialis* in two of the plots and *T. repens* in the third. The ground of the Scots pine ungrazed forest plots is covered with a thick layer of litter, through which *Brachypodium sylvaticum* grows sparsely. The sycamore plots are characterised by patches of bare ground and litter that vary in extent seasonally and, in the grazed plots, dependent on whether the plots are currently, or have recently, been grazed. Between these patches the dominant species are *B. sylvaticum* and/or *H. lanatus* with scattered patches of nettles (*Urtica dioica*). Although the original experiment has now ended, the majority of the treatments at the Glensaugh field site remain intact and the site continues to be maintained for scientific study. Ungrazed forest plots are fenced to prevent access; all other plots are grazed from April to October by sheep and, since 2010, occasionally by cattle. Altitude across the site ranges from 140 m to 205 m, mean annual rainfall is 1168 mm and mean annual temperature is 8.0 °C (2006 to 2011). Soils at the site, classed as leptic podzols or cambisols (dystric) (IUSS Working Group WRB, 2007), developed primarily on glacial drifts derived from quartz-mica-schist and are generally quite stony.

2.2. Sampling design

Trees in the forest plots form a grid pattern, with rows planted in a north-south orientation and spaced at 5 × 5 m (400 trees ha^{-1}) in grazed plots and 2 × 2 m (2500 trees ha^{-1}) in ungrazed plots. The position of each tree within each plot was mapped for this study and the squares formed by the grid were used to define potential sampling locations. After defining a virtual boundary created by the trees at the edge of the plot, squares with one or more sides on this boundary were excluded to minimise edge effects. Squares with one or more trees missing, either because they had failed to grow, had fallen or were felled for another experiment, were also excluded. The remaining squares were then numbered and squares randomly selected for sampling. Within pasture virtual squares of 5 × 5 m were defined to provide potential sampling locations and sampling undertaken at the centre of each selected square.

Five treatments were chosen for sampling (see Figs. 1 & 2):