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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.

Keywords: flooding; soil hydrology; land management; mitigation; tree species; woodland.

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, 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 (Fig. 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 x 5 m (400 trees ha^{-1}) in grazed plots and 2 x 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 x 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 Fig. 1 & 2):

1) grazed pasture (without trees; Fig. 2b);
2) grazed forest planted with sycamore at 400 trees ha^{-1} (Fig. 2c);
3) ungrazed forest planted with sycamore at 2500 trees ha^{-1} (Fig. 2d);
4) grazed forest planted with Scots pine at 400 trees ha^{-1} (Fig. 2e);
5) ungrazed forest planted with Scots pine at 2500 trees ha^{-1} (Fig. 2f).

Field saturated hydraulic conductivity (K_{fs}) in the upper few centimetres of the soil profile was determined from infiltration measurements carried out during summer 2011. Six measurements were undertaken for each treatment in each of the three blocks, giving a total of eighteen measurements per treatment. As grazed forests and ungrazed forests were planted at different densities, a follow up study was carried out in April 2012 to separate the influence of land use (*i.e.* grazed vs. ungrazed) from the influence of tree density, using the following treatments (see Fig. 1):

1) grazed forest planted with sycamore at 400 trees ha^{-1};
2) ungrazed forest planted with sycamore at 400 trees ha^{-1};
3) ungrazed forest planted with sycamore at 2500 trees ha^{-1}.

Six measurements per treatment were undertaken in a single block only (Redstones), as the ungrazed forest planted with sycamore at 400 trees ha^{-1} had been removed from one block and was considered unsuitable for study in the second, owing to edge effects. Without block replication this follow up study lacked the robustness of the first; however it provided useful additional information to aid interpretation of the results from the main study.

2.3 Field saturated hydraulic conductivity

K_{fs} was determined from measurements obtained using small single ring infiltrometers and the pressure infiltrometer method described by Reynolds and Elrick (2002). This method can be applied to ring sizes with an inner diameter of between 10 and 20 cm inserted from 3 to 10 cm into the soil. For practical reasons two ring sizes, with inner diameters 10 and 11 cm, were used in this study. Rings were inserted between 3 and 7 cm into the soil and the infiltration rate timed until a quasi-steady rate was achieved. K_{fs} was then derived using the single-head analysis, with the soil texture-structure parameter (α^*) estimated as 12 m^{-1}. K_{fs} is dependent on both the properties of the soil and the viscosity of the water (Hillel, 1998), which varies with temperature, so the temperature of the water was measured at the time of each test and a correction factor applied to determine K_{fs} at 20° C (Chandler and Chappell, 2008). If no drop in water level was observed in the infiltrometer reservoir within the first hour of observation then measurement was abandoned and K_{fs} recorded as too low to be measureable. Three measurements were recorded as too low to be measureable in the sycamore grazed forest plot in Croft block and one in the Scots pine grazed forest plot in Birnie block.

2.4 Statistical analysis of K_{fs} data

K_{fs} data were analysed using R version 3.0.0 (R Core Team, 2013). Raw data were transformed in order to satisfy the assumption of normality (confirmed by the Shapiro-Wilk test) required by the statistical tests for differences between treatments, ensuring that observations within each treatment met this assumption (Zuur et al., 2010). A logarithmic transformation was applied to the data from the main study, while a square root transformation was applied to the data from the follow up study. A linear mixed-effects model was used to test data from the main study as the hierarchical structure, created by grouping observations by block, can be easily accounted for by setting block as the random factor. This type of model is also able to account for the heteroscedasticity (unequal variance) and missing values in this dataset. The follow up study, undertaken in a single block, was tested with a linear model. The *post hoc* Tukey test provided *p*-values for comparison between individual treatments. K_{fs} values obtained in the follow up study were compared with the values previously obtained in the same plots, in order to test for temporal differences, using the Mann-Whitney test.

2.5 Rainfall intensity-frequency analysis

A number of environmental variables, including meteorological measurements, are recorded at Glensaugh by the Environmental Change Network (Rennie et al., 2015). Rainfall is recorded in hourly intervals by tipping bucket gauge, enabling a rainfall intensity-frequency analysis to be carried out for comparison with K_{fs}. Maximum rainfall intensities (I_{max}) for 2, 5, 10 and 50 year return periods were estimated from annual maximum hourly rainfall values recorded between 1995 and 2010 (Data accessed on 02-08-2012 at http://data.ecn.ac.uk, data citation code: ECN:KC8/12; Rennie et al., 2015) using the Weibull formula (Shaw, 1994).

3. Results

3.1 Distribution of the K_{fs} data

Distributions of the K_{fs} data demonstrated a positive skew, in common with many other studies (Bonell et al., 2010; Chappell and Franks, 1996; Talsma and Hallam, 1980; Zimmermann et al., 2006). The degree of skew varied between treatments (Table 2), with ungrazed forest treatments showing less skew than grazed forest treatments planted with the same tree species. A logarithmic distribution was found to best describe the K_{fs} data collected in the main study, while a square root distribution was found to be more probable for the data collected in the follow up study. Treatments also showed differences in variance, both in the main and follow up study, with lower variance in K_{fs} observed in the grazed treatments than in the ungrazed treatments (Fig. 3). Application of Levene's test showed that, in the main study, this difference was highly significant ($p < 0.001$).

3.2 Comparison of mean K_{fs} values

In the main study K_{fs} was found to be significantly enhanced by the ungrazed forest treatments (Table 2), with mean values one and two orders of magnitude higher in the sycamore and Scots pine ungrazed forests respectively compared with pasture ($p < 0.001$). Ungrazed forest treatments were also found to be significantly different from each other ($p < 0.001$). However, no tree effect was observed in the grazed forest treatments, both of which had a similar mean K_{fs} to pasture ($p > 0.05$) and also significantly lower mean K_{fs} than the ungrazed forest treatments ($p < 0.001$). The grazed forest treatments differ from the ungrazed forest treatments in having both more intense land use and lower planting density, so the effect of both were investigated in the follow up study (Table 2). While no difference was observed between the ungrazed sycamore plots planted at different densities, K_{fs} was significantly greater ($p < 0.05$) in the ungrazed plot planted at 400 trees ha^{-1} than in the grazed forest plot planted at the same density, with the same order of magnitude difference that was previously observed between grazed forest and ungrazed forest (Table 2).

Although saturated hydraulic conductivity can exhibit temporal as well as spatial variation (Bonell et al., 2010), comparison of the K_{fs} data collected in the sycamore ungrazed forest and grazed forest treatments for the follow up study were not found to be significantly different ($p > 0.05$) from the observations recorded in the same plots in the previous year.

3.3 I_{max} vs. K_{fs}

I_{max} estimated for 2, 5, 10 and 50 year return periods are shown in figure 3, superimposed over boxplots illustrating the range of K_{fs} values recorded in the main study.

4. Discussion and conclusions

Prior to the establishment of the field site in 1988 the entire area was used for livestock grazing and therefore subject to a single land use equivalent to the pasture treatment. Differences between treatments consequently reflect the changes that have occurred over the subsequent 23 years as a result of vegetation and land use effects.

4.1 Impact of land use and vegetation type

While mean K_{fs} was at least an order of magnitude greater in ungrazed forest than in pasture, differences between grazed forest and pasture were statistically insignificant. Although the main study compared pasture with grazed and ungrazed forest plots planted at different densities, a follow up study found no statistically significant difference in $\mathrm{K_{fs}}$ between sycamore forest plots planted at the different densities when both were ungrazed. Sharrow (2007) similarly observed higher infiltration under ungrazed forest, but not grazed forest, when comparing both with grazed pasture, attributing the difference to the presence of livestock under the trees. Grazing livestock can exert considerable pressure on the soil surface, causing compaction, which reduces porosity and infiltration (Abdel-Magid et al., 1987; Castellano and Valone, 2007; Wheeler et al., 2002). Willatt and Pullar (1984), for example, recorded a hoof pressure of 83 kPa for sheep and estimated that this could rise to 200 kPa when the animal is walking and only two or three hooves are in contact with the ground. An order of magnitude difference in soil hydraulic properties between forest and pasture, both in temperate and tropical regions, has been reported by other studies (Agnese et al., 2011; Alegre and Cassel, 1996; Archer et al., 2013; Gonzalez-Sosa et al., 2010; Zimmermann et al., 2006); however, this difference has also been observed between grazed and ungrazed grassland (Willatt and Pullar, 1984) and a number of studies have shown improvements in infiltration following cessation of grazing (Castellano and Valone, 2007; Hassler et al., 2011; Nie et al., 1997). So, does the influence of the land use mask the influence of the trees on soil hydraulic properties, or does increased K_{fs} in the ungrazed forest merely reflect the recovery of soil properties in the absence of grazing?

Marshall et al. (2014) performed a grazing exclusion experiment to investigate vegetation effects and found that, seven years after grazing was excluded, infiltration rates in plots planted with broadleaf trees were significantly higher than in plots without trees. Chandler and Chappell (2008) also observed higher K_{fs} around isolated oak trees (*Quercus robur*) compared with surrounding parkland. This suggests that the influence of trees on soil hydraulic properties is masked by a higher intensity land use; however, Kumar et al. (2012), comparing tree and grass buffer zones, found that saturated hydraulic conductivity was higher under grass.

It may also be worth noting here that, although differences in K_{fs} between grazed forest and pasture in this study were statistically insignificant, mean, median and maximum values were, in fact, higher in pasture. This is consistent with the findings of Yeates and Boag (1995) and may reflect the complex interplay between the different drivers of soil physical properties. For example, although infiltration has been shown to be enhanced by the channels created by tree roots (Noguchi et al., 1999), forests of all types have been shown to have a negative impact on the abundance and diversity of earthworms (Muys et al., 1992; Rutgers et al., 2016), which have been shown to positively influence infiltration rates (Lee and Foster, 1991). Yeates and Boag (1995) found in their study that, compared with pasture, earthworm numbers were lower under all treatments containing trees at greater than 50 trees ha^{-1}. Since the burrowing activity of earthworms can rapidly create macropores that enhance infiltration it may be that vegetation that supports an abundant and diverse earthworm population may be more important than vegetation that directly creates macropores to mitigate the direct effects of a high intensity land use.

More work is needed to understand vegetation effects under different land use intensities and how vegetation and land use effects interact; nevertheless, when considering the influence of forest on soil saturated hydraulic conductivity and, indeed, other soil properties, this study emphasises the importance of differentiating between undisturbed forest as a land use and forest as the vegetation cover.

4.2 Influence of tree species

Although there was no significant tree effect on K_{fs} in grazed forests, a significant species effect was observed in ungrazed forests, with mean K_{fs} significantly higher under Scots pine than under sycamore. This species difference, in the absence of grazing, supports the idea that the effect of trees is masked by the influence of land use in grazed forest. If higher K_{fs} in ungrazed forest was only the result of soil recovery after grazing exclusion, then similar values would be expected, regardless of tree species. While there are few studies for comparison, this observation of higher K_{fs} under a coniferous species is in accordance with a study undertaken in Cambodia by Toriyama et al. (2011), who found that K_{fs} was generally higher under evergreen compared with deciduous forests. Wahl et al. (2003), Bens et al. (2007) and Buczko et al. (2006), all studying the soil hydraulic properties for a Scots pine-beech transition in the Kahlenberg forest in Germany did not find a difference between the conifer and broadleaved species; however, the historical effect of Scots pine may still be reflected in the soil properties under the replacement beech forest, making species differences more difficult to detect.

4.3 Potential for surface runoff generation

When rainfall intensity exceeds infiltration rate surface runoff is generated by infiltration excess overland flow (IOF). Superimposing estimated I_{max} values on measured K_{fs} values (Fig. 3) illustrates that IOF is likely to be generated by high intensity rainfall at the field site. Even during a 1 in 2 year storm event, surface runoff will be generated in parts of the pasture and grazed forest plots. It can be seen that the significantly lower variance of K_{fs} in these livestock-grazed treatments also has important implications for runoff generation since, once rainfall intensity exceeds the lower end of the range, small increases affect a much wider area. In contrast, it is evident that IOF is likely to be extremely rare in the ungrazed forest treatments. The range of measured K_{fs} values in ungrazed Scots pine forest far exceed I_{max} for a 1 in 50 year storm and, although ungrazed sycamore forest may experience some runoff during such an event, it is likely to affect only a small area.

4.4 Implications for land management

Strategic tree planting to provide the ecosystem services of water regulation and water purification is based on the concept that trees enhance infiltration of water into the soil, thereby reducing surface runoff that may occur during storm events. The results of this study demonstrate that undisturbed forest has the capacity to not only reduce surface runoff but also to ‘soak up’ runoff generated further up the hillslope. The establishment of forested areas can therefore be a useful land management tool to mitigate diffuse pollution and localised flooding, particularly when planted downslope of areas where soil compaction or poaching is likely occur (SEPA, 2016). However, tree planting alone may not be sufficient to provide these benefits. The absence of a tree effect in silvopasture highlights the importance of land use effects on soil hydraulic properties, which may mask the effect of the trees. Millward et al. (2011) found that even recreational use lowered infiltration rates of an oak forest in Canada by an order of magnitude. Land management decisions to protect water quality and prevent flooding therefore need to take account of both vegetation and land use. While tree species (in ungrazed forest) was also found to have a significant effect on soil hydraulic properties, comparison with predicted rainfall intensities indicated that tree species at this field site had little effect on surface runoff generation, suggesting that choice of tree species may be less important than forest land use for mitigating the effects of surface runoff.

Acknowledgements

This research was carried out as part of a PhD project funded by a BBSRC Targeted Priority Studentship (BB/G018014/1). We would like to thank the James Hutton Institute for allowing us to use the field site and facilities at the Glensaugh Field Research Station, the many students who volunteered their time to assist with fieldwork at Glensaugh over the course of the project, and Nicola Thompson who undertook species identifications of the ground flora. We also thanks Prof. Richard Bardgett for comments on an earlier version of the manuscript.

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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

Table 2. Summary of K_{fs} statistics recorded at the soil surface at Glensaugh, Scotland. Mean values given are the geometric mean for the main study and the back transformed mean from the square root transformed data for the follow up study. Significant differences in mean K_{fs} ($p < 0.05$) within each study are indicated by different letters.

	n	**Mean (mm hr^{-1})**	**Variance (x 10^{-9} mm hr^{-1})**	**Skewness**
Main study				
Grazed pasture	18	32 ^{a}	0.55	1.57
Sycamore grazed forest (400 trees ha^{-1})	15	24 ^{a}	0.40	2.03
Scots pine grazed forest (400 trees ha^{-1})	17	19 ^{a}	0.37	1.32
Sycamore ungrazed forest (2500 trees ha^{-1})	18	379 ^{b}	47.17	1.80
Scots pine ungrazed forest (2500 trees ha^{-1})	18	1239 ^{c}	98.15	0.63
Follow up study				
Sycamore grazed forest (400 trees ha^{-1})	6	46 ^{a}	1.80	1.62
Sycamore ungrazed forest (400 trees ha^{-1})	6	433 ^{b}	6.21	0.43
Sycamore ungrazed forest (2500 trees ha^{-1})	6	386 ^{b}	6.01	-0.44

Figure captions

Figure 1. Plan view of the Glensaugh field site showing the sampled treatments for grazed pasture [PAST], sycamore grazed forest [SYC(G)], Scots pine grazed forest [SP(G)], sycamore ungrazed forest [SYC(U)] and Scots pine ungrazed forest [SP(U)] treatments in a randomised block design.

Figure 2. Photographs of (a) the Glensaugh experimental site, and examples of (b) grazed pasture, (c) sycamore grazed forest, (d) sycamore ungrazed forest, (e) Scots pine grazed forest, and (f) Scots pine ungrazed forest. All examples of experimental treatments are taken from the Redstones block.

Figure 3. Boxplots showing (a) the median and range of K_{fs} recorded at Glensaugh in the main study for grazed pasture [PAST], sycamore grazed forest [SYC(G)], Scots pine grazed forest [SP(G)], sycamore ungrazed forest [SYC(U)] and Scots pine ungrazed forest [SP(U)] treatments, and (b) the grazed treatments only, to differentiate these treatments. Superimposed lines show rainfall intensities for selected return periods of 1 in 2 years (11.8 mm hr^{-1}), 1 in 5 years (17.8 mm hr^{-1}), 1 in 10 years (21.8 mm hr^{-1}) and 1 in 50 years (30.96 mm hr^{-1}).

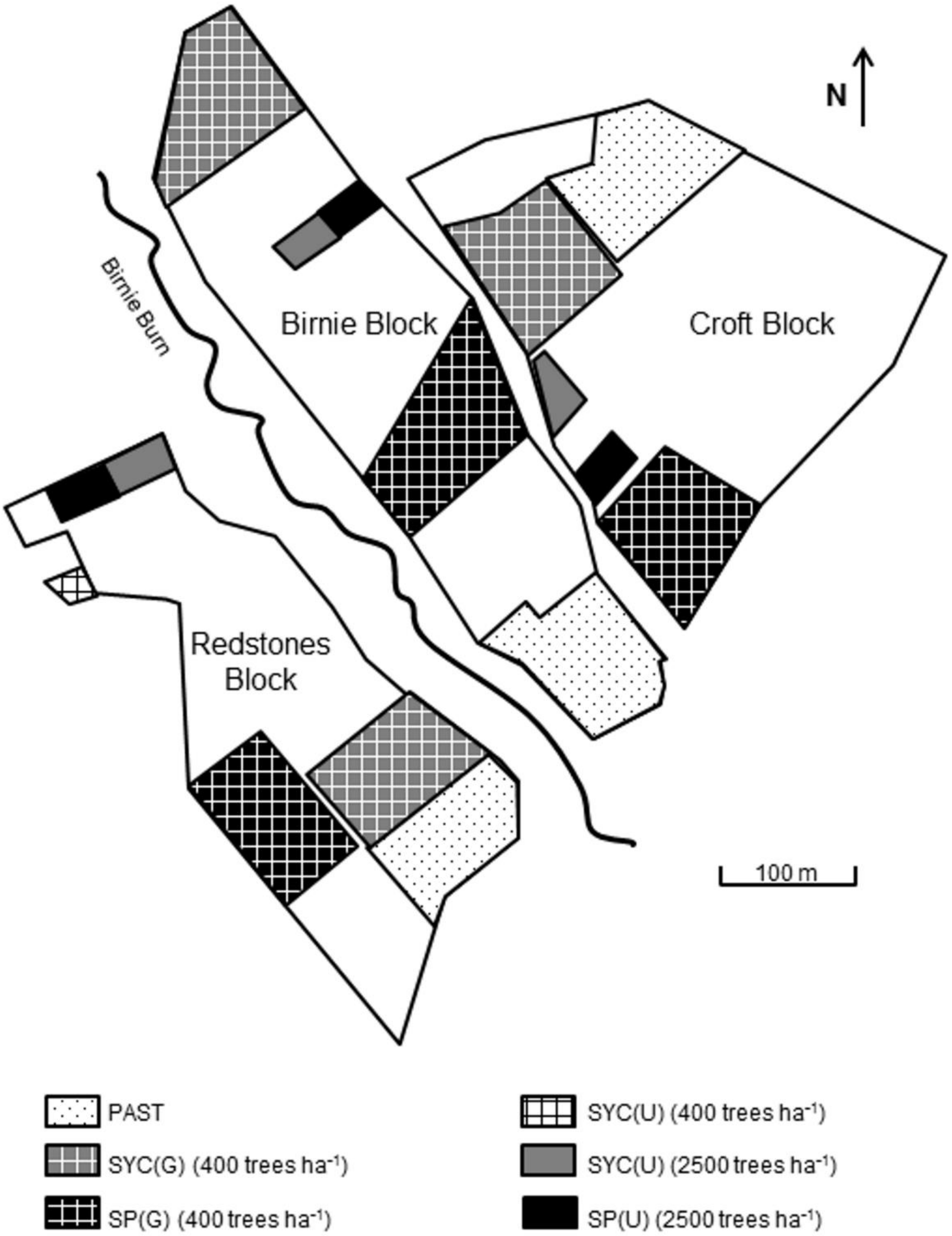
N
Birnie Burn
Birnie Block
Croft Block
Redstones Block
100 m
PAST
SYC(G) (400 trees ha^{-1})
SP(G) (400 trees ha^{-1})
SYC(U) (400 trees ha^{-1})
SYC(U) (2500 trees ha^{-1})
SP(U) (2500 trees ha^{-1})

Figure 1

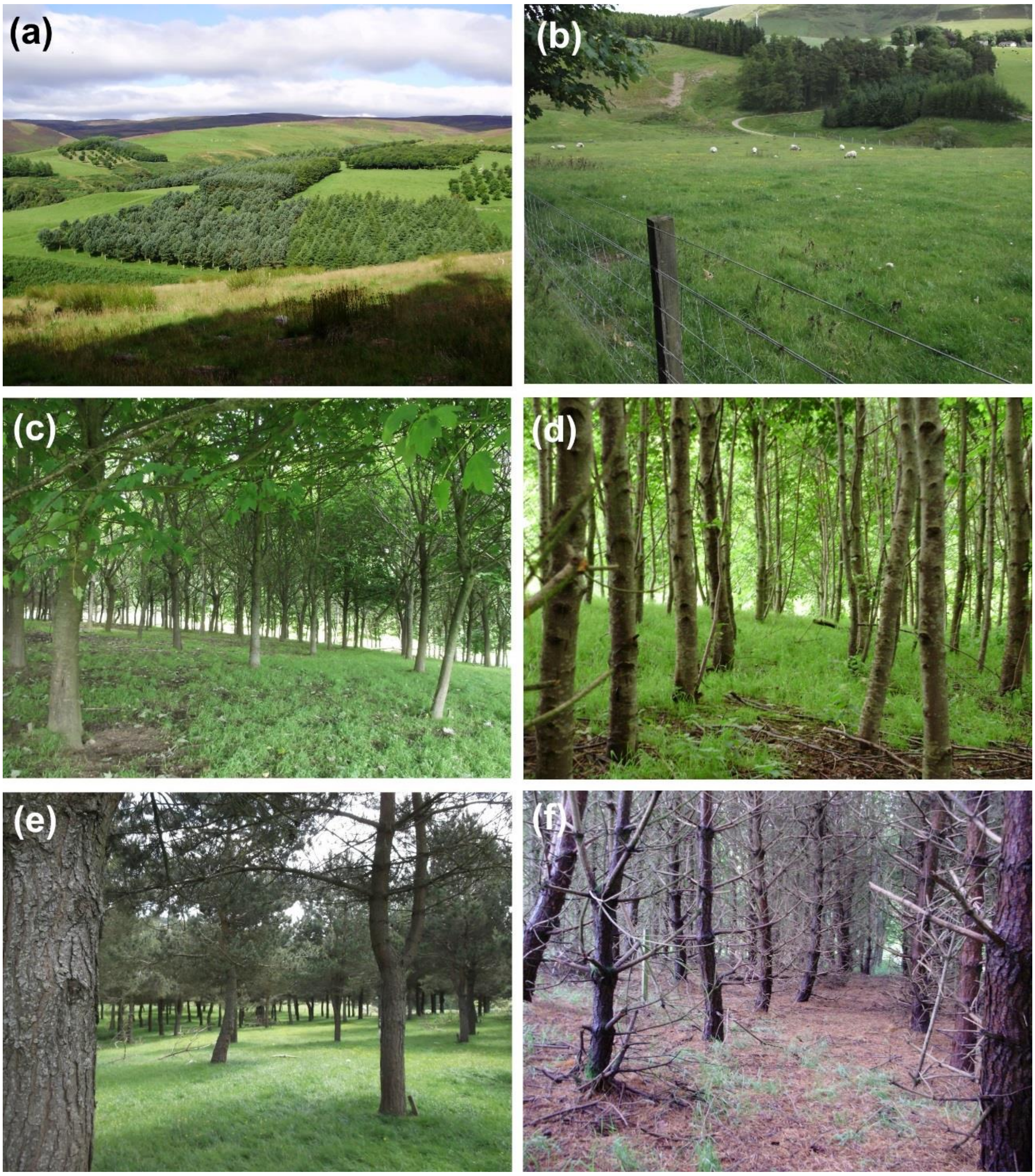

Figure 2

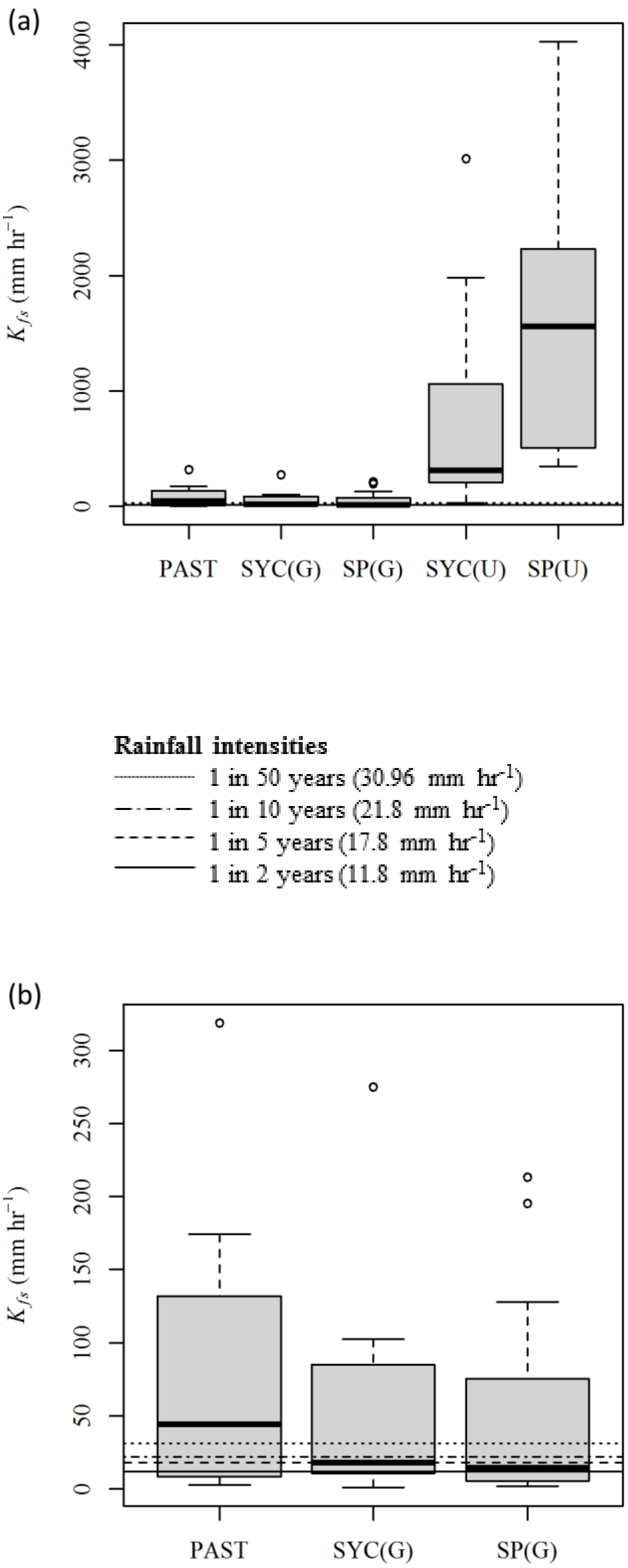
(a)
K_{fs} (mm hr^{-1})
0
1000
2000
3000
4000
PAST
SYC(G)
SP(G)
SYC(U)
SP(U)
Rainfall intensities
1 in 50 years (30.96 mm hr^{-1})
1 in 10 years (21.8 mm hr^{-1})
1 in 5 years (17.8 mm hr^{-1})
1 in 2 years (11.8 mm hr^{-1})
(b)
K_{fs} (mm hr^{-1})
0
50
100
150
200
250
300
PAST
SYC(G)
SP(G)

Figure 3