



Influence of individual oak (*Quercus robur*) trees on saturated hydraulic conductivity

Kathy R. Chandler, Nick A. Chappell*

Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK

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ABSTRACT

The influence of single trees on saturated hydraulic conductivity (K_s) was investigated for six isolated oak trees (*Quercus robur*) growing on a Dystric Gleysol in an area of parkland in northwest England. The K_s was measured within the A soil horizon over a 0.10–0.25 m depth using a borehole permeameter.

A dataset of 119 K_s values was obtained and comprises of 55 values from around 1 oak tree at distances of 1–13 m from the trunk, 45 tests around 5 other oak trees, and 19 tests in open grassland. For the intensively sampled tree, Wilcoxon rank sum tests showed a significant difference ($p < 0.05$) between the median K_s at 3, 5, 7 and 11 m from the trunk and that in the surrounding grassland. At 3 m from this tree, the median and geometric mean K_s were a factor of 2.3 and 3.4, respectively, larger than those of the open grassland. Further, the geometric mean K_s decreased at a rate of $-4 \times 10^{-7} \text{ m s}^{-1} \text{ m}^{-1}$ from 1 to 9 m from the trunk, though it increased at 11 m, before declining again. A similar pattern in geometric mean K_s was observed in the 45 values around the five other oak trees. A literature review of the potential positive and negative effects of trees on K_s was used to provide tentative explanations for the observed patterns and to highlight the new data needed to support more robust interpretations.

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1. Introduction

It is generally accepted that the saturated hydraulic conductivity (K_s or coefficient of permeability; Bear, 1972) of forest soils is higher than that of soils supporting other vegetation types (Pritchett and Fisher, 1987; McCulloch and Robinson, 1993); however, a search of the scientific literature reveals that there are surprisingly few studies testing this hypothesis. While most studies support the idea that trees enhance K_s (Table 1), the results of some suggest that this is not universally true. For example, Jaiyeoba (2001), investigating the effect of reforestation on degraded land in Nigeria, found that a significant increase in K_s was observed under only one of the six plantations studied. Yeates and Boag (1995) reported higher soil permeability in pasture compared with the *Pinus radiata* agro-forestry systems in their study. Likewise, the results of a study by Giertz et al. (2005) showed that within undisturbed areas, savannah soils had higher mean K_s than those under natural forests. Furthermore, a localised reduction in K_s beneath Sitka spruce (*Picea sitchensis*) was reported by Chappell et al. (1996), with a factor of 5.4 reduction in K_s directly

beneath individual conifers compared with soil 2 m away from each tree. Clearly, there is a need for further research to advance our understanding of how trees affect K_s , including consideration of the possible mechanisms by which individual trees influence soils.

The concept of 'single-tree influence circles', first introduced by Zinke (1962), is well established in studies of soil properties such as exchangeable cations and pH (e.g., Hornung, 1985; Boettcher and Kalisz, 1990; Amiotti et al., 2000; Graham et al., 2004). The influence of single trees has also been investigated for soil moisture depletion (Ziemer, 1968), rainfall interception (David et al., 2006) and earthworm abundance (Boettcher and Kalisz, 1991). The work reported here seeks to determine the influence of individual trees on the K_s of the A horizon of a Dystric Gleysol, with a focus on isolated oak trees. The benefits of studying isolated, individual trees are 3-fold. First, comparison of the K_s of a grassland topsoil beneath individual trees can be compared with that in open land in the immediate vicinity, thus reducing the likelihood of catena-related variations in soil type (Chappell and Ternan, 1992) affecting the results. Secondly, the study of isolated trees allows us to investigate the sphere of influence of individual trees on K_s . Finally, quantification of K_s at different distances from tree trunks may help indicate those factors which regulate the influence of trees on K_s , such as fine root density (see Rasse et al., 2000), soil compaction

* Corresponding author. Tel.: +44 1524 593933; fax: +44 1524 593985.
E-mail address: n.chappell@lancaster.ac.uk (N.A. Chappell).

Table 1

Ratio of saturated hydraulic conductivity of the A soil horizon under trees to that under adjacent pasture

| F/G | Soil type ^a | Tree type ^b | Reference |
|------------------|------------------------|----------------------------------|----------------------------|
| 2.0 | Luvisol | <i>Eucalyptus</i> spp. | Lorimer and Douglas (1995) |
| 2.5 | nk | <i>Eucalyptus</i> spp. | Burch et al. (1987) |
| 3.4 ^c | Gleysol | <i>Quercus robur</i> | This study |
| 4.8 | nk | <i>Pinus insularis</i> | Costalles (1979) |
| 5.2 | nk | <i>Pinus halepensis</i> | Berglund et al. (1981) |
| 4.5–7.2 | Cambisol | <i>Quercus robur</i> | Burt et al. (1983) |
| 2.3–12 | Ferralsol | <i>Eucalyptus/Gravillea</i> spp. | Wood (1977) |
| 14 | Nitisol | <i>Hibiscus elatus</i> | Ternan et al. (1987) |
| 20 | Andosol | Podocarp | Jackson (1973) |
| 23–41 | nk ^d | <i>Quercus</i> spp. | Molchanov (1960) |
| 50 ^e | Ultisol | <i>Quercus</i> spp. | Hoover (1949) |
| 17–140 | Cambisol | <i>Eucalyptus</i> spp. | Wood (1977) |

F/G = ratio of the topsoil saturated hydraulic conductivity under trees to that under pasture (ranked by magnitude). (nk) not known.

^a FAO-UNESCO classification.

^b Dominant or representative tree species.

^c At 3 m from Tree No. 1.

^d Reported as 'dark grey soils'.

^e 0.1 m depth.

from tree weight and movement (Chappell et al., 1996), organic matter inputs (Lehmann et al., 2001) and chemical inputs from litter-fall, root decay or leaching from the canopy or roots (Rhoades, 1996).

The trees chosen for study were English oaks (*Quercus robur*), also known as pedunculate or common oaks, growing in a parkland setting. Oaks are considered to be the most important tree in broadleaf forestry within Great Britain, comprising 30% of the total broadleaved forest area (Hibberd, 1991). All of the individuals selected in this study were isolated trees planted in former hedgerows or as the parkland was established in 1899. Indeed, Great Britain has more trees in hedgerows and parkland (>1.8 million; Barr et al., 2001) than in woodlands or forests (Rackham, 2003). In 1998, there were 655,000 oak (*Quercus* spp.) trees in hedgerows in Great Britain (Barr et al., 2001).

The specific objectives of this study are to:

1. Quantify the statistical and spatial variability of K_s at 0.10–0.25 m depth in a Dystric Gleysol under grassland around six isolated oak trees and at more than 20 m away from these trees.
2. Review the literature pertinent to the possible effects of trees on K_s , to allow tentative explanation of the observed spatial variability.

2. Research site and methods

Field measurements were undertaken within a 10 ha area of parkland (54°00'50"N, 2°47'22"E), now part of the campus of Lancaster University, Lancashire, UK. Prior to 1899, this area was divided into three fields of pastureland. The six isolated, mature oak trees within this area were selected for investigation, together with nineteen sampling sites all in excess of 20 m away from any isolated trees or woodland (Fig. 1a). The girth, diameter breast height (*d b h*), crown radius and approximate planting date of these trees are shown in Table 2a. Between 1900 and 1964 the grassland would have been lightly stocked with sheep, but since 1964 grassland has been managed only with a tractor-mounted mower.

Soil of the 10 ha area is a Cambic Stagnogley (Hall and Folland, 1970), which is equivalent to a Dystric Gleysol (FAO-UNESCO, 1990), with similar soils covering 30% of England and Wales (Avery et al., 1974). The soil has developed from glacial till, overlying Millstone Grit bedrock (Hall and Folland, 1970). The A soil horizon (locally 0.02–0.30 m) in the open grassland showed signs of

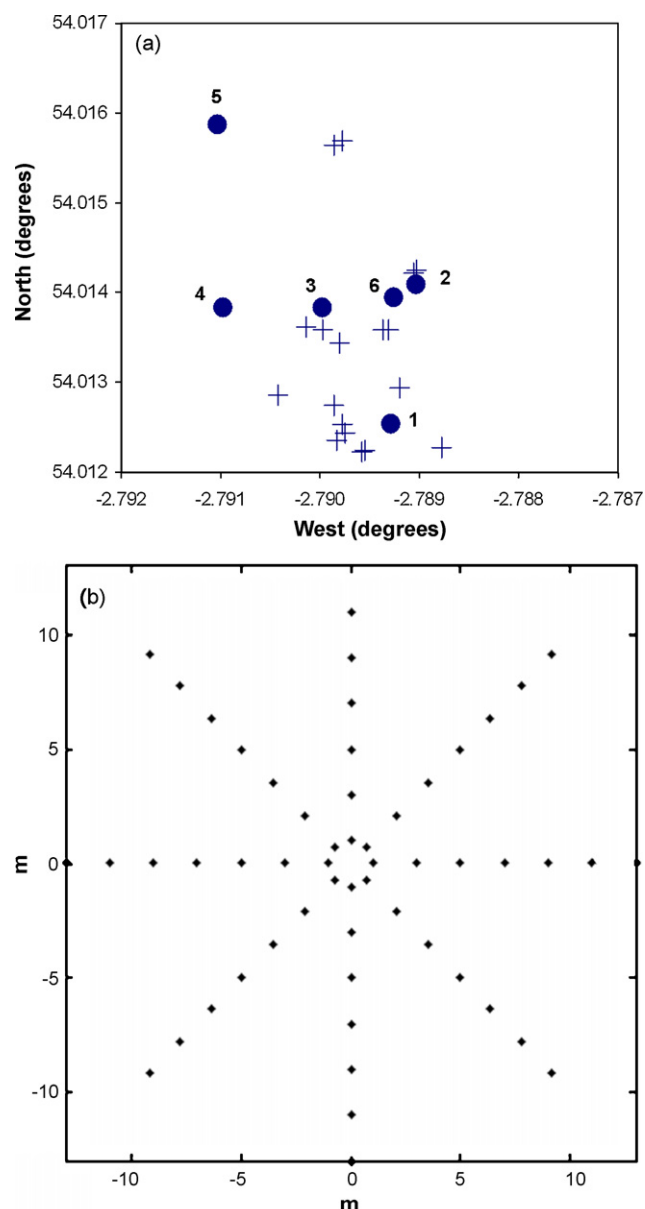


Fig. 1. Sampling sites within a 10 ha area of parkland on the Lancaster University campus (UK) showing: (a) location of the studied oak (*Quercus robur*) trees (e.g., Tree No. 1 show as '● 1'), and (b) the sampling design around Tree No. 1.

mottling, indicating the presence of intermittent water-logging close to the ground-surface.

Field measurement of K_s was performed using the constant-head, borehole permeameter (Talsma and Hallam, 1980; Reynolds et al., 1985). A constant-head of 0.10 m was maintained above the base of a 0.20 m deep auger-hole. The two permeameters used in this study were modified from the original design of Talsma and Hallam (1980) to use a smaller diameter reservoir (i.e., 0.0239 m internal diameter outer-pipe, and 0.0162 m outer diameter inner-pipe) to increase level-change and hence reading accuracy (Chappell and Lancaster, 2007). The method was chosen, because the narrow diameter auger-hole (i.e., 0.05 m diameter) makes it easier to obtain measurements close to individual tree trunks and between the roots, in comparison to alternative core-based techniques. Errors associated with this method are quantified in Reynolds et al. (1985) and Chappell and Lancaster (2007).

Table 2
Site characteristics, including (a) biophysical characteristics of the studied oak trees and (b) soil physico-chemical characteristics beneath Tree No. 1 and within the open grassland

| Tree No. | Girth (m) | Diameter breast height (m) | Crown radius (m) | Planting date ^a | |
|------------|------------|----------------------------|------------------|----------------------------|--------------------|
| (a) | | | | | |
| 1 | 3.12 | 0.993 | 8.9 | 1899–1900 | |
| 2 | 2.87 | 0.914 | 7.9 | 1844–1890 | |
| 3 | 2.90 | 0.923 | 6.4 | 844–1890 | |
| 4 | 4.16 | 1.324 | 7.4 | 1844–1890 | |
| 5 | 2.25 | 0.762 | 7.1 | <1900 | |
| 6 | 3.01 | 0.958 | 8.9 | 1844–1890 | |
| Sample (m) | pH | Particle size | | | Organic matter (%) |
| | | Sand (%) | Silt (%) | Clay (%) | |
| (b) | | | | | |
| 1 | 4.5 ± 0.17 | 64 | 25 | 11 | 3.44 ± 0.007 |
| 5 | 5.0 ± 0.14 | 62 | 27 | 11 | 2.36 ± 0.018 |
| 9 | 4.9 ± 0.30 | 62 | 27 | 11 | 2.14 ± 0.024 |
| 13 | 5.0 ± 0.07 | 62 | 25 | 13 | 2.26 ± 0.013 |
| >20 | 5.1 ± 0.01 | 61 | 28 | 11 | 2.52 ± 0.010 |

^a Based on presence on Ordnance Survey and local estate maps.

The crowns of the study trees extended 6.4–8.9 m from the trunk (Table 2a), so the testing of K_s needed to extend at least to these distances from the tree trunks. Around one of the six trees ('Tree No. 1': Fig. 1a), K_s was measured at 1, 3, 5, 7, 9, 11 and 13 m away from the trunk along eight transects radiating out along bearings of 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360° (Fig. 1b). With one missing value, this gave a total of 55 values. The K_s was measured less intensively around five other oak trees. Around Tree No. 2, 3, 4, and 5 (Fig. 1a), tests were undertaken at 3, 7, 9, 11 and 13 m from the trunk along two opposite transects, and along only one transect for Tree No. 6. Thus, a total of 100 values were measured within 13 m of all six oak trees. A further 19 measurements were taken at random distances of greater than 20 m from any trees within the 10 ha area, with eight being within 20–50 m of the frequently sampled Tree No. 1 (Fig. 1a). The minimum distance of 20 m was selected because the study of Lucot and Bruckert (1992) found that the rooting systems of 150-year-old oaks extend up to 20 m from the trunk. In extreme circumstances, the roots of oak trees can, however, extend up to 30 m from the trunk (Cutler and Richardson, 1989).

The dataset of K_s produced is relatively large compared to other published datasets obtained with the constant-head, borehole permeameter (Bonell et al., 1983; Chappell et al., 1996; Chappell and Lancaster, 2007), making the statistics equally valuable.

The K_s was derived from the borehole permeameter readings using the solution of Elrick et al. (1989):

$$K_s = \frac{CQ}{2\pi H^2 + \pi r 2C + (2\pi H/\alpha^*)} \quad (1)$$

where K_s is the saturated hydraulic conductivity (m s^{-1}), H is the constant head of water in the auger-hole (m), r is the radius of the auger-hole (m), Q is the steady-state discharge from the permeameter ($\text{m}^3 \text{s}^{-1}$), $C = 0.56 + 0.35H^{-1}$, a dimensionless shape factor dependent on the geometry of the section of the auger-hole under test (Bagarello and Giordano, 1999), and α^* is a soil structure term, which was estimated to be 12 m^{-1} from Elrick and Reynolds (1992). Since the K_s is dependent, not only on the properties of the soil, but also on the viscosity of the fluid (Hubbert, 1940), the values of K_s calculated by these equations are representative of the water temperature at the time of each test. Consequently, all values presented were corrected to those at a reference water temperature of 20 °C (Chappell and Ternan, 1997).

As trees can influence K_s through an enhancement of soil acidification (Chappell et al., 1996), greater fines (i.e., clay and silt) translocation (Mackney, 1961) and organic matter accumulation (Berglund et al., 1981), the physical properties of pH, soil texture and organic matter content, respectively, were quantified at a 0.15 m depth at distances of 1, 5, 9 and 13 m from Tree No. 1, along a transect of bearing 180°. Soil pH was determined from a 0.4 g cm^{-3} soil–water suspension using a glass electrode pH-meter (Radojevic and Bashkin, 1999). Soil texture was quantified using a combination of dry sieving and hydrometer methods, after first oxidising the organic matter and dispersing the aggregates (Gee and Bauder, 1986). Soil organic matter was determined by loss on ignition, following the method of Rowell (1994).

The statistical and spatial distribution of the K_s data were analysed using a combination of Box-and-Whisker plots and histograms to show the statistical distribution, Komogorov–Smirnov (KS) tests of normality, Wilcoxon rank sum tests for differences in medians, and the Fisher test for differences in variances (Freund and Wilson, 2002). The Komogorov–Smirnov and Wilcoxon rank sum tests were performed using the Matlab Statistics Toolbox version 6.5.0 (Mathworks, Natick, USA). The Fisher test was performed using Office Excel 2007 (Microsoft Corporation, Redmond, USA).

3. Results

3.1. Statistical distribution of K_s

The asymmetry of the statistical distribution of the 119 K_s values is clear from the asymmetry of a Box-and-Whisker plot of the data (Fig. 2a; Freund and Wilson, 2002). A logarithmic (\log_e) transform of the data does produce a symmetrical plot (Table 2b) indicating that the centroid of the distribution of these data is better represented by the geometric rather than arithmetic mean. Many other K_s studies (e.g., Nielsen et al., 1973; Talsma and Hallam, 1980; Bonell et al., 1983; Chappell and Franks, 1996; Chappell et al., 1998) similarly demonstrate that a geometric mean is a better measure of the first moment of a distribution in comparison to the arithmetic mean. A Kolomogorov–Smirnov test for normality was applied to the raw K_s data and the \log_e -transformed data, but indicated that neither distribution conformed to a normal distribution (p values were both < 0.0001 ,

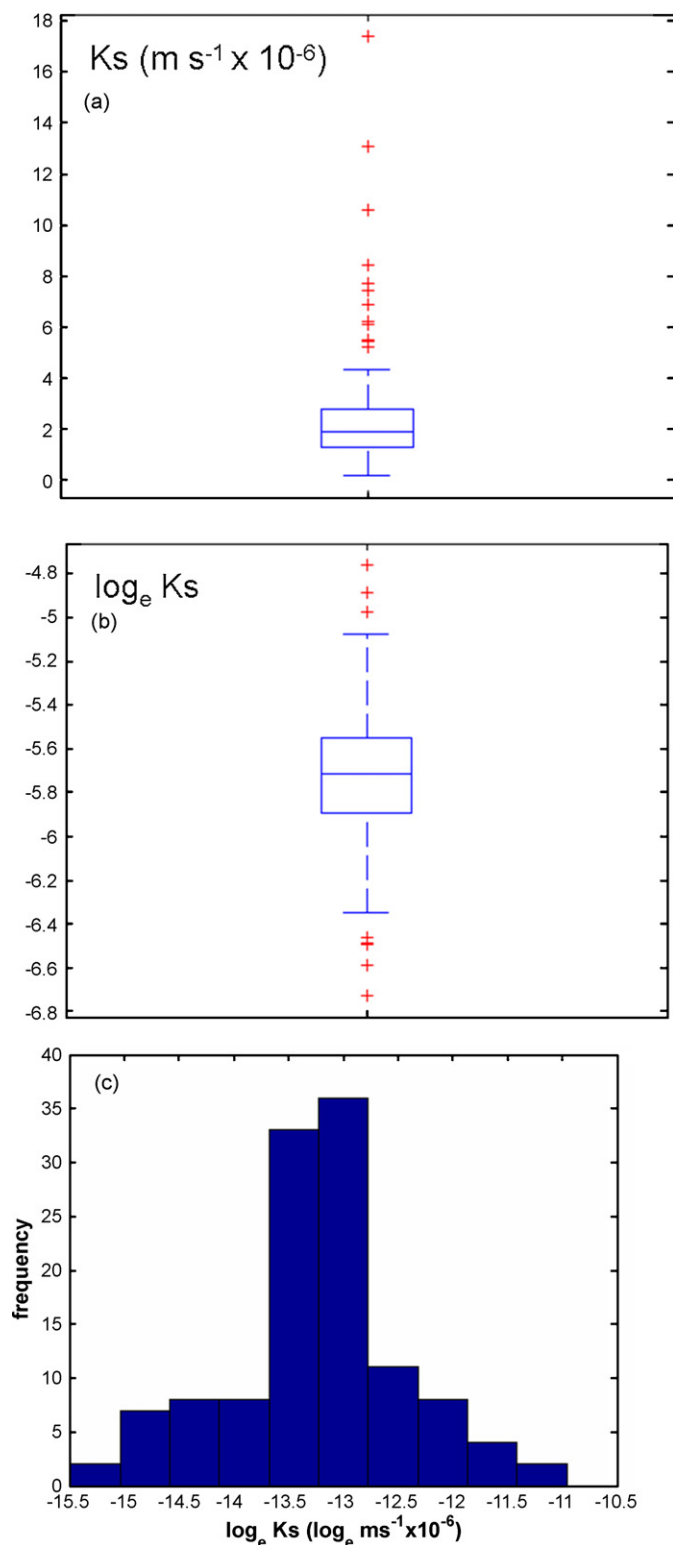


Fig. 2. Statistical distributions of the K_s data (m s^{-1}) collected within the 10 ha area of Dystric Gleysol, presented as: (a) a Box-and-Whisker plot of the raw values, (b) a Box-and-Whisker plot of the \log_e transformed values, and (c) a histogram of the \log_e transformed values.

while KS statistics were 0.5000 and 3.3924, respectively). Indeed, KS tests indicated that $x^{1/2}$, $x^{1/3}$, $x^{1/4}$ and $-1/x$ transforms also failed to normalise the data. The failure of the \log_e -transform to produce a normal distribution is confirmed by the histogram shown in

Table 3

Geometric mean and median K_s ($\text{m s}^{-1} \times 10^{-6}$) at each sampling distance from Tree No. 1 and pooled data from all six trees (including Tree No. 1), together with those from open grassland

| Sampling distance from trunk (m) | Tree No. 1 | | All trees | |
|----------------------------------|----------------------|-------------------|-------------------|-------------------|
| | Geomean ^a | Median | Geomean | Median |
| 1 | 3.53 | 5.22 | – | – |
| 3 | 3.35 | 2.72 | 3.20 | 2.36 |
| 5 | 2.51 | 2.45 | – | – |
| 7 | 2.38 | 2.17 | 2.31 | 2.01 |
| 9 | 1.42 | 2.27 | 1.25 | 1.25 |
| 11 | 1.87 | 1.99 | 1.59 | 1.75 |
| 13 | 1.06 | 1.19 | 1.26 | 1.49 |
| >20 | 0.99 ^b | 1.21 ^b | 1.15 ^c | 1.55 ^c |

^a Geometric mean.

^b 8 Values in the open grassland at 20–40 m from Tree No. 1.

^c 19 Values in open grassland from the whole 10 ha area.

Fig. 2c, which does not have a bell-shaped curve. Consequently, the examination of whether the centroid of the K_s values at different distances from individual oak trees is dissimilar to that in open grassland, utilised a non-parametric test, known as the Wilcoxon rank sum test.

3.2. Spatial distribution of K_s around isolated oak trees

The geometric mean K_s values for Tree No. 1 at each sampling distance together with the values for open grassland and the pooled dataset from below all six trees is shown in Table 3. The median values used in the Wilcoxon rank sum tests are also shown in the same table.

The Wilcoxon rank sum tests show that the median K_s values for the distances of 3, 5, 7, and 11 m away from Tree No. 1 are significantly different ($p < 0.05$) from those measured in the open grassland (Table 4). Only those measurements at 1, 9 and 13 m away from the tree were not different to those in the open grassland. When data for all six trees were lumped (100 values), similarly significant differences ($p < 0.05$) were seen between the topsoil close to the isolated oak trees (i.e., at 3 and 7 m) and those at greater than 20 m from any tree (Table 4). Measurements at 9, 11 and 13 m within the whole dataset were not significantly different to those in the open grassland.

The geometric mean K_s values at each distance from the studied oak trees are plotted in Fig. 3. Within the crown radius of Tree No. 1 (i.e., within ca. 9 m of the trunk) the geometric mean K_s decreased away from the tree trunk at a rate of rate of $-4 \times 10^{-7} \text{ m s}^{-1} \text{ m}^{-1}$. For the same tree, the geometric mean K_s at 3 m ($3.35 \times 10^{-6} \text{ m s}^{-1}$) from the trunk was a factor of 3.4 larger than that in the open grassland, and a factor of 2.3 larger for the median (Table 3). For all six trees, the geometric mean K_s at 3 m from a trunk was a factor of 2.8 larger than that in the open grassland, and a factor of 1.5 larger for the median (Table 3).

Table 4

Level of significance (p value) of Wilcoxon rank sum test results for topsoil K_s data for Tree No. 1 and pooled data from all six trees (including Tree No. 1) versus that from open grassland

| Dataset | Distance from tree trunk | | | | | | |
|-------------------------|--------------------------|-------|-------|-------|-------|-------|-------|
| | 1 m | 3 m | 5 m | 7 m | 9 m | 11 m | 13 m |
| Tree No. 1 ^a | 0.054 | 0.003 | 0.003 | 0.003 | 0.488 | 0.028 | 0.820 |
| All trees ^b | – | 0.002 | – | 0.003 | 0.950 | 0.136 | 0.568 |

^a Values sampled within 13 m of Tree No. 1 were compared with 8 values in the open grassland at 20–40 m from Tree No. 1.

^b Values sampled within 13 m of all six trees were compared with 19 values in the 10 ha open grassland.

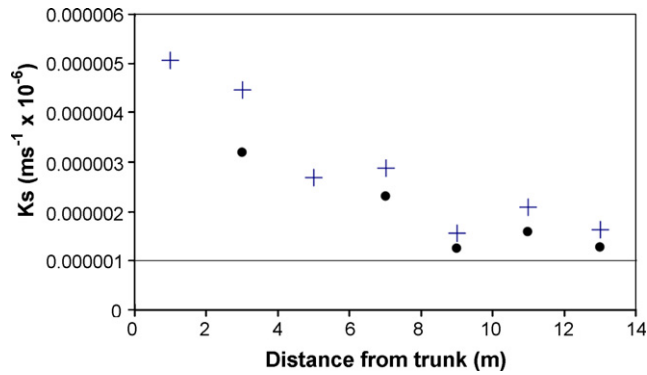


Fig. 3. Geometric mean topsoil K_s ($\text{m s}^{-1} \times 10^{-6}$) versus distance (m) from the tree trunk for Tree No. 1 (+) and pooled for all six trees (●). The geometric mean K_s for the eight open grassland locations (shown with a horizontal line), 20–50 m away from Tree No. 1 (Fig. 1a) was $9.87 \times 10^{-7} \text{ m s}^{-1}$, and for all 19 open grassland locations was $1.15 \times 10^{-6} \text{ m s}^{-1}$.

A non-monotonic decline of geometric mean and median K_s with distance from the trunk of Tree No. 1 is observed (Fig. 3; Table 3), with the K_s at 11 m being statistically different (p 0.0281) from that of the open grassland, while the values at 9 and 13 m are not (Table 4). The same pattern of elevated levels of K_s close to tree trunks reducing towards the canopy edge (6.4–8.9 m) and then increasing just beyond this (e.g., 11 m), before decreasing to that of the open grassland is also observed within the pooled dataset for all six trees (Fig. 3). For the pooled dataset, the elevated mean K_s value at 11 m (see Fig. 3; Table 3) is, however, not statistically different from that in the open grassland (Table 4).

The coefficients of variation (CVs) for the datasets collected at the different sampling distances from the isolated oak trees are shown in Table 5a. Fisher tests showed that none of these data have a statistically distinct variance. The CV values are also towards the higher end of the range of values in published studies for forest soil horizons (Table 5b).

4. Discussion

4.1. Review of the positive and negative impacts of trees on K_s

Consideration of why K_s may be different close to individual oak trees planted within grassland requires a new and possibly unique review of a broad range of scientific literature. This review would suggest that there are several mechanisms that might increase K_s

close to isolated oak trees, and a similar number of mechanisms that could reduce it.

4.1.1. Positive effects of trees on K_s

Both living and decayed roots can create well-connected pores in the topsoil called 'macropores' (Gaiser, 1952; Aubertin, 1971; Beven and Germann, 1982). Flow through macropores can be up to several hundred times faster than flow through the soil matrix, making K_s very sensitive to small changes in the numbers of macropores (Aubertin, 1971; Buttle and House, 1997). As the root system of oak trees extends well beyond the crown (Hocker, 1979; Cutler and Richardson, 1989; Lucot and Bruckert, 1992), root-associated macropores might account for increased K_s beyond the crown radius.

Compared to open pasture, the reduced precipitation received beneath tree canopies due to enhanced wet-canopy evaporation (David et al., 2006) combined with greater root abstraction to support transpiration can lead to considerably greater topsoil drying during rain-free periods (Ziemer, 1968; Katul et al., 1997). Extreme soil drying can open structural cracks in soils that do not close with subsequent rewetting and consequently maintain elevated levels of K_s (Holden and Burt, 2003).

Increased organic inputs beneath trees from litter-fall or root decay (Berglund et al., 1981) can have a positive impact on aggregate structure (Chaney and Swift, 1984; Graham et al., 1995; Chappell et al., 1999; Lehmann et al., 2001), which then can result in an increased K_s (Wood, 1977).

4.1.2. Negative effects of trees on K_s

The weight of a tree, combined with the movement of structural roots during windy conditions, can compress soils over centimetre-scales to reduce K_s (Chappell et al., 1996).

Soil acidification due to an increase in the rate of dissolution of soil minerals beneath trees (Quideau et al., 1996; Augusto et al., 2000), acidic litter-fall (Satchel and Lowe, 1967; Muys et al., 1992) or acidic exudates (Nilsson et al., 1982) has been shown to reduce soil structural stability (Ranger and Nys, 1994). This reduced stability can lead to a reduction in porosity and, therefore, K_s as aggregates collapse (Baumgartl and Horn, 1991). High rates of leaching by infiltrating stem-flow can exacerbate the acidification effect (Nys, 1981). The acidity of the soil also affects the presence and abundance of soil fauna, such as earthworms (Boettcher and Kalisz, 1991; Neiryneck et al., 2000). As earthworm activity creates more stable soil aggregates (Graham et al., 1995) and adds macroporosity (Beven and Germann, 1982), reduced abundance would be expected to reduce K_s .

Table 5

Coefficient of variation (%) of K_s for specific soil horizons for: (a) the A soil horizon sites within this study, and (b) published values for forest soils

| Distance | 1 | 3 | 5 | 7 | 9 | 11 | 13 | >20 m |
|-------------------------|------------------------|-----|--------------|----|--------|----|---------------------------|-------|
| (a) | | | | | | | | |
| Tree No. 1 | 70 | 89 | 40 | 67 | 52 | 45 | 106 | 52 |
| All trees ^a | – | 101 | – | 68 | 53 | 55 | 81 | 55 |
| Forest type | Soil type ^b | | Soil horizon | | CV | | Reference | |
| (b) | | | | | | | | |
| Mesophyll vine | Acrisol | | A | | 11 | | Bonell et al. (1983) | |
| <i>Hibiscus elatus</i> | Nitisol | | A | | 18 | | Ternan et al. (1987) | |
| Dipterocarpaceae | Acrisol | | A | | 24 | | Sherlock et al. (1995) | |
| Dipterocarpaceae | Acrisol | | B | | 35 | | Sherlock et al. (1995) | |
| Sclerophyll | nk | | B | | 30–107 | | Clothier and White (1981) | |
| <i>Picea sitchensis</i> | Podzol | | B | | 133 | | Chappell et al. (1996) | |
| <i>Picea sitchensis</i> | Histosol | | B | | 143 | | Chappell et al. (1996) | |

^a 'nk' is not known.

^a Includes Tree No. 1.

^b FAO-UNESCO classification.

At the millimetre scale, the growth of tree roots can locally increase the density of soil and have a very localised negative impact on K_s (Blevins et al., 1970; Whalley et al., 2004).

Isolated trees within natural grasslands or in rural parklands can have an indirect impact on K_s . Wild and domesticated animals use isolated trees for shelter during rainstorms or for shade from intense solar radiation. This congregation of animals, particularly at times when the soil is wet, can compact the soil and thereby reduce the K_s of the A soil horizon (Drewry et al., 2000).

4.2. Explaining observed patterns around the six sampled oak trees

The magnitude of the apparent increase in K_s beneath the studied trees lies towards the lower end of the range of published values for forest versus grassland topsoil (Table 1). The relatively small impact may be because tree density at the study site is much lower than that in the natural forests and plantations of the published studies.

The higher K_s within 9 m of the trunk of the isolated oak trees studied compared to open grassland (Fig. 3; Tables 3 and 4) may be related to the positive effect of increased macroporosity resulting from the presence of tree roots. Equally, the zone of elevated K_s beyond the tree crown (e.g., 11 m from the trunk of Tree No. 1) may result from the presence of tree roots, given that oak trees have been shown to extend roots beyond the crown (Hocker, 1979; Cutler and Richardson, 1989; Lucot and Bruckert, 1992). Future studies could confirm this association by measuring root biomass (Barton and Montagu, 2004) and macroporosity (Buttle and McDonald, 2000) alongside K_s measurements.

Greater soil moisture abstraction by the roots of oak trees, as shown by Katul et al. (1997) can affect soil structure. Indeed, Chappell and Lancaster (2007) show for the same Gleysol only 12 km away, that desiccation cracks can increase topsoil K_s by 50-fold. Qualitative evidence of the presence of this enhanced drying beneath the six studied trees is gained from the observation that mottling visible in topsoil in the open grassland is absent in the topsoil beneath the canopy of the oak trees. Future measurements of volumetric moisture content as well as macroporosity and K_s would allow this association to be tested.

The very limited number of measurements of organic matter at the study site exhibit only small changes with distance from the trunk. Moreover, only the two replicates at 1 m from the trunk show values higher than those in the open grassland (Table 2b). The observation that the organic matter content at 5, 9 and 13 m from the trunk is similar to that in the open grassland would suggest that a strong correlation between organic matter and K_s may not be observed if a larger dataset were to be collected.

The decrease in the resultant effect of Tree No. 1 on K_s towards the canopy edge (ca. 9 m) followed by a statistically significant increase just beyond this (at 11 m), before decreasing to that of the open grassland by a distance of 13 m (Fig. 3) is noteworthy. It is worth considering a hypothesis to explain such a non-monotonic trend, because it may be partial evidence for the presence of negative tree-related effects on K_s . Highlighting such a possibility would encourage future studies to measure the factors that could lead to such a reduction in K_s . Given the review, it is clearly possible that K_s patterns around trees could be the result of the interaction between negative effects on K_s within the radius of the canopy and positive effects, over the wider radius of the root network. This hypothesis is illustrated in Fig. 4, where hypothetical, monotonic positive and negative trends can be calibrated to the observed K_s trend around Tree No. 1 (broad solid line). This conceptual model shows that if smaller negative effects cease at 11 m and larger positive effects stop at 13 m, a smaller K_s value at 9 m compared to 11 m can be produced.

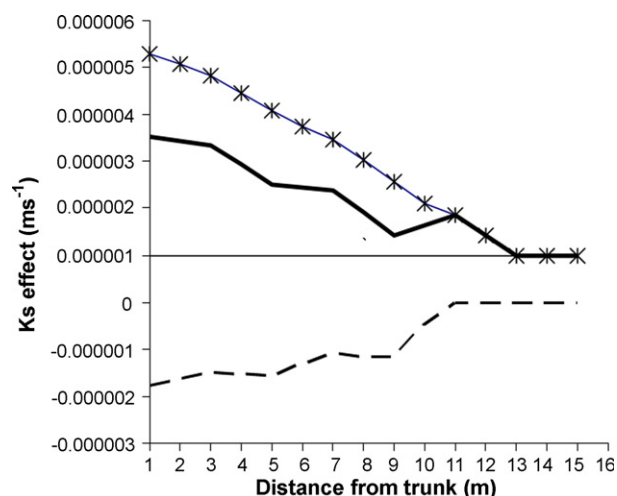


Fig. 4. A conceptual model of the non-monotonic decline of topsoil K_s (m s^{-1}) with distance (m) from the trunk of Tree No. 1, showing the combined effect of monotonic positive influences (fine line with asterisks), monotonic negative influences ceasing at the canopy edge (broken line), and the resultant non-monotonic trend in K_s (broad solid line).

Further evidence for the presence of a negative effect of oak trees on K_s comes from the review. This review shows that while soil acidification by oak trees is less than that by coniferous trees, an increase in soil acidity relative to that beneath open grassland has been reported under oak stands (Mackney, 1961; Moffat and Boswell, 1990). Moffat and Boswell (1990) report a 0.5 of a unit decrease in soil pH value under oak stands in Yorkshire, UK. The two samples collected at 1 m from the trunk of Tree No. 1 do show a lower pH value (4.5 ± 0.17) compared to those in the open grassland ($\text{pH } 5.1 \pm 0.01$; Table 2b). The observation that the pH at 5, 9 and 13 m from the trunk is similar to that in the open grassland does however, suggest that a strong correlation between pH and K_s may not be observed if a larger dataset were to be collected. The possible effect of acidity in reducing earthworm abundance (and hence reduced macroporosity) beneath oak woodland compared to open grassland observed by Muys et al. (1992), could be tested for isolated oak trees with concurrent measurements of earthworm populations, macroporosity, pH and K_s .

The possible negative impact of the six oak trees on soil compaction beneath the trunk and structural roots was not investigated due to the shallow depth of sampling. Future studies could address this issue by taking undisturbed cores from beneath the structural roots and trunk of isolated oak trees for the laboratory determination of dry bulk density, as within the conifer study of Chappell et al. (1996).

4.3. Implications for watershed management

In Great Britain, isolated trees, particularly oak and ash trees cover more soil than do woods and forests (Barr et al., 2001; Rackham, 2003). As these isolated trees are considered important habitats within Great Britain (Anon, 1995), quantification of the impact of isolated oak trees on the most important soil hydrological characteristic, namely K_s , must be a key element of any assessment of soil ecology and biodiversity (Bardgett et al., 2001).

Globally, the presence of overland flow on hillslopes can result in the accelerated loss of productive topsoil and soil nutrients (Chappell et al., 1990; Sidle et al., 2006; Yusop et al., 2006). Gleysol tends to have lower topsoil K_s in comparison to other soil types (Chappell and Ternan, 1992) and consequently a greater incidence of infiltration-excess overland flow. Thus, increases in topsoil K_s beneath isolated trees on Gleysol could have a localised but

beneficial effect on reducing the extent of overland flow by providing local infiltration zones for surface flow generated on upslope areas (Bramley et al., 2003; Chappell et al., 2006). Even a small enhancement of infiltration within riparian areas would have a disproportionate impact on reducing the channel input of dissolved contaminants (Nisbet, 2001; Burt, 2005) or eroded slope sediments (Gomi et al., 2006). Clearly, increasing the planting frequency towards complete tree cover within riparian zones would have an even greater influence on infiltration enhancement. Furthermore, tree planting on flood plain and riparian zones provides roughness elements that reduce the velocity of overbank flows and thereby further promote infiltration.

Consequently, the 'hydrological ecosystem services' provided by different densities of individual trees could be an important management consideration when planning flood-relief, agro-forestry or plantation systems, particularly in areas with relatively low K_s and high rates of infiltration-excess overland flow (Rhoades, 1996; Bramley et al., 2003; Bruijnzeel, 2004; Chappell et al., 2007).

5. Conclusions

Four conclusions arise from this study, namely:

- (i) The research is the first to quantify the local effect of individual trees on the K_s using a borehole permeameter in a radial sampling pattern. As such, it provides a sampling strategy the future more extensive sampling that may allow generalisation across different soils and tree species.
- (ii) The local impact of isolated English oaks (*Q. robur*) on the K_s of an A soil horizon beneath grassland was observable for the Gleysol tested. The local effect was smaller than the published differences between many forest soils and nearby open pastureland. The findings specific to isolated English oaks however are important given their ubiquitous presence within the British landscape.
- (iii) The literature review shows that individual trees can have a positive effect on soils by organic matter incorporation, the way their roots enhance soil macroporosity, and via structural cracking after accelerated soil drying. It also shows that trees can also have negative impacts through compaction by the trunk and structural roots and soil structural deterioration by acidification, sometimes via the impact on soil macrofauna. The measurements undertaken within this study of six oak trees could not preclude any of these possible mechanisms, but instead provided limited evidence for the presence of negative as well as positive impacts being present for the same trees. Further, the study has helped identify the measurements needed to test the hypotheses of the role of each mechanism within future, more comprehensive studies.
- (iv) Lastly, the study may indicate that the local enhancement of infiltration by individual trees may be a useful tool in riparian management and erosion control. More research is needed to identify necessary planting densities and tree species that best provide these 'hydrological ecosystem services'.

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