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Near-surface macropore flow and saturated hydraulic conductivity in drained and restored blanket peatlands

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Abstract

The impact of blanket peatland management upon water tables, near-surface macropore flow and saturated hydraulic conductivity were investigated using automated dipwells and mini-disk tension infiltrometers. Three neighbouring hillslopes which were undisturbed, drained and restored by drain-blocking were studied. Mean water table depths at the undisturbed sites were slightly shallower than at the restored site and water tables at both sites were significantly shallower relative to the drained treatment. Through time, however, the water table at the restored treatment behaved in a markedly different way to that observed in the undisturbed site. Complete saturation of the peat to the surface occurred only 2 % of the time for the drained and restored treatments compared to 18 % of the time for the undisturbed treatment. The proportion of runoff flowing through macropores located in the near-surface layers of the peat was found to be large (≥ 60 %) across all three treatments, yet functional macroporosity was found to be significantly greater in the undisturbed peat relative to the two other treatments. Meanwhile, saturated hydraulic conductivity was found to be significantly higher at the restored treatment relative to the two other treatments, with mean conductivities ~ 1.5 times greater, suggesting a form of heightened soil-water interaction. Combined, these data suggest that although restoration by ditch blocking may result in a relatively successful water table recovery, it may not necessarily lead to the full reinstatement of peatland hydrological processes.

Keywords

Peat, macropores, runoff, infiltration, tension infiltrometer, water table, hydraulic conductivity

1. Introduction

Runoff production in undisturbed blanket peatlands tends to be flashy in nature, being dominated by a quickflow response with very little baseflow (Price, 1992; Holden & Burt, 2003a; Holden & Burt, 2003b; Holden, 2006a). Flow production is typically governed by shallow water tables combined with the low hydraulic conductivity of the peat layers, such that near-surface flow and saturation-excess overland flow tend to be the dominant hydrological processes (Evans et al., 1999; Holden & Burt, 2003b; Holden et al., 2007). Bypassing flow has also been shown to be an important process in peatland systems (Ingram *et al.*, 1974; Baird, 1997; Holden *et al.*, 2001; Holden & Burt, 2002b; Holden *et al.*, 2002; Jones, 2004; Holden, 2005; Holden, 2006b; Holden, 2009a). For example, Holden and Burt (2002b) found that natural soil pipes (>1 cm in diameter) in peat contributed up to 10 % of discharge to the stream in deep peat catchments, while Blodau and Moore (2002) identified that up to 50 % of tracer materials could be recovered from peat depths at which the tracer would have not reached if preferential bypass flow had not occurred. Others have shown that macropore structures (>1mm diameter) can locally impact the rate of water transmission through peat soils (Ingram et al., 1974; Chanson & Siegel, 1986). For example, using a tension infiltrometer Baird (1997) found that macropore flow contributed between 51 and 78 % of the flow at the surface of a fenland peat. Further, Carey et al. (2007) employed tension infiltrometer measurements and image analysis on subarctic organic soils and found that macropores accounted for approximately 65% of the water flux at saturation.

To date, little research has been undertaken to assess the comparative roles of macropores under different land management treatments in blanket peat. Most research has been done on mined peat stockpiles for power stations in order to determine the most productive water retention and rewetting characteristics. For example, Holden & Ward (1996) found that the water content at depth in the profile of a sample of rewetted peat stores was greater than near the surface, suggesting a short-circuiting of water flow through the soil. Some evidence came from 'wet fingers' observed in the field (Holden & Ward, 1997), while further evidence came from cores of air-dried milled peat from the surface of a drained bog Holden, (1998) where outflow was found to be similar to the spray rate and little water accumulated in the peat suggesting bypassing flow paths formed readily.

The degree of macroporosity is an important component to consider for the transportation of solutes, such as dissolved organic carbon (DOC) (Ours et al., 1997; Reeve et al., 2001) and it can also indirectly influence peatland greenhouse gas exchange (Siegel et al., 1995). As the majority of runoff in blanket peatlands is generated within the upper peat layers, these areas are also important in terms of solute production and transportation (Clark et al., 2008). Runoff emerging from blanket peat catchments typically suffers several water quality issues, including high concentrations of DOC that, due to the prevalence of strongly coloured humic components, is often associated with incidents of significant water discolouration and thus water treatment. An issue further compounded by the fact that the water colour – DOC relationship has been found to vary significantly between peat layers and land management, and also through time (Wallage & Holden, 2010).

In the British Isles which host 15 % of the world's blanket peat deposit (Tallis *et al.*, 1998), headwater blanket peat catchments are sources of increasingly large quantities of solutional, discolouring organic compounds, which are an expensive and growing problem for local water supply companies (Evans *et al.*, 2006). Understanding whether different peatland management techniques influence the proportion of flow through macropores would help improve hydrological transport models, and aid our understanding of solute production and transportation (e.g. DOC). This is since the flow pathway, combined with the size, tortuosity and continuity of pores will impact water residence times and thus the interactive surface area that a solution comes into contact with (Allaire et al., 2002a; Allaire et al., 2002b).

Historically, many peatlands have been drained via the installation of artificial drainage ditches (Burke, 1975; Ahti, 1980; Waddington & Price, 2000; Holden et al., 2004; Holden et al., 2006). More recently, however, there has been a drive to restore and conserve peatlands as they are now recognised as a significant terrestrial carbon store. In recent years therefore, investment in peatland restoration has escalated and often includes resources aimed at blocking the drainage ditches to encourage water table recovery, reduce erosion and utlimately stabilise this important carbon reserve (Armstrong et al., 2009). However, up until now there has been distinct lack of data detailing the response of peatland properties to such restoration activities, expecially over the medium to long-term, since most monitoring experiments are conducted over the first few months after restoration (e.g. Worrall et al., 2007). The availability of longer-term reponse data is important because if peat is significantly aerated and dried out, rewetting may not necessarily lead to a return of the physical and chemical properties prevalent before the drying process (Eggelsmann et al., 1993).

This paper examines the variability in the proportion of near-surface macropore flow and the range in saturated hydraulic conductivity for an undisturbed blanket peat relative to neighbouring sites subjected to historical drainage and restoration via drain blocking. In this instance the restoration took place six years prior to the monitoring and experimentation carried out in this paper. As such, the paper is a comparative study of different treatments rather than a time series investigation of response before, during and after management change. The paper tests whether water tables, near-surface functional macroporosity and saturated hydraulic conductivity are significantly different between undisturbed, drained and restored treatments.

2. Methods

Macroporosity and hydraulic conductivity were determined using a mini-disk tension infiltrometer, which provides a rapid and convenient means of obtaining a large amount of field infiltration data, and is recognised as being a reliable and useful tool for the *in-situ* determination of saturated and near saturated hydraulic properties, as well as soil structural conditions at and near the soil surface (e.g. Baird, 1997; Azevedo et al., 1998; Zhang et al., 1999). However, while the technique has been shown to be valid and reliable for peat (Holden et al., 2001), to date only a limited number of studies have used tension infiltrometers on peat (Baird, 1997; Holden et al., 2001; Holden, 2009a; Holden, 2009b)

Tension infiltrometers measure infiltration rates at water pressures that are negative with respect to atmospheric pressure (Jarvis et al., 1987). In this way, the pre-ponding conditions characteristic of the early stages of rainfall can be simulated as the tension infiltrometer allows infiltration of water into the soil matrix, but does not allow flow into larger macropores that may otherwise dominate the infiltration process and short-circuit the flow (Jarvis et al., 1987; Holden et al., 2001).

Although definitions of macropores vary widely and the choice of an effective size to delimit macropores is arbitrary, Luxmoore (1981), Watson and Luxmoore (1986) and Baird (1997) all use the value of -3 cm tension to distinguish between macropores that drain at field capacity and smaller meso- and micropores, which according to capillary theory indicates macropores are >1 mm in diameter (Luxmoore et al., 1990). By maintaining the supply head at a range of negative pressure values it is possible to determine the role of macropores and meso/micropores during infiltration, as by subtraction, the hydrological role of the larger (macro) pores during the infiltration process can be evaluated (Jarvis et al., 1987; Joel et al., 2002). For example, since capillary pressure can be related to an equivalent pore diameter, the difference in infiltration rates between two differing tensions can be associated with the pore classes defined by the tension range, with the proportion of field saturated hydraulic conductivity governed by macropores being calculated by subtracting the infiltration rate at -3 cm tension from the field saturated hydraulic conductivity (Baird, 1997).

Mini-disk tension infiltrometer measurements were taken during July 2005 when it was thought the water table would be at its lowest allowing for the greatest differences between sites to be observed, and to comply with the assumption that the unsaturated hydraulic conductivity of the soil prior to the test would be significantly lower than the hydraulic conductivity under the imposed infiltration conditions (Baird, 1997). A total of 14 replicate experimental runs were conducted on each of three treatments; i) an undisturbed peatland (Intact), ii) a drained peatland (Drained) and iii) a restored peatland (Blocked). These three treatments were located on Oughtershaw Moss, a blanket peat headwater catchment in northern England (see Wallage et al., 2006 for full site details). The treatments were located within 400 m of each other on adjacent hillslopes with similar slope, aspect and peat depth, but which did not hydrologically interact. The Drained treatment had ditches installed during the 1960s at approximately 15 m intervals following the slope contour, while the Blocked treatment exhibited the same layout but had undergone restoration in 1999 in the form of drain blocking, via the installation of peat dams spaced at 10 m intervals along each ditch (Armstrong et al., 2009). In contrast, the Intact treatment had not been subjected to any drainage or restoration management. For the Drained and Blocked treatments, infiltration sample points were chosen on both the up- and down-slope sides of the drains, while sample locations across the Intact treatment were chosen to replicate the same topographic positions as represented at the other two treatments, but without reference to any drains as these were absent.

At each of the 42 sample-points any vegetation present was carefully cut back to reveal the bare peat surface and any surface irregularities removed with a serrated knife before a layer of moist fine sand of the same diameter as the circular base of the mini-disk tension infiltrometer was applied to smooth out any remaining irregularities at the peat surface and improve the contact between the infiltrometer and the soil surface (Baird, 1997; Holden et al., 2001). Moist sand was used as it maintains good hydraulic connectivity and does not fall down into surface-vented macropores forming 'wicks' as would air-dry sand (Messing & Jarvis, 1993). The infiltrometer was then placed on the sand.

Infiltration measurements were performed at tensions of -1 cm -3 cm and -5 cm, and were conducted using the lowest supply head (-5 cm) first, as reversal may lead to hysteresis where drainage occurs close to the disk while wetting continues near and at the infiltration front (Reynolds & Elrick, 1991b). Infiltration measurements continued until a steady state was achieved, and the instrument was shaded in an attempt to reduce the impact of any solar radiation heating the supply reservoir (Baird, 1997). Hydraulic conductivity rates were obtained from the steady-state infiltrometer data using the method outlined by Reynolds and Elrick (1991a) and as performed by Baird (1997) and Holden et al (2001), whereby Wooding's (1968) solution for infiltration from a shallow pond is combined with Gardner's (1958) unsaturated hydraulic conductivity function. As the supply reservoir of the mini-disk infiltrometer was small, the total volume of water held in the instrument was low, which not only reduced the likelihood of peat compression, but also aided more accurate measurements (Holden et al., 2001).

To gather background information to aid interpretation of the tension-disk infiltrometer data bulk density and water table data were also collected. Soil samples were extracted for bulk density determination from each of the three treatments from 14 neighbouring locations at soil depths of 5, 10, 20 and 40 cm. Samples were collected by carefully digging soil pits and extracting soil at the relevant depths from inside the pit walls to prevent the soil structure being disturbed during the excavation process. Once collected, the soil samples were placed in air tight bags and kept out of direct sunlight and were refrigerated within 24 hrs of collection. Subsequently, the samples were oven dried at 105°C for 24 hours, and the weight of oven-dried soil required to fill a predetermined volume recorded. Water table depths were recorded using pressure transducers housed within nine perforated PVC dipwells located along hillslope transects on each treatment. Measurements were automatically recorded at 20 minutes intervals over an 18 month period.

Initial assessment of the complete dataset, using values from all three treatments (Intact; Drained; Blocked), identified that the data pertaining to water table depth, proportion of macropore flow, hydraulic conductivity and soil bulk density were all normally distributed, and were subsequently checked for equality of variances before parametric tests of differences were applied, which included ANOVA and Student's t-test.

3. Results

Data captured from the automated pressure transducers identified that water table depth across the three sites was typically shallow, with mean values of -5.8 cm for the Intact treatment, -10.1 cm for the Drained treatment and -7.3 cm for the Blocked treatment. Further temporal analysis showed the peat was fully saturated for 18 % of the time at the Intact site compared to 2.0 % of the time at the Drained and Blocked treatments. The average interquartile range for the dipwells was of the order Drained (6.4 cm) > Blocked (4.8 cm) > Intact (4.0 cm).

The tension infiltrometer data demonstrated that near-surface flow was dominated by a relatively high proportion of macropore flow, with all three treatments exhibiting values >60 %. However, significant (p = 0.001) differences were observed in the proportion of macropore flow between the three treatments (Figure 1), and independent t-tests revealed the contribution to throughflow from macropores at the Intact treatment (74 %) was significantly (p <0.002) greater relative to both the Drained (66 %) and Blocked treatments (60 %). Meanwhile, differences between the Drained and Blocked treatments was not found to be significant (p = 0.068).

Tension-infiltration experiments revealed statistically significant (p = 0.001) variations in surface hydraulic conductivity across the three sites, with rates varying by up to an order of magnitude. For example, mean rates of surface hydraulic conductivity at the Intact, Drained and Blocked treatments were 1.07 x 10^{-3} cm s^{-1}, 9.87 x 10^{-4} cm s^{-1}, and 1.56 x 10^{-3} cm s^{-1} respectively (Figure 2). Thus, even though the Blocked treatment exhibited the lowest proportion of macropore flow, it actually exhibited a significantly higher rate of saturated hydraulic conductivity compared to both the Intact (p = 0.008) and Drained (p <0.001) treatments. No significant difference in the mean saturated hydraulic conductivity rate was identified between the Drained and Intact treatments.

Assessment of “pooled-depth” bulk density data identified no significant (p = 0.605) differences between the three treatments. When the data were analysed by depth a trend of increasing bulk density with peat depth was observed for the Blocked treatment (Table 1), while the drained site exhibited no differences and thus presented a more homogenous peat profile in the upper 40 cm. When values from corresponding peat depths were compared between treatments, significant differences were identified at 5 cm where the bulk density for the Blocked treatment was found to be lower (p = 0.034) relative to the Drained treatment.

4. Discussion

Mini-disk tension infiltrometer measurements demonstrated that water movement in the upper layers of the blanket peat is dominated by macropore flow, and although the proportion of flow moving through these structures appears large (>60%), the values are comparable with that presented for earlier peatland macropore studies. For example, Silins and Rothwell (1998) observed that 84 % of subsurface flow in a Canadian peat occurred within pores >0.6mm in diameter; while Baird (1997) identified approximately 64 % of subsurface flow in a lowland fen occurred though macropores. Meanwhile, Holden (2009a) found pores > 0.25 mm in diameter typically accounted for between 70 and 80 % of the flow produced in a blanket peat, and pores > 1mm in diameter accounted for between 21 and 68 % of the total water movement at the peat surface.

Importantly, this paper has examined the potential impact of peatland drainage and restoration on the proportion of near-surface macropore flow. It is recognised that the data were not collected before and after management change at the same location, but the sites were adjacent and as data from the restored site was collected six years after restoration, rather than in the immediate aftermath, this paper therefore provides a potentially longer-term understanding of the structural changes and thus physical processes operating in response to water table restoration relative to neighbouring intact and drained treatments.

The mean depth of the water table at the Blocked treatment was found to reside more closely to that observed at the Intact site than the Drained treatment. The water table at the Blocked treatment also exhibited significantly reduced variability in its response to fluctuations relative to the Drained treatment. Nonetheless, the water tables were still significantly deeper compared to the Intact treatment, and also exhibited a larger interquartile range, which suggests that the 'recovery' (towards the status of the intact treatment) over the six years since blocking had been partial rather than complete. Additional evidence is provided from the data on the proportion of time for which the peat was fully saturated, and thus when saturation-excess overland flow could be generated. Total soil saturation was recorded for 18 % of the time at the Intact treatment, but only 2 % for both the Drained and Blocked treatments. Thus, while restoration meant the water table was shallower across the Blocked treatment, full saturation was still a rare occurrence and was similar in nature to that observed for the Drained treatment.

Combined, these data suggest that the upper peat layers at the Blocked treatment enable greater movement of water as throughflow compared to the Intact treatment. Indeed this is supported by hydraulic conductivity data which exhibited a significantly faster rate in the near-surface layers of the Blocked treatment compared to the two other sites. Although the reasons for such a response clearly require further testing, it may relate to a period of stimulated peat growth following restoration. Indeed the bulk density was significantly lower for the uppermost layer of peat sampled at the Blocked treatment, relative to the two other treatments, which suggests less compaction and therefore potentially rapid new peat development.

The significantly lower proportion of macropore flow observed at the two disturbed treatments compared to the Intact site corroborates the findings of Burghardt & Ilnicki (1978), Egglesmann (1975) and Silins & Rothwell (1998) who all observed that a lowering of the water table associated with peatland drainage resulted in the subsidence of the surface layers and an associated collapse of readily drainable macropores, subsequently increasing the residence time of percolating waters. Further, Ingram (1992) suggested that in drier conditions rates of aerobic decomposition accelerate and vertical subsidence and compaction of the peat can occur, which increases the proportion of space occupied by solids thus reducing the volume of fast-draining macropores and the level of permeability.

However, the bulk density data presented in this paper do not show strong evidence to support the predicted compression of the peat (Price & Schlotzhauer, 1999). For example, the mean bulk density at the Drained site (0.112 g cm^{-3}) was slightly higher than that recorded at the Intact site (0.108 g cm^{-3}), and there was far less variation in values between soil depths, with values ranging from 0.108 g cm^{-3} at 5 cm to 0.118 g cm^{-3} at 40 cm. Although this could suggest a lowering of the water table initiates compaction and enhanced homogeneity as a result of subsidence, the differences in bulk density (when all depth data were combined) were not found to be significant between treatments.

Interestingly, the smaller proportion of macropore flow observed at the Drained and Blocked treatments directly contrasts the observations on blanket peat of Holden & Burt (2002a) who suggested that, although aeration may result in significant changes to soil structure, the shrinkage and cracking associated with surface drying would potentially result in more rapid levels of infiltration and vertical water movements through the development of macropore structures. In their study, Holden & Burt (2002a) found that experimentally manipulated blanket peat soil cores exposed to drought conditions experienced a reduction in moisture content and an increased level of macroporosity within the surface layers, resulting in preferential flow that extended to greater depths than in non-drought controls. However, because Holden & Burt (2002a) studied laboratory manipulated soil cores they may have experienced different conditions to those existing in the field given that drainage of the lower peat layers is probably more restricted under field conditions. Therefore, in field saturated peat with less lateral flow, additional macropores might not emerge under drought conditions or they may close more rapidly afterwards (Worrall *et al.*, 2006), while rapid flow through macropores under laboratory conditions may enlarge or sustain preferential flow paths. Additionally, Holden & Burt (2002a) only exposed their peat cores to a relatively short four week experimental drought, whereas the open drains at Oughtershaw were in place for 40 years prior to data collection. Thus, it may well be that the initial response of a de-saturated peat is shrinking and cracking at the soil surface and an increase in macroporosity; but in the long-term, the de-watering and ultimate compaction of the peat may reduce macropore flow.

With regards to solute transportation, Wallage et al (2006) found that pore waters sampled at the Drained treatment exhibited significantly higher DOC concentrations than the Blocked or Intact treatments. Thus, in addition to a possible stimulation of microbial activity and therefore DOC production (Wallage et al, in review), the reduction in the proportion of macropore flow at the Drained site may have increased the residence time of percolating waters, such that there is a greater level of peat-water interaction resulting in enhanced mobility and transportation of these decompositional products. This hypothesis clearly requires further testing, but suggests a potential role in DOC export for peatland management driven changes in near-surface water flow pathways.

In summary, six years after drain blocking, the restored peat exhibited a significantly smaller proportion of flow occurring through near-surface macropores relative to a nearby undisturbed blanket peat, as well as significantly higher saturated hydraulic conductivity compared to both the Drained and Intact sites. As such, blanket peat restoration by ditch blocking may not necessarily lead to an immediate reversal of the modified hydrological properties observed at a drained site, despite a recovery of the mean water table depth. Rather, there may be additional changes to peatland hydrological processes such that the peatland functions quite differently to that of an undisturbed peatland at least in the short to medium-term.

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Table 1. Descriptive statistics for mean bulk density by treatment and soil depth

Bulk Density ($g\ cm^{-3}$)	**Treatment**					
	Intact		**Drained**		**Blocked**	
Soil Depth	**Mean**	**St Error**	**Mean**	**St Error**	**Mean**	**St Error**
5 cm	0.095	0.015	0.108	0.015	0.075	0.007
10 cm	0.099	0.016	0.109	0.007	0.102	0.011
20 cm	0.116	0.009	0.114	0.010	0.103	0.014
40 cm	0.121	0.013	0.118	0.009	0.133	0.017
Mean	**0.108**	**0.007**	**0.112**	**0.005**	**0.103**	**0.007**
ANOVA	**$F_{(3, 20)} = 0.909$, $p = 0.454$**		**$F_{(3, 20)} = 0.215$, $p = 0.885$**		**$F_{(3, 20)} = 3.578$, $p = 0.032$**	

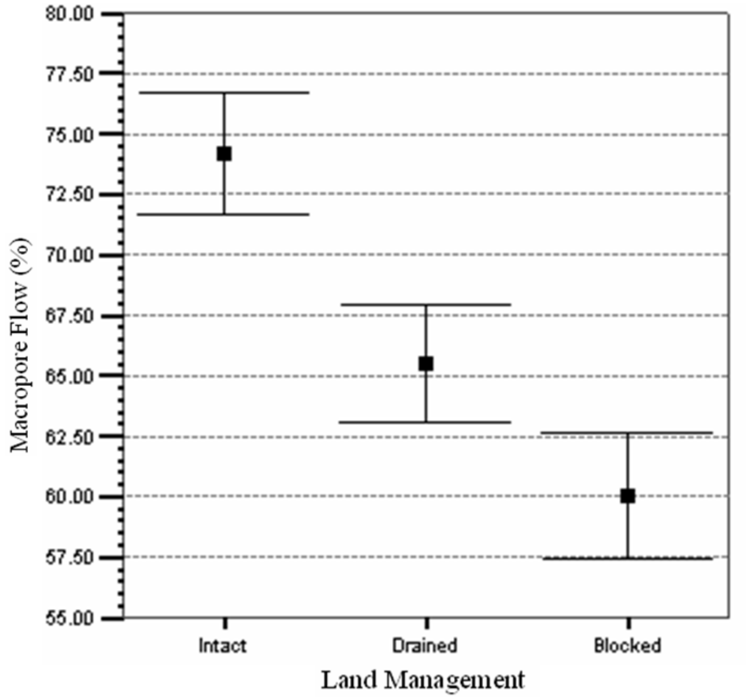

Figure 1. Mean percentage macropore flow for each treatment, including ± 1 SE of the mean.

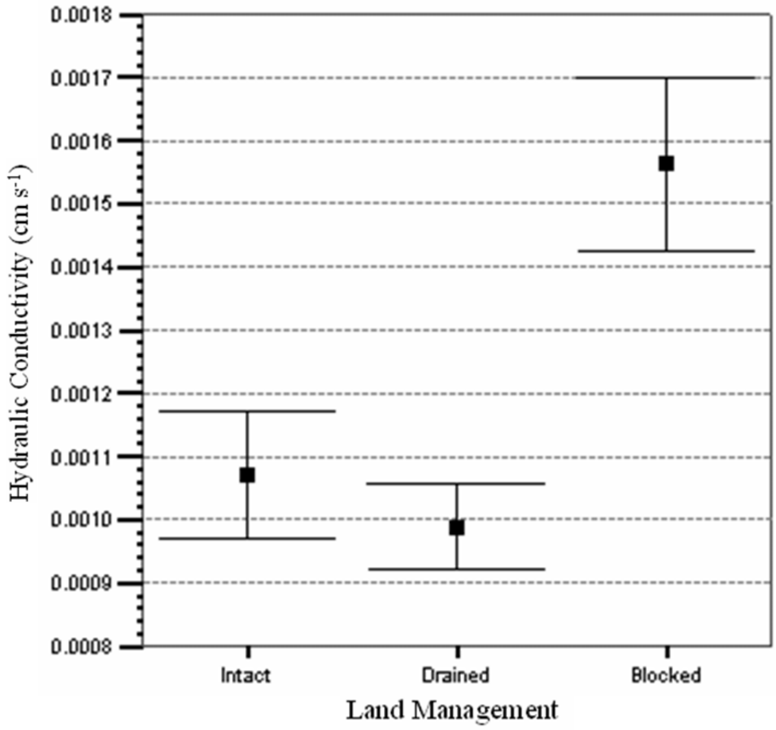

Figure 2. Mean rate of hydraulic conductivity for each treatment, including ± 1 SE of the mean.