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Abstract: Climate and land cover are two major factors affecting the water fluxes and balance across spatiotemporal scales. These two factors and their impacts on hydrology are often interlinked. The quantification and differentiation of such impacts is important for developing sustainable land and water management strategies. Here, we calibrated the well-known Hydrus-1D model in a data-rich boreal headwater catchment in Scotland to assess the role of two dominant vegetation types (shrubs vs. trees) in regulating the soil water partitioning and balance. We also applied previously established climate projections for the area and replaced shrubs with trees to imitate current land use change proposals in the region, so as to quantify the potential impacts of climate and land cover changes on soil hydrology. Under tree cover, evapotranspiration and deep percolation to recharge groundwater was about 44% and 57% of annual precipitation, whilst they were about 10% lower and 9% higher respectively under shrub cover in this humid, low energy environment. Meanwhile, tree canopies intercepted 39% of annual precipitation in comparison to 23% by shrubs. Soils with shrub cover stored more water than tree cover. Land cover change was shown to have stronger impacts than projected climate change. With a complete replacement of shrubs with trees under future climate projections at this site, evapotranspiration is expected to increase by ~39% while percolation to decrease by 21% relative to the current level, more pronounced than the modest changes in the two components (<8%) with climate change only. The impacts would be particularly marked in warm seasons, which may result in water stress experienced by the vegetation. The findings provide an important evidence base for adaptive management strategies of future changes in low-energy humid environments, where vegetation growth is usually restricted by radiative energy and not water availability while few studies that quantify soil water partitioning exist.

Response to Reviewers:

Highlights

- Land cover and climate change impacts on soil water balance were modelled
- Vegetation effects were mainly reflected by evapotranspiration and interception
- Land cover change is expected to exert stronger impacts than climate change
- More marked impacts were projected to occur in warm seasons than cold seasons

Modelling the effects of land cover and climate change on soil water partitioning in a boreal headwater catchment

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1. Introduction

Changes in land surface hydrology reflect the combined effects of climate, vegetation and soil (Rodriguez-Iturbe *et al.*, 2001; Li *et al.*, 2017). Climate, hydrology and vegetation are intricately linked and the ecohydrological consequences of climate change (CC) have been broadly discussed (Carey *et al.*, 2010; Tetzlaff *et al.*, 2013; Xu *et al.*, 2013). For example, warming temperatures and increasing annual precipitation (*P*) have resulted in an advanced vegetation green-up timing and extended growing season in the northern hemisphere (Richardson *et al.*, 2013; Yang *et al.*, 2015), and reduced snow accumulation with earlier melt (Knighton *et al.*, 2017). Reduced summer rainfall and increased evapotranspiration (*ET*) also affect streamflow generation (Déry and Wood, 2005; Deutscher *et al.*, 2016) and soil water and groundwater storage (Barnett *et al.*, 2005; McNamara *et al.*, 2005; House *et al.*, 2016).

In addition to climate change, land cover change (LC) has been recognized as a key factor that influences catchment hydrology (Zhang *et al.*, 2001; Li *et al.*, 2017). It is estimated that vegetation covers ~70% of the global land surface (Dolman *et al.*, 2014), influencing water, carbon and energy exchanges driven by hydrological and climatological factors (LeMone *et al.*, 2007). In particular, it has been estimated that transpiration (*T*) contributes more than half the global terrestrial *ET* (Jasechko *et al.*, 2013), whilst precipitation interception (*I*) by the vegetation canopy can significantly influence water redistribution (Carlyle-Moses and Gash, 2011; Soulsby *et al.*, 2017a).

Changes in land cover can have profound hydrological implications. For example, a shift from grasses to trees would generally increase *I* and enhance *ET* (Brown *et al.*, 2005; Nunes *et al.*, 2011). Replacement of natural ecosystems by rain-fed agriculture often results in increases in recharge and rising water tables (Allison *et al.*, 1990; Scanlon *et al.*, 2005), while afforestation by deep rooted trees can reduce drainage and lower water tables (Engel *et al.*, 2005). Many other studies (Favreau *et al.*, 2009) have also demonstrated that LC can alter the catchment water balance significantly.

Climate change and vegetation development are interlinked and often coevolve (Walther, 2010). Climate change impacts can be observed in the long term, for instance, from precipitation and runoff data (Serreze *et al.*, 2000; Meng *et al.*, 2016), whereas the impacts of land cover change can be expressed rapidly in runoff and water chemistry responses (Séguis *et al.*, 2004; Guan *et al.*, 2013). In some cases, climate change has been found to influence the hydrology of systems less dramatically than land use/land cover change (Schilling *et al.*, 2010; Li *et al.*, 2017), whilst others came to the opposite conclusion (Legesse *et al.*, 2003; Liu *et al.*, 2013). Differentiation of their impacts on hydrological processes can help guide future strategies to manage land and water in a more sustainable way.

The northern high-latitude regions are particularly sensitive to climate change (IPCC, 2014), though these changes will have significant spatial variability. It is estimated that annual zonally averaged *P* increased by 7%–12% for latitudes of 30^{o} N–85^{o} N over the 20^{th} century (Dore, 2005). The figure for Canada was >10% on average over a similar period (Mekis and Hogg, 1999), while over the United States it was 5%–10% since 1900, most pronounced during warm seasons (Groisman *et al.*, 1999). The spatial variation of climate change results in different impacts on local catchment hydrology, especially in headwater catchments, which are important sources of stream flow and groundwater recharge (Viviroli *et al.*, 2003). In many northern high latitudes such as the Scottish Highlands, vegetation growth and productivity is usually restricted by radiative energy and not water availability (Wang *et al.*, 2017a). The natural vegetation over much of the Scottish Highlands would have been forests dominated by Scots pine (*Pinus sylvestris*), but a long history of clearance, burning and overgrazing has reduced forest cover dramatically (Steven and Carlisle, 1959). With frequent rainfall, low radiation and high humidity, plants are usually not under water stress during most of the year (Haria and Price, 2000). However, future projections of intensified warming and decreased rainfall during growing seasons (Gosling, 2012; Capell *et al.*, 2013), in addition to plans to increase Scots pine cover to replace shrubs for conservation and biofuel objectives (Hrachowitz *et al.*, 2010), may result in trees experiencing increased water stress in certain summer periods as well as an increased annual *ET* and decreased water storage. Whilst this may have advantages in terms of natural flood alleviation (Soulsby *et al.*, 2017b), it may also reduce river flows to the detriment of in-stream ecology (Fabris *et al.*, 2017).

Numerous models have been developed to investigate soil water balance and its interactions with climate and land cover changes (Romano, 2014; Ferguson *et al.*, 2016; Koch *et al.*, 2016). Among the most commonly used numerical solutions based on the Richards equation for variably saturated water flow, the Hydrus-1D model has been widely and successfully adopted for many cases ranging from laboratory experiments to field study (Sutanto *et al.*, 2012; Ebel, 2013; Balugani *et al.*, 2017). In the most recent development, an interception module has been incorporated to account for the role of vegetation in *P* redistribution (Šimůnek *et al.*, 2016).

In this study, we applied the Hydrus-1D model (the latest version 4.16) for podzolic soils with two dominant vegetation covers (heather shrubs: *Ericaceae* vs. trees: *Pinus sylvestris*) in two plots located in a Scottish headwater catchment (Bruntland Burn catchment). The catchment's hydrology in terms of water transport, connectivity and storage in the surface and subsurface, as well as runoff generation processes has been extensively investigated using different advanced measurements and modeling techniques such as stable water isotopes, geophysical surveys and tracer-aided models (Tetzlaff *et al.*, 2014; Soulsby *et al.*, 2015, 2016b; van Huijgevoort *et al.*, 2016; Benettin *et al.*, 2017). In the context of likely foreseeable CCs and LCs, the role of vegetation in regulating the water balance in the unsaturated soils seems more important (Geris *et al.*, 2015c) but is not yet fully understood (Tetzlaff *et al.*, 2015). Therefore, the aims of this study are to quantitatively use a modelling approach to: (1) investigate the effects of different vegetation covers on soil water balance components, including *I*, *ET*, deep percolation (*D*) to groundwater recharge, and soil water storage (*S*) in a boreal headwater catchment; and (2) examine and differentiate the impacts of projected climate change and land cover change on the above soil water balance components. The results will provide an evidence base and approach to guide adaptive management in similar boreal sites, where such quantifications have not been conducted before.

2. Data and methods

2.1.Study site

The Bruntland Burn catchment (3.2 km^2, 57.04°N, 3.13°W) is located in NE Scotland (Figure 1), and described in detail elsewhere (Tetzlaff *et al.*, 2014; Ala-aho *et al.*, 2017). The climate is boreal oceanic. Based on the last decade of observations, mean monthly maximum temperature is 19.4±1.3°C in July, and mean monthly minimum temperature is −1.0±1.6°C in January. Mean annual P is around 1000 mm, relatively evenly distributed throughout the year, but generally lower (~65 mm/month) in April-July and higher (~105 mm/month) in October-February. Snow is generally <5% of annual P and tends to lie for short periods (a few days to a few weeks) in January and February and melts quickly. Annual mean potential evapotranspiration (ET_p) based on the Penman-Monteith method (Allen *et al.*, 1998) is ~450 mm and annual runoff at the catchment outlet is around 700 mm (Soulsby *et al.*, 2015).

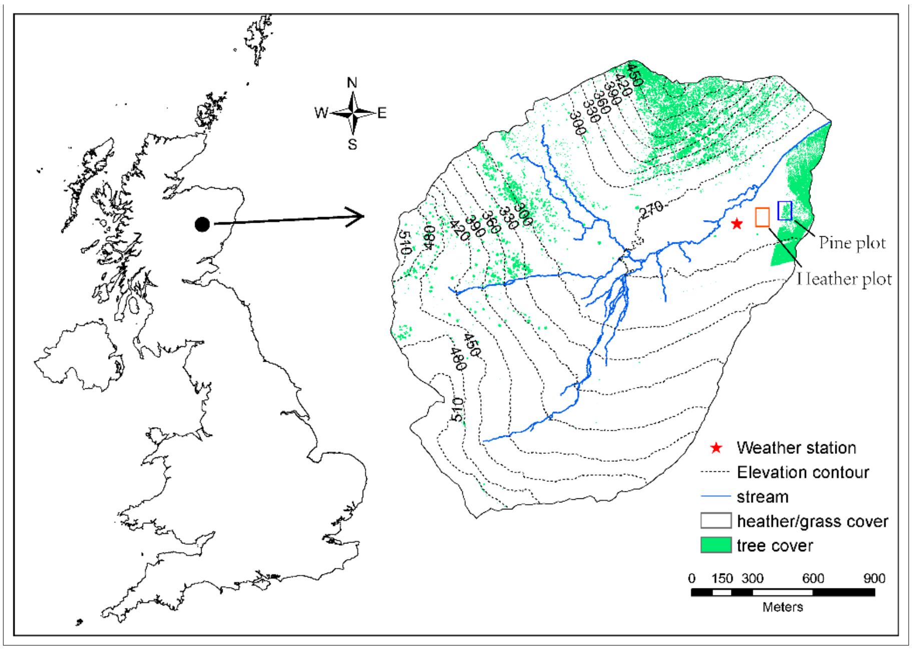

Figure 1 The Bruntland Burn catchment and its location on the map of the United Kingdom. The pine site was equipped with sap flow sensors and the heather site with iButton sensors for transpiration estimation. Soil moisture probes were installed at depths of 10, 20 and 40 cm in both the heather and pine plots. Numbers on contour lines are elevation in m.a.s.l. Tree mapping in the figure is based on 1 m resolution LiDAR data with the canopy height threshold set to 1.5 m.

Elevation in the catchment ranges from around 250 m.a.s.l at the valley bottom to about 550 m on the ridge. Most of the underlying bedrock is granite, with Ca-rich and Si-rich meta-sediments. Glacial drift deposits cover large parts of the catchment (~70%) reaching up to 40 m deep in the valley bottom where this drift overlays the bedrock (Soulsby *et al.*, 2007). In the valley bottom, the drift is comprised of a silty-sand matrix with abundant larger clasts and has low permeability. In contrast, the steeper hillslopes are veiled by shallower (~5 m deep), more permeable lateral moraines and ice marginal deposits (Soulsby *et al.*, 2016b). Organic-rich soils dominate the catchment, with large areas of deep peats (>1 m) in valley bottoms and shallow peats (<0.5 m) on the lower hillslopes. On the steeper slopes, the dominant soils covering ~60% of the catchment are podzols with a 0.1–0.2 m deep O horizon on top. The dominant vegetation is heather (*Calluna vulgaris* and *Erica tetralix*) shrubs with a canopy height of 0.3–0.6 m, distributed throughout the valley and hillslopes. Trees, mostly Scots pine (*Pinus sylvestris*), cover about 10% of the catchment, mainly in plantations near the outlet and natural forest on the south-facing steeper slopes (Figure 1). Both heather and pine are evergreen vegetation that have dense canopy. The majority of roots of heather and pine are present in the upper 0.15 and 0.3 m of the soils, respectively (Geris *et al.*, 2015a; Sprenger *et al.*, 2017).

2.2. Measurements

An automatic weather station (*Environmental Measurement Limited*, North Shields, UK) was set up in the valley bottom of the catchment (Figure 1), continuously recording 15-minute meteorological data, including temperature, relative humidity, wind speed and direction, pressure, precipitation and net radiation and ground heat flux. To estimate transpiration (*T*) from Scots pine, we installed 32 sets of sap flow sensors (Thermal Dissipation Probes, *Dynamax Inc.* Huston, USA) on 10 trees at trunk positions around 1.3 m above ground during 08/07-28/09/2015 (Wang *et al.*, 2017a). Transpiration of the plot was up-scaled by multiplying the sap flow rate per sapwood area by sapwood area index (ratio of sapwood area to ground area) estimated by the relationship between sapwood area (measured using wood cores e.g., Wang *et al.*, (2016a)) and trunk diameter at 1.3 m height. Meanwhile, heather *T* between 31/07-31/10/2015 and 21/04-04/08/2016 was estimated using a model based on the theory of maximum entropy production (MEP) (Wang and Bras, 2011), with canopy temperature and humidity data collected every 15 minutes by 15 shielded iButton sensors (DS1923 model, *Maxim Integrated*, USA). The sensors were fixed directly over the heather canopy to minimize the influence of evaporation from interception on rainy days, and were distributed in a 4 m by 8 m plot, which allows an estimation of the spatial variability of water vapor distribution (Wang *et al.*, 2017b). Despite the uncertainties related to the MEP model, transpiration was comparable to other independent estimates (Wang *et al.*, 2017b). Soil water content was measured using TDR probes (CS616, *Campbell Scientific, Inc*. USA) at both sites at depths of 10, 20 and 40 cm below the surface. All data were aggregated to daily values for further comparisons and analysis. In addition, soil at different depths was sampled for textural analysis. Leaf area index (LAI) was measured for pine (2.5 m^2/m^2) and heather (1.7 m^2/m^2) using a plant canopy analyser LAI-2200C (*LI-COR Environmental*, USA), and assumed to be constant throughout the year because both heather and pine are evergreen and over 20 and 30 years old.

2.3. Hydrus model configuration for heather and pine sites

2.3.1. Governing equations in the Hydrus model

Simulation of the water fluxes and soil water storage dynamics were performed using the Hydrus-1D model. We argue that the use of a 1D model for the unsaturated zone is justified due to negligible lateral water flow along the small topographic gradients at the study sites. Šimůnek *et al.*, (2013a) described the model structure and function in detail. Only the dominant equations used in our study are summarised below.

One-dimensional variably-saturated water flow in the soil was modelled with the modified Richards equation to account for the root water uptake by the sink term $S(h)$:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h,x)\left(\frac{\partial h}{\partial x}+1\right)\right] - S(h) \qquad (1)$$

where θ is the volumetric water content (cm^3/cm^3), h is the water pressure head (cm), t is time (day), x is the spatial coordinate (cm, positive upward), K is the unsaturated hydraulic conductivity (cm/day). Unsaturated soil hydraulic properties $\theta(h)$ and $K(h)$ are given by *van Genuchten* (1980):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^{1-1/n}} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (2)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{1-1/n}}\right)^{1-1/n}\right]^2 \quad (3)$$

where θ_r and θ_s are residual and saturated soil water content, respectively. α is the inverse of the air-entry value (or bubbling pressure). n is an empirical coefficient influencing the shape of hydraulic functions (dimensionless). K_s is saturated hydraulic conductivity (cm/day), l is the pore connectivity parameter prescribed as 0.5. S_e is effective saturation defined as the ratio of actual to maximum available soil water.

The sink term S (cm/day) for root water uptake calculation is defined in van Genuchten (1987):

$$S(h) = f(h)\beta(x)T_p \quad (4)$$

$$f(h) = \frac{1}{1 + \left(\dfrac{h}{h_{50}}\right)^p} \quad (5)$$

where $f(h)$ is a water stress response function, and $\beta(x)$ is the root distribution function (ranging 0-1) which linearly decreased in this study from the soil surface to 15 and 30 cm below for heather and pine, respectively. h_{50} represents the water head at which the water extraction rate is reduced by 50%; p determines the $f(h)$ curve shape. These two parameters vary for vegetation and soils (Gribb *et al.*, 2009; Huang *et al.*, 2015).

In this study, we used -800 cm for h_{50} for both vegetation types; p was set to 3 initially and tuned during calibration against transpiration estimates for heather and pine. Potential transpiration (T_p) was calculated from ET_p and soil cover fraction (f_s) in equation (6). ET_p was calculated separately for heather and pine following Dunn and Mackay (1995).

$$T_p = f_s ET_p = (1 - e^{-\kappa \cdot LAI}) ET_p \tag{6}$$

κ is the light extinction coefficient, 0.56 for heather and 0.50 for pine according to Zhang *et al*., (2014). Evaporation is calculated following Feddes *et al*., (Feddes *et al.*, 1974), that is, when the pressure head at the soil surface is higher than the minimum allowed pressure head (h_A), which is related to relative humidity and temperature, the actual evaporation is equal to the potential evaporation (E_p). Once the surface pressure head drops to h_A, the actual evaporation is decreased from E_p by solving equation (1).

In the Hydrus-1D version 4.16, precipitation interception by canopy is calculated following Kroes et al., (2008):

$$I = a \cdot LAI \cdot \left(1 - \frac{1}{1 + \frac{f_s \cdot P}{a \cdot LAI}} \right) \tag{7}$$

where P is precipitation (mm/day). The interception constant (a) was obtained by dividing the daily interception thresholds by LAI. Daily thresholds for heather and pine were 2.65 and 7.5 mm/day, respectively (Calder *et al.*, 1984; Haria and Price, 2000).

2.3.2. Boundary conditions and soil hydraulic parameters

The upper boundary of the model was set as “atmospheric boundary (daily P and ET_p) with surface runoff”, and the lower boundary was set as “free drainage” as the groundwater table is usually deep on the hillslopes (>1 m) during the growing season. Since root water uptake mainly occurs in the root-zone of the soils, we set up the model for the upper 50 cm deep soil and configured the soil as two layers taking into account the observed rooting depths: 0-15 cm and 15-50 cm for heather, and 0-30 cm and 30-50 cm for pine.

The soil hydraulic parameters were initialized using the Rosetta (Schaap *et al.*, 2001) estimates based on measured soil bulk density and texture (Geris *et al.*, 2015b; Sprenger *et al.*, 2017), and then optimized with a Marquardt-Levenberg type parameter estimation technique by inverse modelling (Šimůnek and Hopmans, 2002) using θ observations at the depths of 10, 20 and 40 cm. The objective function was to minimize the sum of squared difference between the observations and simulations at each depth, and the goodness of fit was assessed by the coefficient of determination (R^2) (Šimůnek *et al.*, 2013b). This method gives the mean as well as standard error of parameter values, and has been tested in many studies and proved sufficient for soil hydraulic parameter estimation (Schneider *et al.*, 2013; Li *et al.*, 2015; Bourgeois *et al.*, 2016). Among the parameters in the soil hydraulic functions, the residual soil moisture in equation (2) is considered not to influence model performance significantly (Jacques *et al.*, 2002); therefore, it was fixed based on the Rosetta estimates to reduce the number of parameters to calibrate.

2.3.3. Model validation

We chose two periods to calibrate the model covering both drying and wetting conditions. Model performance was tested by comparing the simulations with direct observations of soil moisture and also transpiration over two growing seasons using data from sap flow (Wang *et al.*, 2017a) and iButton sensors (Wang *et al.*, 2017b) in 2015 and 2016. As measures of goodness of fit between simulations and observations of both soil moisture and transpiration we applied R^2 and root mean square error (*RMSE*) from linear regressions.

2.4. Climate and land cover change scenarios

We firstly ran a daily simulation for 05/2011-04/2016 to quantify the water partitioning under two vegetation covers under current climate conditions. To examine possible CC impacts, we then applied the projections for P and ET_p in the area for the 2050s by Capell *et al.*, (2013), derived based on an average greenhouse gas emission scenario (IPCC scenario A1B) in the UK Climate Projection 2009 (UKCP09) network, which downscaled Regional Climate Model predictions to 5 km resolution. Specifically, compared to the current condition, P is projected to decrease by 10% in April-October while it is projected to increase by 10% in November-March; ET_p is projected to increase by 15% in all months because of warming temperatures throughout the year. Lastly, to assess the possible LC impacts within a modelling experiment, we assumed a 100% change from heather to pine running the simulations with pine parameters in place of heather for the heather soil profile. The rationale for this was the historic and current policy drive to increase tree cover in the Scottish Highlands for conservation, biomass production, natural flood management, and mitigating rising temperatures in streams for important species like Atlantic salmon (Tudor *et al.*, 1999; Hrachowitz *et al.*, 2010). Monthly averages of the water balance components (equation 8) within the soil columns over the 5-year period were compared to investigate the impacts of LC under future climate scenarios.

$$\Delta S = P - ET - D \tag{8}$$

Where ΔS is the water storage change in the 50 cm deep soil columns, D is the deep percolation leaving the 50 cm soil columns. Lateral fluxes are neglected due to the relatively flat terrain conditions. To examine the significance of difference for each component among the three scenarios (current, climate, climate plus land cover change), we, firstly, performed an analysis of variance (ANOVA) and then a post hoc Tukey test with the significance level of 0.05. The data used for the test were yearly data from 2011 to 2016.

3. Results

3.1. Model test against soil moisture and transpiration

Table 1 Calibrated mean soil hydraulic parameters in equation 2-3 for both sites. In brackets is standard error of each parameter. θ_s is saturated soil water content, K_s is saturated hydraulic conductivity, α is the inverse of the air-entry value (or bubbling pressure), and n is an empirical coefficient influencing the shape of hydraulic functions.

Site	Depth (cm)	θ_s (cm³/cm³)	α (1/cm)	n (-)	K_s (cm/d)
Heather	0-10	0.5188 (0.0100)	0.0874 (0.0087)	1.1182 (0.0069)	195.02 (40.64)
	10-50	0.4965 (0.0098)	0.0386 (0.0035)	1.3090 (0.0089)	359.75 (62.19)
Pine	0-30	0.5736 (0.0154)	0.0706 (0.0070)	1.2088 (0.0077)	327.38 (72.32)
	30-50	0.3119 (0.0050)	0.0257 (0.0022)	1.1305 (0.0083)	308.33 (42.30)

The parameters of the soil hydraulic functions were calibrated by inverse solution of the soil water content at 10, 20 and 40 cm depths. Optimized mean parameter values as well as the standard deviation are given in Table 1. The textures of the soils under heather and pine cover had no distinct difference (Sprenger *et al.*, 2017), thus, the calibrated parameters of the soil hydraulic functions were mostly similar, except θ_s and K_s. In general, the top layer had higher θ_s than the lower layer consistent with a higher organic matter content near the surface; also average K_s was higher at the pine site than the heather site, consistent with likely greater root biomass in the forest. The small standard deviations of the parameter values indicate that the inverse solution gave generally stable estimates with small uncertainties.

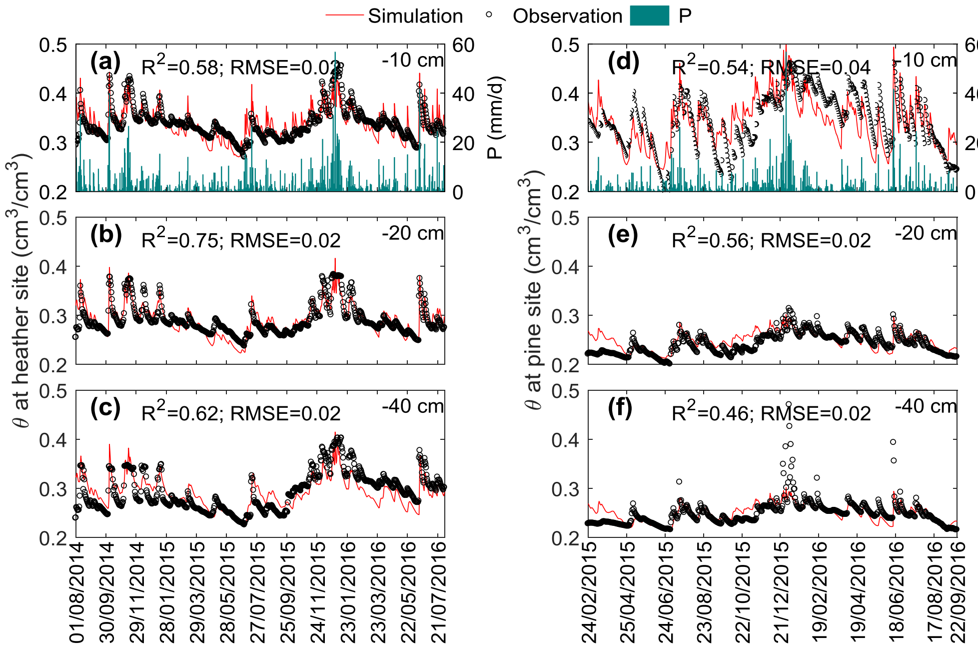

Figure 2 Comparison of simulated and measured soil water content (θ) over the calibration periods. Plots *a-c* are for heather site at the depths of 10, 20 and 40 cm, and plots *d-f* are for pine site at the same depths. *P* is precipitation. R^2 is coefficient of determination, and *RMSE* is the root mean square error, with the unit of cm^3/cm^3.

Model performance was firstly tested against soil moisture (Figure 2). Simulations generally agreed well with observations in terms of both the temporal dynamics reflected by R^2 (0.58-0.75 for the heather site and 0.46-0.56 for the pine site), and water content reflected by *RMSE* (0.02 cm^3/cm^3 at all three depths for heather, and 0.02 cm^3/cm^3 at 20 and 40 cm depths and 0.04 cm^3/cm^3 at 10 cm depth for pine). It was notable that the forest top soil showed much greater variability in moisture content than the heather site, probably due to more root water uptake by pines and faster drainage through the shallower organic layer to dry the soils. It is also noticeable that soil moisture contents were lower and less variable at the forest site than the heather site, reflecting the much coarser subsoil characteristics (Dick *et al.*, 2017). Whilst at the heather site there was a tendency to slightly overestimate moisture content in wet periods, for the forest site the model over-anticipated the wet-up following summer 2015 and exaggerated the dry-down following very large rainfall inputs in December 2015/January 2016. However, the over/under-estimations did not consistently occur throughout the entire calibration periods. The soils at 40 cm depth were similar to and slightly drier than at 20 cm depth indicating a generally free-draining characteristic and a deep groundwater table (at least >0.5 m) at both sites, though in the December 2015 event, very high water content was briefly observed in the subsoil of the forest which was not captured by the model.

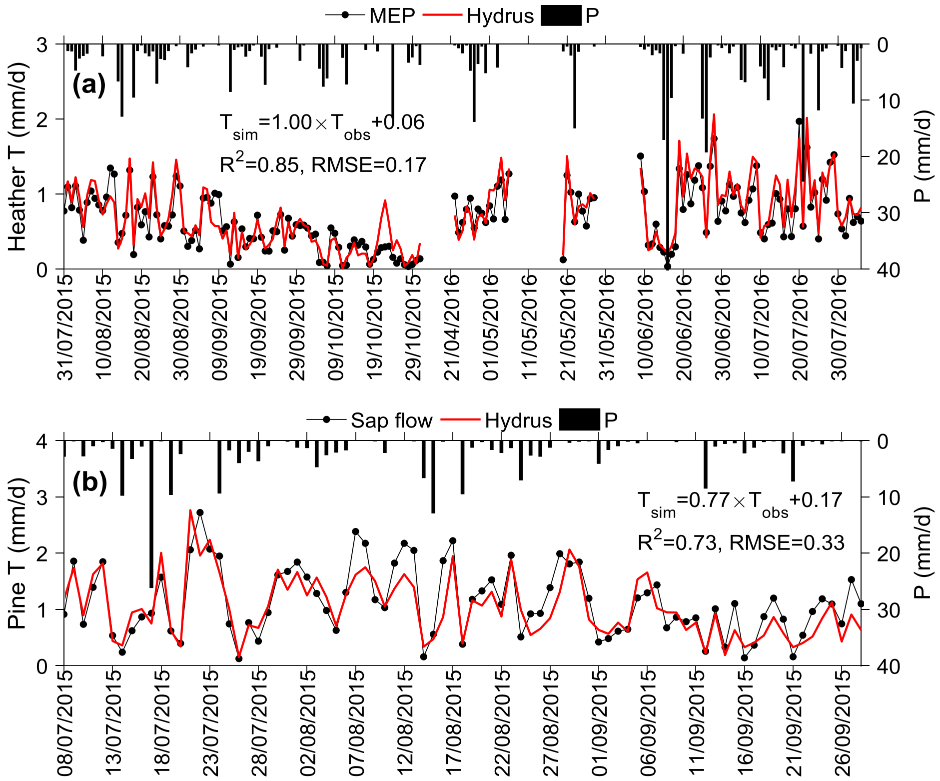

Figure 3 Comparison of transpiration (*T*) simulated by Hydrus and estimated from independent methods for (a) heather and (b) pine site. *T* at heather site was derived using the MEP method, and measured at pine site using the sap flow technique. *RMSE* is the root mean square error, in the unit of mm/d. Equations in the figure are linear regressions between Hydrus simulations and MEP-derived and sap flow measured *T*.

In addition to soil water content, model performance for transpiration simulations (Figure 3) was also tested against direct measurement or independent estimations from data driven models (i.e. measured via sap flow for Scots pine; derived from the MEP method for heather). Again, the Hydrus model showed good agreement with the *T* estimates for both vegetation types, capturing the dynamics well with a high R^2 and giving similar absolute fluxes shown with the low *RMSE*. There was a general tendency for the model to occasionally underestimate the observed values on some days but again this was not systematic. Noticeably, heather *T* (peak value ~2 mm/d) was lower than pine *T* (peak ~3 mm/d). For the period from summer towards autumn, there was a decreasing tendency of *T* from both heather and pine in response to declining solar radiation (Wang *et al.*, 2017a). Overall, the good agreements between Hydrus simulations and observations of soil water content and independent estimates of transpiration increased confidence that the model was able to represent the soil water flow and plant water uptake processes reasonably well.

3.2. Simulations of water balance components under two vegetation covers

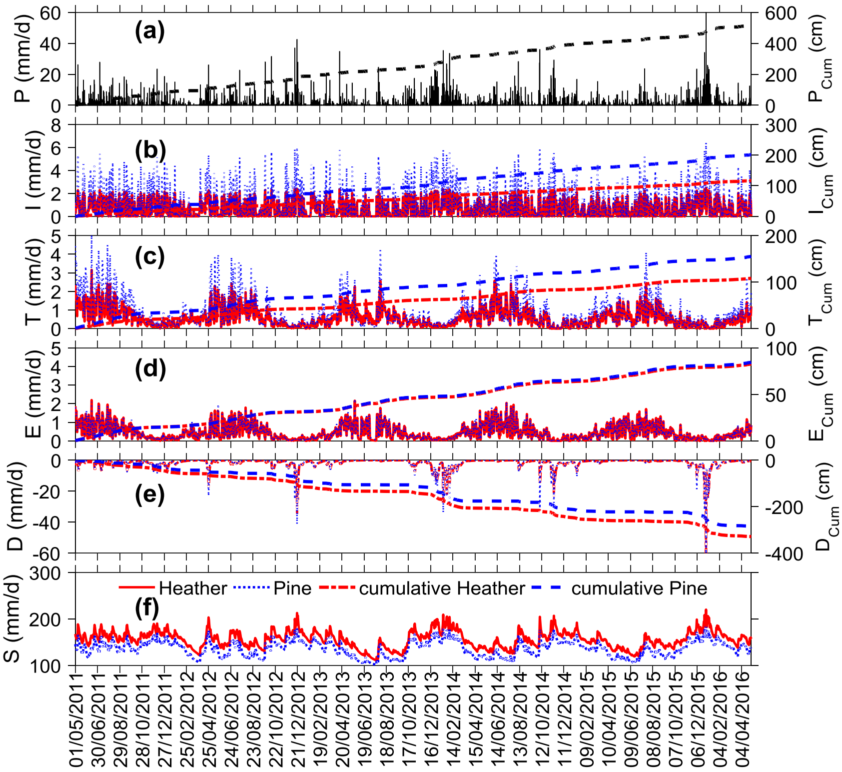

Figure 4 Comparison of key water balance components between heather and pine sites. (a) *P*: precipitation, (b) *I*: total intercepted precipitation by canopy, (c) *T*: transpiration, (d) *E*: evaporation, (e) *D*: deep percolation leaving the 50cm deep soils, and (f) *S*: total water storage in the 50cm soil profile. Right axes in the plots (a-e) show the cumulative values of the corresponding variables.

To compare the influence of vegetation cover on water partitioning, daily as well as cumulative values of *P* and simulated water balance components are given in Figure 4 over a 5-year period from 05/2011 to 04/2016. *P* was relatively evenly distributed throughout the year, though slightly higher in winter than in summer. Similar to *P*, there was no strong seasonality in the total intercepted precipitation (*I*). Possibly unsurprising, Scots pine canopy intercepted more precipitation than the heather canopy (1.7-fold). This corroborates recent empirical work that has suggested interception losses of ~40% in the forest (Soulsby *et al.*, 2017a) and 22% from the heather (Wang *et al.*, 2017b). Transpiration was also higher from Scots pine than from heather shrubs, showing the 5-year accumulation of ~1500 mm from pine compared to ~1000 mm from heather; whereas evaporation (*E*) was similar at both sites (5-year accumulation of ~760 mm), and significantly lower than transpiration. *ET* was high between April-October and low during the rest of the year. Deep percolation to recharge deeper soils (>50 cm) at the heather site was more than the pine site. Largest percolation occurred in winter such as January 2016 during large rain events. In summer, when *P* was low and *ET* was high, percolation effectively ceased for prolonged periods. Soil water storage (*S*), defined as the total amount of water that is stored in the soil profile and calculated as the available soil water storage capacity multiplied by the soil depth, was high (nearly 200 mm) in winter and low (~100 mm) in summer, which inversely reflected *ET* and corresponded positively to rainfall. On average, *S* was around 159 mm at the heather site, and ~20 mm less at the pine site.

Table 2 Average annual water balance components in the upper 50 cm soils under heather and pine covers from 05/2011 to 04/2016. Percentage in brackets shows the mean (± standard deviation) proportion of annual precipitation for each relevant component. *P*-precipitation, *ET*-evapotranspiration, and *D*-deep percolation. Δ*S* is the water storage change which was calculated as *P*-*ET*-*D*.

Site	*P* (mm)	*ET* (mm)	*D* (mm)	Δ*S* (mm)
Heather	1039.3±86.4	355.0±31.2 (34.2±3.0%)	693.9±69.9 (66.8±6.7%)	-9.6±16.7 (-0.9±1.6%)
Pine		459.1±60.1 (44.2±5.8%)	596.4±69.5 (57.4±6.7%)	-16.3±18.1 (-1.6±1.7%)

The average annual amounts of the water balance components under different vegetation types over the 5-year period are given in Table 2. The annual precipitation was 1039 mm, and more than half of it drained below the top 50 cm soils to recharge deeper soil water or groundwater. In contrast, around 34±3% of annual precipitation was lost through *ET* from the heather site, and 10% more from the pine site. The average annual water storage change in the soils was only a small portion of precipitation. In addition, the interception calculations showed that heather intercepted 23±2% of annual *P* whereas pine intercepted 39±3%. Based on the results, we can conclude that at our site vegetation effects on soil water balance are mostly reflected in *ET* and net precipitation, which consequently changes the recharge to deeper soils.

3.3.Impacts of land cover and climate changes on the soil water balance

Table 3 Changes in annual water balance components at the heather and pine sites under scenarios of climate and land cover changes relative to the current condition. Percentages show the average (±standard deviation) projected increase (positive) or decrease (negative) in each component. *P*-precipitation, *ET*-evapotranspiration, and *D*-deep percolation. Δ*S* is the water storage change calculated as the residual of *P*, *ET*, and *D*. Heather* means running the model with soil properties of the heather site but vegetation parameters of Scots pine. ** indicates that the Tukey test *p* value was <0.05.

Site	Scenario	*P*	*ET*	*D*	Δ*S*
Heather	Climate change	-1.0±3.2%	7.6±3.5%	-5.2±6.7%	13.1±41.7%
Pine			4.5±5.2%	-4.9±9.7%	11.6±21.2%
Heather*	Climate change + land cover change		39.5±15.1%**	-21.3±12.0%	33.3±92.7%**

Climate trends and projections indicate a warming environment in northern high latitudes, changes in seasonal temperature distributions as well as altered precipitation regimes are expected to exert impacts on water balance. These changes will be spatially variable and need to be clearly quantified locally. Here, we show firstly the corresponding changes in water balance components under projected climate change for the 2050s (annual P and ET_p) in comparison to the current condition in Table 3. These were derived from running the calibrated Hydrus model for the two sites with climatic data modified according to the IPCC average greenhouse gas emission scenario for the region. As annual P is only expected to decrease slightly by the 2050s (and the change was not statistically significant with the Tukey test p=0.93), ET was modelled to increase by 7.6±3.5% at the heather site and 4.5±5.2% at the pine site (both with a p=0.62). The smaller increase in ET at the pine site may indicate that more constraints from root-zone soil water availability would be expected by the trees. As a result of reduced P and enhanced ET, deep percolation was projected to decrease by 5.2% (p=0.95) and 4.9% (p=0.79) for heather and pine, respectively. It is notable that D remained the largest water component in the soils. The dynamics of ΔS were modelled as increasing at both sites, by 13.1% (p=0.78) and 11.6% (p=0.41) for heather and pine with large variability. The absolute value of annual ΔS for heather and pine under future climate was small, amounting to -10.9 and -18.2 mm/year, respectively. In addition, with the reduced P, intercepted precipitation was modelled to decrease by 1.2±1.3% (p=0.99) from pine and 1.0±0.8% (p=0.90) from heather. Overall, climate change would have impacts on the soil water balance components but the impacts were tested not statistically significant.

As there are policy drivers to promote changes in land cover from heather to pine to mitigate future CC impacts, we also ran the simulations for the heather-covered soils but replaced the relevant heather vegetation parameters by pine values (i.e. root distribution, LAI, light extinction coefficient, interception capacity and constant a, and ET_p), and calculated the changes in water budgets in Table 3. Compared to the current conditions, when considering both CC and LC, we found that *ET* would increase dramatically by 39.5±15.1% (p<0.001), and deep percolation would decrease by 21.3±12.0% (p=0.42). The shift of land cover types would mainly result in changes of annual *ET* and percolation, and consequently, Δ*S* would increase by 33.3% from -9.6 to -12.8 mm/year (p=0.01), but with large variability. Moreover, shifting from heather to pine under future climate was estimated to increase canopy intercepted water significantly by 71.2±5.8% (p<0.001) compared to the current heather dominated conditions. Therefore, the complete replacement of heather with pine under future climate is expected to alter evapotranspiration, canopy interception and soil water storage most significantly.

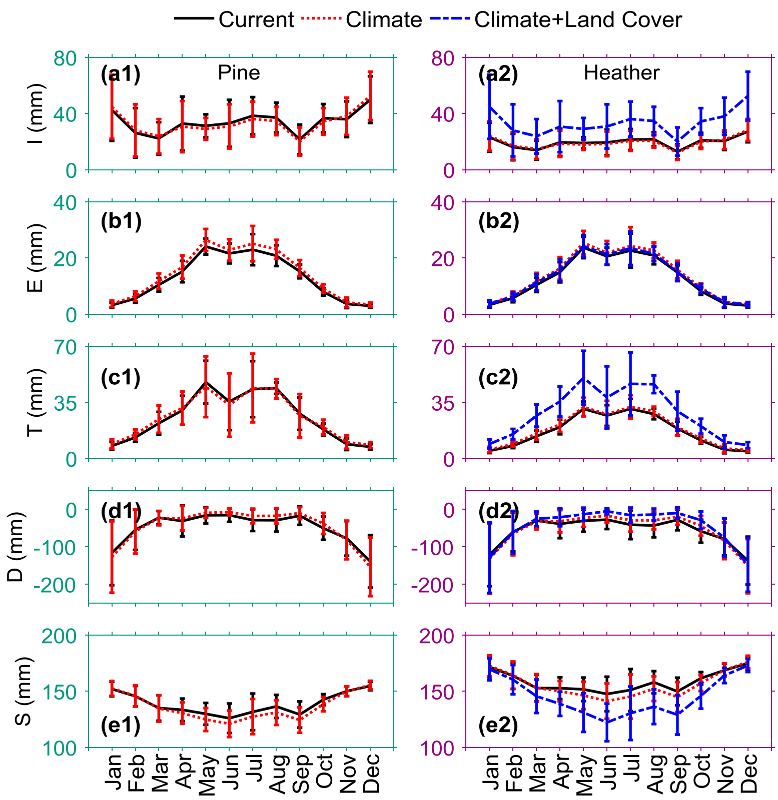

Figure 5 (a1-e1) Climatological mean monthly soil water balance components for current condition and projected climate change at the pine site; and (a2-e2) mean monthly soil water balance components for current condition, projected climate change, and climate change plus land cover change at the heather site. Error bars represent standard deviation of the monthly values for each variable in 5 years. *I*-canopy interception of precipitation, *E*-evaporation, *T*-transpiration, *D*-deep percolation, *S*-total water storage in the 50 cm soils.

To examine the seasonality of hydrological variables as well as the degree of probable impacts of CC and LC, we also calculated the monthly average of the water balance components over the 5-year period, and results are given in Figure 5. Canopy interception of precipitation showed similar dynamics to *P*, i.e. generally high in January and December and low in February and March. *ET*, *D* and *S* showed much stronger seasonal variations than interception. *ET* was higher in April-September than in other months, whilst *D* and *S* were smaller in summer than winter. Large variability corresponds to seasons with a large amount of water components. It is worth mentioning that changes in evaporation in all cases were projected to be negligible, probably due to the limited radiation below the dense canopies of both vegetation. Therefore, the increase in *ET* would be primarily contributed by transpiration. Climate change would have relatively modest impacts on all examined water balance components. In contrast, land cover change of increased forest cover has a stronger potential influence. The simulations show that shifting from heather to Scots pine would result in more plant interception and transpiration, lower soil water storage and reduced recharge especially in growing seasons.

4. Discussion

4.1. Role of vegetation in soil water partitioning

The northern high latitudes are experiencing land cover changes (Kelly and Goulden, 2008; Bi *et al.*, 2013), which are likely to increase through time and have the potential to exert strong but variable influence on the hydrology of this region (Tetzlaff *et al.*, 2015). Different land cover types have contrasting effects on water partitioning. Generally, trees transpire more water, and lose more water from precipitation interception than grass and shrubs (Zhang *et al.*, 2001; Kroes *et al.*, 2008), and thus, runoff generation is usually higher in areas with more grass/shrub cover than forest cover (Sterling *et al.*, 2012). Therefore, manipulating vegetation cover has potential for land and water conservation, e.g., to buffer soil erosion or losses of water (Nunes *et al.*, 2011) through high *ET* or rapid runoff (Van Der Linden *et al.*, 2003). Results from our work show that the role of vegetation in partitioning water is primarily mediated by interception and subsequent transpiration, which eventually results in differing summer water use and soil moisture storage under two distinct vegetation covers as also shown by Vivoni *et al*., (2008). These results are consistent with previous forest hydrology studies in the UK (Dunn and Mackay, 1995; Haria and Price, 2000; Sprenger *et al.*, 2017) in that *ET* from Scots pine was much higher than heather, reflecting the greater water use through transpiration and higher interception capacity of Scots pine due to the higher LAI (Haria and Price, 2000). The surface runoff was negligible in our simulations because the two sites under survey are on gentle slopes with well-vegetated, free-draining soil profiles (Tetzlaff *et al.*, 2007). In addition, rainfall intensities are usually low, though some empirical evidence suggested overland flow may have occurred after the largest rainfall events in winter

2015/2016 (Figure 4). However, the frequency of such events is low and the annual average amount of surface runoff was trivial compared to other water balance components (Ala-aho *et al.*, 2017). The resulting percolation of water to groundwater recharge is consistent with the role of deeper subsurface flows being the dominant contribution to catchment runoff generation from the podzolic soils (Blumstock *et al.*, 2016; Soulsby *et al.*, 2016b). Note that the soil textures show limited differences at both sites, therefore, the difference in water balance components is primarily resulted from vegetation cover effects.

In our low-energy humid environment, *ET* is primarily driven by solar radiation (Tetzlaff *et al.*, 2015; Wang *et al.*, 2017a), unlike in semi-arid areas where *ET* is also significantly controlled by soil water availability (Wang *et al.*, 2016b). Global land surface *ET* is dominated by *T*, and the annual average *T*/*ET* ratio given in Miralles *et al*., (2011) was 0.80, in the upper range reported by others with a lower average ratio of 0.67 (Jasechko *et al.*, 2013; Schlesinger and Jasechko, 2014). In our study, the annual average *T*/*ET* ratio was 0.57 at the heather site and 0.67 at the pine site, within the range previously reported. Meanwhile, the proportion of *ET* in *P* at the heather and pine sites was ~34% and 44%, lower than the average value of 58% for Europe (Miralles *et al.*, 2011), but comparable to similar work on Scots pine plots in Belgium (Verstraeten *et al.*, 2005). Noticeably, the biggest difference in water partitioning in this study compared to those in drier regions (Li and Shao, 2014) lies in the high recharge to deeper soil horizons and groundwater. We found that more than half of the precipitation drained to the deeper (>0.5 m) soils. The abundant *P* and *D* ensures that groundwater storage is recharged in the autumn and winter to sustain baseflows (Figure 4-5), whilst soil moisture deficits are usually negligible at the start of the growing season and water is available for vegetation uptake (Tetzlaff *et al.*, 2007; Soulsby *et al.*, 2016a). The downslope movement of groundwater storage from the hillslopes also sustains saturated conditions in the valley-bottom riparian zones where most of total water storage in the catchment resides (Soulsby *et al.*, 2016b).

4.2. The impacts of climate change and land cover change

Climate change and ecosystem composition shifts as well as their impacts on hydrology often occur concurrently (Kelly and Goulden, 2008). However, the exact influences are variable and contrasting in different regions (Legesse *et al.*, 2003; Li *et al.*, 2017). Thus, understanding both the integrated and separate effects of CC and LC on local water balance components is of particular importance to project likely future changes and adapt to them (Ray *et al.*, 2010). In our study, we showed that with the UKCP09 projected changes in P and ET_p by the 2050s, the most pronounced change would be transpiration and interception loss from both vegetation types. Similar findings have been reported by others across different climates and landscapes (Ivits *et al.*, 2014; House *et al.*, 2016). Currently, the vegetation in our catchment rarely experiences water stress during growing seasons (Wang *et al.*, 2017a); however, with the projected drier and warmer summers in that region, plants are more likely to experience water shortages, partly because they are mostly established on shallow podzolic soils on hillslopes with high percolation rates recharging groundwater which is usually below the rooting zones (Geris *et al.*, 2015a), and also because more soil water storage would be lost through ET than it is now (Table 3). Thus, with a reduction in S and an increase in ET, the water available for vegetation, groundwater recharge and baseflow maintenance would be decreased. However, it should be stressed that these changes are relatively modest.

The simulations suggest that potential LCs have a stronger impact on the soil water balance than CC at this particular site. The most pronounced influence was projected to be an increased vegetation water use with a complete shift from heather shrubs to trees. The results are consistent with similar studies such as Beringer *et al*., (2005) who showed an increase in *ET* with the shift from tundra shrubs to trees in Alaska, and Scanlon *et al*., (2005) who showed replacement of rangeland by agriculture resulted in less *ET* and more recharge in southwestern US. Looking into the 5-year average monthly values, we found the changes in water balance would primarily occur in warm and dry seasons (April-October) rather than in cold and wet seasons (November-March) though an increase in temperature (and ET_p) is expected to occur throughout the year (Capell *et al.*, 2012; Gosling, 2012). It should be noted that in this study we only considered the change in amount but not the change in intensity of precipitation which could influence the interception as well as recharge (Love *et al.*, 2010; Zhang *et al.*, 2016). Current scenarios suggest an increase in summer rainfall intensities, which could reduce interception losses that tend to be high when rainfall intensity is low (Soulsby *et al.*, 2017a). Moreover, the LC scenario was also set to a complete status by the 2050s; the transitional period from clearance of heather to maturity of Scots pine was not considered in the simulations. During this period, the quantitative effects of vegetation on soil hydrology would likely be different. Nonetheless, the results are instructive and can help with the understanding of both climate and land cover impacts on soil hydrology in the catchment and other boreal environments in the long term.

5. Conclusions

We applied the Hydrus-1D model to two representative soil-vegetation units in a boreal headwater environment to quantify the soil water balance and to investigate the potential climate change and land cover impacts. Our work showed that the role of vegetation in partitioning water is primarily mediated by interception and subsequent transpiration, which eventually results in differing summer water use and soil moisture storage, as well as the recharge to deeper soils. Transpiration and interception both are higher from Scots pine than heather shrubs. Soil water storage shows the reverse pattern, higher from heather, though differences are seasonally focused in the summer when evapotranspiration is highest. With climate projections and proposed land cover changes, the majority of changes to soil water balance are projected to occur in the growing seasons. Potential land cover changes seem to have stronger impacts than current climate change projections on local water balances at the study site. This study applies integrated field data and modelling approaches to enhance our understanding of potential land cover and climate change impacts on the soil hydrology in a boreal, humid environment, and as such provides an evidence base for policy development and land use planning to protect water supplies and ecosystem services.

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