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Research papers

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

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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.

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

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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 rainfed 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°N–85°N over the 20th 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 modelling 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 (Fig. 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).

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 metasediments. 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 (Fig. 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).