Agricultural and Forest Meteorology 197 (2014) 76–90

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Transpiration and canopy conductance of two contrasting forest types in the Lesser Himalaya of Central Nepal

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ARTICLE INFO

Article history:
Received 15 January 2014
Received in revised form 19 May 2014
Accepted 23 May 2014
Available online 29 June 2014

Keywords:
Dry season streamflow
Forest hydrology
Pine reforestation
Sap flow
Soil water
Subtropical montane forest

ABSTRACT

As part of a broader investigation of the hydrological implications of reforesting degraded pastures in the Middle Mountain Zone of Central Nepal, tree transpiration (E_t) and canopy conductance (g_c) of a natural broad-leaved forest and a mature planted pine forest were quantified using sap flow measurements and concurrent climatic and soil water observations. Estimated annual E_t totals were subsequently combined with the corresponding interception losses (E_i) to calculate annual evapotranspiration totals (ET) for the two forests. Calculated E_t was strongly dependent on atmospheric vapour pressure deficit (VPD) but much less on short-wave radiation (R_s) while there was little evidence of any limitation by soil water deficits despite a strongly seasonal rainfall regime. Both forests transpired readily throughout the dry season, except during the period of maximum leaf fall (March–April). Annual E_t by the tree stratum amounted to 163 mm and 280 mm in the natural and planted forest, respectively, representing 12.2% and 19.6% of the corresponding incident rainfall totals. Estimated annual ET (including understory and litter evaporation) values were 524 mm and 577 mm, respectively (39.3% and 40.5% of rainfall). Maximum daily estimates of canopy conductance g_c ranged from 4.85 mm s^{-1} in the natural forest to 11.46 mm s^{-1} in the planted forest and averaged 1.69 (±0.74) and 3.28 (±1.55) mm s^{-1}, respectively. A strong response of g_c to changes in VPD was detected in both forests. Combined, the higher ET of the planted forest (particularly during the dry season), plus the heavy usage of the forest by the local population and its correspondingly poor soil hydrological functioning (Ghimire et al., 2013b), are considered to be important factors in the observed decline in dry season streamflow volumes following large-scale reforestation of degraded pasture- and scrubland with pines in the region.

1. Introduction

The Himalayas have been called the 'water tower' of Asia as more than 3 billion people are estimated to depend on the combined flows of the major rivers originating in the region (Bandyopadhyay, 2013). Although recent concerns about the sustainability of streamflow amounts from the area relate primarily to the state and fate of Himalayan glaciers under a changing climate (Scherler et al., 2011; Immerzeel et al., 2013), the rivers originating in the most densely populated part of the mountain range (the Middle Mountain Zone) are mostly rain-fed (Bookhagen and Burbank, 2010; Andermann et al., 2012). Under such conditions, land surface degradation after deforestation on steep unstable slopes may rapidly progress to a point where rainfall infiltration becomes seriously impaired, with reduced replenishment of soil water and groundwater reserves – and therefore streamflow volumes during the dry season – as a result (Bartarya, 1989; Bruijnzeel and Bremmer, 1989; Tiwari et al., 2011; Tyagi et al., 2013). Partly in response to the latter, and in the hope to increase streamflow volumes again through improved infiltration after tree planting (cf. Ilstedt et al., 2007), some 23,000 ha of severely degraded pasture and shrubland in the Middle Mountain Zone of Central Nepal were planted with fast-growing coniferous tree species (mainly *Pinus roxburghii* and *P. patula*) between 1980 and 2000 (District Forest Offices, Kabhre and Sindhupalchok, Nepal, unpublished data, 2010). However, similar large-scale reforestations elsewhere in the world have been shown to have a profound negative effect on local and regional streamflow

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http://dx.doi.org/10.1016/j.agrformet.2014.05.012
0168-1923/

production because of increased evapotranspiration (ET) (Waterloo et al., 1999; Jackson et al., 2005; Scott et al., 2005). Indeed, villagers and farmers in Central Nepal have expressed serious concern about diminishing dry season streamflow following the large-scale planting of the pines (República, 2012). Water is an increasingly scarce resource in this area (Merz et al., 2003; Schreier et al., 2006), which receives about 80% of its annual rainfall during the main monsoon season (June–September; Merz, 2004). Detailed knowledge of the seasonal variation in vegetation water use and the factors affecting its regulation is, therefore, vital to understanding the impacts of reforestation on streamflow regime in this strongly seasonal environment (cf. Ghimire et al., 2013b; Krishnaswamy et al., 2013).

The magnitude of total ET in forested areas is strongly influenced by the tree transpiration component (E_t), i.e., the water lost through the stomatal pores of the leaves (Bruijnzeel, 2000). The canopy conductance (g_c) regulates the evaporative exchange between plants and the atmosphere and may respond to several environmental variables, notably the vapour pressure deficit (VPD) of the atmosphere, radiation levels, and soil water status (Meinzer et al., 1997; Kumagai et al., 2004; García-Santos et al., 2009), with wind speed exerting an influence in some cases (Chu et al., 2009).

Sapflow-based methods provide a simple, relatively inexpensive and increasingly robust means of continuous measurement of E_t from trees (Granier et al., 1996; Do and Rocheteau, 2002; Nadezhdina et al., 2002, 2012). Furthermore, measured sap flow rates have been used successfully to derive values of canopy conductance for a range of tropical and subtropical vegetation types by inverse application of the Penman–Monteith equation (e.g., Wullschleger et al., 2000; Motzer et al., 2005; García-Santos et al., 2009; Alvarado-Barrientos, 2013). The canopy conductance estimated in this way is helpful in better understanding the bulk behaviour of stomata in terms of regulating canopy-scale transpiration in response to changing environmental conditions. However, to the best of our knowledge these canopy processes have not yet been studied quantitatively in the forests of the Himalaya, although spot measurements of stomatal conductance, as well as pre-dawn and mid-day leaf water potentials for natural pine and oak forests in the Kumaun Himalaya (northwest India) have been reported by Zobel et al. (2001a,b) and for several oak species by Garkoti et al. (2000) and Tewari (2000). Similar porometer measurements for five broad-leaved species were conducted outside the monsoon season in the Middle Hills of Central Nepal by Poudyal et al. (2004) but sapflow-based techniques have not been applied in the region thus far.

The primary objective of the present study was, therefore, to examine the sapflow-based diurnal and seasonal variations of transpiration rates and canopy conductance for a natural broad-leaved montane forest (dominated by *Castanopsis tribuloides*) and a nearby mature planted coniferous forest (*P. roxburghii*) in the Middle Mountain Zone of Central Nepal. In addition, the information on dry-canopy evaporation (transpiration) is combined with the corresponding wet-canopy evaporation totals (i.e., rainfall interception) obtained for the same sites by Ghimire et al. (2012) and estimates for evaporation from the understory (where present) and the litter layer, to quantify annual ET. Finally, the implications of the present findings for the likely changes in regional dry season streamflows are discussed briefly.

2. Study area

The Middle Mountain Zone or Lesser Himalaya, which is situated between ~800 and ~2400 m above mean sea level (a.m.s.l.) and occupies about 30% of Nepal is home to ca. 45% of the country's population (based on the 2011 population census; http://cbs.gov.np/). The region is characterized by a complex geology which has resulted in equally complex topography, soil and vegetation patterns (Dobremez, 1976). The geology of the Central Nepalese Middle Mountains consists chiefly of phyllites, schists and quartzites (Stocklin and Bhattarai, 1977). Depending on elevation the climate is humid subtropical to warm-temperate and strongly seasonal with most of the rain falling between June and September. Rainfall varies with elevation and exposure to the prevailing monsoonal air masses (Merz, 2004; cf. Bookhagen and Burbank, 2006). At higher elevations (>2000 m a.m.s.l.) pines and broad-leaved trees are mixed whereas at lower elevations (<1000 m a.s.l.) the forest is dominated by deciduous *Shorea robusta*. At intermediate elevations (1000–2000 m a.m.s.l.) a largely evergreen mixed broad-leaved forest dominated by various chestnuts and oaks (*Castanopsis* spp., *Quercus* spp.) and *Schima wallichii* is found, with admixtures of *Rhododendron arboreum* above ca. 1500 m a.m.s.l. Due to the high population pressure, much of this species-rich forest has disappeared (<10% remaining), except on slopes that are too steep for agricultural activity (Dobremez, 1976; Merz, 2004).

The present study was conducted in the Jikhu Khola Catchment (JKC). The 111.4 km^2 JKC (27°35′–27°41′N; 85°32′–85°41′E) is situated approximately 45 km east of Kathmandu (the Capital of Nepal) along the Araniko Highway in the Kabhre district between 796 and 2019 m elevation (Fig. 1). The general aspect of the catchment is southeast and the topography ranges from flat valleys to steep upland slopes (Maharjan, 1991). The geology consists of sedimentary rocks affected by various degrees of metamorphism and includes phyllites, quartzites, and various schists (Nakarmi, 2000). In general, soils in the upper half of the JKC are Cambisols (FAO, 2007) of loamy texture and moderately well to rapidly drained (Maharjan, 1991).

The climate of the JKC is largely humid subtropical, grading to warm-temperate around 2000 m a.m.s.l. Mean (±SD) annual rainfall measured at mid-elevation (1560 m a.m.s.l.) for the period 1993–1998 was 1487 (±155) mm (Merz, 2004). The main seasons are the monsoon (June–September), the post-monsoon (October–November), winter (December–February), and the pre-monsoon (March–May). The rainy season (monsoon) begins in early June and ends by late September. During the monsoon about 80% of the total annual precipitation is delivered. In general, July is the wettest month with about 27% of the annual rainfall. The driest months are November to February, each accounting for about 1% of the annual rainfall (Merz, 2004). The streamflow regime as monitored at the outlet of the entire JKC (1993–2000) is also highly seasonal with a maximum specific discharge of 270 l km^{-2} s^{-1} during the monsoon season and a minimum of as little as 0.09 l km^{-2} s^{-1} during the late dry season (Merz, 2004). Average monthly temperatures measured at 1560 m a.m.s.l. range from 7.7 °C in January to 22.6 °C in June whereas average monthly relative humidity varies from 55% in March to 95% in September. Strong winds are common during thunderstorms before the onset of the main monsoon, but these are momentary and average monthly wind speeds are always less than 2 m s^{-1} with slight seasonal variation. Annual reference evapotranspiration ET_o [Allen et al., 1998] for the period 1993–2000, was 1170 mm [Merz, 2004]. Vegetation cover in the catchment consists of ~30% forest (both natural and planted), 7% shrubland and 6% pasture, with the remaining 57% largely under agriculture (Merz, 2004). The JKC was subjected to active reforestation until 2004 as part of the Nepal-Australia Forestry Project (NAFP).

Two forest plots, one in natural forest and the other in mature planted pine forest, were selected for the year-round measurement of sap flow at comparable elevations within the JKC for the current study. The natural forest plot was located on a north-west facing