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Analyzing the dynamics and inter-linkages of carbon and water fluxes in subtropical pine (*Pinus roxburghii*) ecosystem

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ABSTRACT

The carbon and water fluxes are key aspects of ecosystem functions. Their coupling processes are complicated over terrestrial ecosystems. To understand the seasonal dynamics and coupling mechanism between these fluxes in deciduous subtropical coniferous vegetation in the western Himalayas, the present study involved systematic and concurrent measurements of micrometeorological variables and ecophysiological characteristics within a uniformly distributed young pine forest ecosystem at Forest Research Institute, India. Micrometeorological data were measured continuously for a 14-month period along with key ecophysiological measurements during a growth cycle (2010–2011). These measurements allowed an examination of daytime net canopy assimilation (Cnar), evapotranspiration (ET), light use efficiency (LUE), and water use efficiency (WUE) of this coniferous ecosystem. Results showed that daily variations of ET, Cnar, LUE and WUE were strong functions of temperature and vapour pressure deficit (VPD) but within optimal limits, while these efficiency terms had a close relationship with LAI dynamics and phenology on the seasonal scale. ET being the principal component of water balance (~50% of rainfall), varied between 0.7 and 4.2 mm d^{-1} depending on LAI and seasonal cycle. It was primarily driven by evaporative demand (VPD) ($R^2 = 0.696$, $P < 0.001$) and air temperature ($R^2 = 0.92$, $P < 0.001$) in addition to radiation and PAR. Significant and stronger correlation of ET against VPD as compared to soil water content ($R^2 = 0.35$) in pine ecosystem is indicative of dominant role of stomatal control. The seasonal course of Cnar (peak in post-monsoon and minimum during winter) followed the LAI dynamics except during monsoon. The Cnar of pine varied between 1.2 and 10.5 μmol CO_2 m^{-2} s^{-1} while that of understory (*Lantana camara*) varied between 3.7 and 17.3 μmol CO_2 m^{-2} s^{-1}. Pooled data over the seasons showed significant linear relation between Cnar and ET or evaporative fraction. The degree of coupling between water and carbon exchange was strongest in the post-monsoon and spring seasons, and weaker during winter and monsoon seasons. A remarkable strong link between resource use efficiencies (WUE and LUE) was observed particularly in the dry season. This study highlights specifically the response of carbon and water exchange to environmental conditions that would help in forest management by optimizing water resource use. The optimal mix of resource use efficiencies may be the ecophysiological reason of pine ingression into higher reaches of oak forests in the western Himalaya.

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1. Introduction

Vegetation influences water, energy and carbon fluxes through ecophysiological, phenological and biophysical responses to different environmental conditions. Shifts in vegetation types lead major changes in hydrology and ecosystem functioning in the climate system that are strongly linked to the climate–ecosystem–hydrology feedbacks (Adams et al., 2009; Warren et al., 2011).

The subtropical coniferous chir pine (*Pinus roxburghii*) forests in the western Himalayan region are spread over about 18,627 km^2 and are the most dominant vegetation within the altitudinal range of 600–2000 m. This constitutes about ~6% of total forested area of India (FSI, 2011). Since the past few decades, vast areas of oak (*Qurecus leucotricophora*) forests in western Himalayan region are being replaced by chir pine within the altitudinal range of 2000–3000 m (Singh and Singh, 1992; Singh et al., 2006). This has been largely

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driven by increasing anthropogenic disturbances, increasing temperature, decreasing rainfalls (GBPIHED, 2009). Chir pine being stress tolerant, water conservative can potentially colonize the disturbed and moisture-deficient sites (Singh and Singh, 1992; Ryan and Yoder, 1997). The eco-hydrological behaviour of the two forest types is different. Pine forest ecosystem has open canopy as compared to the oak so subjected to higher surface temperature and having lower soil moisture retention capacity. In contrast, oak forest ecosystem can retain soil moisture for longer duration (Singh et al., 2006).

In the scenario of vegetation shift and changing forest surface characteristics, there is a need to study the inter-linking and dynamics of carbon–water fluxes in water conservative coniferous forests because this may have consequence on the regional eco-hydrology (Bonan, 2008; Turner and Annamalai, 2012). Additionally, with climatic change evidenced through trends in increasing temperature and decreasing rainfall, it is expected that some forests will switch from being primarily energy-limited to primarily water-limited regime (Das et al., 2013). Thus, invasion of pine into oak needs to be investigated, given that pine is majorly a species of water-limited environment. However, at the given altitudinal location (600–2000 m), pines are sustaining in energy-limited environment, with water-limited phase restricted mainly to summer (April–May) months only. Here, we characterize the annual ecophysiological behaviour of chir pine in this data-scarce region, energy-limited environment in relation to physical and biophysical controls. Moreover, after gaining insight into this coniferous ecosystem functioning, the next step should be to perform coupled micrometeorological and ecophysiological experimentation at higher reaches where pines are replacing oaks.

Earlier studies have investigated the inter-relationship between carbon uptake and water vapour loss in different ecosystems and biomes across the world (Law et al., 2002; Beer et al., 2007; Yu et al., 2008), since these processes are reciprocal and operate through stomata. Further, carbon–water relationship assumes great significance on forest ecosystem production and carbon storage through energy and water limitation phases (Goulden et al., 1997; Law et al., 2002). Thus, understanding of resource use efficiencies (light and water) of vegetation and their controls are pre-requisite in addressing carbon and water cycles in forests (Price and Black, 1990; Lamaud et al., 1996; Law et al., 2002). These efficiency terms are prime indicators in climate change research and hydrological studies, as these reflect how the carbon and water cycles are coupled and are effective integral traits for assessing the responses of vegetated systems to climate change.

The carbon fluxes such as photosynthesis, respiration and carbon stock at ecosystem level are tightly coupled to the water availability (Mu et al., 2011; Ruehra et al., 2012). Moreover, subtropical Himalayan pine ecosystem is characteristically different from evergreen pines elsewhere in the world because needles have life span of only one year. They have the lowest LAI during spring–summer (March–April) and maximum during post-monsoon (September–October). This enhances the regional spring–summer surface albedo. Thus, these ecosystems, having distinct leaf-emergence and leaf-fall seasons, may exert greater influence on regional energy balance, temperature, and climate as a whole (Singh et al., 2012). Thereby, it is imperative as well as interesting to understand the variation of carbon exchange in relation to the water availability across seasons for the deciduous pine ecosystem.

Water use efficiency (WUE), the ratio of carbon gain during plant photosynthesis to water loss, represents coupling of carbon and water cycle. It can be calculated in many ways depending on the scales and question of interest. Physiologists consider WUE as carbon assimilation and transpiration ratio at leaf-plant scale. For an agricultural scientist, it is an index of yield to the total water requirement. For the ecosystems, ecologists use the ratio of net or gross ecosystem production to the water loss (Law et al., 2002; Kuglitsch et al., 2008).

The application of eddy covariance (EC) technique has helped us better understand the diurnal variation and seasonality in the fluxes of CO_2 and H_2O and their responses to the environmental variables (Law et al., 2002). It is deployed as a network throughout the world to study the fluxes of CO_2 and H_2O over time and space. The EC technique is debatable in terms of merits and demerits (details are in Kuglitsch et al., 2008; Li et al., 2008). We applied alternative, chamber based up-scaling method, which is time consuming but quite cheaper to measure canopy level assimilation. To achieve our goal of understanding the coupling of CO_2 and H_2O fluxes, we employed combination of micrometeorological and up-scaled ecophysiological measurements for estimating evapotranspiration and canopy photosynthesis, respectively, and subsequently better interpretation of seasonal variability in water and light use efficiencies.

By looking into the importance of investigating energy and mass exchange in climatically sensitive western Himalayan subtropical pine ecosystem, we set-forth two objectives: (i) to understand the seasonal behaviour of CO_2 and H_2O exchanges in pine forest and their responses to biophysical and environmental conditions, and (ii) to analyze linkages between both the mass fluxes.

2. Materials and methods

2.1. Site description

2.1.1. Vegetation

The experimental site consists of young (8.5 years old) chir pine plantation patch (400 m × 500 m) within the reserve forest at the Forest Research Institute campus, Dehradun, India (30°20′4″ N, 78°00′01″ E, elevation: 640 m). The present mean height of the young pine is ~6.5 m, which is increasing at ~1.0 m $year^{-1}$. Mean DBH (diameter at breast height) is ~13.8 cm, is increasing at ~1.0 cm $year^{-1}$. Average crown (cone shaped) height is 3.9 m, expanding at ~0.33 m $year^{-1}$. The average rooting depth is about 3.0 m. The dominant understory, the *Lantana camara* (Verbenaceae) is an invasive species. To favour the growth of young chir pines, the *Lantana* bushes are usually cleared in the post-monsoon period (October–November). However, for understanding and comparing the effects of understory on ecosystem-water use efficiency, the understory *Lantana* was not cleared in the year 2011.

2.1.2. Climate and soil

The research site occurs in the subtropical coniferous vegetation type according to Champion and Seth (1968). Based on long-term meteorological data (1940–2010), the mean monthly air temperature varies between 11.5 °C (January) and 27 °C (June). The mean monthly relative humidity ranges from 52% (April) to 85% (August). The mean annual rainfall is ~2020 mm and July to September is the monsoon season. Maximum rainfall occurs in August (~570 mm) and minimum in November (~4.0 mm). The sunshine hour varies from 4.4 h day^{-1} to 9.3 h day^{-1} with a minimum during July–August and maximum during May. The mean monthly open pan evaporation varies from 1.2 mm to 7.2 mm with the lowest during December and the highest during May.

The soil is deeply weathered Mollisols, 3–8 m in thickness. Soil is nutrient rich with a porosity range of 40–60% having pH in acidic range (4.5–6.0). The texture is sandy clay loam with 35% sand, 40% clay and 25% silt. The bulk density is ~1.03 g cm^{-3} (1030 kg m^{-3}). The soil water content (SWC) of the site ranges from 10% in peak summer days to above 24% during rainy season (mean of three-soil layer: 0.05, 0.2 and 0.45 m). The soil moisture tensiometers

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