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RESEARCH

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Impact of monsoon season rainfall spells on the ecosystem carbon exchanges of Himalayan Chir-Pine and Banj-Oak-dominated forests: a comparative assessment

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Abstract The Chir-Pine (*Pinus roxburghii*) and Banj-Oak (*Quercus leucotrichophora*)-dominated ecosystems of central Himalaya provide significant green services. However, responses of these ecosystems, with respect to ecosystem carbon flux variability, to changing microclimate are not yet studied. Since quantification of ecosystem responses to fluctuation in the microclimate, particularly rainfall, is expected to be beneficial for management of these ecosystems, this study aims (i) to quantify and compare amplitude of rainfall-induced change in the carbon fluxes of Chir-Pine and Banj-Oak-dominated ecosystems using wavelet methods, and (ii) to quantify and compare dissimilarities in the ecosystem exchanges due to varying rainfall spell and amount. Eddy covariance–based continuous daily micrometeorological and flux data, during the 2016–2017 monsoon seasons (total 244 days, 122 days of June–September), from two sites in Uttarakhand, India, are used for this purpose. We find that both Chir-Pine and Banj-Oak-dominated ecosystems are the sinks of carbon, and Chir-Pine-dominated ecosystem sequesters around 1.8 times higher carbon than the Banj-Oak. A systematic enhancement in the carbon assimilation of the Chir-Pine-dominated ecosystem is noted with increasing rainfall spell following a statistically significant power-law relationship. We have also identified a rainfall amount threshold for Chir-Pine and Banj-Oak-dominated ecosystems (10 ± 0.7 and 17 ± 1.2 mm, respectively) that resulted in highest ecosystem carbon assimilation in monsoon. The general inference of this study accentuates that

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Banj-Oak-dominated ecosystem is more sensitive to maximum rain within a spell whereas the Chir-Pine-dominated ecosystem is more responsive to increasing rainfall spell duration.

Keywords Ecosystem carbon flux · Himalaya · *Pinus roxburghii* and *Quercus leucotrichophora* · Rainfall

Introduction

The two dominant mid-elevation tree species of the central Himalaya are early succession, coniferous Chir-Pine (*Pinus roxburghii* Sarg.) and late succession, evergreen broad-leaf Banj-Oak (*Quercus leucotrichophora* A. Camus) which form pure and mixed forest patches. These two tree species are having differences in their anatomy and leaf structure (i.e. needle and broad-leaf), provide substantial ecosystem services to the region, and represent a significant forest cover with unique ecosystems (Joshi & Negi, 2011). Having different characteristics and ecosystem services, *P. roxburghii* forests generally occur at elevations of 900–2200 m above mean sea level and naturally found on the driest and rockiest slopes, and have spread greatly under the influence of cutting and burning (Rawat et al., 2011). On the other side, *Q. leucotrichophora* forests of the central Himalaya are generally found between elevations of 1000 and 2500 m above mean sea level (Rawat & Singh, 1988). Banj-Oak forests are also important to the subsistence agricultural economy of the hill people (Singh & Singh, 1987). In the Uttarakhand state of India, around 5.24% (1284 km^2) of the total forest area is occupied by the Banj-Oak (Oak Spp.) (Dhyani et al., 2020); whereas 16% is occupied by Chir-Pine (Pine Spp.) (Rawat et al., 2011). Since *P. roxburghii* and *Q. leucotrichophora*–dominated ecosystems are highly responsive to microclimate, particularly with respect to temperature and rainfall (Singh & Singh, 1987), and the central Himalayan region is significantly experiencing climate and anthropogenic changes, quantification of physiological and ecosystem changes of these dominant forest types to microclimatic fluctuations are of paramount importance. Moreover, a comprehensive knowledge of these forest-ecosystem functioning as a response to changes in the microclimate is necessary to frame forest adaptive measures and conservation policies.

Long-term changes in air temperature and rainfall can be responsible for vegetation migration and changes in phenology (Huntely, 1991). Under the changing climate of the western and central Himalayan region (Ballav et al., 2021; Mukherjee, 2021; Mukherjee et al., 2015, 2019), the forest ecosystems are also expected to respond heterogeneously, and it is now being reported that different vegetations of the Himalayan region are strongly responding to these climatic fluctuations and changes (Schickhoff et al., 2016). Concurrent temperature and herbarium data have confirmed the advancement of flowering in the *Rhododendron arboreum* by 88–97 days over the last 100 years due to warming in the Himalayas (Gaira et al., 2014). Similarly, the impact of temperature rise to Himalayan vegetations was analyzed using numerical models, and advancement in the flowering time for western Himalayan alpine/sub-alpine species of *Arnebia benthamii*, *Meconopsis aculeata*, and *Podophyllum hexandrum* and temperate species of *Delphinium denudatum* and *Dioscorea deltoidea* was noted, while delayed flowering was noted for *Swertia cordata* (Gaira & Dhar, 2020).

Sub-daily to annual timescale fluctuation in the rainfall is also known to largely modulate carbon assimilation of grassland and forested ecosystems. Recently, Thompson et al. (2020) have shown that the severe drought of 2018 in Europe has substantially modulated the net ecosystem exchange. The rainfall variability is also known to affect the phenology of ecosystems (Ni et al., 2016); and studies conducted by Huxman et al. (2004), Hao et al., (2013, 2017), and Yuhui et al. (2018) established that rainfall amount and spell can significantly modulate the exchanges of carbon and water. Small amount of precipitation is also widely reported to increase heterotrophic respiration resulting loss of carbon from various ecosystems (Parton et al., 2012; Reynolds et al., 2004). However, most of the above-mentioned assessments of the impact of sub-daily to annual timescale fluctuation in the rainfall to ecosystem fluxes are carried out for the grassland ecosystems outside the Indian Himalayas; hence, almost no such assessments are available for the major forest and vegetation types of Himalaya. Although it is being reported that the canopy-atmosphere decoupling coefficient is highest for the *P. roxburghii*–dominated forest of Himalaya during the monsoon period due to high surface conductance, when compared to the deciduous broad-leaf forest of Kaziranga National Park (Deb Burman et al., 2021), the impact of alteration in the atmospheric parameters, particularly changes in the rainfall spell and amount to atmosphere-biosphere exchanges of the *P. roxburghii* and *Q. leucotrichophora*–dominated ecosystems, are not known. An in-depth knowledge of these forest responses to changes in the rainfall spell and amount is expected to be highly beneficial for the conservation of these ecosystems under warming scenarios.

In order to address the above mentioned knowledge gaps, this study particularly aims to quantify changes in the ecosystem carbon exchanges as a response to changing rainfall spell and amount during monsoon season for the *P.roxburghii* and *Q. leucotrichophora*–dominated ecosystems of central Himalaya. Therefore, specific objectives addressed in this study are twofold, i.e., (i) to quantify and compare the amplitude of rainfall triggering the highest variation in the ecosystem carbon fluxes of the *P. roxburghii* and *Q. leucotrichophora*–dominated ecosystems using daily average net ecosystem exchange (NEE), gross primary productivity (GPP), terrestrial ecosystem respiration (RE), and daily total rainfall. The second objective is (ii) to quantify dissimilarities in the NEE of the *P. roxburghii* and *Q. leucotrichophora*–dominated ecosystems due to varying rainfall spells and amounts. Subsequently, efforts are made to identify the optimum time duration resulting in the highest carbon assimilation by the *P. roxburghii* and *Q. leucotrichophora*–dominated ecosystems after a maximum rainfall event within a rainfall spell. The objectives of this study are addressed using the modified methodologies of Sun et al. (2017), Tang et al. (2018), Yuhui et al. (2018), and Hao et al. (2020). It is also to emphasize that no effort is made in this study to identify the relative role of any other meteorological variables controlling biosphere–atmosphere interactions. Moreover, there is no replication of eddy covariance measurements as each forest patch considered in this study has a dedicated flux tower. Furthermore, the impact of elevation difference on measured NEE was not evaluated in this study. Our emphasis to rainfall-induced ecosystem carbon flux variability during monsoon is attributed to the locations of the ecosystems in the Himalayan terrain which, like most of the central Indian forests, experience more than 70% of the annual rainfall during the monsoon period (June–September) resulting in vegetative growth. In actuality, the quantification of physiological responses of an ecosystem under naturally varying meteorological conditions is multidimensional in nature and nontrivial, but efforts are made to quantify only the role of rainfall modulating responses of the *P. roxburghii* and *Q. leucotrichophora*–dominated ecosystems in terms of carbon flux variability under the assumption that both ecosystems are dominant over relatively water-limiting conditions, and rainfall is the most important factor that stimulates growth.

Site, instrumentation, and data

Flux tower location and instrumentation

The rainfall and ecosystem flux data were collected from two sites of central Indian Himalaya having Chir-Pine (*P. roxburghii*, hereafter Chir-Pine site) and Banj-Oak (*Q. leucotrichophora*, hereafter Banj-Oak site) as the dominant tree species (Fig. 1). The first field station was dominated by *P. roxburghii* with average tree age of 20–25 years. Flux and meteorological data from the Chir-Pine site were collected using a 32-m instrumented eddy covariance flux tower situated at Kosi-Katarmal, Almora, India (29.38° N, 79.37° E), at an elevation of 1217 m above mean sea level. The average canopy height of the surrounding vegetation was 12–15 m. The flux measurements were carried out at 30 m above ground using 10 Hz high-frequency sensors (CSAT3 and EC110/150, Campbell Sci, USA) along with net radiation sensors (CNR-4, Kipp and Zonnen, Netherlands), and raingauge (TE525, Campbell Sci, USA). Subsequently, 30-min runs of CO_2/H_2O flux, 3-D wind, and sonic temperature were stored for further processing. The site had similar roughness length signature for the monsoon and winter periods due to the Chir-Pine-dominated mixed vegetation (Lohani & Mukherjee, 2021).

The second field station was dominated by *Q. leucotrichophora* with a dense canopy throughout the year with average tree age of 20–30 years and an average canopy height of 8.0 m. The co-dominant species

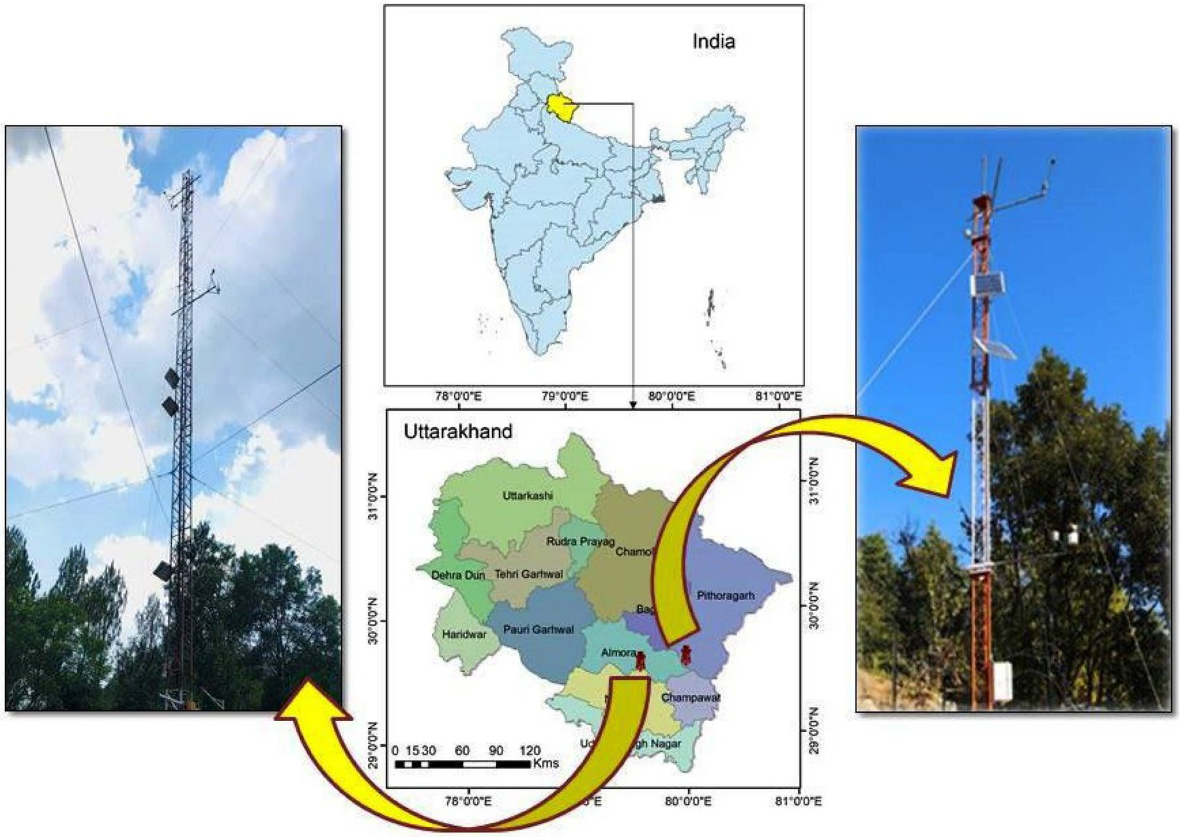


Fig. 1 Locations of the eddy covariance towers over Chir-Pine (left) and Banj-Oak (right)-dominated ecosystems

surrounding the site was *Cedrus deodara*. The flux and meteorological data were collected using a 10-m instrumented flux tower. The site was situated in Gangolihat block, Pithoragarh, Uttarakhand, India (80.02° E, 29.39° N), at an elevation of 1650 m above mean sea level. The study site is located under the Kali river watershed in India with 54.5% of the total area having forest cover. Out of the 54.5% of forests, around 38.4% area had *Q.leucotrichophora* trees in dominance (Joshi et al., 2019, 2020). A 3-D sonic anemometer (CSAT3, Campbell Sci, USA) along with an infrared CO_2/H_2O gas analyzer (EC150/110, Campbell Sci, USA), installed at 10 m height having a frequency of 10 Hz, was used to measure 3-D wind vectors, gas flux, sonic temperature, air temperature, and relative humidity. Furthermore, a net radiation sensor (NR Lite, Kipp and Zonnen, Netherlands) and a raingauge (TE525, Campbell Sci, USA) was also mounted at 10 m height measuring at 30-min interval.

For both Chir-Pine and Banj-Oak sites, flux measurements were carried out within the constant flux layers of atmospheric boundary layers. The convective boundary layer flux footprint analysis for the Chir-Pine site indicated the maximum distance of 90% fluxes was 443 m (Mukherjee et al., 2021), whereas the same for the Banj-Oak site was 179.9 m.

In order to identify the plant composition around the flux towers, a phytosociological survey was conducted. Quadrats of 10×10 m for trees and 5×5 m for shrubs were laid to record the number of individuals, circumference at breast height (CBH), etc. as per the standard ecological methodology (Misra, 1968; Muller-Dombois and Ellenberg, 1974). For the Chir-Pine site, a total of 11 tree species were recorded in which *Pinus roxburghii* was dominated having 893 ind/ha^{-1}, whereas *Quercus leucotrichophora* was found as co-dominant species with 166 ind/ha^{-1}. Apart from *Pinus* and *Quercus*, other species like *Populus ciliata* (40 ind/ha^{-1}), *Celtis australis* (33.33 ind/ha^{-1}), *Prunus cerasoides* (13.33 ind/ha^{-1}), *Melia azedarach* (13.33 ind/ha^{-1}), *Toona ciliata* (13.33 ind/ha^{-1}), *Grevillea robusta* (6.6 ind/ha^{-1}), *Morus alba* (6.66 ind/ha^{-1}), *Pyrus pashia* (6.6 ind/ha^{-1}), and *Quercus glauca* (6.66 ind/ha^{-1}) were also recorded around the site. High species richness was recorded in the Chir-Pine site as the site is situated in the GBPNIHE, Almora, campus and the area is generally protected from forest fire and other destructive activities. The total basal area (TBA) recorded for the Chir-Pine site was 48.59 m^2/ha^{-1}, among which *Pinus roxburghii* contributed 44.49 m^2/ha^{-1} and the *Quercus leucotrichophora with* 1.29 m^2/ha^{-1}. Similarly, for the Banj-Oak site, a total of 3 trees were recorded out of which *Quercus leucotrichophora* was found to be the dominant species with 660 ind/ha^{-1} whereas *Prunus cerrasoides* was found to be co-dominant species with 40 ind/ha^{-1}. Additionally, *Cedurs deodara* was also recorded with a density of 20 ind/ha^{-1}. The total basal area (TBA) of the Banj-Oak site was recorded as 36.85 m^2/ha^{-1}, among which the *Quercus leucotrichophora* contributed 34.37 m^2/ha^{-1}, and *Cedrus deodara contributed* 1.26 m^2/ha^{-1}. The understory species i.e. shrub density was recorded maximum in the Banj-Oak site (1440 ind/ ha^{-1}) in comparison to the Chir-Pine site (906 ind/ ha^{-1}) as generally Chir-Pine vegetation has less underground vegetation, especially the shrub (Joshi et al., 2022). *Berberis asiatica* was dominated in Chir-Pine site with a density of 306 ind/ha^{-1}, whereas *Pyracantha crenulata* dominated in Banj-Oak site with a density of 640 ind/ha^{-1}. It can be concluded from the phytosociology survey that both sites do not have fairly pure stands, hence, can be called Chir-Pine and Banj-Oak-dominated forests.

Flux data processing

The Chir-Pine and Banj-Oak site data presented in this study were considered only for monsoon seasons of 2016–2017, i.e., for the period of 00:00 h of 1 June 2016 to 23:30 h 30 Sep 2016 and 00:00 h of 1 June 2017 to 23:30 h 30 Sep 2017. Therefore, a total of 244 days of data were used. The rationale for considering the monsoon season is twofold; (i) both the study sites received around 70% of the total annual rainfall during monsoon, and (ii) both Chir-Pine and Banj-Oak-dominated ecosystems had the highest growth during the monsoon. The 10 Hz raw data quality assessment for both sites was performed using the EddyPro software (v6.0, LiCor-Bioscience, USA) and following similar approaches presented in Mukherjee et al., (2018, 2020), Lohani and Mukherjee (2021), and Deb Burman et al. (2021). However, a brief description of the quality assessment procedures used in the flux data is provided here. The general quality check assessments were made as per Vickers and Mahrt (1997); the sonic temperature corrections were made following Schotanus et al. (1983); the WPL corrections were made following Webb et al. (1980); the low and high-pass filtering was made using Moncrieff et al., (1997, 2004); the tilt correction was made using Wilczak et al. (2001). Additionally, displacement height was computed using the average canopy height at both sites and following the numerical model of Foken and Nappo (2008).

Moreover, spikes in the data were detected and removed as per Papale et al. (2006), and data gaps were filled using methods of Reichstein et al. (2005) and REddyPro (v 1.1.5). The flux partitioning of NEE into GPP and RE was carried out using Lasslop et al.'s (2010) model. Since the ecosystem carbon exchanges are to be quantified with respect to rainfall spell and amount, and it is being reported that the high-frequency CO_2/H_2O sensors and sonic anemometers often fail to record actual 3-D wind and flux values (Zhang et al., 2016), only those 30-min values were considered in this study wherein both 30-min rainfall and flux values were available with no flag for poor data quality. Finally, daily averages of NEE, GPP, and RE were computed for the observation period of 244 days for the Chir-Pine and Banj-Oak sites, where a negative NEE implies carbon assimilation by an ecosystem.

Methods

Quantification of the Amplitude of Rainfall and Ecosystem Exchange

To quantify the amplitude of rainfall, triggering the highest change in the ecosystem fluxes, temporal variability of the daily total rainfall and NEE, GPP, and RE was investigated using wavelet spectra. Initially, the continuous wavelet spectra of NEE, GPP, and RE were produced for Chir-Pine and Banj-Oak systems as they provide information in the frequency domain having many overlapping time scales (Domingues et al., 2005; Grinsted et al., 2004; Salmond, 2005; Torrence & Compo, 1998). Furthermore, cross-wavelet spectra between rainfall and NEE, GPP, and RE were produced for Chir-Pine and Banj-Oak ecosystems and compared. The rationale for using the cross-wavelet spectra was to compare phase relationships and local correlations between the ecosystem fluxes and rainfall during the monsoon period. A brief description of the wavelet spectral method used in this study could be found in Mukherjee et al. (2018) with a description of the axes and color used in the scalograms.

Quantification of the impact of rainfall spell on net ecosystem exchanges

Since it has been established for many ecosystems that rainfall spell and amount within a season can significantly modulate the exchanges of carbon and water (Hao et al., 2013, 2017; Huxman et al., 2004; Potts et al., 2006), responses of the *P. roxburghii* and *Q. leucotrichophora*–dominated ecosystems with respect to varying rainfall spells were quantified by analyzing changes only in NEE. As indicated earlier, the maximum growth of Chir-Pine and Banj-Oak-dominated ecosystems of Himalaya is observed around the wet monsoon season (June–September) of a year (Singh & Singh, 1987); hence, the impact of rainfall spell on the ecosystem exchanges was quantified only for the monsoon season.

The impact of rainfall spells on NEE was estimated based on the successive rainfall events where "0-day" and "rainfall event + 01-day" had no rainfall. Consequently, successive rainy days of a monsoon season were considered up to 10 days from 0 day of initiation where 0 day and 11 days implied no rain (length of rainfall spell, hereafter). The analysis was carried out till 10 days from the 0th day of rainfall initiation due to the fact that the maximum successive rainy day for both the monsoon seasons of 2016–2017 was 10 days for the Chir-Pine site and 9 days for the Banj-Oak site. The analysis steps were as follows:

- Counted rainy days (i.e., any day having rainfall greater than 0 mm) of monsoon season based on the length of rainfall spell (continuous rainfall spell up to 10 days from 0 day of initiation), i.e., counted all those days having 1-day, 2-day, 3-day,…, 10-day continuous rainfall.
- The 0-day and rainfall event + 01-day of counting initiation was represented with no rainfall. For example, a 1-day spell indicated no rain on 0 day and 2 day.
- Seasonal total rainfall of all such rainfall spells (1–10 days) was counted for 2016–2017. Subsequently, the average rainfall amount and NEE (for both Chir-Pine and Banj-Oak ecosystems) were computed for all such rainfall spells of 2016–2017.

A scatter diagram of the average NEE and associated length of rainfall spells was produced to identify the impact of rainfall spells on carbon assimilation by each ecosystem. Consequently, the average NEE was modeled with a rainfall spell using a power-law equation: $NEE = aS^b$, where S is the spell duration and a and b are the constants for optimization. A nonlinear least square curve fitting method that uses a "trust-region-reflective" algorithm (Coleman & Li, 1996) was used to find the actual values of a and b. The curve fitting method was initiated with the set input of [1 1]. The final coefficients were then used to construct the model $NEE = aS^b$ and correlation coefficients (CC) were computed at a p-value < 0.005.

Quantification of the impact of rainfall amount on the net ecosystem exchanges

It is reported by Yuhui et al. (2018) that the amount of precipitation within a rainfall spell can also be a significant stimulator of ecosystem growth. Subsequently, two approaches were opted to evaluate the impact of rainfall amount on the carbon assimilation by the ecosystems of this study. In the first approach, an effort was made to assess the impact of maximum rainfall within a rainfall spell on carbon assimilation. Subsequently, the following steps were adopted:

- Identification of maximum rainfall within a length of rainfall spell was initiated from a 2-day rainfall spell. It was assumed that the maximum rainfall amount was observed within a rainfall spell at the r_d day.

- To check the impact of the maximum rainfall of a spell on the NEE of subsequent days, prepared an array of all the NEE values during r_d, r_d+1, r_d+2, and r_d+3 days of each rainfall spell duration.
- Next, to find the duration of the highest carbon assimilation by each ecosystem after a maximum rainfall within a spell, irrespective of spell duration, box plots of all the NEEs were produced for each r_d, r_d+1, r_d+2, and r_d+3 days.

Finally, the boxplots were used to identify the highest carbon assimilation by an ecosystem after the maximum rainfall irrespective of rainfall spells. In the second approach, the impact of rainfall amount on carbon assimilation was estimated by quantifying the rainfall threshold that had resulted maximum carbon assimilation for Chir-Pine and Banj-Oak-dominated ecosystems, respectively. However, only successive rainfall events up to 5-day rainfall were considered for the analysis under the assumption that a rainfall spell greater than 5 days is generally categorized as a "heavy rainfall spell" (Qing et al., 2015 and Tang et al., 2018). The analysis was carried out as per the following steps:

- Selected rainy days (i.e., any day having rainfall greater than 0 mm) of monsoon season based on continuous rainfall spell up to 5 days from 0 day of initiation, i.e., counted all those days having 1-day, 2-day, 3-day, 5-day continuous rainfall.
- The average rainfall of all such rainfall spells (1 to 5 days) was computed for 2016–2017. Subsequently, the average NEE for both Chir-Pine and Banj-Oak-dominated ecosystems was computed for all such rainfall spells of 2016–2017.
- A scatter diagram of the average NEE and associated rainfall amount, irrespective of the rainfall spell, was produced to identify the rainfall amount that has resulted the highest carbon assimilation by each ecosystem.

Finally, to model the rainfall amount with NEE, a quadratic equation (i.e., $\mathrm{NEE}=aR_m^{\ 2}+bR_m+c$, where R_m is the rainfall amount) was fitted to each scatter plot, and the *Y*-axis minimum of each plot was identified as the optimum rainfall amount resulting in highest carbon assimilation. The quadratic equation model was also evaluated with respect to observations, and r^2 values were computed.

Results and discussions

Background surface meteorological conditions

Surface meteorological and boundary layer conditions of the Chir-Pine site are already discussed in detail by Mukherjee et al., (2018, 2021, Lohani and Mukherjee (2021) and Deb Burman et al. (2021). However, a comparison of meteorological characteristics during monsoon, particularly air temperature, relative humidity, wind speed, net radiation, and rainfall, observed over the Chir-Pine and Banj-Oak sites is provided in Fig. 2 for comprehension of similarities in the background conditions. The averages of air temperature during the monsoon over Chir-Pine and Banj-Oak sites were 23.09 ($\pm$0.03) and 21.9 ($\pm$0.02) °C, respectively, in 2016, and 22.18 ($\pm$0.05) and 19.7 ($\pm$0.03) °C, respectively, in 2017, where values in parentheses are standard errors. The marginally lower minimum temperature at the Banj-Oak site corroborates well with the earlier observation of Singh and Singh (1986), who also reported Banj-Oak ecosystems of Uttarakhand, India, to be found where temperature lies between −6.7 and 35 °C. The monsoon season average relative humidity at Chir-Pine (66.7$\pm$0.11%) and Banj-Oak (66.4$\pm$0.15%) sites were comparable and no year-to-year significant variation was observed. Although both sites are having almost the same humidity conditions, in general, Banj-Oak is an evergreen broad-leaf species having a closed canopy and a small amount of radiation reaches the forest floor. Therefore, it retains moisture throughout the year and generally has higher microbial activities.

The average wind speeds for the monsoon seasons were 0.96 ($\pm$0.005) $\mathrm{ms^{-1}}$ and 0.79 ($\pm$0.007) $\mathrm{ms^{-1}}$ over Chir-Pine and Banj-Oak sites, respectively. The average wind statistics at Chir-Pine and Banj-Oak sites were similar and no significant variation was observed between the years.

Similarly, the averages of net radiation for the Chir-Pine site were 280.3 and 259.5 $\mathrm{Wm^{-2}}$ during 2016–2017, whereas the same for the Banj-Oak site

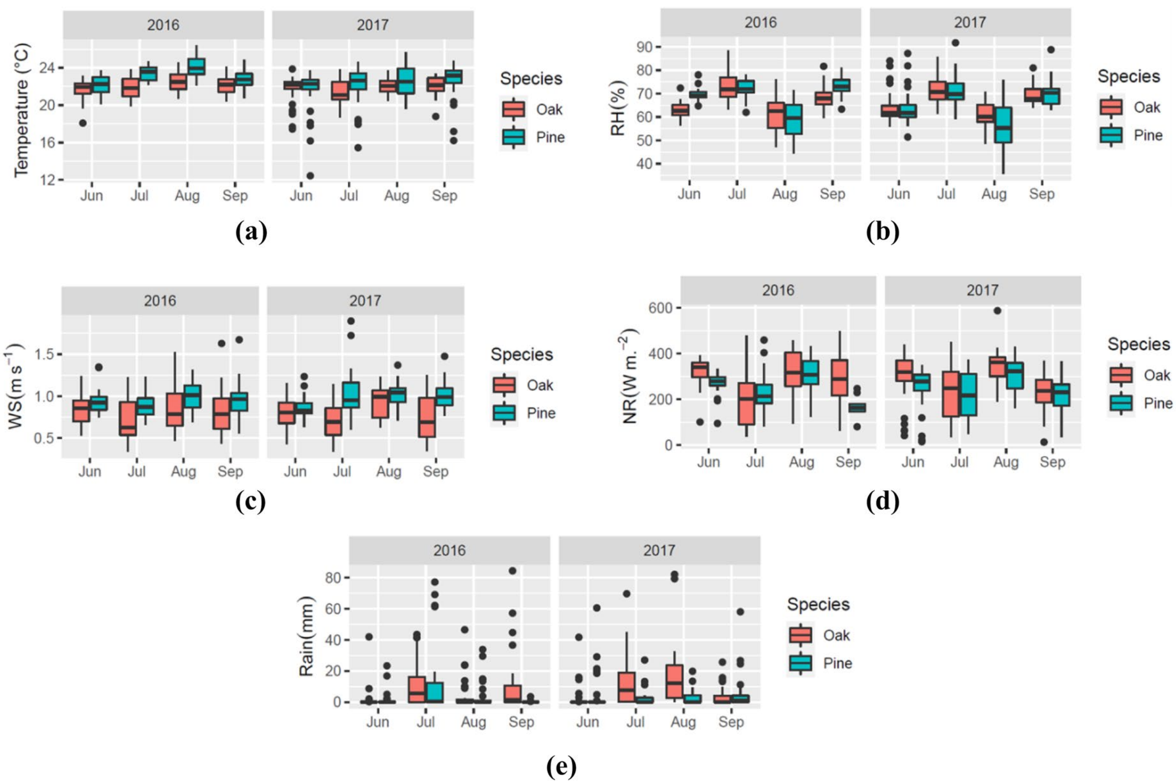


Fig. 2 Monthly variations of **a** air temperature, **b** relative humidity, **c** wind speed, **d** net radiation, and **e** total rainfall are presented for monsoon season of 2016 and 2017, respectively

were 260.4 and 246.5 Wm^{-2}, respectively. The general comparison of air temperature, relative humidity, wind speed, and net radiation between the Chir-Pine and Banj-Oak sites did not show substantial differences. Subsequently, long-term changes in the air temperature are responsible for phenological earliness (Menzel, 2003; Parmesan & Yohe, 2003), even in the Himalayas (Khanduri et al., 2008; Shrestha et al., 2012). Since no significant change in the surface air temperature, relative humidity, and net radiation was observed for both sites, it could be inferred that the general climatological responses of both ecosystems did not change substantially during the monsoon period of 2016–2017 except for the changes triggered by rainfall fluctuations.

The monsoon season total rainfall at the Chir-Pine site was 545 and 489 mm during 2016–2017, whereas, the same for the Banj-Oak site was 874 and 944.3 mm, respectively, indicating that the Banj-Oak-dominated ecosystem had received higher rainfall in the monsoon months than the Chir-Pine-dominated ecosystem. The characteristic features of the monsoon rainfall events, that is, rainfall spell and amount distributions, are provided in Table 1. It was noted that, except for the 1-day rainfall spell (06 for Chir-Pine and 17 for Banj-Oak site in 2016–2017), where 0 day indicates no rain, there was no significant difference in the rainfall spell counts of Chir-Pine and Banj-Oak ecosystems. However, the rainfall amount associated to each rainfall spell for the Banj-Oak site was always higher for each spell, except for the 9-day spell. Hence, it could be inferred that the Banj-Oak site had a more systematic supply of water through regular rainfall than the Chir-Pine site. These characteristic features of monsoon rainfall were further used to quantify ecosystem exchanges for both Chir-Pine and Banj-Oak-dominated ecosystems.

Table 1 The numbers of rainfall spell associated with mean rainfall amount (mm) and standard error (mm) are represented for monsoon season of 2016–2017. The 0-day and rainfall event + 01-day of each spell indicate no rain where s. e. is standard error

System	Spell (mean ± s. e.)									
	1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days	10 days
Chir-Pine	6 (4.8 ± 1.5)	9 (6.1 ± 0.5)	5 (5.9 ± 0.6)	4 (14.4 ± 1.3)	4 (10.0 ± 0.7)	–	1 (7.1 ± 1.3)	–	1 (19.7 ± 3.2)	1 (5.5 ± 0.6)
Banj-Oak	17 (10.5 ± 0.78)	10 (10.9 ± 0.6)	5 (7.6 ± 0.70)	3 (16.9 ± 1.2)	2 (23.3 ± 2.7)	2 (6.8 ± 0.51)	–	2 (20.8 ± 1.23)	1 (30.4 ± 3.3)	–

Spectral properties of ecosystem fluxes

The ecosystem-atmosphere CO_2 exchange for the Chir-Pine site is already reported and elaborated in detail by Mukherjee et al. (2018) and Deb Burman et al. (2021) using NEE, GPP, and RE data from 2014–2016. Hence, this section is focused on presenting the comparative assessment of fluxes from both sites and their daily to seasonal scale changes. Subsequently, to quantify the amplitude of rainfall triggering the highest change in the ecosystem fluxes, temporal variability of the daily total rainfall and NEE, GPP, and RE was investigated using wavelet spectra emphasizing the monsoon period.

The monthly values of NEE, GPP, and RE for Chir-Pine and Banj-Oak sites were compared and presented in Fig. 3. We found that both Chir-Pine and Banj-Oak-dominated ecosystems were sinks of carbon during monsoon season as the average NEE for the period of observations (2016–17) was − 4.44 (± 0.15) gC m^{-2} day^{-1} and − 4.54 (± 0.17) gC m^{-2} day^{-1} for the Chir-Pine-dominated ecosystem. The same for the Banj-Oak-dominated ecosystem was found to be − 2.41 (± 0.16) gC m^{-2} day^{-1} and − 3.01 (± 0.15) gC m^{-2} day^{-1}, respectively, for 2016–2017.

Similarly, the monsoon season average GPP values of 2016–2017 for the Chir-Pine-dominated ecosystem were 12.3 (± 0.001) gC m^{-2} day^{-1} and 11.9 (± 0.001) gC m^{-2} day^{-1}. The same for the Banj-Oak-dominated ecosystem were 12.3 (± 0.03) gC m^{-2} day^{-1} and 11.7 (± 0.0017) gC m^{-2} day^{-1}), respectively. Values in parentheses are standard errors. When the RE values were compared, we found that the average RE of the Banj-Oak-dominated ecosystem during the monsoon of 2016 was 3.90 (± 0.02) gC m^{-2} day^{-1}, almost 2.0 times higher than the Chir-Pine-dominated ecosystem, i.e., 1.59 (± 0.01) gC m^{-2} day^{-1} which changed to 4.53 (± 0.04) gC m^{-2} day^{-1} and 1.88 (± 0.17) gC m^{-2} day^{-1} in 2017. The low RE value of the Chir-Pine-dominated ecosystem can be attributed to the rather acidic nature of topsoil having a relatively smaller thickness under the Chir-Pine stands of Himalaya restricting the microbial activity. Such low total respiration from the acidic soils of *P. roxburghii* vegetations of Himalaya is already reported by Joshi et al. (1991), indicating top soil under *P. roxburghii* stand respired 10.8–55.2 gC m^{-2} $day^{-1}$with a pH of 5.7. Moreover, several factors including high lignin content of litter, excessive burning, litter removal,

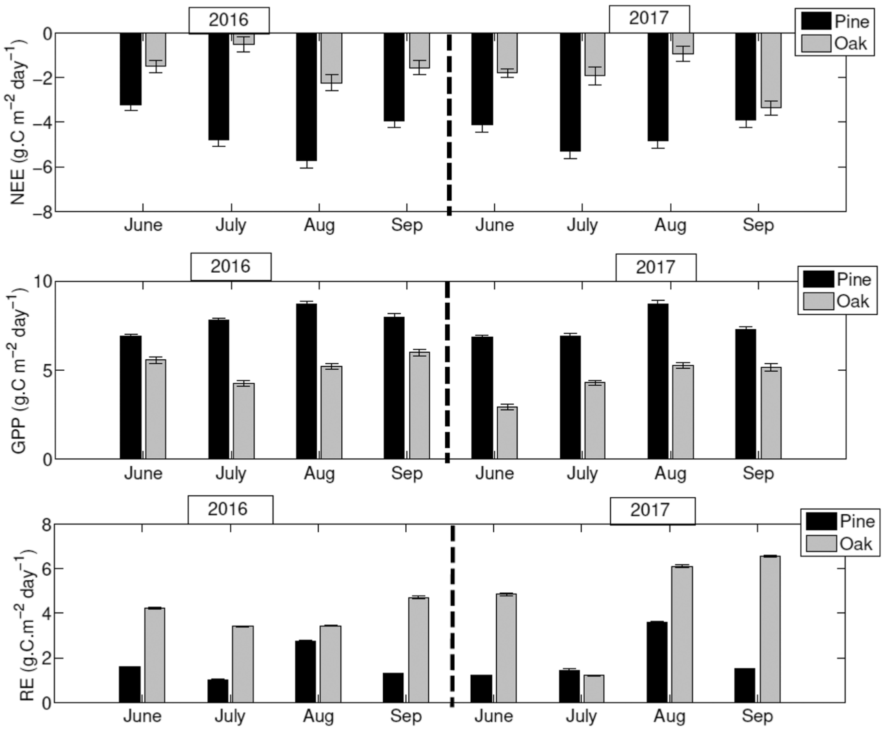


Fig. 3 Monthly variation of **a** NEE, **b** GPP, and **c** RE for the monsoon seasons. The vertical lines are standard errors

and low soil moisture could be responsible for lower microbial activities under *P.roxburghii* stands. The higher RE values of the Banj-Oak-dominated ecosystem could be attributed to higher leaf-litter-assisted microbial activities. A recent study by Rawat et al. (2020) has further estimated the soil respiration of Himalayan *Q. leucotrichophora*–dominated forests and reported range of RE between 0 and 10.36 gC m^{-2} day^{-1} that largely depends on the availability of soil organic carbon. Hence, it could be inferred that the Chir-Pine-dominated ecosystem sequestered almost 1.8 times higher carbon than the evergreen broad-leaf Banj-Oak-dominated ecosystem of Himalaya due to lesser ecosystem respiration. Furthermore, the average NEE values of the Chir-Pine-dominated ecosystem were found to be 1.3 times higher than the NEE of a mixed forest (particularly, *Holoptelea integrifolia*, *Dalbergia sissoo*, *Acacia catechu*, and *Albizia procera*) at the Himalayan foothill of Uttarakhand, India, (NEE = −3.24 gC m^{-2} day^{-1}), as reported by Watham et al. (2014). The GPP values of Chir-Pine and Banj-Oak-dominated ecosystems of this study were also relatively higher than that of temperate coniferous forests (GPP = 5.7–6.84 gC m^{-2} day^{-1}) as reported by Falge et al. (2002). The increased carbon uptake during monsoon season by the Chir-Pine-dominated ecosystem could be due to the prevalent drier condition and subsequent faster response of the system through photosynthesis due to rainfall-induced increase in the moisture condition. Moreover, the enhanced carbon uptake by the Chir-Pine-dominated ecosystem of this study could be linked to earlier observations of Shin et al. (2020) who reported that due to the higher canopy height of the needle-leaf trees, the absorbance of direct and diffuse radiation is higher compared to trees having moderate canopy height hence resulted in accelerated growth.

In order to quantify the amplitude of rainfall triggering the highest change in the ecosystem fluxes, the continuous wavelet spectra of NEE, GPP, and RE were produced using 2016–2017 daily values of monsoon season and are provided in Fig. 4a and b. It can be clearly observed from the wavelet spectra of NEE that compressed high-frequency variations having smaller scales (2–4 scales) were present in the Chir-Pine-dominated ecosystem, which signified abrupt changes in the NEE for the system, whereas stretched wavelets with larger scale (4–8 scales) variation of NEE of the Banj-Oak-dominated ecosystem signified slow varying changes.

The high-frequency variations of NEE in the Chir-Pine-dominated ecosystem could be linked to a higher response of the ecosystem to the environmental changes in comparison to the Banj-Oak-dominated ecosystem. However, unlike NEE, the comparison of RE wavelet spectra between Chir-Pine and Banj-Oak-dominated ecosystems showed high-frequency variation with smaller scales (2–4 scales) for the Banj-Oak-dominated ecosystem indicating abrupt changes in the terrestrial ecosystem respiration. The low variation in RE values over the Chir-Pine-dominated ecosystem was associated to low soil moisture availability and microbial activities (Joshi et al., 1991).

To understand relationships between ecosystem fluxes and rainfall in different time–frequency spaces during monsoon seasonal variation, cross-wavelet spectra were produced (Fig. 5). In the cross-wavelet spectra, the red area enclosed by the thick solid line represented statistically significant local correlation (i.e., 95% confidence level) between two variables, i.e., NEE/GPP/RE and rainfall that signifies ecosystem fluxes are more sensitive to changes in rainfall. The darker-colored contour in the cross-wavelet spectra indicated a higher local correlation in the time–frequency space. Phase (lag-lead) relationships are shown by the arrows, a positive correlation is represented by an arrow pointing to the right, and a negative correlation is represented by one to the left. The leadership of the first variable is shown by a downward pointing arrow, and if it lags, the relationship is represented by an upward pointing arrow (Mukherjee et al., 2018).

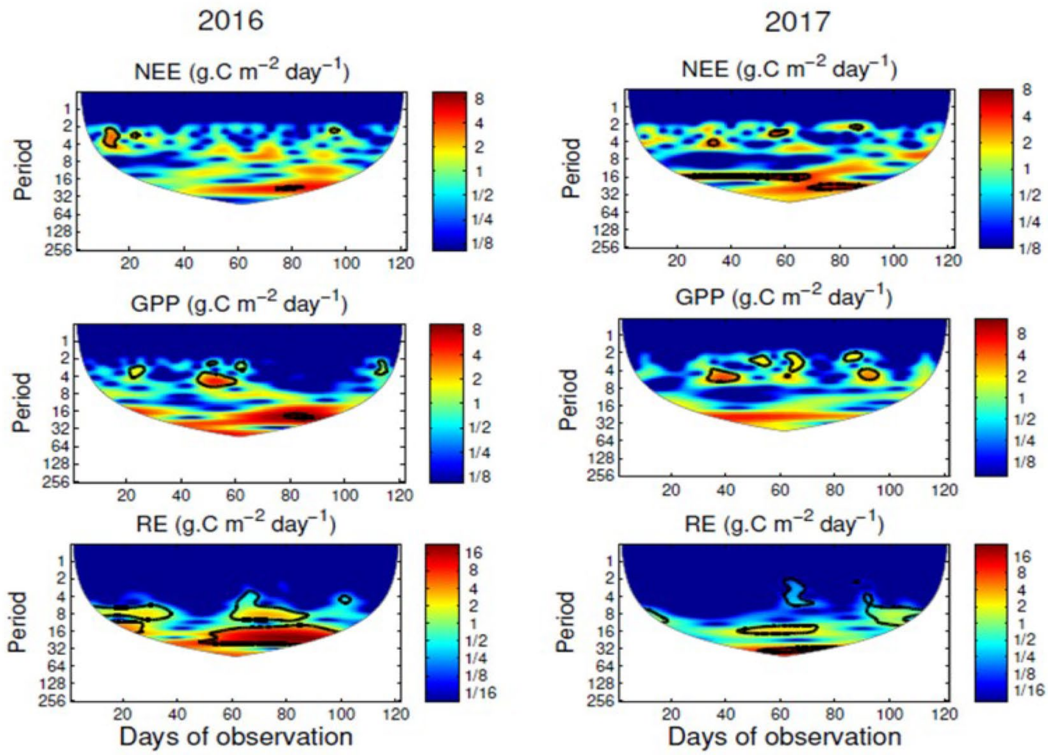
Seasonal common powers with respect to rainfall and all three fluxes can easily be identified from Fig. 5a and b with periods varying significantly between 2 - 16 days for the Chir-Pine-dominated ecosystem and 2–8 days for the Banj-Oak-dominated ecosystem while intermittent phase-locked relationship was observed for a limited time period in the Banj-Oak-dominated ecosystem. The cross-wavelet spectra of GPP with rainfall (Fig. 5c, d) indicated marginally different behavior than NEE–rainfall scalograms as arrows were pointing marginally downward, indicating the GPP of Banj-Oak-dominated ecosystem had restrained responses to rainfall than the Chir-Pine-dominated ecosystem. The comparison of the RE–rainfall scalogram (Fig. 5e, f) indicated increasing rainfall leading to enhancing RE over the Banj-Oak-dominated ecosystem; however, no such signatures were observed over the Chir-Pine-dominated ecosystems.

Response of the ecosystem fluxes to rainfall spell

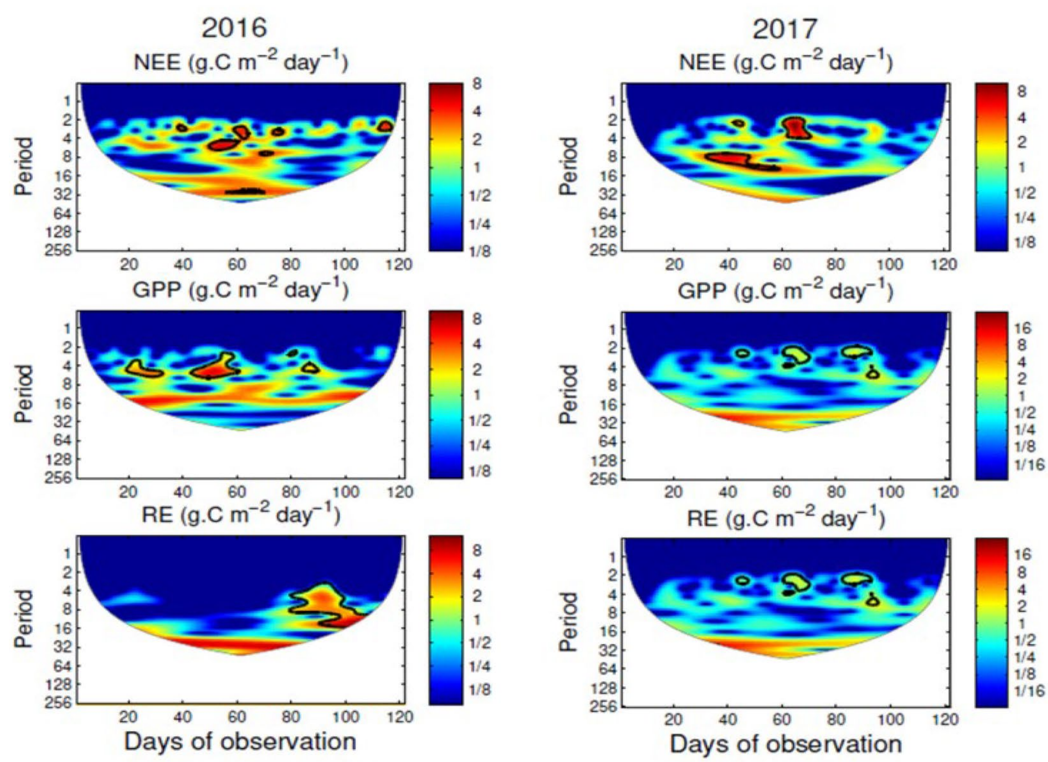
The three important rainfall parameters that control ecosystem exchanges are spell duration, amount, and threshold (Yuhui et al., 2018). As indicated in the method section, dissimilarities in the ecosystem fluxes of Chir-Pine and Banj-Oak-dominated ecosystems due to varying rainfall spells were quantified using the monsoon season data. Subsequently, successive rainy days of a monsoon season were considered up to 10 days from 0-day of initiation where 0-day and rainfall event + 01-day implied no rain. Total rainfall spell was calculated for each monsoon season of 2016 and 2017 for Chir-Pine and Banj-Oak-dominated ecosystems (Table 1), and it can be noted that, irrespective of sites and observation years, a total of 31 and 42 rainfall spells were recorded for Chir-Pine and Banj-Oak-dominated ecosystems, respectively. Additionally, 02-day rainfall spells were found to have a maximum occurrence (09) at the Chir-Pine site, whereas 01-day rainfall spells (17) were maximum at the Banj-Oak site.

To identify the impact of rainfall spell on carbon assimilation, a scatter diagram of the average NEE and associated length of rainfall spell was produced (Fig. 6a and b). It was noted from Fig. 6a and b that a 01-day rainfall spell within the monsoon period had resulted in the lowest average carbon sequestration among all the rainy days (-2.98 gC m^{-2} day^{-1}) by the Chir-Pine-dominated ecosystem while 3-day consecutive rainfall spell had the lowest carbon sequestration among all the rainy days (-1.93 gC m^{-2} day^{-1}) by the Banj-Oak-dominated ecosystem. However, with increasing successive rainy days within a monsoon season, enhanced carbon sequestration by the Chir-Pine-dominated ecosystem having maximum carbon assimilation (-5.17 gC m^{-2} day^{-1}) for a continuous rainfall spell of 09-day was observed.

Subsequently, it was noted that the enhancement in the successive rainy days within a monsoon season did not enhance carbon sequestration by the Chir-Pine-dominated ecosystem after the 09-day spell. Change in the systematic enhancement of carbon assimilation in the Chir-Pine site after the


2016
2017
NEE (g.C m-2 day-1)
GPP (g.C m-2 day-1)
RE (g.C m-2 day-1)
Period
Days of observation

(a)


2016
2017
NEE (g.C m-2 day-1)
GPP (g.C m-2 day-1)
RE (g.C m-2 day-1)
Period
Days of observation

(b)

◂**Fig. 4** Power spectra of daily average ecosystem fluxes (NEE, GPP, and RE) for the **a** Chir-Pine and **b** Banj-Oak-dominated ecosystems

09-day spell could be attributed to the fact that sustained precipitation leading to detrimental photosynthetic activity by means of physical damage to the stomata, as reported by Qing et al. (2015) and Sun et al. (2017).

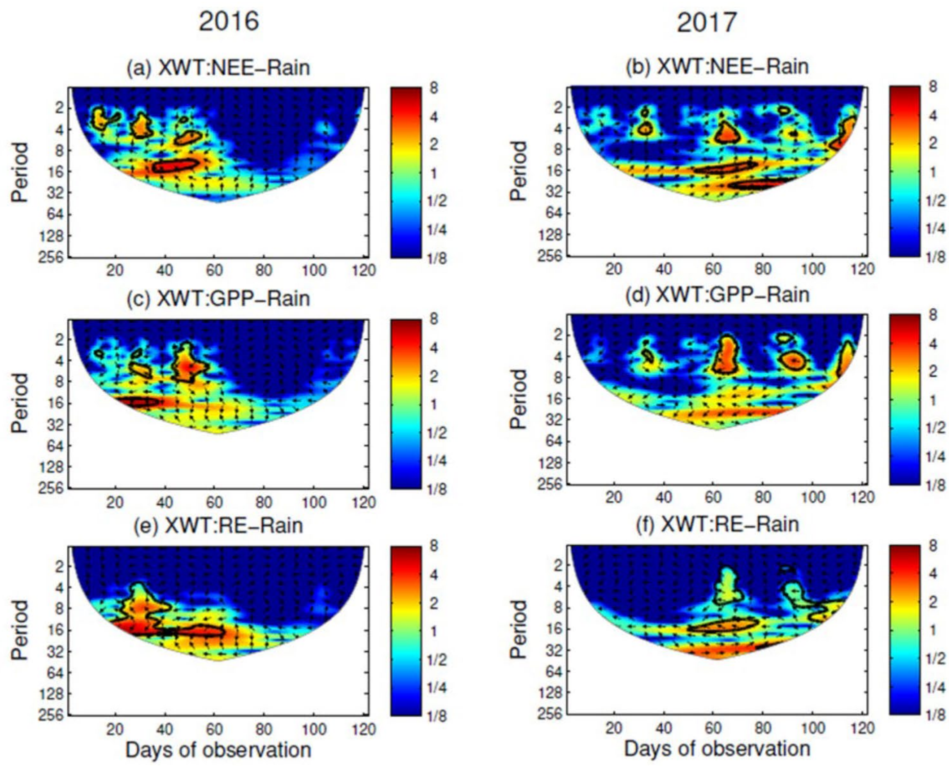
Contrary to the Chir-Pine-dominated ecosystem, no statistically significant relationship was observed between NEE and rainfall spell for the Banj-Oak-dominated ecosystem. The solid line in Fig. 6a and b depicts the fitted curve of $NEE = aS^b$, where S is the rainfall spell. The comparison of power-law relationships between Chir-Pine and Banj-Oak-dominated ecosystems indicated the Chir-Pine-dominated ecosystem had a systematic response to rainfall spell ($NEE = -3.2S^{0.13}$ with a correlation coefficient of 0.85 at p-value < 0.001), whereas the Banj-Oak-dominated ecosystem did not systematically respond to rainfall spell ($NEE = -2.83S^{0.08}$ with a correlation coefficient of 0.20 with no statistical significance).

Response of the ecosystem fluxes to rainfall amount

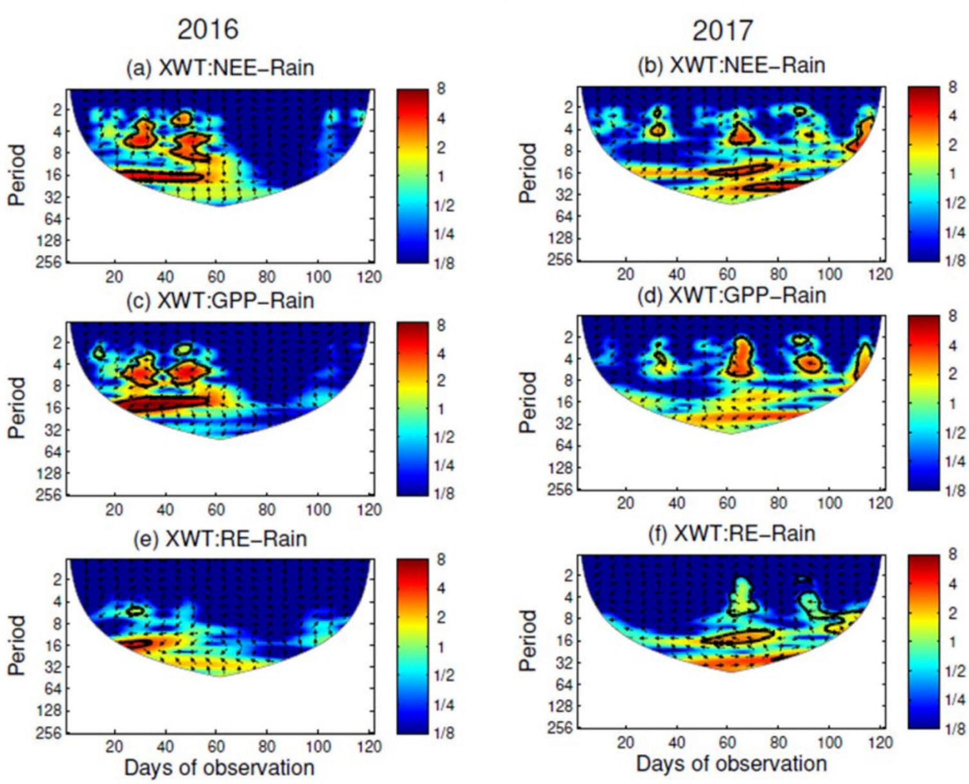
In general, plants are highly sensitive to variations in rainfall amount (Yuhui et al., 2018), and over the Himalayan terrain, monsoon seasonal precipitation has a larger impact on carbon assimilation than any other season (Deb Burman et al., 2021). To assess the impact of maximum rainfall within a rainfall spell on carbon assimilation, boxplots were used to identify the highest carbon assimilation by an ecosystem after the maximum rainfall irrespective of rainfall spells (Fig. 7). It can be clearly observed from Fig. 7 that both Chir-Pine and Banj-Oak-dominated ecosystems had sequestered the highest amount of carbon (−4.65 and −4.91 gCm^{-2} day^{-1}, respectively) just after the day having maximum rainfall. Subsequently, it can be inferred that maximum rainfall within a spell increased the ecosystem responses of both Chir-Pine and Banj-Oak-dominated ecosystems resulting in increased productivity. Our observations corroborate well with the earlier observations of Austin et al. (2004) and Schwinning and Sala (2004) who illustrated that water uptake by the plants in water-limiting conditions accelerated after a large precipitation event through increased photosynthesis capacity.

To identify the rainfall threshold that had resulted maximum carbon assimilation by the Chir-Pine and Banj-Oak-dominated ecosystems, a scatter diagram of the average NEE and associated rainfall amount, irrespective of the rainfall spells, was produced (Fig. 8). However, the rainfall threshold was quantified by only considering 5-day consecutive rainfall events as more than 5 consecutive rainfall days could be considered as heavy rainfall spell following Tang et al. (2018). The rainfall thresholds resulting highest carbon assimilations in Chir-Pine and Banj-Oak-dominated ecosystems are easily noticeable from Fig. 8, and the thresholds were 10(±0.7) mm and 17(±1.2) mm amount of rainfall for Chir-Pine and Banj-Oak-dominated ecosystems having highest carbon assimilation of −4.46 and −4.44 gC m^{-2} day^{-1}, respectively. The fitted quadratic models for Chir-Pine and Banj-Oak-dominated systems were found to be $NEE = 0.03R_m^2 - 0.85R_m - 0.04$ for Chir-Pine having $r^2 = 0.82$; and $NEE = 0.03R_m^2 - 1.02R_m + 4.28$ for Banj-Oak having $r^2 = 0.87$.

Although the impact of rainfall spell and the amount on the ecosystem exchanges of various forest types are relatively less studied, Yuhui et al. (2018) reported that 1–2 mm of rainfall was necessary for the desert grassland of Inner Mongolia to stimulate plant activities. Similarly, a relatively lower value (4.5 mm) was recorded by Tang et al. (2018) for temperate grassland ecosystems. As the forest ecosystems considered in this study are significantly different from grasslands in terms of structure and functioning, it can be anticipated that rainfall thresholds identified in this study would be markedly different from grasslands. While both Chir-Pine and Banj-Oak-dominated ecosystems have similar climatological conditions, in terms of physiological responses and carbon sequestration, contrasting behavior by both Chir-Pine and Banj-Oak-dominated ecosystems was observed. The monsoon season average gross primary productivity of both ecosystems was almost equal, but there were major differences in the ecosystem respiration. Moreover, the Chir-Pine-dominated ecosystem had almost 1.8 times higher carbon sink capacity than the Banj-Oak-dominated ecosystem during monsoon due


2016
2017
(a) XWT:NEE–Rain
(b) XWT:NEE–Rain
(c) XWT:GPP–Rain
(d) XWT:GPP–Rain
(e) XWT:RE–Rain
(f) XWT:RE–Rain
Period
Days of observation

(a)


2016
2017
(a) XWT:NEE–Rain
(b) XWT:NEE–Rain
(c) XWT:GPP–Rain
(d) XWT:GPP–Rain
(e) XWT:RE–Rain
(f) XWT:RE–Rain
Period
Days of observation

(b)

◂**Fig. 5** Cross-wavelet spectra of daily averaged ecosystem fluxes and rainfall of the **a** Chir-Pine and **b** Banj-Oak-dominated ecosystems

to lower soil microbial activities and lesser amount of litter decomposition. Our observations related to ecosystem respiration corroborates with Rawat et al. (2020). We have also noted that the Chir-Pine-dominated ecosystem had high-frequency rapid and abrupt changes in the NEE with respect to changing environmental conditions, while the Banj-Oak-dominated ecosystem was resilient to environmental changes primarily due to the availability of nutrient-rich soil and water (Singh and Bisht, 1992).

Summary and conclusion

The *Pinus roxburghii* (i.e., Chir-Pine) and *Quercus leucotrichophora* (i.e., Banj-Oak) are major tree species found in the forests of central Himalaya predominantly between 800 and 2200 m above mean sea level. These tree species form pure and mixed ecosystems. However, responses of Chir-Pine and Banj-Oak-dominated forests with respect to changing microclimate, particularly rainfall spell, amount, and frequencies, are not yet investigated. Therefore, in the absence of scientific understanding of the coupling mechanism between rainfall and ecosystem fluxes, this study is aimed at quantifying the amplitude of rainfall triggering the highest variation in ecosystem carbon fluxes during monsoon (June–September), and quantifying the dissimilarities in the NEE of these ecosystems due to varying rainfall spell and amount. We found that the Chir-Pine and Banj-Oak-dominated ecosystems were the sink of CO_2 during monsoon seasons, and the Chir-Pine dominated ecosystem sequestered around 1.8 times higher carbon than the evergreen broad-leaf Banj-Oak dominated ecosystem during the observation period of 2016–2017. The monsoon period rainfall events resulted in 3–50 and 5–30 days band periods having statistically significant correlations with NEE, respectively, for the Chir-Pine and Banj-Oak-dominated ecosystems. We also noted that rainfall had a larger impact on the carbon sequestration rate of the Chir-Pine than the Banj-Oak-dominated ecosystem. Unlike the Banj-Oak-dominated ecosystem, a systematic enhancement in the carbon assimilation by the Chir-Pine-dominated ecosystem was noted with increasing rainfall spells that followed a statistically significant power-law relationship. However, when the impact of maximum rainfall was investigated, irrespective of rainfall spell duration, both Chir-Pine and Banj-Oak-dominated ecosystems showed the highest carbon assimilation after the day having maximum rain with almost similar average carbon sequestration rates (-4.65 and -4.91gC m^{-2} day^{-1}, respectively, for Chir-Pine and Banj-Oak-dominated ecosystems). However, the interesting observation for the Banj-Oak-dominated ecosystem was around 4 times enhancement of carbon sequestration after a maximum rainfall within a

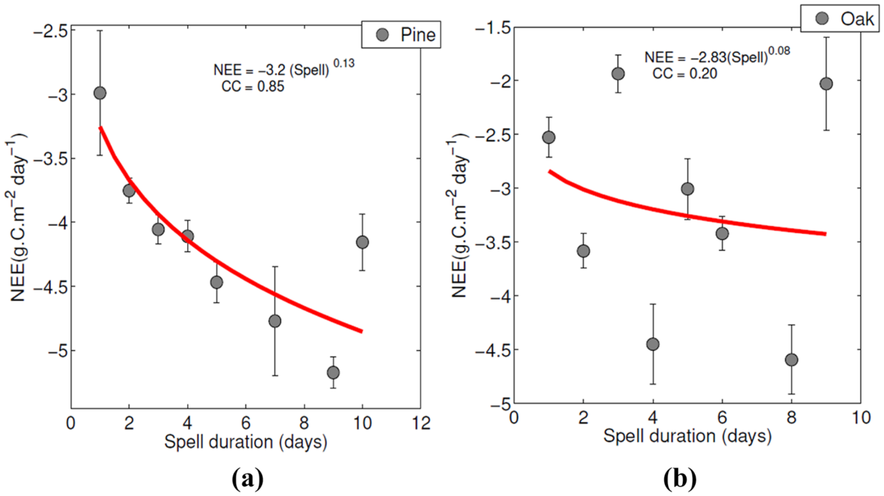


Fig. 6 Subplots show average net ecosystem exchange (NEE) of the monsoon seasons of 2016–2017 for a length of rainfall spell where 0-day and rainfall + 01-day implied no rain

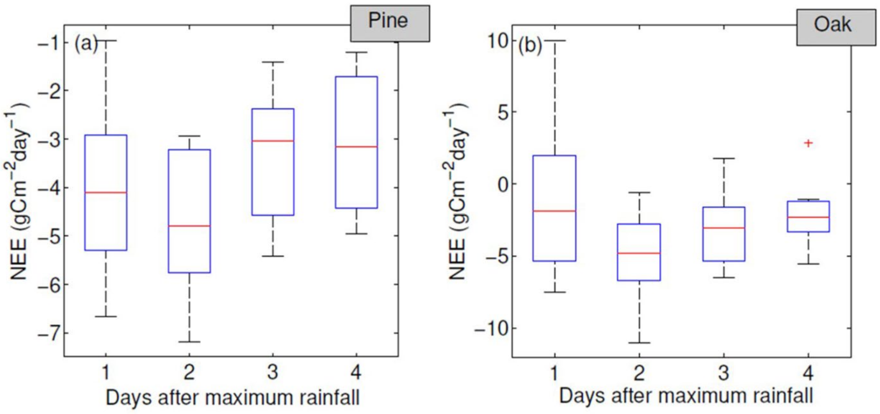


Fig. 7 Box plots show net ecosystem exchange (NEE) for each r_d, r_d+1, r_d+2, and r_d+3 days

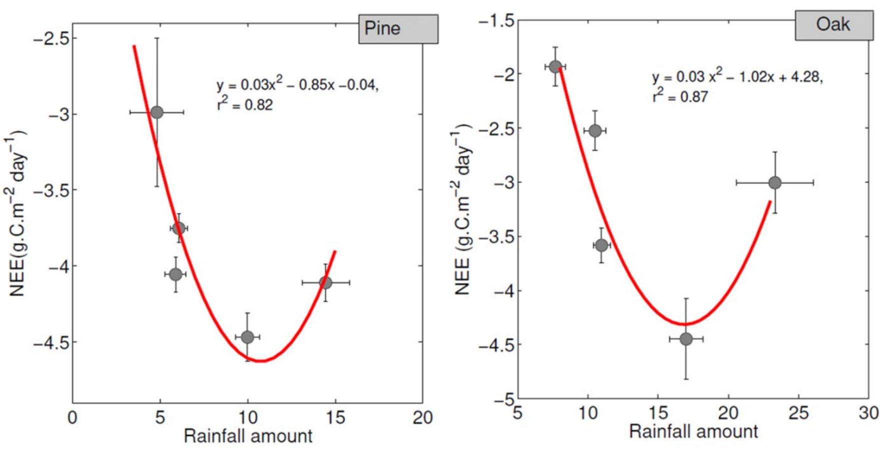


Fig. 8 Subplots represent the variation of net ecosystem exchange (NEE) with rainfall amount. The vertical and horizontal lines represent standard errors. The red lines indicate fitted quadratic equation where "*y*" is NEE and "*x*" is rainfall amount

rainfall spell, which was only around 1.5 times for the Chir-Pine-dominated ecosystem. Hence, we can infer that although the Chir-Pine-dominated ecosystem generally has higher responses to rainfall, the Banj-Oak-dominated ecosystem was more sensitive to maximum rain. Our study could also detect a rainfall amount threshold for both Chir-Pine and Banj-Oak dominated ecosystems (10 ± 0.7 and 17 ± 1.2 mm, respectively) that resulted in the highest ecosystem carbon assimilation, and we were able to model the NEE of both sites with respect to the rainfall amount using a quadratic equation.

This study presents the initial assessments of monsoon season rainfall impacts on ecosystem carbon exchanges of Chir-Pine and Banj-Oak-dominated vegetations of central Himalaya. In view of the climate change-induced expected changes in the rainfall patterns over Himalaya, insights of this research outcome are expected to be beneficial for the long-term conservation and management of the Chir-Pine and Banj-Oak-dominated ecosystems of Himalaya.

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Author contribution PL and SM: Conceptualisation, data collection and processing, manuscript writing; KCS, PM: Vegetation data analysis and correction of the manuscript; KK, APD: Conceptualisation, final manuscript correction, and overall supervision. All authors have read, understood, and complied as applicable with the statement on ethical 'responsibilities of authors' as found in the instructions for authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

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Data availability The rainfall and ecosystem exchange data are available with S. Mukherjee and further data sharing needs approval from the competent authority of GBPNIHE, Almora, India.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Consents for publication from all the co-authors are received.

Conflict of interest The authors declare no competing interests.

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