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RESEARCH ARTICLE

Interactive effects of soil moisture and temperature on soil respiration under native and non-native tree species in semi-arid forest of Delhi, India

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Abstract
We assessed the impacts of native and non-native tree species and seasonal variation on in situ soil respiration rates for four seasons. A portable infrared carbon dioxide (CO_2) gas analyzer (Q-Box SR1LP) was used for in situ measurements. Seven tree species were selected, out of which three are native to Delhi ridge, viz., *Vachellia leucophloea*, *Ficus religiosa* and *Millettia pinnata* and four are non-native, viz., *Albizia lebbeck*, *Prosopis juliflora*, *Azadirachta indica* and *Cassia fistula*. Our results showed a significant seasonal variation and effect of native and non-native tree species on soil respiration. Soil respiration was high during monsoon and low in winter. The highest annual soil respiration was observed under the canopy of *F. religiosa* (18.72 µmol CO_2 m^{-2} s^{-1} $year^{-1}$) and lowest under *A. indica* (4.58 µmol CO_2 m^{-2} s^{-1} $year^{-1}$). The tree species showed the pattern: *F. religiosa* > *A. lebbeck* > *P. juliflora* > *V. leucophloea* > *M. pinnata* > *C. fistula* > *A. indica*. Soil respiration showed a positive correlation with soil moisture and temperature ($P < 0.05$) showing an interplay of both in controlling soil respiration. Our findings also highlighted the effect of litter quality and quantity on soil respiration as low C/N ratio and positive correlation of litter quantity with soil respiration enhanced its rate under *F. religiosa*. The maximum soil respiration under the canopy of native species than non-native ones suggests their importance in the vital ecosystem functions, and thus, in managing the forest ecosystem of Delhi.

Keywords C/N ratio · Delhi ridge · Ecosystem function · In situ soil respiration · Litter quality · Native and non-native species · Semi-arid forest

Introduction

In the terrestrial ecosystem, soil carbon dioxide (CO_2) efflux is the largest source of CO_2. The two main components of soil respiration are autotrophic respiration from plant roots and heterotrophic respiration from soil fauna and microbial activities (Hanson et al. 2000). Globally, soil temperature and moisture have been considered the most important abiotic parameters affecting soil respiration and its underlying processes (Kutsch et al. 2010). Due to increasing concentrations of atmospheric CO_2 and its relationship with global warming and climatic changes (IPCC 2014), carbon cycle has received global attention. Studies have estimated global soil CO_2 emissions in the range of 98 ± 12 Pg $year^{-1}$, with annual increase of 0.1 Pg with the increase in temperature (Bond-Lamberty and Thomson 2010). Globally, soils can store ~ 2500 Pg of carbon (including organic and inorganic carbon) which is equivalent to 3.3 and 4.5 times the amount of carbon in the atmosphere (760 Pg) and terrestrial plants (560 Pg), respectively (Lal 2004). Hence, minute variations in the soil carbon pool will severely influence atmospheric CO_2 concentrations and have severe implications on our climate (Trumbore and Czimczik 2008).

Several studies have been conducted to understand the causes of the seasonal variability of soil respiration (Deng et al. 2013; Shabaga et al. 2015; Liu et al. 2019) that mainly involve abiotic factors (i.e., soil temperature and moisture), but very few have investigated the role of biotic factors in spatial variability (Brechet et al. 2009). Tree species have the potential to influence soil processes majorly by controlling the quantity and quality of both aboveground and belowground litter production, and also through root-derived

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respiration (i.e., including both root respiration and root exudates). Site fertility was shown to depend on the biological nutrient cycling, with a pre-dominant role played by litter quality (Prescott 2002). Initial leaf chemistry and nutrient resorption in senescing leaves ultimately determine the litter quality (usually through C/N ratio or lignin concentration) and decomposition rate (Hattenschwiler et al. 2008). Tree species composition of a given forest ecosystem might also affect site fertility through litter quantity (Catovsky and Bazzaz 2002). The foliage characteristics of tree species might have both qualitative and quantitative influence on soil respiration. The influence of plant species richness on the abundance and activity of decomposers was related to both altered substrate quality (Chung et al. 2007) and quantity, i.e., reduction in plant biomass with a decrease in diversity (Spehn et al. 2000) in grassland studies. The influence of tree species on microbial activities in the soil has also been recognized in temperate forest (Xu et al. 2007). Fine root chemistry, for instance, might affect the decomposition rate of soil organic matter by altering microbial community composition (Brant et al. 2006).

Soil temperature is majorly increased due to warming of earth surface which is a crucial factor controlling the plant growth and microbial activity (Huang et al. 2015). Therefore, variation in soil respiration by warming which can induce variations in the soil environment is still unclear. An analysis showed that warming, elevated N deposition and precipitation significantly increased soil respiration in China (Feng et al. 2017). Some studies have shown dependency of soil respiration on soil moisture in a dry forest soil (Li et al. 2017), whereas few have shown dependency on soil temperature (Carlyle and Than 1988). Thus, how different factors and their interactions impact soil respiration is still unclear. Therefore, an in situ experiment was carried out in the semi-arid region of India to see the seasonal variation and impact of different native and non-native tree species on soil respiration. This would help in understanding the response of soil respiration to climate change and highlight the main driving factors regulating this vital ecosystem function.

In different ecosystems, the rate of respiration varies and is usually the dominant component of ecosystem respiration (Raich and Schlesinger 1992). Dry land ecosystem comprises ~ 40% of the terrestrial surface (Lal 2004), thus, even a small change in soil CO_2 flux can modify the global carbon budget (Hashimoto et al. 2015; Carey et al. 2016; Makhnykina et al. 2018). In arid and semi-arid ecosystems, soil respiration has not been investigated intensively as required than in other ecosystems (Bond-Lamberty and Thomson 2010). Studies on urban soil respiration in semi-arid regions are extremely limited with data available for sub-tropical, dry tropical riparian and temperate forests of India (Jha and Mohapatra 2011; Singh et al. 2017). Thus, it becomes important to investigate the soil respiration process in semi-arid regions more extensively which is the major component of C balance in the terrestrial ecosystem. The main characteristics of semi-arid regions are unpredictable rainfall that interacts with season, large spatial variability and uneven distribution of resources, environmental conditions, roots and the microbial community responsible for organic matter decomposition (Rey et al. 2011). Thus, such diversity in soil characteristics in these ecosystems is very poorly understood (Gonzalez-Polo and Austin 2009).

As the global demands of tree-derived ecosystem services are increasing (Castro-Diez et al. 2019), many stress-tolerant fast-growing tree species are planted outside their native lands (Dickie et al. 2014; Brundu and Richardson 2016). Due to the plantation of non-native tree species, alteration in ecosystem occurs via changes in nutrient cycling (Vitousek and Walker 1989), species composition (Castro-Diez et al. 2012) and water cycle (Ehrenfield 2003). Many of these plants are also known for depletion of soil nutrients and water resources (Castro-Diez et al. 2012; Shackltеon et al. 2014). These negative aspects are worsened when non-natives naturalize, and spread invasively outside their original boundaries (Brundu and Richardson 2016). Therefore, careful understanding and planning of the non-native tree species with their benefits as well as ill effects are required, which will serve as a contingency plan for planned proliferation of non-native species along with native ones (Dickie et al. 2014). The presence of non-native tree species may affect nutrient cycling directly, by influencing microbial activities via bringing changes in litter quality and quantity in the soil, or indirectly, by influencing the soil physico-chemical properties beneath the tree canopy (Follstad Shah et al. 2010).

In the present study, our specific objectives were to: (1) quantify the variation in soil respiration under native and non-native tree species, and (2) explore the correlation of soil moisture and temperature with soil respiration.

Materials and methods

Site description

The study was conducted in Delhi, the capital of India. Delhi basically has four distinct patches of forests known as ridge areas. The Delhi ridge areas have been declared as reserved forests under the Indian Forest Act, 1927. The ridge forest falls under semi-arid open scrub as per forest type classification (Champion and Seth 1968). The ridge area is the rocky elevation of Aravalli hills in Delhi. Aravalli hills are one of the oldest mountains in the world starting from Rajasthan (Western India) and Gujarat (Southwestern India) and extending up to Delhi. The ridge areas in Delhi are classified as: (1) Northern Ridge (87 ha.), (2) Southern Ridge

(6200 ha.), (3) Central Ridge (864 ha.) and (4) South-Central Ridge (626 ha.). The present study was conducted at South-Central ridge popularly known as Sanjay Van, near Vasant Kunj—Kishangarh area (28°31′42.0″N and 77°10′21.0″E).

Classification of seasons was done based on rainfall events and temperature. Thus, the present study site was mainly classified with four seasons which are as follows: (1) pre-monsoon (March–May), (2) monsoon (June–August), (3) post-monsoon (September–November) and (4) winter (December–February). Mean annual precipitation was 165.15 mm with highly fluctuating rainfall out of which 52% occur during late June to mid-September (Fig. 1). This region is characterized by typical seasonal and semi-arid climate. The soil is yellow-brown with a sandy loam texture and pH ranging from 6.78 to 8.91. Mean maximum seasonal air temperature was 32.5 °C, ranging from 24.5 °C during winter to 39.3 °C during summer, whereas mean seasonal soil temperature was 26.2 °C, ranging from 20.2 °C during winter to 30.1 °C during summer (Fig. 1).

The vegetation is mainly characterized by middle storied thorny trees many of which were introduced and planted to increase the forest area and others being naturally present. For better productivity under the South-Central ridge, plantation of several different tree species is under process while taking care of the natural patches present in the forest. The most common tree species present are *Balanites roxburghii* (Planch.), *Vachellia leucophloea* (Roxb.) Maslin, Seigler and Ebinger, *Salvedora oleoides* (Decne.), *Vachellia nilotica* (L.) P. J. H. Hurter & Mabb., *Vachellia catechu* (L.f.) P. J. H. Hurter & Mabb.*,* *Millettia pinnata* (L.), and *Ficus religiosa* (L.), whereas *Prosopis juliflora* (Sw.) DC. is the invasive species dominating the forest area. The other non-native tree species present are *Albizia lebbeck* (L.) Benth, *Azadirachta indica* (A.) Juss., *Cassia fistula* (L.), *Ficus racemose* (L.), *Bombax ceiba* (L.), etc. The most common shrubs present are *Capparis sepiaria* (L.), *Adhatoda zeylanica* (Medic.), *Carissa spinarum* (L.)*, Asparagus racemosus* (Willd.)*, Lantana camara* (L.), and *Grewia tenax* (L.). The most common herbaceous species present are *Calotropis procera* (Aiton) W. T. Aiton, *Withania somnifera* (L.) Dunal, *Achyranthes aspera* (L.), *Tridax procumbens* (L.), *Brachiaria villosa* (Lam.) A. Camus and *Parthenium argentatum* A. Gray.

The tree species selected for the present study were *Vachellia leucophloea*, *Ficus religiosa*, and *Millettia pinnata* belonging to native species, whereas the non-native tree species chosen were *Albizia lebbeck*, *Azadirachta indica*, *Prosopis juliflora* and *Cassia fistula*. The classification of tree species into native and non-native was done using Flora of Delhi (Maheshwari 1963). Based on visual field observation, these tree species were selected as they contributed to the forest via leaf litter, their canopy size and abundance. They represent the dominant trees in other semi-arid regions of India as well which will help in estimating the effects of tree canopy cover on soil respiration in the forest.

In situ soil respiration

Soil respiration was measured seasonally for four seasons from winter to post-monsoon in 2017 (thrice in each season). In situ soil respiration was measured using Q-Box SR1LP soil respiration package (Qubit Systems). Soil respiration was measured as the rate of CO_2 accumulation by the Q-S151 CO_2 analyzer using closed flow system. It consists of a G180 soil chamber (10.16 cm dia. and 20 cm height) with a collar. The soil chambers were inserted into the field about 2 weeks before the first reading to be taken and were left there for the complete season. The measurement of soil respiration was done at 0–10 cm depth under every individual of selected tree species, which were present at random locations in the study site.

Measurements in triplicates were taken under three individuals of each species ($n = 9$/species). Before inserting the soil chamber into the soil surface, it was made sure that the surface is free from all live vegetation and litter. Soil respiration was measured in the morning between 09:00 and 11:00 a.m. to avoid errors in readings due to high day temperature

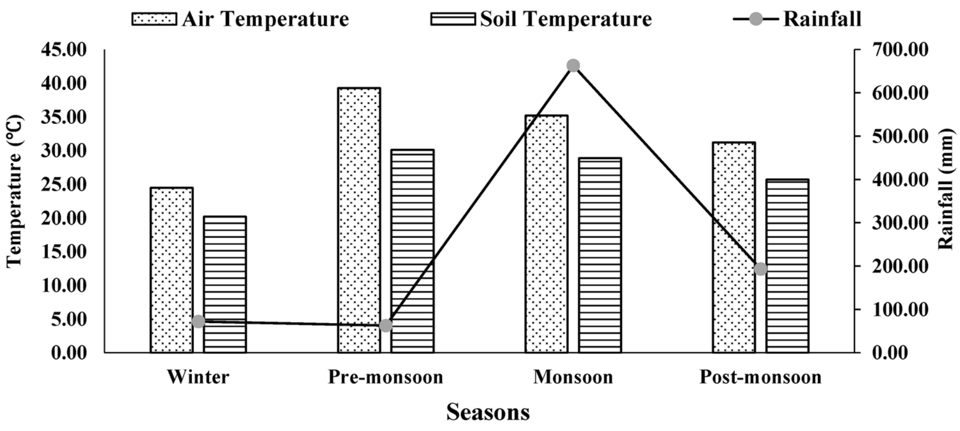

Fig. 1 Seasonal pattern of rainfall, air and soil temperature in the study site Source for rainfall data: Agromet observatory, Division of Agricultural Physics, IARI, New Delhi

in this region. Soil temperature was also measured by the probe attached with the system near each soil chamber.

Data analysis

To estimate soil respiration, Q-Box SR1LP Software was used to analyze the readings taken. For a closed flow system, the software of soil respiration package gives a slope for each reading. The slope of the line represents soil respiration rate in ppm CO_2 s^{-1}. This rate was first converted into µL CO_2 L^{-1} s^{-1} noting that 1 ppm = 1 µL L^{-1} of gas in the system. To obtain respiration rate of soil in the system, the volume of the system was calculated, which came out to be 0.9 L after adding the volume of all the individual components including the tubing. The rate of CO_2 accumulation in µL CO_2 L^{-1} of system/s. was then multiplied by the volume of the system to get µL CO_2 min^{-1}. Finally, the rate of CO_2 accumulation in µL s^{-1} was converted to µmol CO_2 s^{-1} and corrected for standard temperature (273 °K) using the following equation:

$$\frac{x}{\left[\frac{(273+T)}{273}\times 22.41\right]}\quad \mu\text{mol of } CO_2,$$

where x is the rate of CO_2 accumulation in µL min^{-1} and 22.41 is the volume of any gas in µL that is occupied by 1 µmol at standard temperature and pressure. T is the temperature of the gas (C) as measured by the Q-S161 RH/Temp. sensor.

To convert soil respiration rate from µmol CO_2 s^{-1} to µmol CO_2 m^{-2} of soil surface area/s., the rate in µmol CO_2 s^{-1} was divided by the soil surface area. The surface area of the soil that was converted by the G180 soil chamber with a diameter of 10.16 cm is 81.1 cm^2 (0.00811 m^2). Therefore, the rate in µmol CO_2 s^{-1} was divided by 0.00811 to get µmol CO_2 m^{-2} s^{-1}.

Leaf litterfall and soil moisture analysis

One litter trap in the middle of the tree canopy of 1 × 1 m and 20 cm high above the ground were laid under each tree species ($n = 3$/species). Leaf litter was collected at seasonal intervals. The litter was taken to the laboratory, rinsed with fresh water. Dry weight of litter was determined by drying to a constant weight at 80 °C for 24–48 h and the mean seasonal value was given on a unit area basis g m^{-2}. The seasonal litter data were then summed to obtain the annual leaf litter production.

For soil moisture, soil samples were collected under the canopy of each tree species ($n = 3$/individual) and brought back to laboratory. 10 g (W_1) of fresh soil was taken in a petri plate and the sample was oven dried for 48 h at 105 °C until constant weight was achieved and then the final weight (W_2) was measured. Soil moisture was measured following Allen et al. (1974).

Statistical analysis

Two-way analysis of variance (ANOVA) was performed to examine the effects of seasons and different tree species on soil respiration rate. Tukey post hoc test was performed to distinguish differences at the 0.05 level. Pearson's correlation analysis was performed to establish the correlation between soil temperature, moisture, leaf litterfall production and soil respiration. All statistical analyses were done using SPSS version 21.

Results

Seasonal variation in soil respiration

During monsoon season, soil respiration was observed to be highest and lowest during winter (Fig. 2). We

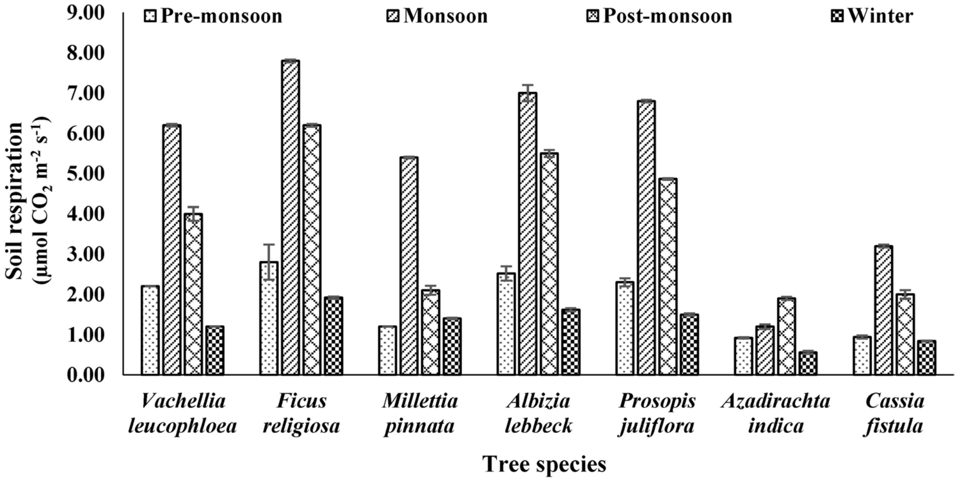

Fig. 2 Mean soil respiration during different seasons across different tree species

observed statistically significant variation in soil respiration across different seasons ($F = 226.13$, $P < 0.01$). In the entire study period, soil respiration was highest during monsoon, i.e., 7.80 µmol CO_2 m^{-2} s^{-1} and lowest during winter, i.e., 0.56 µmol CO_2 m^{-2} s^{-1}. The general trend observed in soil respiration across seasons was monsoon > post-monsoon > pre-monsoon > winter.

Soil respiration among different tree species

Among different native tree species, *F. religiosa* showed the highest annual soil respiration rate (18.72 µmol CO_2 m^{-2} s^{-1} $year^{-1}$) followed by *V. leucophloea* (13.60 µmol CO_2 m^{-2} s^{-1} $year^{-1}$) and *M. pinnata* (10.10 µmol CO_2 m^{-2} s^{-1} $year^{-1}$). However, among non-native ones, *A. lebbeck* (16.64 µmol CO_2 m^{-2} s^{-1} $year^{-1}$) showed the maximum rate of soil respiration followed by *P. juliflora* (15.47 µmol CO_2 m^{-2} s^{-1} $year^{-1}$), *C. fistula* (6.98 µmol CO_2 m^{-2} s^{-1} $year^{-1}$) and *A. indica* (4.58 µmol CO_2 m^{-2} s^{-1} $year^{-1}$) (Fig. 2). Significant variation was observed in soil respiration among different tree species ($F = 226.13$, $P < 0.01$). The general trend followed by tree species is as follows: *F. religiosa* > *A. lebbeck* > *P. juliflora* > *V. leucophloea* > *M. pinnata* > *C. fistula* > *A. indica*.

However, out of the seven tree species, mean annual soil respiration under all the three native species was observed to be 14.14 µmol CO_2 m^{-2} s^{-1} $year^{-1}$, whereas under all the four non-native tree species, it was 10.92 µmol CO_2 m^{-2} s^{-1} $year^{-1}$.

Leaf litterfall, soil moisture and temperature

In the current study, the maximum amount of seasonal mean litterfall was collected and observed under the tree canopy of *F. religiosa*, whereas minimum was observed under *V. leucophloea*. The litterfall production showed the following pattern: *F. religiosa* > *A. lebbeck* > *P. juliflora* > *M. pinnata* > *C. fistula* > *A. indica* > *V. leucophloea* (Fig. 3). Mean seasonal leaf litterfall under all the tree species across all the seasons ranged from 5.14 g m^{-2} (*V. leucophloea*) to 88.80 g m^{-2} (*F. religiosa*), whereas annual leaf litterfall production ranged from 0.29 to 2.79 Mg ha^{-1} $year^{-1}$. There was marked variation across different tree species (Fig. 3).

Soil moisture was analyzed seasonally and there was variation under different tree species and across seasons. It was observed to be highest under *F. religiosa* during monsoon and lowest during pre-monsoon, whereas mean annual soil moisture was maximum under *F. religiosa* (11.04%) and minimum under *C. fistula* (7.57%) (Fig. 3). Soil moisture showed the following pattern across different tree species: *F. religiosa* > *V. leucophloea* > *A. indica* > *P. juliflora* > *A. lebbeck* > *M. pinnata* > *C. fistula*. Moreover, soil temperature under different tree species ranged from 15.50 to 30.20 °C across four seasons. However, it was observed to be maximum during pre-monsoon under *F. religiosa* and minimum during winter under *C. fistula*. It showed the following pattern across seasons: pre-monsoon > monsoon > post-monsoon > winter.

Correlation analysis

In this study, soil respiration was positively correlated with soil temperature and moisture. During the study period, all the tree species were significantly correlated with soil moisture except *Azadirachta indica* which showed no significant correlation with either soil temperature ($P = 0.36$, $r = 0.30$) or moisture ($P = 0.57$, $r = 0.18$). Although soil respiration and leaf litterfall production are weakly correlated, it was observed to be positive under all the tree species ($P = 0.31$, $r = 0.45$). However, a strong negative correlation was observed across all the tree species between C/N ratio of leaf litterfall with soil respiration ($P = 0.03$, $r = -0.80$).

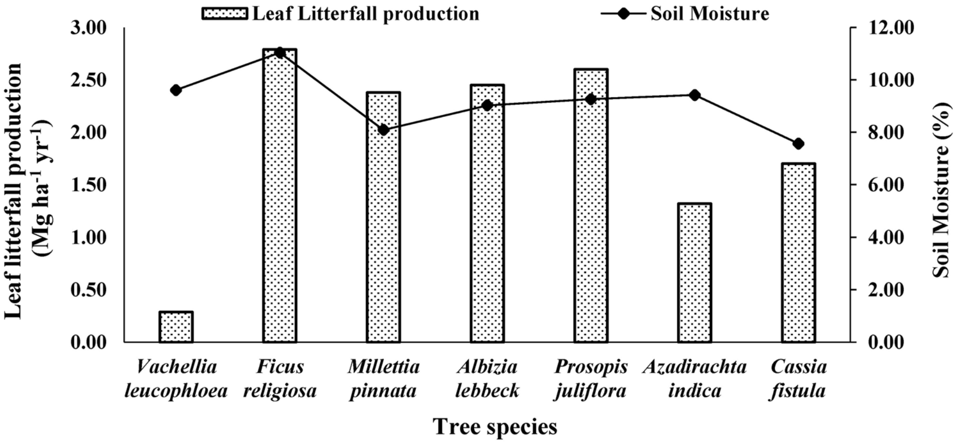

Fig. 3 Site-specific annual leaf litterfall production and mean soil moisture under different tree species

Discussion

Effect of tree species on soil respiration

Effect of tree species on soil respiration was evident in our study and was concordant to a study conducted in Istanbul, Turkey (Akburak and Makineci 2013). Variation in plant species causes variations in the energy balance, the biogeochemical cycles and in the quality and quantity of organic matter, which suggests that factors such as soil temperature and soil moisture that control soil respiration rates may also mutually change (Raich and Schlesinger 1992; Raich et al. 2002).

In the current study, the minimum rate of soil respiration was under *A. indica,* whereas the maximum was under *F. religiosa* which can be associated with variations in litterfall biomass and litter chemistry. The main process through which plant species can control soil respiration rate is via the production of litter, which ultimately feeds soil micro-organisms. Raich and Nadelhoffer (1989) found that with the increase in litterfall, soil respiration also increased in mature forest ecosystems. The amount and quality of litter *F. religiosa* contributes to the forest are high (Fig. 3) which might have provided varying substrates to the microbes (Hernandez and Hobbie 2010), and thus, high soil respiration. This can be further supported by the positive correlation observed between litterfall production and soil respiration in the current study. A major flux of C is represented by litterfall from the vegetation to the soil (Valverde-Barrantes 2007) and our study clearly showed a large spatial variation in litterfall which is subjected to enhance this relationship (Brechet et al. 2009). The litter produced by *A. indica* is less (Fig. 3), hence, the minimum respiration rate.

Apart from the influence of the quantity of aboveground litter inputs, our results also suggest major effects of the quality of leaf litterfall on soil respiration. Many studies have highlighted the role of litter composition, particularly related to the nitrogen content (expressed as C/N ratio), on decomposition rate (Aerts 1997; Hattenschwiler et al. 2005). In the current study, a strong negative correlation was observed between C/N ratio and soil respiration. As it was observed that leaf litter under *A. indica* showed the highest C/N ratio (28.44) followed by *C. fistula* (22.00) and consequently the lowest soil respiration, whereas *F. religiosa* showed the lowest C/N ratio (13.38) followed by *V. leucophloea* (15.21) and *A. lebbeck* (20.08) and consequently, the highest rate of soil respiration. Although the amount of litter produced by *V. leucophloea* is the minimum of all the tree species, its litter quality is better in terms of C/N ratio than *A. indica*, hence, the respiration rate is comparatively high in *V. leucophloea*. It has been observed that low C/N ratio accelerates the decomposition rate and consequently soil respiration. Also, microbes have a low C/N ratio and when they are provided with litter of low C/N ratio, the nutrient demand of micro-organisms is satisfied and results in faster mineralization of soil organic nutrients (Hadas et al. 2004). For instance, Nguyen and Marschner (2016) provided residues with low and high C/N ratios to the soil samples and observed that respiration rates increased after the addition of residue with low C/N ratio particularly due to the supply of nitrogen from residues which exceeded the microbial demand.

Soil respiration under different vegetation varies, as plant canopy cover has different effects on soil microclimate and structure (Raich and Tufekcioglu 2000). In the present study, high soil respiration under *F. religiosa* can also be due to its huge canopy which maintains the soil moisture and temperature under its canopy, and thus, maintains the optimum conditions for microbes to perform efficiently during warm conditions also. The pattern of C allocation is strongly influenced by vegetation structure and species composition (Wang et al. 2006). In the present study, the soil respiration rate for native tree species was significantly greater than that for the non-native ones (Fig. 2). One potential factor is the availability of substrate (Ryan and Law 2005). The soil respiration rate was majorly influenced by the chemical composition of litter and its quantity along with soil quality.

Seasonal variation in soil respiration

Soil respiration exhibited seasonal variation in our study which is consistent with numerous other studies in forest ecosystems (Jha and Mohapatra 2011; Shabaga et al. 2015; Arora and Chaudhary 2017; Liu et al. 2019). In the present study, soil respiration was maximum during monsoon and lowest during winter due to the efficient activity of microbes during monsoon than winter, which affected the decomposition rate (Bargali et al. 2015) and respiration process (Adachi et al. 2009). Increased soil water availability after rainfall can lead to lysis of microbial cells or the rapid mineralization of cytoplasmic solutes and release the mineralized product into the surrounding environment, which has accumulated during the dry period (Schimel et al. 2007). We associated seasonal variation with differences in soil temperature and moisture in different seasons. The range of soil respiration reported in the present study was similar to other semi-arid ecosystems (Ying et al. 2009; Shi et al. 2012; Zhang et al. 2015; Sun et al. 2018).

Arora and Chaudhary (2017) reported similar trends with increased respiration rate during monsoon and lower in winter season in different tree plantations of Kurukshetra, India. They observed a significant correlation of soil respiration with soil moisture and not with temperature which is consistent with our study, where a correlation analysis of soil respiration under different tree species indicated a slight dependence of soil temperature on soil respiration.

With rise in temperature, the soil respiration is also expected to rise but at a particular threshold level as with high temperature the moisture from the soil also depletes causing respiration to slow down which may be due to enzyme inhibition or physiological processes within plant and microbial cell at high temperature consequently, hindering the microbial activity (Jha and Mohapatra 2011). Thus, we conclude that interactive effects of soil temperature and moisture are majorly regulating the soil respiration rates in our study site. As during monsoon and post-monsoon, soil moisture and temperature both are optimum, whereas during pre-monsoon and winter, either soil temperature is high or soil moisture is very low. In a study by Carlyle and Than (1988), it was observed that soil moisture content was so low that even fluctuations in temperature had no effect on soil respiration suggesting that soil temperature is not independent of soil moisture affecting the soil respiration which supports our study.

Moreover, in the present study, high soil moisture along with optimum temperature during monsoon and post-monsoon (Figs. 1, 3) could have led to an increase in root activity due to percolation of water to the rhizosphere and consequently increased autotrophic respiration (Huxman et al. 2004). A similar finding was seen in China, where maximum soil respiration was observed when soil moisture was at its peak along with optimum soil temperature which indicated that to anticipate the rate of soil respiration, soil temperature alone is not enough (Yang et al. 2007). Another reason could be the wetting of soil during monsoon which might have elevated the process of photosynthesis and provided the direct supply of carbon from aboveground to roots. Another possible reason behind this could be the oxidation of labile soil organic matter by microbial activity (Pandey et al. 2006) which released a large amount of CO_2 by the physical disruption of soil aggregates. This is similar to the study conducted in secondary forest and agroforestry fields in Laguna, Philippines where soil respiration showed seasonal variation and maximum value during wet period. The researchers found that despite no variation in fine root biomass and microbial biomass, the respiration rate varied with seasons (Bae et al. 2013) which confirms our findings.

Conclusions

In general, soil respiration rates under each tree species are largely determined by the interplay between soil moisture and temperature availability. During monsoon and post-monsoon, the respiration rate was high, because soil moisture and temperature both were optimum as compared to winter and pre-monsoon when soil temperature or moisture was low, respectively. Soil respiration was majorly affected by C/N ratio of litter in our study site. Lower C/N ratio accelerated soil respiration rates under native tree species *F. religiosa* than non-native ones suggesting the importance of native species in maintaining the forest ecosystem which will be useful for better management of the ridge forest of Delhi.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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