



## Soil greenhouse gas fluxes from different tree species on Taihang Mountain, North China

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**Abstract.** The objectives of this study were to investigate seasonal variation of greenhouse gas fluxes from soils on sites dominated by plantation (*Robinia pseudoacacia*, *Punica granatum*, and *Ziziphus jujube*) and natural regenerated forests (*Vitex negundo* var. *heterophylla*, *Leptodermis oblonga*, and *Bothriochloa ischcemum*), and to identify how tree species, litter exclusion, and soil properties (soil temperature, soil moisture, soil organic carbon, total N, soil bulk density, and soil pH) explained the temporal and spatial variation in soil greenhouse gas fluxes. Fluxes of greenhouse gases were measured using static chamber and gas chromatography techniques. Six static chambers were randomly installed in each tree species. Three chambers were randomly designated to measure the impacts of surface litter exclusion, and the remaining three were used as a control. Field measurements were conducted biweekly from May 2010 to April 2012. Soil CO<sub>2</sub> emissions from all tree species were significantly affected by soil temperature, soil moisture, and their interaction. Driven by the seasonality of temperature and precipitation, soil CO<sub>2</sub> emissions demonstrated a clear seasonal pattern, with fluxes significantly higher during the rainy season than during the dry season. Soil CH<sub>4</sub> and N<sub>2</sub>O fluxes were not significantly correlated with soil temperature, soil moisture, or their interaction, and no significant seasonal differences were detected. Soil organic carbon and total N were significantly positively correlated with CO<sub>2</sub> and N<sub>2</sub>O fluxes. Soil bulk density was significantly negatively correlated with CO<sub>2</sub> and N<sub>2</sub>O fluxes. Soil pH was not correlated with CO<sub>2</sub> and N<sub>2</sub>O emissions. Soil CH<sub>4</sub> fluxes did not dis-

play pronounced dependency on soil organic carbon, total N, soil bulk density, and soil pH. Removal of surface litter significantly decreased in CO<sub>2</sub> emissions and CH<sub>4</sub> uptakes. Soils in six tree species acted as sinks for atmospheric CH<sub>4</sub>. With the exception of *Ziziphus jujube*, soils in all tree species acted as sinks for atmospheric N<sub>2</sub>O. Tree species had a significant effect on CO<sub>2</sub> and N<sub>2</sub>O releases but not on CH<sub>4</sub> uptake. The lower net global warming potential in natural regenerated vegetation suggested that natural regenerated vegetation were more desirable plant species in reducing global warming.

### 1 Introduction

Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) are three major greenhouse gases (GHG) that contribute to global warming (Lang et al., 2010). Forest soils have been identified as sinks for CH<sub>4</sub> (Tang et al., 2006; Liu et al., 2008; Luo et al., 2012), and sources of CO<sub>2</sub> and N<sub>2</sub>O (Tang et al., 2006; Liu et al., 2008; Peichl et al., 2010; Christiansen et al., 2012). Differences in forest types (Tang et al., 2006; Zheng et al., 2008), successional stages (Law et al., 2001; Peichl et al., 2010), and human activities (Yang et al., 2005; Sharma et al., 2011), such as deforestation and reforestation, have been shown to affect GHG fluxes. Many studies have indicated that tree species are an important determinant of GHG fluxes (Dewar and Cannell, 1992; Grigal and Ohmann, 1992; Borken et al., 2003; Borken and Beese, 2005;

Vesterdal et al., 2008, 2012; Zheng et al., 2008). Vesterdal et al. (2008) found that different tree species planted on the same site were linked with different amounts of soil organic carbon (SOC), especially in forest floor carbon pools. Vesterdal et al. (2012) later pointed out that soil CO<sub>2</sub> effluxes differed significantly among tree species and sites over the year in Denmark. Boroken et al. (2003) reported a strong influence of forest type on the soil CH<sub>4</sub> sink, based on an investigation of natural mature beech forests and mature pine and spruce plantations in two study areas in Germany. On the contrary, Boroken and Beese (2005) observed no differences in soil N<sub>2</sub>O emissions between European beech, Scots pine and Norway spruce forests in two study areas in Germany with distinct climate, N deposition and soils. However, few studies have reported GHG fluxes from different tree species within similar climates and soils (Post and Kwon, 2000; Ladegaard-Pedersen et al., 2005; Berger et al., 2010). Therefore, determining how tree species influence soil CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions are necessary steps in assessing potential impacts of environmental change (Raich and Tufekcioglu, 2000).

The wide range of magnitude and uncertainty in GHG exchanges from soils arises from soil-plant system heterogeneity and from the complex interactions among the physical, chemical, and biological variables controlling their respective production and consumption (Liu et al., 2006; Peichl et al., 2010). CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O exchanges are dependent on a number of parameters that may affect gas diffusivity, soil aeration, and soil microorganisms, such as soil temperature (ST), soil moisture (SM), bulk density (BD), litter layer characteristics, and substrate supply and quality (Campbell and Law, 2005; Davidson et al., 2006; Vose and Bolstad, 2006; Peichl et al., 2010).

Taihang Mountain in northern China has been overexploited for farming, grazing, and timber production. Therefore, most plant communities in the area are in a secondary stage of disturbance following the near complete eradication of primary, broad-leaved deciduous forests (Zhang et al., 2006). Most forests have been converted to shrubs or herbaceous vegetation resulting in a deterioration of their ecological environment, with some areas experiencing desertification and a near complete lack of vegetation (Liu et al., 2010, 2011). In 1999, the Chinese government initiated the Grain-for-Green (GfG) program designed to reduce the deterioration of natural forests and grasslands, increase vegetation coverage on steep slopes, protect water resources, and promote sustainable development in mountainous areas (Zhang et al., 2000). The large scale of afforestation, along with the restoration of natural forests under the GfG program on Taihang Mountain, both substantially affect SOC dynamics (Li et al., 2002; Zhang et al., 2010) and hence the exchange of GHGs between the soil and atmosphere (Zhou et al., 2004).

Understanding the effects of tree species from new plantations and naturally regenerated forests on GHG emissions can provide important information for ecosystem manage-

ment practices and international policies to mitigate greenhouse gas emissions (Canadell and Raupach, 2008; Zhang et al., 2010). However, a comprehensive assessment of GHG fluxes from different types of trees on new plantations and naturally regenerated forests has not been reported in China to date. The objectives of this study were to: (1) investigate the seasonal variation of GHG fluxes from soils planted with different tree species on new plantations and naturally regenerated forests; and (2) identify how tree species, litter exclusion and soil properties (ST, SM, SOC, total N (TN), BD and pH) can help explain the temporal and spatial variation in greenhouse gas fluxes from soils on Taihang Mountain.

## 2 Materials and methods

### 2.1 Site description

The study site is located in Niujiashuang Catchment (area: 9.3 km<sup>2</sup>) in the middle of Taihang Mountain (114°15'50" E, 37°52'44" N), which is situated approximately 50 km southwest of the city of Shijiazhuang, the capital city of Hebei Province in northern China (Fig. 1). The catchment is the site of the Hilly Ecosystem Experimental Station in Taihang Mountain which is run by the Chinese Academy of Sciences. Elevation ranges from 247 to 1040 m a.s.l., with slopes in the catchment ranging from 20 to 45°. The climate is generally dry from October to May and rainy from June to September. Annual precipitation averages 560 mm, ranging from 390 to 750 mm, with nearly 68% occurring between June and September. Annual evaporation averages 1934 mm. The long-term average annual temperature is 13 °C (ranging from −1.6 °C in January to 26.3 °C in July).

Parent materials in the study area are composed primarily of granite, granite porphyry, limestone, sandstone, and shale. Soils in the area are generally classified as mountainous cinnamon soils (Ustalf), which are calcareous soils formed mainly from the weathering of gneissic granitoids, partly by limestone and shale. Soil depth in the study area varies from approximately 20 cm on south-facing slopes to 120 cm on north-facing slopes. Soils are generally poorly stratified with a thin O horizon (0 to 2 cm in thickness) and poorly developed A (3 to 10 cm) and B horizons (20 to 70 cm), and contain abundant gravel. The soils are well-drained and generally nutrient-poor, with a weak capacity to retain fertilizer and water.

Vegetation in the catchment is a mosaic of shrubs, herbs, plantation, deciduous and coniferous forests, and agricultural crops. The naturally regenerated shrub-herb community is dominated by *V. negundo* var. *heterophylla*, *L. oblonga*, *Z. jujuba* var. *spinosa*, *B. ischcemum*, *A. sacrorum*, and *T. japonica*. The planted species are *R. pseudoacacia*, *P. granatum*, and *Z. jujube*, *Diospyros kaki*, *J. regia*, and *Armeniaca sibirica*. *R. pseudoacacia* is widely used in reforestation, forest shelter construction, and various ecological



**Table 1.** General characteristics for six tree species located on Taihang Mountain in Northern China\*.

Site	Elevation (m)	Slope (°)	Slope aspect	Forest type	Age (year)	Height (m)	Understory	Forest coverage (%)	Root biomass (g m <sup>-2</sup> )	Litter biomass (g m <sup>-2</sup> )
<i>Robinia pseudoacacia</i>	469	30	East	Deciduous arbor	20	5.8	1, 2, 3, 4, 6, 8, 11, 13, 14	91.9	3845	569
<i>Vitex negundo</i> var. <i>heterophylla</i>	531	31	South	Deciduous shrub	–	1.6	2, 3, 4, 5, 6, 7, 8, 9, 10	95.2	1266	677
<i>Leptodermis oblonga</i>	493	36	North	Deciduous shrub	–	0.6	2, 3, 4, 7, 10, 11, 12	93.7	1200	650
<i>Punica granatum</i>	489	32	South	Deciduous small arbor	20	3.3	2, 3, 4, 5, 6, 7, 10, 13	77.0	2420	488
<i>Ziziphus jujube</i>	464	30	South	Deciduous small arbor	20	4.6	2, 3, 5, 6, 8, 13, 14, 15, 16	78.3	2000	466
<i>Bothriochloa ischcemum</i>	635	34	North	Perennial herb	–	0.4	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	100.0	922	520

Note: \*: Data are cited from Liu et al. (2010, 2011). Soil properties were measured at 0 to 10 cm depth.

1, *Vitex negundo* var. *heterophylla*; 2, *Artemisia sacrorum*; 3, *Bothriochloa ischcemum*; 4, *Themeda japonica*; 5, *Cleistogenes chinensis*; 6, *Setaria viridis*; 7, *Festuca ovina*; 8, *Rubia cordifolia*; 9, *Dianthus chinensis*; 10, *Dendranthema indicum*; 11, *Bupleurum chinense*; 12, *Euphorbia pekinensis*; 13, *Ziziphus jujuba* var. *spinosa*; 14, *Bidens pilosa*; 15, *Salsola collina*; 16, *Rehmannia glutinosa*

sparingly planted secondary forest and experienced a gradual invasion of *V. negundo* var. *heterophylla* through natural succession. The overstory trees have an average diameter of 4.5 cm at breast height and an average height of 5.8 m.

The *P. granatum* and *Z. jujube* forests were established by local residents in the 1990s, and are distributed primarily in the lands near villages at lower elevation and with gentle slopes. These sites have a long history of human disturbance. Prior to planting, these sites were primarily scrublands, containing species such as *V. negundo* var. *heterophylla* or *L. oblonga*. Since planting, these forests have been generally managed using mineral fertilization (nitrogen (N), phosphorus (P), and potassium (K)), as well as herbicide and pesticide applications. Annual rates of inorganic N, phosphorus pentoxide (P<sub>2</sub>O<sub>5</sub>), and potassium oxide (K<sub>2</sub>O) supplied to *P. granatum* and *Z. jujube* forests have typically averaged approximately 200, 150, and 150 kg ha<sup>-1</sup>, respectively, applied in the fall and 150, 100, and 100 kg ha<sup>-1</sup> applied in the spring (Table 2). Neither fertilizer nor manure was applied during the experiment outlined in this paper. The *P. granatum* trees had an average basal diameter of 6.0 cm, and an average height of 3.25 m. The *Z. jujube* trees had an average diameter at breast height (dbh) of 2.8 cm and an average height of 4.63 m.

The *V. negundo* var. *heterophylla*, *L. oblonga*, and *B. ischcemum* forests have been protected from human disturbance for more than 20 years. *L. oblonga* is accustomed to growing in the shade, whereas *V. negundo* var. *heterophylla* prefers dryness. *B. ischcemum*, a kind of perennial herbage, is found on shaded sites. The mean heights of *V. negundo* var. *heterophylla*, *L. oblonga*, and *B. ischcemum* were 1.60, 0.59, and 0.44 m, respectively. Forest coverage on the sam-

pling plots was generally over 90 %, and on some sites the coverage of *L. oblonga* and *B. ischcemum* reached 100 %.

## 2.2 Measurement of fluxes

Six static chambers were randomly installed on each plot. Three of the chambers were randomly designated to measure the effect of surface litter exclusion (i.e. bare soil or BS treatment), and the remaining three were used as the control (i.e. soil with surface litter or SL treatment). For the BS treatment, litter was removed carefully at least 1 h before each sampling (Liu et al., 2008). Field measurements were conducted biweekly (total of 6 tree species × 2 treatments × 3 replicates × 48 times = 1728) from May 2010 to April 2012.

The static chamber consisted of a permanently installed polyvinyl chloride base (without top and bottom, 30 cm in length, 20 cm in width, and 5 and 15 cm in height on the upper and the lower slopes with slopes in the catchment ranging from 20 to 45°, respectively) with a U-shaped groove at the top edge to hold a mobile polymethyl methacrylate cover box (without bottom, 30 cm × 20 cm × 30 cm). With the lid placed on the base, the groove was filled with water to a depth of 5 cm, which acted as an air seal. A battery-operated fan inside the polymethyl methacrylate box homogenized the air in the chamber. The cover was fitted with a temperature sensor and a three-way sampling stopcock (Liu et al., 2008). Sampling was conducted between 9.00 and 11.00 in the morning. Gas samples (50 mL each) were collected with a 60 mL gas-tight syringe 10, 20, 30 and 40 min after closure through a tube inserted into the chamber headspace. Air samples were transferred from the syringe into a pre-evacuated 150 mL aluminum foil gas-collecting bag (Dalian Delin Gas Packing Co., Ltd, China) in the field. CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O concentrations in the samples were analyzed in

**Table 2.** The main management measures of plantations.

	Fertilizing	Watering	Weeding
<i>Robinia pseudoacacia</i>	No	Watering in the first year of planting to ensure survival	No
<i>Punica granatum</i>	Twice a year (autumn and spring)	Three times a year (flowering, fruiting, and harvesting periods)	Twice a year (summer)
<i>Ziziphus jujube</i>	Twice a year (autumn and spring)	No	Twice a year (summer)

the laboratory within 1 week of collection. An HP 4890 gas chromatograph (Agilent Technologies, Palo Alto, California, USA) equipped with an electron capture detector (ECD) was used for N<sub>2</sub>O detection at 330 °C. A methanizer and a flame ionization detector (FID) were used for CH<sub>4</sub> and CO<sub>2</sub> detection at 200 °C. The gas chromatography configurations and calculation of the fluxes of each gas followed procedures described by Wang and Wang (2003) and Yao et al. (2010). Data from individual collars occasionally had to be discarded if changes in gas concentrations did not follow a constant linear increase or decrease. GHG flux was calculated based on the rate of change in GHG concentration within the chamber, which was estimated as the slope of the linear regression between concentration and time (Liu et al., 2008). All coefficients of determination ( $r^2$  values) for the linear regressions in the study were greater than 0.80 (the success rate of flux measurements was more than 98 % for CO<sub>2</sub> and 85 % for CH<sub>4</sub> and N<sub>2</sub>O).

### 2.3 Calculation of fluxes

Gas flux was estimated using the following equation:

$$J = \rho \cdot \frac{V}{A} \cdot \frac{dc}{dt} \cdot \frac{273}{273 + T} \quad (1)$$

where  $J$  is the flux (mg m<sup>-2</sup> h<sup>-1</sup>),  $\rho$  is the gas density of GHGs, and  $\rho = P/RT$  (g m<sup>-3</sup>),  $P$  is air pressure,  $T$  is the air temperature inside the chamber,  $R$  is the gas constant,  $V$  is the volume of the sampling chamber (m<sup>3</sup>),  $A$  is the bottom area of the sampling chamber (m<sup>2</sup>), and  $dc/dt$  is the ratio of change in the gas concentration ( $c$ ) inside the chamber per unit time ( $t$ ) during the sampling period (m<sup>3</sup> m<sup>-3</sup> h<sup>-1</sup>).  $T$  is the air temperature (°C).

The relationship between ST and soil CO<sub>2</sub> fluxes was modeled by the exponential equation:

$$R = R_0 e^{bT} \quad (2)$$

where  $R$  is the soil CO<sub>2</sub> emission rate (mg m<sup>-2</sup> h<sup>-1</sup>),  $T$  is the ST (°C) at 5 cm depth,  $R_0$  and  $b$  are best-fitting coefficients. For each tree species, a specific exponential relation could be fitted by Eq. (2).  $Q_{10}$  values were used as parameters of temperature sensitivity of soil CO<sub>2</sub> fluxes, based on the equation:

$$Q_{10} = e^{(10b)} \quad (3)$$

The relationship between ST and air temperature was modeled by the following equation:

$$T = aT_a + b \quad (4)$$

where  $T_a$  is the daily air temperature (°C),  $a$  and  $b$  are best-fitting coefficients.

Annual soil CO<sub>2</sub> fluxes were calculated as the sum of the daily soil respiration rates:

$$Y = \sum 24 \times R_0 e^{bT} \quad (5)$$

where  $Y$  is the accumulative soil CO<sub>2</sub> flux (Mg ha<sup>-1</sup> yr<sup>-1</sup>).

Annual soil CH<sub>4</sub> and N<sub>2</sub>O fluxes were determined from the accumulated emission rates between every two consecutive days of measurements by the following equation:

$$Y = \sum_{i=1}^n (X_i + X_{i+1}) / 2 \times (t_{i+1} - t_i) \times 24 \quad (6)$$

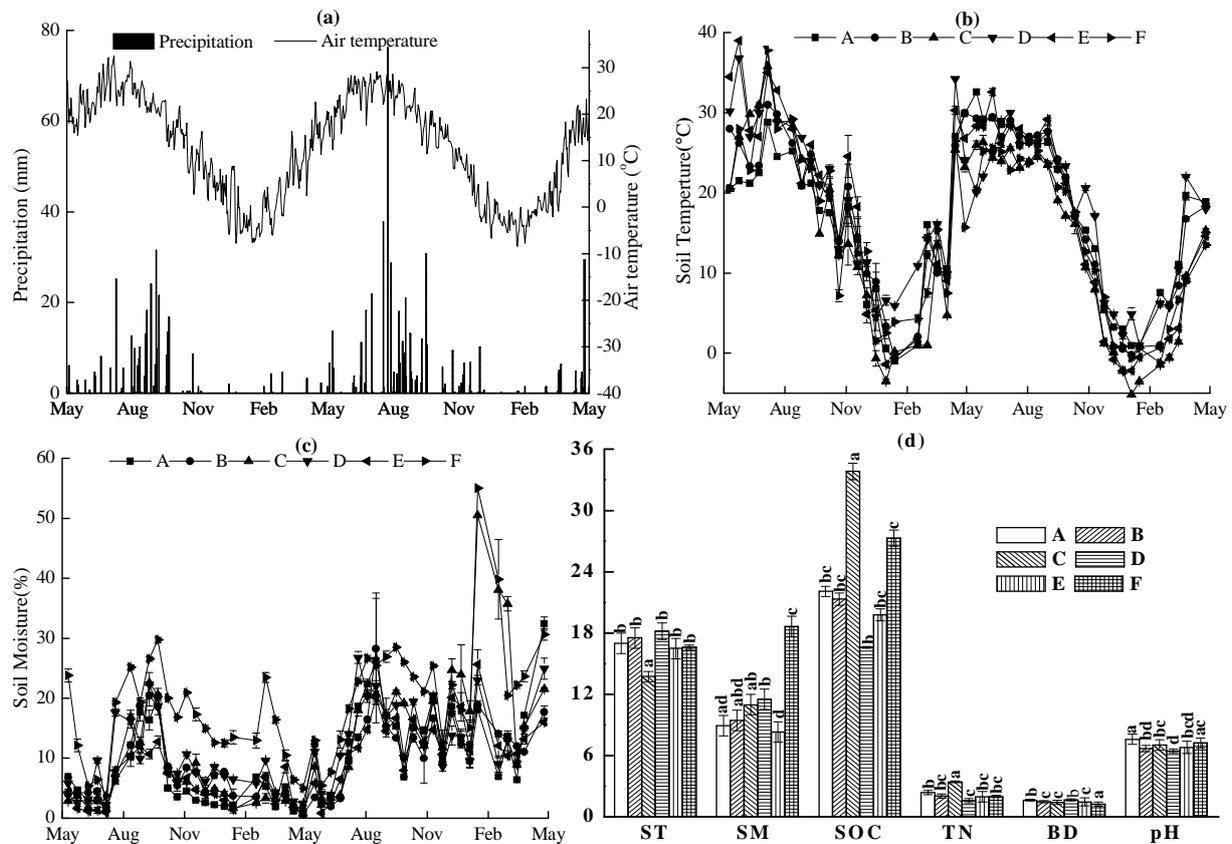
where  $Y$  is the accumulative soil CH<sub>4</sub> or N<sub>2</sub>O flux (kg ha<sup>-1</sup> yr<sup>-1</sup>),  $X$  is the soil CH<sub>4</sub> or N<sub>2</sub>O emission rate (µg m<sup>-2</sup> h<sup>-1</sup>),  $i$  is the  $i$ th measurement, the term of  $(t_{i+1} - t_i)$  is the days between two adjacent measurements, and  $n$  is the total number of measurements performed.

The mean of the coefficients of variation from adjacent sampling dates was applied to the integrated flux estimate. The uncertainty around the integrated flux over the entire year was estimated from the square root of propagated error products (Peichl et al., 2010).

The overall balance of net exchanges of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O constitutes the GWP of a tree species. The global warming potential (GWP) of CH<sub>4</sub> and N<sub>2</sub>O are 21 and 310 times that of CO<sub>2</sub>. Therefore, GWP was estimated by multiplying annual CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O fluxes by 1, 21, and 310, respectively, and summing the results (USEPA, 2012).

### 2.4 Soil temperature and moisture measurements

Alongside GHG flux measurements, gravimetric SM content was determined by collecting soil samples (0.1 kg) within



**Fig. 2.** Seasonal patterns of daily air temperature and precipitation (a), soil temperature at 5 cm depth (b), soil gravimetric moisture (c), and soil properties (d) measured in six tree species on Taihang Mountain from May 2010 to April 2012. The tree species are (A) *Robinia pseudoacacia*, (B) *Vitex negundo* var. *heterophylla*, (C) *Leptodermis oblonga*, (D) *Punica granatum*, (E) *Ziziphus jujube*, and (F) *Bothriochloa ischcemum*. The error bars represent standard errors ( $n = 3$ ). ST: soil temperature ( $^{\circ}\text{C}$ ), SM: soil moisture (%), SOC: soil organic carbon ( $\times 10^3 \text{ mg kg}^{-1}$ ), TN: total N ( $\times 10^3 \text{ mg kg}^{-1}$ ), BD: bulk density ( $\text{g cm}^{-3}$ ), pH: soil pH (in water).

50 cm distance of the chambers at 0 to 10 cm depth. Fresh soil samples were weighed and transported to the laboratory, where they were oven-dried at  $105^{\circ}\text{C}$  for 24 h and weighed again, following which SM content was determined. ST at 5 cm depth was measured with a standard soil thermometer. Climatic data (daily precipitation and daily air temperature) were obtained from a weather station at the Hilly Ecosystem Experimental Station in Taihang Mountain, Chinese Academy of Sciences.

## 2.5 Data analyses

Statistical analyses were performed using the SPSS software package for Windows (Version 18.0, SPSS Inc., Chicago, IL, USA). Data sets were tested for normal distribution by the Kolmogorov-Smirnov test. The differences of soil environmental variables (ST (at 5 cm depth), SM (0–10 cm), SOC (0–10 cm), TN (0–10 cm), BD (0–10 cm), and pH (0–10 cm)) among six tree species, and the impacts of season, surface litter removal, and site under different tree species on GHG fluxes were evaluated using one-way ANOVA followed by a

Tukey multiple-comparison test at  $P < 0.05$ . A paired  $t$  test was performed to examine the difference in GHG fluxes between rainy season and dry season for the same tree species. Simple linear regression was used to evaluate the relationships between soil environmental variables and mean annual GHG fluxes of each static chamber separately. The effect of ST and SM on GHG fluxes was evaluated by multiple linear regression. Stepwise regression was used to test the influence of soil environmental variables on mean annual GHG fluxes.

## 3 Results

### 3.1 Environmental variables

Precipitation over the two years ranged from 317 to 573 mm, which was similar to the long-term average annual rainfall (560 mm). Precipitation showed very strong seasonality, with 77 % occurring during the rainy season (June to September) (Fig. 2a). Mean annual air temperature was  $12.8^{\circ}\text{C}$ , with monthly average temperature values ranging from  $-8.4^{\circ}\text{C}$  (January 2012) to  $32.6^{\circ}\text{C}$  (July 2010) (Fig. 2a). ST in the

top 5 cm showed clear seasonal variation, with monthly low temperatures across the six tree species ranging from  $-5.2$  to  $1.0$  °C and high temperatures ranging from  $31.0$  to  $38.0$  °C (Fig. 2b). Gravimetric SM also varied seasonally, with lows across the six tree species ranging between  $0.6$  and  $3.7$  % and highs ranging from  $28.3$  to  $55.0$  % (Fig. 2c). SM data were consistent with rainfall data and were higher during the rainy season.

*P. granatum* had the highest ST, followed by *V. negundo* var. *heterophylla*, the lowest value was recorded at *L. oblonga*, and there was significant difference between *L. oblonga* and other five tree species ( $P < 0.05$ ) (Fig. 2d). In terms of SM, *B. ischcemum* had the highest value ( $18.6$  %), followed by *P. granatum* ( $11.5$  %), and *Z. jujube* had the lowest value ( $8.3$  %) (Fig. 2d). There were significantly different soil concentrations of SOC and TN ( $P < 0.05$ ) among different tree species, with higher values at the *L. oblonga* and *B. ischcemum* (Fig. 2d). *L. oblonga* had the highest SOC concentration, followed by *B. ischcemum* and *R. pseudoacacia*, and the lowest concentration was found in *P. granatum* (Fig. 2d). As seen with SOC content, the higher TN contents were found at *L. oblonga* and *R. pseudoacacia*, ranging from  $2368.1$  to  $3424.7$  mg kg<sup>-1</sup>, while *P. granatum* had low TN content, with mean value of  $1581.3$  mg kg<sup>-1</sup> (Fig. 2d). *P. granatum* had the highest BD, followed by *R. pseudoacacia*, and *L. oblonga* and *B. ischcemum* had the lowest value. The soil pH ranges from  $6.5$  to  $7.6$  (Fig. 2d).

### 3.2 CO<sub>2</sub> fluxes

CO<sub>2</sub> flux rates averaged across the BS and SL treatments over the two year in *R. pseudoacacia*, *V. negundo* var. *heterophylla*, *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* were on average (mean ± S.E.)  $285.6 \pm 31.1$ ,  $203.9 \pm 25.9$ ,  $119.7 \pm 13.1$ ,  $212.3 \pm 26.1$ ,  $329.2 \pm 41.6$ , and  $171.9 \pm 16.3$  mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>, respectively (Table 3). There were significant differences in annual mean CO<sub>2</sub> fluxes among tree species (Tables 3 and 4). CO<sub>2</sub> emissions from the six tree species were significantly higher during the rainy season ( $P < 0.01$ ) (Fig. 3, Table 3). The seasonality of CO<sub>2</sub> emissions was more pronounced in the control (SL) treatment than in the litter exclusion (BS) treatment across the six tree species (Fig. 3). Removal of the litter layer reduced soil CO<sub>2</sub> emissions from all tree species (Fig. 3, Table 4). CO<sub>2</sub> emissions were significantly higher in the SL treatment than in the BS treatment ( $P < 0.01$ ) (Fig. 3, Table 4). CO<sub>2</sub> emissions from all tree species over the two years showed a significant positive correlation with ST ( $P < 0.01$ ), SM ( $P < 0.01$ ), and their interaction ( $P < 0.01$ ) (Table 5). CO<sub>2</sub> fluxes were significantly positively correlated with SOC and TN when *B. ischcemum* ( $P > 0.05$ ) were excluded, and negatively correlated with BD in *V. negundo* var. *heterophylla* ( $P < 0.05$ ), *L. oblonga* ( $P < 0.01$ ), *P. granatum* ( $P < 0.01$ ), and *B. ischcemum* ( $P < 0.01$ ), while positively correlated with BD in *Z. jujube* ( $P < 0.01$ ) (Table 5). The stepwise

regression analysis showed that a combination of ST, SM, and BD could best predict CO<sub>2</sub> emissions from *R. pseudoacacia* (Table 6), SM and BD, and SM and TN could explain the variation in CO<sub>2</sub> fluxes from *L. oblonga* and *B. ischcemum* observed at a significant level, respectively (Table 6), SOC showed a significant positive correlation with CO<sub>2</sub> fluxes from *V. negundo* var. *heterophylla* and *P. granatum*, and BD was the most important factor for CO<sub>2</sub> emissions from *Z. jujube* (Table 6). With the exception of *R. pseudoacacia* ( $P < 0.01$ ), pH did not show any correlation with the CO<sub>2</sub> fluxes ( $P > 0.05$ ) (Table 5).

### 3.3 CH<sub>4</sub> fluxes

CH<sub>4</sub> flux rates averaged across the BS and SL treatments over the two year from *R. pseudoacacia*, *V. negundo* var. *heterophylla*, *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* were on average (mean ± S.E.)  $-151.9 \pm 20.2$ ,  $-101.3 \pm 21.7$ ,  $-215.1 \pm 74.3$ ,  $-131.5 \pm 30.0$ ,  $-95.0 \pm 15.9$ , and  $-99.1 \pm 15.8$  μg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup>, respectively (Table 3). For all tree species, soils acted as sinks for atmospheric CH<sub>4</sub> (Table 7). Differences in annual mean CH<sub>4</sub> fluxes among tree species were not significant ( $P > 0.05$ ) (Table 4). There were no significant seasonal differences in CH<sub>4</sub> fluxes over the two years for any species (Fig. 4, Tables 3 and 4). Litter removal significantly reduced CH<sub>4</sub> uptakes ( $P < 0.01$ ) (Table 4). With the exception of *L. oblonga* ( $P < 0.01$ ), CH<sub>4</sub> flux rates from all tree species over the two years showed no significant correlation with ST (Table 5). CH<sub>4</sub> flux rates over the two years showed no significant correlation with SM when *R. pseudoacacia* ( $P < 0.01$ ) were excluded (Table 5). CH<sub>4</sub> fluxes showed no correlation with SOC ( $P > 0.05$ ), TN ( $P > 0.05$ ), BD ( $P > 0.05$ ) or pH ( $P > 0.05$ ) (Table 5). However, the stepwise regression analysis showed that a combination of SM, TN and BD, and ST and SOC could best predict CH<sub>4</sub> fluxes from *L. oblonga* and *B. ischcemum*, respectively (Table 6).

### 3.4 N<sub>2</sub>O fluxes

N<sub>2</sub>O flux rates averaged across the BS and SL treatments over the two year from *R. pseudoacacia*, *V. negundo* var. *heterophylla*, *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* were on average (mean ± S.E.)  $-16.8 \pm 8.3$ ,  $-10.0 \pm 5.6$ ,  $-34.4 \pm 12.0$ ,  $-49.5 \pm 22.1$ ,  $25.5 \pm 10.0$ , and  $0.6 \pm 0.3$  μg N<sub>2</sub>O m<sup>-2</sup> h<sup>-1</sup>, respectively (Table 3). Differences in annual mean N<sub>2</sub>O emissions between *L. oblonga* ( $P < 0.01$ ), *P. granatum* ( $P < 0.01$ ), and *Z. jujube*, *P. granatum* ( $P < 0.05$ ) and *B. ischcemum* were significant (Tables 3 and 4). Seasonal shifts in N<sub>2</sub>O emissions were found to be significant (Fig. 5). N<sub>2</sub>O fluxes mainly fluctuated around zero during the dry season (Fig. 5, Table 3). However, the rain initially triggered a positive N<sub>2</sub>O flux, but overall, fluxes were negative during the rainy season (Fig. 5). For all tree species

**Table 3.** Effects of season, tree species on GHG fluxes, soil temperature, and soil moisture (mean  $\pm$  S.E.) of six tree species.

		CO <sub>2</sub> flux (mg CO <sub>2</sub> m <sup>-2</sup> h <sup>-1</sup> )	CH <sub>4</sub> flux ( $\mu$ g CH <sub>4</sub> m <sup>-2</sup> h <sup>-1</sup> )	N <sub>2</sub> O flux ( $\mu$ g N <sub>2</sub> O m <sup>-2</sup> h <sup>-1</sup> )	Soil temperature (°C)	Soil moisture (%)
<i>Robinia pseudoacacia</i>	Rainy season	541.3 $\pm$ 61.2 <sup>a</sup>	-177.4 $\pm$ 38.9	-42.6 $\pm$ 22.0 <sup>b</sup>	24.6 $\pm$ 0.8 <sup>a</sup>	11.9 $\pm$ 1.9
	Dry season	139.7 $\pm$ 16.2 <sup>a</sup>	-139.5 $\pm$ 23.3	-2.6 $\pm$ 1.8 <sup>b</sup>	12.8 $\pm$ 1.7 <sup>a</sup>	8.7 $\pm$ 1.3
	Mean	285.6 $\pm$ 31.1a	-151.9 $\pm$ 20.2	-16.8 $\pm$ 8.3	17.0 $\pm$ 1.4	9.8 $\pm$ 1.1
<i>Vitex negundo</i> var. <i>heterophylla</i>	Rainy season	378.7 $\pm$ 51.6 <sup>a</sup>	-102.0 $\pm$ 52.2	-45.8 $\pm$ 24.5 <sup>b</sup>	25.9 $\pm$ 0.8 <sup>a</sup>	11.9 $\pm$ 1.8
	Dry season	95.7 $\pm$ 17.7 <sup>a</sup>	-100.9 $\pm$ 17.8	9.6 $\pm$ 8.6 <sup>b</sup>	12.7 $\pm$ 1.8 <sup>a</sup>	8.6 $\pm$ 0.9
	Mean	203.9 $\pm$ 25.9ab	-101.3 $\pm$ 21.7a	-10.0 $\pm$ 5.6	17.4 $\pm$ 1.5	9.8 $\pm$ 0.9
<i>Leptodermis oblonga</i>	Rainy season	206.9 $\pm$ 25.9 <sup>a</sup>	-184.0 $\pm$ 49.5	-86.4 $\pm$ 30.0 <sup>a</sup>	24.8 $\pm$ 1.2 <sup>a</sup>	12.9 $\pm$ 1.9
	Dry season	66.8 $\pm$ 9.8 <sup>a</sup>	-232.1 $\pm$ 112.2	-5.8 $\pm$ 4.5 <sup>a</sup>	10.8 $\pm$ 2.7 <sup>a</sup>	11.0 $\pm$ 1.8
	Mean	119.7 $\pm$ 13.1abc	-215.1 $\pm$ 74.3ab	-34.4 $\pm$ 12.0a	15.7 $\pm$ 2.1	11.7 $\pm$ 1.3
<i>Punica granatum</i>	Rainy season	402.0 $\pm$ 57.3 <sup>a</sup>	-190.5 $\pm$ 68.8	-77.0 $\pm$ 27.5	27.1 $\pm$ 0.9 <sup>a</sup>	16.0 $\pm$ 2.2 <sup>a</sup>
	Dry season	108.3 $\pm$ 13.1 <sup>a</sup>	-101.9 $\pm$ 28.7	-34.3 $\pm$ 13.7	14.5 $\pm$ 1.7 <sup>a</sup>	9.9 $\pm$ 1.1 <sup>a</sup>
	Mean	212.3 $\pm$ 26.1cd	-131.5 $\pm$ 30	-49.5 $\pm$ 22.1b	19.0 $\pm$ 1.4	12.0 $\pm$ 1.1
<i>Ziziphus jujube</i>	Rainy season	689.0 $\pm$ 86.5 <sup>a</sup>	-105.9 $\pm$ 37.0	54.9 $\pm$ 27.5 <sup>b</sup>	27.3 $\pm$ 0.9 <sup>a</sup>	9.6 $\pm$ 1.4
	Dry season	137.3 $\pm$ 14.1 <sup>a</sup>	-89.4 $\pm$ 15.1	9.8 $\pm$ 3.6 <sup>b</sup>	12.0 $\pm$ 2.2 <sup>a</sup>	8.7 $\pm$ 1.1
	Mean	329.2 $\pm$ 41.6bcde	-95.0 $\pm$ 15.9bc	25.5 $\pm$ 10.0abc	17.4 $\pm$ 1.8	9.0 $\pm$ 0.9
<i>Bothriochloa ischcemum</i>	Rainy season	322.4 $\pm$ 28.7 <sup>a</sup>	-79.1 $\pm$ 19.0	51.5 $\pm$ 14.8	25.1 $\pm$ 1.1 <sup>a</sup>	19.5 $\pm$ 2.2
	Dry season	89.4 $\pm$ 9.0 <sup>a</sup>	-110.0 $\pm$ 22.2	-27.3 $\pm$ 9.0	10.7 $\pm$ 1.5 <sup>a</sup>	19.1 $\pm$ 1.9
	Mean	171.9 $\pm$ 16.3ae	-99.1 $\pm$ 15.8bd	0.6 $\pm$ 0.3bd	15.8 $\pm$ 1.5	19.3 $\pm$ 1.4

Note: S.E. stands for standard error.

<sup>a</sup> Along the columns denote significance of the impacts of season on GHG fluxes, soil temperature, and soil moisture, Significant impact at  $\alpha < 0.01$ ;

<sup>b</sup> Significant impact at  $\alpha < 0.05$ .

The values within a column that are followed by the same letter are significantly different at an  $\alpha = 0.05$ .

**Table 4.** Significance of the impacts of tree species, litter removal treatment, season, and their interactions on GHG fluxes.

	CO <sub>2</sub> flux	CH <sub>4</sub> flux	N <sub>2</sub> O flux
Tree species	0.000*	0.230	0.000*
Treatment	0.000*	0.000*	0.505
Season	0.000*	0.712	0.219
Tree species $\times$ treatment	0.002*	0.912	0.000*
Tree species $\times$ season	0.000*	0.841	0.001*
Treatment $\times$ season	0.001*	0.427	0.801
Tree species $\times$ treatment $\times$ season	0.056	0.822	0.004*

\* Significant impact at  $\alpha < 0.01$ .

apart from *Z. jujube*, soils acted as sinks for atmospheric N<sub>2</sub>O (Table 7). Litter removal did not have an important effect on N<sub>2</sub>O emissions ( $P > 0.05$ ) (Table 4). N<sub>2</sub>O flux rates were significantly negatively correlated with ST ( $P < 0.05$ ) in *R. pseudoacacia* and SM ( $P < 0.05$ ) in *L. oblonga* (Table 5). N<sub>2</sub>O fluxes were significantly positively correlated with SOC and TN when *B. ischcemum* ( $P > 0.05$ ) were excluded (Table 5). N<sub>2</sub>O fluxes were significantly negatively correlated with BD when *R. pseudoacacia* ( $P > 0.05$ ) and *V. negundo* var. *heterophylla* ( $P > 0.05$ ) were excluded (Table 5). The

stepwise regression analysis showed that a combination of SOC and TN, and SM and TN could best predict N<sub>2</sub>O fluxes from *V. negundo* var. *heterophylla* and *B. ischcemum*, respectively, SOC was the most important factor for N<sub>2</sub>O emissions from *R. pseudoacacia*, *P. granatum* and *Z. jujube*, and N<sub>2</sub>O fluxes from *L. oblonga* were significantly negatively correlated with BD (Table 6). N<sub>2</sub>O fluxes were significantly positively correlated with pH ( $P < 0.01$ ) in *R. pseudoacacia* (Table 5).

### 3.5 Global warming potential

The GWPs of managed vegetation *R. pseudoacacia*, *P. granatum*, and *Z. jujube* were high (16.7–25.6 Mg CO<sub>2</sub>-C equivalent ha<sup>-1</sup> yr<sup>-1</sup>) compared to naturally regenerated vegetation *V. negundo* var. *heterophylla*, *L. oblonga*, and *B. ischcemum* (8.4–15.8 Mg CO<sub>2</sub>-C equivalent ha<sup>-1</sup> yr<sup>-1</sup>) (Table 7).

## 4 Discussion

### 4.1 CO<sub>2</sub>

We found soil CO<sub>2</sub> emissions from managed forest plots to be higher than those from natural forest areas, similar to

**Table 5.** Linear regressions for the relationship between soil properties and GHG fluxes.

		CO <sub>2</sub> flux (mg CO <sub>2</sub> m <sup>-2</sup> h <sup>-1</sup> )	CH <sub>4</sub> flux (μg CH <sub>4</sub> m <sup>-2</sup> h <sup>-1</sup> )	N <sub>2</sub> O flux (μg N <sub>2</sub> O m <sup>-2</sup> h <sup>-1</sup> )
<i>Robinia pseudoacacia</i>	Soil temperature	0.545 <sup>a</sup>	-0.032	-0.217 <sup>b</sup>
	Soil moisture	0.566 <sup>a</sup>	-0.268 <sup>a</sup>	0.020
	Soil temperature × soil moisture	0.764 <sup>a</sup>	0.268	0.219
	Soil organic carbon	0.861 <sup>a</sup>	0.252	0.860 <sup>a</sup>
	Total N	0.654 <sup>b</sup>	0.293	0.642 <sup>b</sup>
	Soil bulk density	0.294	0.500	-0.429
	Soil pH	-0.844 <sup>a</sup>	0.053	0.910 <sup>a</sup>
<i>Vitex negundo</i> var. <i>heterophylla</i>	Soil temperature	0.482 <sup>a</sup>	0.049	-0.187
	Soil moisture	0.510 <sup>a</sup>	-0.084	-0.035
	Soil temperature × soil moisture	0.731 <sup>a</sup>	0.093	0.195
	Soil organic carbon	0.829 <sup>a</sup>	-0.023	0.916 <sup>a</sup>
	Total N	0.729 <sup>a</sup>	-0.004	0.800 <sup>a</sup>
	Soil bulk density	-0.548 <sup>b</sup>	0.280	-0.566
	Soil pH	-0.157	0.400	0.228
<i>Leptodermis oblonga</i>	Soil temperature	0.472 <sup>a</sup>	-0.418 <sup>a</sup>	-0.060
	Soil moisture	0.274 <sup>a</sup>	-0.105	-0.205 <sup>b</sup>
	Soil temperature × soil moisture	0.587 <sup>a</sup>	0.461 <sup>a</sup>	0.229
	Soil organic carbon	0.729 <sup>a</sup>	0.362	0.804 <sup>a</sup>
	Total N	0.683 <sup>b</sup>	0.536	0.712 <sup>a</sup>
	Soil bulk density	-0.701 <sup>a</sup>	-0.321	-0.900 <sup>a</sup>
	Soil pH	0.090	0.342	0.025
<i>Punica granatum</i>	Soil temperature	0.418 <sup>a</sup>	-0.036	-0.114
	Soil moisture	0.534 <sup>a</sup>	-0.193	0.080
	Soil temperature × soil moisture	0.672 <sup>a</sup>	0.195	0.141
	Soil organic carbon	0.973 <sup>a</sup>	0.206	0.953 <sup>a</sup>
	Total N	0.730 <sup>a</sup>	0.342	0.821 <sup>a</sup>
	Soil bulk density	-0.721 <sup>a</sup>	-0.146	-0.936 <sup>a</sup>
	Soil pH	-0.017	-0.260	-0.078
<i>Ziziphus jujube</i>	Soil temperature	0.498 <sup>a</sup>	-0.010	0.167
	Soil moisture	0.328 <sup>a</sup>	-0.266 <sup>b</sup>	0.011
	Soil temperature × soil moisture	0.690 <sup>a</sup>	0.275 <sup>b</sup>	0.177
	Soil organic carbon	0.903 <sup>a</sup>	-0.095	0.891 <sup>a</sup>
	Total N	0.639 <sup>b</sup>	-0.063	0.851 <sup>a</sup>
	Soil bulk density	0.546 <sup>a</sup>	0.131	-0.862 <sup>a</sup>
	Soil pH	-0.467	-0.375	0.317
<i>Bothriochloa ischcemum</i>	Soil temperature	0.532 <sup>a</sup>	0.106	0.118
	Soil moisture	0.313 <sup>a</sup>	-0.041	0.006
	Soil temperature × soil moisture	0.716 <sup>a</sup>	0.107	0.125
	Soil organic carbon	0.437	-0.467	0.378
	Total N	0.448	-0.543	0.405
	Soil bulk density	-0.663 <sup>a</sup>	0.042	-0.863 <sup>a</sup>
	Soil pH	0.183	-0.568	-0.200

<sup>a</sup> Significant correlation at  $\alpha < 0.01$ .<sup>b</sup> Significant correlation at  $\alpha < 0.05$ .

the observations of Iqbal et al. (2009) who reported higher CO<sub>2</sub> fluxes from orchards than from woodland soil in mid-subtropical red soil of southern China. Differences in soil fluxes of greenhouse gases between natural and managed

forests may be attributed to variations in SOC (Young et al., 2005), soil microclimate (Raich and Tufekcioglu, 2000), and below- and above-ground plant metabolism (Campbell and Law, 2005). Iqbal et al. (2009) attributed the higher CO<sub>2</sub> flux

**Table 6.** Stepwise regressions for the relationship between soil properties and GHG fluxes.

		CO <sub>2</sub>		CH <sub>4</sub>		N <sub>2</sub> O	
		<i>r</i> <sup>a</sup>	<i>p</i> <sup>b</sup>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
<i>Robinia pseudoacacia</i>	Soil temperature	0.428	0.021				
	Soil moisture	0.530	0.007				
	Soil bulk density	0.269	0.000				
	Soil pH	–				–0.874	0.000
	Overall model <sup>c</sup>		0.000	–	–		0.000
<i>Vitex negundo</i> var. <i>heterophylla</i>	Soil organic carbon	0.950	0.000			1.819	0.001
	Total N					0.942	0.023
	Overall model		0.001	–	–		0.000
<i>Leptodermis oblonga</i>	Soil moisture	0.533	0.004	–1.338	0.002		
	Total N			0.650	0.029		
	Soil bulk density	–0.482	0.006	–1.319	0.004	–0.900	0.000
	Overall model		0.000		0.003		0.000
<i>Punica granatum</i>	Soil organic carbon	0.973	0.000			0.953	0.000
	Overall model		0.000	–	–		0.000
<i>Ziziphus jujube</i>	Soil organic carbon					0.891	0.000
	Soil bulk density	0.963	0.000				
	Overall model		0.000	–	–		0.000
<i>Bothriochloa ischcemum</i>	Soil temperature			0.699	0.005		
	Soil moisture	0.809	0.000			0.898	0.000
	Soil organic carbon			–0.588	0.012		
	Total N	0.324	0.040			0.267	0.006
	Overall model		0.000		0.005		0.000

<sup>a</sup> The partial regression coefficient (*r*) value in the stepwise regression.

<sup>b</sup> The partial *p* value for the specific factor.

<sup>c</sup> The statistics for the regression model combining all factors that were significant at *p* < 0.01.

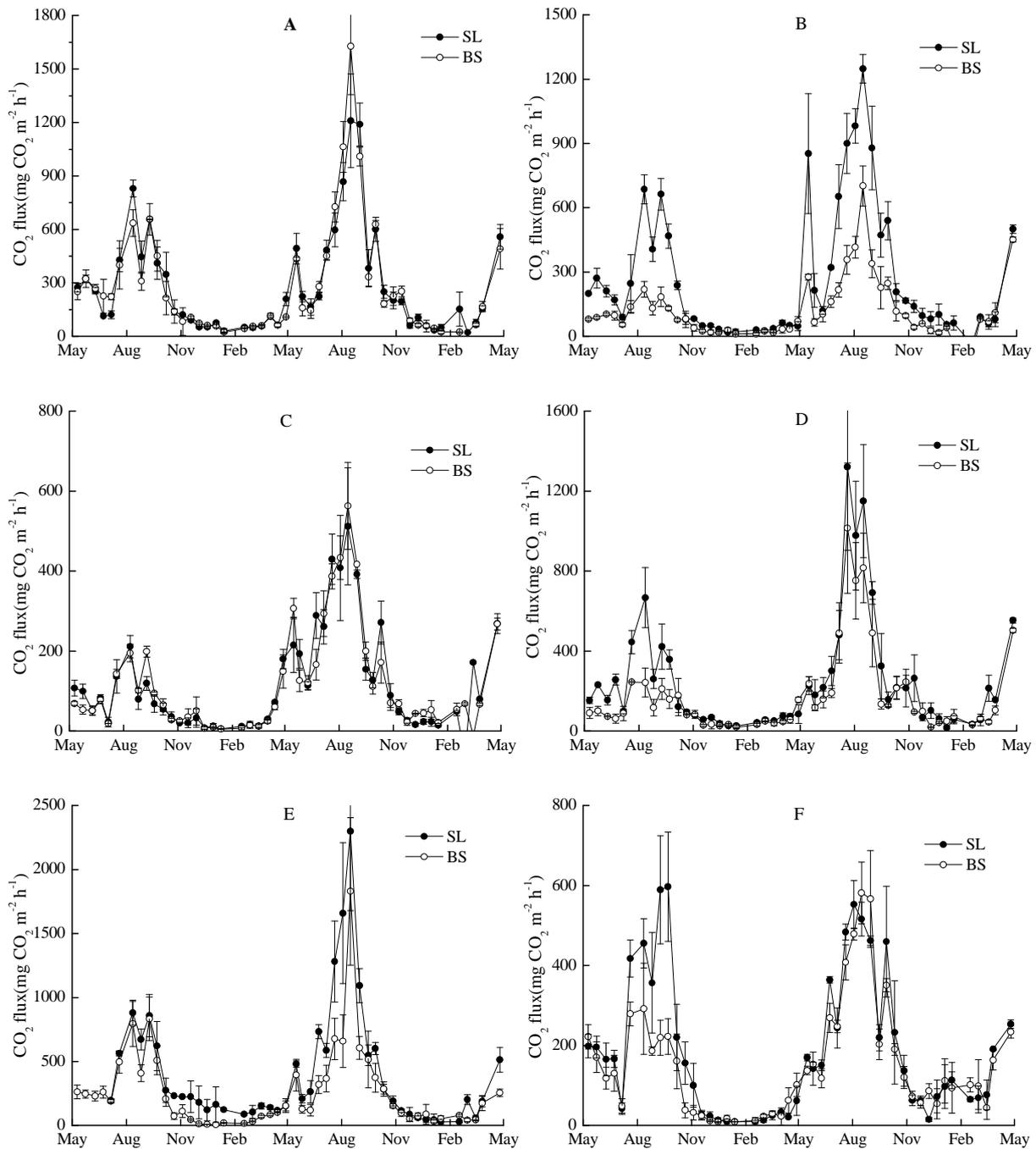
**Table 7.** Effect of tree species on global warming potential (GWP) and contribution of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O to GWP.

Tree species	GWP Mg CO <sub>2</sub> -C eq. ha <sup>–1</sup> yr <sup>–1</sup>	Percent of total contribution to GWP		
		CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O
<i>Robinia pseudoacacia</i>	22.1 ± 0.6	103.1	–1.2	–1.9
<i>Vitex negundo</i> var. <i>heterophylla</i>	15.8 ± 6.5	103.7	–1.1	–2.6
<i>Leptodermis oblonga</i>	8.4 ± 0.5	115.2	–3.6	–11.7
<i>Punica granatum</i>	16.7 ± 1.9	107.5	–1.4	–6.1
<i>Ziziphus jujube</i>	25.6 ± 5.1	98.4	–0.7	2.2
<i>Bothriochloa ischcemum</i>	14.6 ± 1.8	101.6	–1.3	–0.3

from orchards primarily to the change in the quality of the substrate (the substance on which an enzyme acts) as compared to woodland, which had the most resistant and least active carbon pool. In this study, *R. pseudoacacia* and *Z. jujube* had abundant gravel and higher soil macroporosity, furthermore, forest management (e.g. weeding) in *Z. jujube* helped to expose soil to atmosphere and increase the topsoil macroporosity, which therefore facilitated oxygen entrance into the

soil and subsequently aerobic respiration, as well as the enhanced CO<sub>2</sub> emissions (Fang et al., 1998; Chen et al., 2010).

Not surprisingly, we found seasonal changes in CO<sub>2</sub> flux from soils to be positively correlated with ST, with maximum flux rates in the summer months, minimum rates in winter, and intermediate rates in spring and autumn (Fig. 3). Tang et al. (2006) and Liu et al. (2008) obtained similar results. As with Yan et al. (2006) and Peichl et al. (2010), removal of surface litter reduced soil respiration rates in our study by

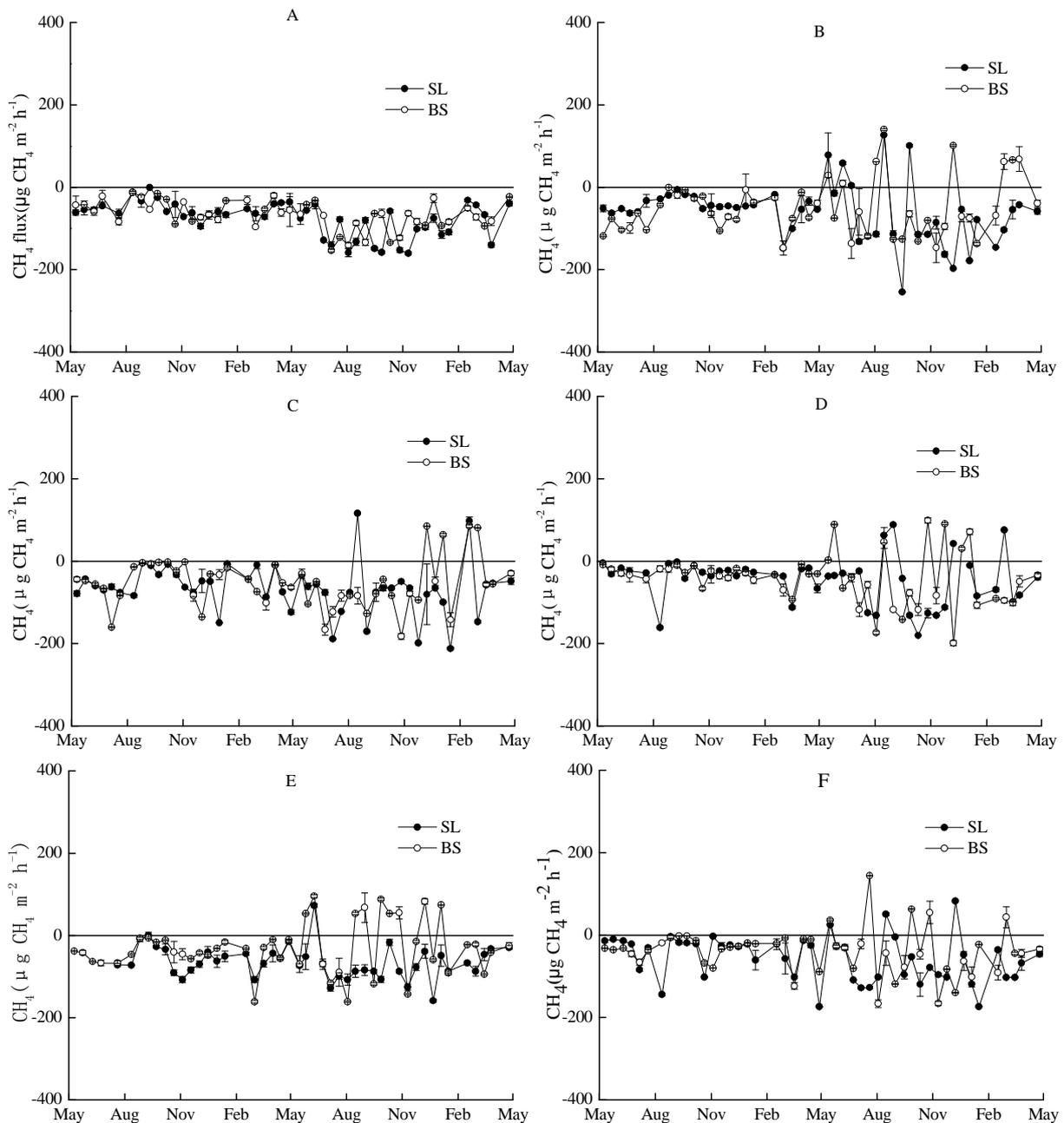


**Fig. 3.** Seasonal patterns of CO<sub>2</sub> flux rates measured in six tree species on Taihang Mountain with (SL) or without (BS) surface litter from May 2010 to April 2012. The tree species are (A) *Robinia pseudoacacia*, (B) *Vitex negundo* var. *heterophylla*, (C) *Leptodermis oblonga*, (D) *Punica granatum*, (E) *Ziziphus jujube*, and (F) *Bothriochloa ischcemum*. The error bars represent standard errors ( $n = 3$ ).

eliminating CO<sub>2</sub> efflux directly from the litter (Fig. 3, Table 4).

CO<sub>2</sub> emissions from all tree species over the two years showed a significant positive correlation with ST, SM, and their interaction (Table 5). The high to moderate CO<sub>2</sub> flux between June and September was observed when ST and SM were high (Fig. 3). Similarly, low to negligible CO<sub>2</sub> fluxes

were observed between October and May, when ST and SM content were low (Fig. 3). Our findings are comparable to numerous field studies that have documented strong relationships between ST, SM and CO<sub>2</sub> fluxes (e.g., Xu and Qi, 2001; Saiz et al., 2006; Tang et al., 2006; Liu et al., 2008; Iqbal et al., 2009; Iqbal et al., 2010; Peichl et al., 2010). ST and SM as the significant predictor of CO<sub>2</sub> fluxes from *R. pseudoacacia*,

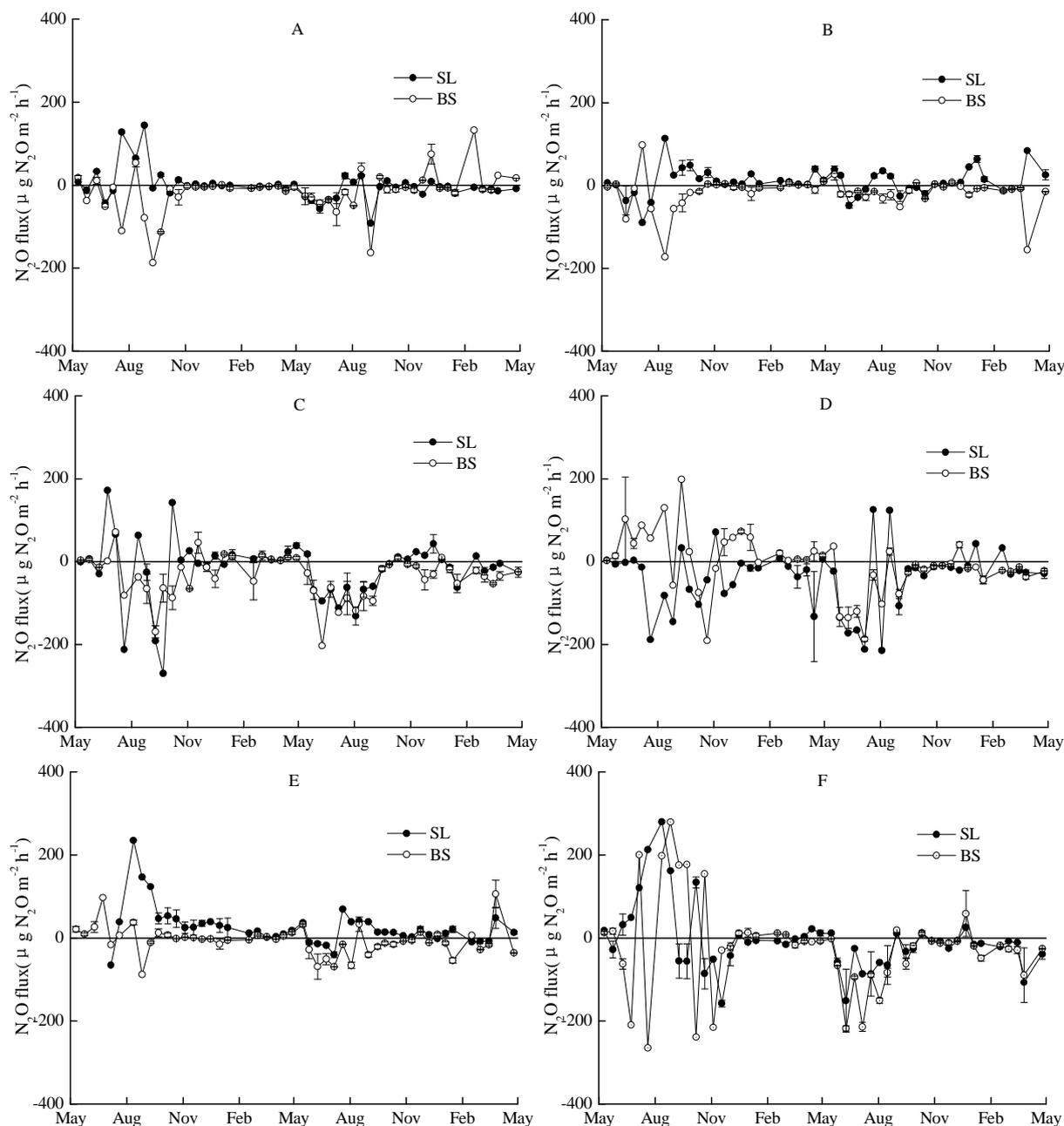


**Fig. 4.** Seasonal patterns of CH<sub>4</sub> flux rates measured in six tree species on Taihang Mountain with (SL) or without (BS) surface litter from May 2010 to April 2012. The tree species are (A) *Robinia pseudoacacia*, (B) *Vitex negundo* var. *heterophylla*, (C) *Leptodermis oblonga*, (D) *Punica granatum*, (E) *Ziziphus jujube*, and (F) *Bothriochloa ischcemum*. The error bars represent standard errors ( $n = 3$ ).

*L. oblonga*, and *B. ischcemum* in stepwise regression may be attributed to their sampling points were located shady. Conversely, the stepwise regression did not reveal the correlation between ST, SM and CO<sub>2</sub> fluxes from *V. negundo* var. *heterophylla*, *P. granatum*, and *Z. jujube*, since the responses in CO<sub>2</sub> emissions to ST or SM were low compared to responses to other changes.

Forest management would destroy soil aggregates and decrease inputs of soil nutrients into soil by clearing under-

growth herbaceous vegetation (i.e. grasses, forbs, and herbs), all these practices led to a lower content of SOC and TN in *P. granatum* and *Z. jujube* than in natural forests (Iqbal et al., 2009). CO<sub>2</sub> fluxes were significantly positively correlated with SOC and TN (Tables 5–6), in contrast to Shrestha et al. (2009) who found no correlation between soil C and N concentrations and CO<sub>2</sub> fluxes. Our results showed that SOC and TN directly or indirectly affect soil CO<sub>2</sub> emissions in a relatively stable environment (Chapman and Thurlow,



**Fig. 5.** Seasonal patterns of  $\text{N}_2\text{O}$  flux rates measured in six tree species on Taihang Mountain with (SL) or without (BS) surface litter from May 2010 to April 2012. The tree species are (A) *Robinia pseudoacacia*, (B) *Vitex negundo* var. *heterophylla*, (C) *Leptodermis oblonga*, (D) *Punica granatum*, (E) *Ziziphus jujube*, and (F) *Bothriochloa ischcemum*. The error bars represent standard errors ( $n = 3$ ).

1996). The variations in topsoil BD probably result from influences of both forest management and variability of topsoil texture. Higher topsoil BD in *P. granatum* could be attributed to forestry management, while BD on *R. pseudoacacia* and *Z. jujube* mainly because of abundant gravel. Positive (Shrestha et al., 2009) as well as negative (Saiz et al., 2006; Shrestha et al., 2009) effects of BD with soil  $\text{CO}_2$  flux have previously been reported. In our study,  $\text{CO}_2$  fluxes were sig-

nificantly negatively correlated with BD when *R. pseudoacacia* and *R. pseudoacacia* were excluded (Tables 5–6).

#### 4.2 $\text{CH}_4$

$\text{CH}_4$  fluxes in the first sampling year were negative across the six species, but fluctuated between positive and negative values when the rain started in the second sampling year. Soil  $\text{CH}_4$  fluxes during the second year of sampling were highly

variable, and did not exhibit any well-defined pattern (Fig. 4). These findings suggest that CH<sub>4</sub> production is switched on and off in relatively dry soils, as has been previously reported (Angel et al., 2012). With increasing precipitation in relatively dry soils, populations of methanogenic organisms increase and methanogenesis is initiated (Mayer and Conrad, 1990) because methanogenesis requires strictly anaerobic conditions (Le Mer and Roger, 2001). However, if soils become aerobic, methanogenic activity is reduced (Inubushi et al., 2003). The soils in our study acted as sinks for atmospheric CH<sub>4</sub> on an annual basis, and the mean CH<sub>4</sub> flux across all of our tree species ( $-139.8 \mu\text{g CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ ) was similar in magnitude to that determined in semi-arid zones in other studies (Wang et al., 2005; Yao et al., 2010). However, we found no significant differences in annual or seasonal CH<sub>4</sub> fluxes among the different tree species (Table 3, Fig. 4), in agreement with several previous studies (e.g. Liu et al., 2008; Shrestha et al., 2009; Christiansen and Gundersen, 2011). In contrast, Degelmann et al. (2009) found coniferous forest soils consume less CH<sub>4</sub> than deciduous forest soils.

CH<sub>4</sub> flux is influenced by soil properties, such as soil diffusivity, pH, BD, and SOC, has been reported in numerous studies (Verchot et al., 2000; Bodelier and Laanbroek, 2004; Merino et al., 2004), but Shrestha et al. (2009) and our study did not observe any response of CH<sub>4</sub> fluxes to single environment factor (Table 5). However, stepwise regression analysis showed that a combination of SM, TN and BD, and ST and SOC could best predict CH<sub>4</sub> fluxes from *L. oblonga* and *B. ischcemum*, respectively (Table 6). This suggested that the relationship between single environmental factor and CH<sub>4</sub> fluxes to be of limited significance, with the combination of multiple environment factors attaining more importance. The lack of dependence of CH<sub>4</sub> fluxes from *R. pseudoacacia*, *V. negundo* var. *heterophylla*, *P. granatum*, and *Z. jujube* on environmental factors suggested that environmental factors other than those measured in this study may have exerted a greater impact on soil CH<sub>4</sub> fluxes, or that insufficient samples were collected to fully capture the higher spatial and temporal variability of these parameters (Tang et al., 2006; Vincent et al., 2006).

### 4.3 N<sub>2</sub>O

Average N<sub>2</sub>O emission rates and total annual emissions recorded in our study were similar to those reported by Yao et al. (2010) for semi-arid zones. N<sub>2</sub>O fluxes were low during winter and high through spring, peaking in summer. Soil served as a N<sub>2</sub>O sink during the drought period, quickly becoming a source of atmospheric N<sub>2</sub>O when the rain began. Soil water status thus appear to be important driving factors for N<sub>2</sub>O capture (Goldberg and Gebauer, 2009; Peichl et al., 2010; Gundersen et al., 2012). Forest soils serving as sinks for atmospheric N<sub>2</sub>O have been reported across a broad spectrum of studies (Chapuis-Lardy et al., 2007; Kellman and Kavanaugh, 2008; Peichl et al., 2010; Eickenscheidt and

Brumme, 2012; Inclán et al., 2012; Ma et al., 2012; Stewart et al., 2012). Rosenkranz et al. (2006) pointed out that the negative N<sub>2</sub>O fluxes were mainly due to very low N availability and high soil C content. They considered aerobic denitrification by heterotrophic nitrifiers as a possible pathway, denitrifying bacteria might use atmospheric N<sub>2</sub>O as an alternative electron acceptor to nitrate when the latter was in short supply. Moreover, Inclán et al. (2012) demonstrated that N<sub>2</sub>O sink was possibly attributed to high total dissolved organic carbon content and high SM, combined with low levels of SM and nitrogen. However, N<sub>2</sub>O sinks have often been overlooked and the driving factors for these sinks are poorly understood (Goldberg and Gebauer, 2009; Stewart et al., 2012).

N<sub>2</sub>O fluxes differed significantly among plant species of *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* (Table 3). In general, the annual N<sub>2</sub>O fluxes differed significantly between species, similar to the results of Shrestha et al. (2009). It is very likely that the differences between N<sub>2</sub>O fluxes from different tree species can be explained by differences in soil properties. SOC and TN were considered as part of the explanation for these differences as reasoned by Beauchamp (1997) and Dobbie et al. (1999). Annual N<sub>2</sub>O fluxes were significantly positively correlated with SOC and TN (Table 5). Stepwise regression analysis showed that SOC could explain the variation in N<sub>2</sub>O fluxes from *R. pseudoacacia*, *P. granatum* and *Z. jujube*, a combination of SOC and TN, SM and TN could best predict N<sub>2</sub>O fluxes from *V. negundo* var. *heterophylla* and *B. ischcemum*, respectively (Table 6). This indicated that soil N<sub>2</sub>O fluxes were mostly limited by SOC and TN, in agreement with previous studies (Nishina et al., 2009; Shrestha et al., 2009; Mapanda et al., 2010; Yao et al., 2010). One important difference between plantations and naturally regenerated forests was the development of an upper organic horizon. According to Borken and Brumme (1997), the contribution of organic layer to N<sub>2</sub>O fluxes can be significant, although the response depends on the type of organic horizons. Under *L. oblonga* and *B. ischcemum*, the higher SOC input on the forest floor increases the nutrient content and improves soil structure. It is possible that the improvement in soil structure and aeration produced conditions that were less anaerobic and subsequently, anaerobic microorganisms were less likely to be present (Merino et al., 2004). This could explain the differences in N<sub>2</sub>O fluxes from other stands. The relatively high annual N<sub>2</sub>O emissions we recorded for the *Z. jujube* were similar to the findings of Shrestha et al. (2009), where the high N<sub>2</sub>O fluxes from the *Z. jujube* forest may be attributed to the missing of organic layer and higher soil TN concentrations from regular fertilization ( $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ). Litter removal did not have an important effect on N<sub>2</sub>O emissions, as found by Tang et al. (2006) and Peichl et al. (2010), suggesting that nitrification and denitrification mainly take place in the mineral soil rather than in the surface litter (Tang et al., 2006). N<sub>2</sub>O fluxes showed no significant correlation with ST or SM (Table 5), which is not uncommon to encounter (Groffman et

al., 2000). However, N<sub>2</sub>O fluxes from *L. oblonga*, *P. granatum*, and *Z. jujube* were significantly positively correlated with BD (Table 5). Soil pH showed no correlation with soil N<sub>2</sub>O fluxes in our study, indicating that slightly alkaline conditions do not support high N<sub>2</sub>O production (Weslien et al., 2009).

#### 4.4 Global warming potential

The combined effect of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O exchanges contribute to the net ecosystem GWP. The average net GWP of naturally regenerated and managed forest was 12.9 and 21.5 Mg CO<sub>2</sub>-C equivalent ha<sup>-1</sup> yr<sup>-1</sup>, respectively (Table 7). Dalal and Allen (2008) reported a decrease in GWP in natural forest ecosystems, mostly as CO<sub>2</sub> sinks in plant biomass, microbial biomass, and soil C. The lower net GWPs of natural vegetation suggest that GWP can be minimized through preservation or restoration of existing ecosystems. In terms of GWP, the relative contribution of CO<sub>2</sub> on net GWP was 104.9%, and the contribution of CH<sub>4</sub> and N<sub>2</sub>O was -1.6 and -3.4%, respectively (Table 7). CO<sub>2</sub> was the overwhelmingly dominant GHG in all tree species studied, and CH<sub>4</sub> and N<sub>2</sub>O sinks had limited impacts on each individual GHG and net GWP of the three GHGs combined.

#### 4.5 Forest management

Forest management practices include fertilization, irrigation, and weeding. In the local Taihang Mountain area, the typical forest management practices of *R. pseudoacacia*, *P. granatum*, and *Z. jujube* are given in Table 2. Forest management of plantation has an obvious effect on GHG emissions by changing soil hydrothermal condition, soil nutrient content, and soil structure (Waterworth and Richards, 2008). Haynes and Gower (1995) showed that the addition of mineral fertilizer (N, P, K, Ca, Mg, S) induced a decrease in soil respiration and fine root production of a coniferous forest soil. Weeding loosens the soil, improves soil aeration, increases the exposure of soil organic matter and speeds up organic matter oxidation, intensifying CO<sub>2</sub> emission from the soil to the atmosphere (Jabro et al., 2008). In arid and semi-arid regions, Irrigation increases CO<sub>2</sub> emission from the soil surface to the atmosphere by changing soil temperature and soil moisture (Jabro et al., 2008). In this study, no control experiments were set up to evaluate the impact of management practices on soil GHG fluxes, hence it is unknown whether the difference of GHG fluxes between *P. granatum* and *Z. jujube* is caused by tree species or by forest management. It is recommended that the impact of forest management on GHG emissions from *P. granatum* and *Z. jujube* be explored in future study. Management practices were not implemented in *R. pseudoacacia* forest except for the first year of planting (Table 2). Tree species differences lead to the differences in GHG emissions among *R. pseudoacacia*, *P. granatum*, and *Z. jujube*. Different tree species differ in productivity, litter

quality and quantity, canopy structure, and nitrogen deposition, eventually lead to large differences in soil GHG emissions (Oostra et al., 2006).

## 5 Conclusions

Soil CO<sub>2</sub> emissions from all tree species were significantly affected by ST, SM, and their interaction. CO<sub>2</sub> emissions also demonstrated clear seasonal patterns, with fluxes being significantly higher during the warm rainy season than during the cool dry season. However, soil CH<sub>4</sub> and N<sub>2</sub>O fluxes were not significantly correlated with ST, soil SM, or their interaction, and no significant seasonal differences were detected. SOC and TN were significantly positively correlated with CO<sub>2</sub> and N<sub>2</sub>O fluxes, BD was significantly positively correlated with CO<sub>2</sub> fluxes and negatively correlated with N<sub>2</sub>O fluxes, while pH did not correlate with CO<sub>2</sub> and N<sub>2</sub>O emissions. Soil CH<sub>4</sub> fluxes showed no dependency on SOC, TN, BD or soil pH. Soil surface litter removal resulted in significant decreases in CO<sub>2</sub> emissions and CH<sub>4</sub> uptakes, but had no significant influence on N<sub>2</sub>O fluxes.

For all six tree species, soils acted as sinks for atmospheric CH<sub>4</sub>. With the exception of *B. ischcemum*, soils acted as sinks for atmospheric N<sub>2</sub>O. Tree species significantly affected CO<sub>2</sub> and N<sub>2</sub>O fluxes but not CH<sub>4</sub> uptakes, with higher rates from managed forests than that from naturally regenerated forests. GHG emission potentials evaluated for different tree species indicated the net GWPs were lower in naturally regenerated vegetation, suggesting that natural vegetation is more desirable in reducing global warming. Enhanced GHG fluxes between soils and the atmosphere in managed forests suggest that the soil-atmospheric GHG fluxes in forests on Taihang Mountain may increase further if the large areas of secondary forests are destroyed. Thus, preservation or restoration of existing ecosystems should be the primary goal of carbon sequestration.

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