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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 variance 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 through April 2012. Soil CO₂ 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 CO₂ emissions demonstrated a clear seasonal pattern, with fluxes significantly higher during the rainy season than during the dry season. Soil CH₄ and N₂O fluxes were not significantly correlated with soil temperature, soil moisture, or their interaction, and no significant seasonal differences were detected. Soil CO₂ and N₂O fluxes were significantly correlated with soil organic carbon, total N, and soil bulk density, while soil pH was not correlated with CO₂ and N₂O emissions. Soil CH₄ fluxes did not display pronounced dependency on soil organic carbon, total N, soil bulk density, and soil pH. Removal of surface litter resulted in significant decreases in CO₂ emissions and CH₄ uptakes, but had no significant influence on N₂O fluxes. Soils in six tree species acted as sinks for atmospheric CH₄. With the exception of *Ziziphus jujube*, Soils in all sites acted as sinks for atmospheric N₂O. Tree species had a significant effect on CO₂ and N₂O fluxes but not on CH₄ 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.

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1 Introduction

Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are three major greenhouse gases (GHG) that contribute to global warming (Lang et al., 2010). Forest soils have been identified as significant sinks for CH₄ (Liu et al., 2008; Luo et al., 2012; Tang et al., 2006), and significant sources of CO₂ and N₂O (Christiansen et al., 2012; Liu et al., 2008; Peichl et al., 2010; Tang et al., 2006). 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 (Sharma et al., 2011; Yang et al., 2005), such as deforestation and reforestation, have been shown to affect GHG fluxes. Many studies indicated that tree species is an important determinant of GHG fluxes (Borken et al., 2003; Borken and Beese, 2005; Dewar and Cannell, 1992; Grigal and Ohmann, 1992; Vesterdal et al., 2008, 2012; Zheng et al., 2008). Vesterdal et al. (2008) indicated that different tree species planted within the same sites have different amounts of soil organic carbon (SOC), especially in forest floor carbon pools. Vesterdal et al. (2012) reported that soil CO₂ effluxes differed significantly among tree species and sites over the year in Denmark. Borken et al. (2003) reported soil CH₄ uptake from natural mature beech forests and from mature pine and spruce plantations in two study areas of Germany with distinct climate and soils, and found a strong impact of forest type on the soil CH₄ sink. Borken and Beese (2005) reported soil N₂O emission from European beech, Scots pine and Norway spruce forests in two study areas of Germany with distinct climate, N deposition and soils, and found tree species had no effect on N₂O emissions. However, few studies reported GHG fluxes of different tree species within similar climates and soils (Berger et al., 2010; Ladegaard-Pedersen et al., 2005; Post and Kwon, 2000). Therefore, identifying how tree species influence soil CO₂, CH₄, and N₂O emissions and determining their effects on emission rates are necessary steps in assessing potential impacts of environmental change (Raich and Tufekcioglu, 2000).

Taihang Mountain in Northern China has been overused for farming, grazing, and timber production. Therefore, most plant communities in the area are in a secondary

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stage of disturbance following the near complete eradication of primary, broad-leaved deciduous forests (Zhang et al., 2006). Most forests were 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 GfG requires that all cropland cultivated on the mountainous area with a slope higher than 25° be returned to forest or pastureland. The farmers participating in the GfG program will be compensated with free grain and cash, and the seedlings were also provided by the government (Zhou et al., 2009). A variety of strategies including fencing of natural forests, planting of trees and grasses, afforestation by aerial seeding, restricting access to protected areas, and integrated management of small watersheds are all key to promoting ecosystem diversity, preserving native species, and enhancing ecological services.

The large scale of afforestation and natural regenerated forests restoration under the GfG program can substantially affect SOC dynamics (Li et al., 2002; Zhang et al., 2010) and exchanges of GHG between the soil and atmosphere (Zhou et al., 2004). Understanding the effects of tree species from new plantation and natural regenerated forests on GHG emissions can provide important information for ecosystem management practices and international policies on greenhouse gas emissions mitigation (Canadell and Raupach, 2008; Zhang et al., 2010). However, so far there has not been a comprehensive assessment of the changes in GHG fluxes from tree species of new plantation and natural regenerated forests. The wide range in magnitude and uncertainty in GHG exchanges from soils arises from soil-plant system heterogeneity and from the complex interactions which occur among the physical, chemical, and biological variables controlling their respective production and consumption processes (Liu et al., 2006; Peichl et al., 2010). CO₂, CH₄, and N₂O exchanges are more dependent

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on a number of parameters that may affect gas diffusivity and soil aeration, such as soil temperature, soil moisture, bulk density, litter layer characteristics, and substrate supply and quality (Ball et al., 1997; Campbell and Law, 2005; Davidson et al., 2006; Dong et al., 1998; Landsberg and Gower, 1997; Peichl et al., 2010; Raich and Schlesinger, 1992; Smith et al., 2003; Vose and Bolstad, 2006). The objectives of this study were (1) to investigate seasonal variation of GHG fluxes from soils under different tree species of new plantation and natural regenerated forests, and (2) to identify how tree species, litter exclusion, and soil properties (soil temperature, soil moisture, SOC, total N, soil bulk density, and soil pH) can help explain the temporal and spatial variance of greenhouse gas fluxes from soils on Taihang Mountain.

2 Materials and methods

2.1 Site description

The study site is located in Niujiazhuang Catchment (area: 9.3 km²) 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 administered 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

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the weathering of gneissic granitoids, partly by limestone and shale. Ustalfs are Alfisols that have an ustic moisture regime, have chroma too high for Aqualfs or do not experience aquic conditions within 50 cm of the mineral soil surface for extended periods in normal years, and have a frigid, mesic, isomesic, or warmer temperature regime (Soil Survey Staff, 1999). 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 containing abundant gravel. The soils are well-drained and generally nutrient poor, with a weak capacity to retain fertilizer and water. General soil properties are listed in Table 1.

The vegetation in the catchment is a mosaic of shrubs, herbs, plantation, deciduous and coniferous forests, and agricultural crops. The natural 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 were *R. pseudoacacia*, *P. granatum*, and *Z. jujube*, *Diospyros kaki*, *J. regia*, and *Armeniaca sibirica*. *R. pseudoacacia* is the plant species widely used in reforestation, shelter forest construction, and various ecological projects in China. Economic forests had great levels of vegetation cover in the GfG program in China because it could bring huge economic interests to local farmers, and *P. granatum* and *Z. jujube* are typical tree species planted on Taihang Mountain. *V. negundo* var. *heterophylla*, *L. oblonga*, and *B. ischcemum* are representative natural regenerated vegetation on Taihang Mountain. Therefore, as representative tree species, *R. pseudoacacia*, *P. granatum*, *Z. jujube*, *V. negundo* var. *heterophylla*, *L. oblonga*, and *B. ischcemum* were selected to represent both natural regenerated and managed vegetation in the region. One sampling plot (20 m × 20 m) was randomly placed in each tree species to be the representative of that vegetation. The sampling plots of *P. granatum* and *Z. jujube* forests were managed as usual using mineral fertilization (N, P, and K), herbicide, and pesticide. The dominant species and the main characteristics for each of the plots are listed in Table 1.

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The *R. pseudoacacia* forests, the most common forest in middle Taihang Mountain, developed from a sparse planted secondary forest and was experiencing a gradual invasion of *V. negundo* var. *heterophylla* through natural succession. The overstory trees had 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 because they are easily accessible by nearby villagers. Prior to planting, these sites were primarily scrublands, containing species such as *V. negundo* var. *heterophylla* or *L. oblonga*. Since planting, these forests are generally managed using mineral fertilization (N, P, and K), as well as herbicide and pesticide applications. Annual rates of inorganic N, P₂O₅, and K₂O supplied to *P. granatum* and *Z. jujube* forests typically average approximately 200, 150, and 150 kg ha⁻¹, respectively, applied in the fall and 150, 100, and 100 kg ha⁻¹ applied in the spring. 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 yr. *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. Canopy coverage on the sampling plots was generally over 90 %, and on some sites the coverage of *L. oblonga* and *B. ischcemum* reached 100 %.

2.2 Flux measurement

Six static chambers were randomly installed within each plot. Three of the chambers were randomly designated to measure the effect of surface litter exclusion (i.e., the 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 \times 2 treatment \times 3 replicates \times 48 times = 1728) from May 2010 to April 2012.

5 Fluxes of GHG were measured with the use of static chamber and gas chromatography techniques (Wang and Wang, 2003). 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, 10 30 cm \times 20 cm \times 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). 15 Sampling was conducted between 9:00 and 11:00 a.m. Gas samples were collected with a 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. CO₂, CH₄, and N₂O concentrations of the samples were analyzed 20 in 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 N₂O detection at 330 °C. A methanizer and a flame ionization detector (FID) were used for CH₄ and CO₂ detection at 200 °C. The gas chromatography configurations and calculation of the fluxes of each gas followed procedures described 25 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 deter-

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mination (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 CO₂ and 85 % for CH₄ and N₂O).

Gas flux was estimated using the following equation:

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

where J is the flux (mg m⁻² h⁻¹), ρ is the gas density of GHGs, and $\rho = P/RT$ (g m⁻³), 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 (cm³), A is the bottom area of the sampling chamber (cm²), dc/dt is the ratio of change in the gas concentration (c) inside the chamber per unit time (t) during the sampling period (m³ m⁻³ h⁻¹). T is the air temperature (°C).

2.3 Soil temperature and moisture measurements

Simultaneous with soil respiration measurements, gravimetric soil moisture content was determined by collecting soil samples close to the chambers at 0 to 10 cm depth. Fresh soil samples were weighed and transported to the lab, where they were oven-dried at 105 °C for 24 h, weighed again, and soil moisture content was determined. Soil temperature 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.

2.4 Data analyses

GHG fluxes, soil temperature, and soil moisture for both the BS and SL treatments were taken as the average of the three replicates on each sampling day. Multiple comparisons analysis was used for the difference of vegetation and soil characteristics of

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different tree species. Multiple comparisons between classes were made using Duncan's multi-range test in cases where data had a significantly non-normal distribution. Unless otherwise indicated, an alpha of 0.05 was used for significance tests. Univariate analysis of variance was used to test the impacts of season, surface litter removal, and tree species on GHG fluxes. Multiple linear regression analysis was used for the relationship between soil temperature, soil moisture, SOC, total N, soil bulk density, soil pH, and GHG fluxes. Statistical procedures were conducted using SPSS 13.0 (SPSS Inc., Chicago, IL). Figures were conducted using Origin 8.0 (OriginLab, Corp., Northampton, MA).

To integrate GHG fluxes from individual daily measurements to annual averages, the mean of daily flux estimates from three adjacent sampling dates was multiplied by the number of days in the period between the two sampling dates to calculate the total flux for the respective time period (Peichl et al., 2010). The mean of the coefficients of variation from adjacent sampling dates was applied on 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 global warming potential (GWP) of CH₄ and N₂O are 21 and 310 times that of CO₂. Therefore, GWP was estimated by multiplying annual CO₂, CH₄, and N₂O fluxes by 1, 21, and 310, respectively, and summing the results (USEPA, 2012).

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 had very strong seasonality, with about 77 % occurring during the rainy season (June–September) (Fig. 2a). Mean annual air temperature was 12.8 °C, with monthly average temperature values ranging from −8.4 (January 2012) to 32.6 °C (July 2010) (Fig. 2a). Soil temperature 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 soil moisture also varied seasonally with lows across the six tree species ranging between 0.6 and 3.7% and highs ranging from 28.3 and 55.0% (Fig. 2c). Soil moisture data were consistent with rainfall data and were higher during the rainy season than during the dry season.

3.2 CO₂ fluxes

Average CO₂ flux rates (mean \pm S.E.) both in the BS and SL treatment over the two years in *R. pseudoacacia*, *V. negundo* var. *heterophylla*, *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* averaged 285.57 ± 31.05 , 203.85 ± 25.88 , 119.73 ± 13.06 , 212.27 ± 26.14 , 329.19 ± 41.58 , and 171.92 ± 16.30 mg CO₂ m⁻² h⁻¹, respectively (Table 2). There were significant differences on annual mean CO₂ fluxes among tree species (Tables 2, 3). CO₂ emissions at all six sites were significantly higher during the rainy season than during the dry season ($p < 0.01$) (Fig. 3, Tables 2–4). The seasonality of CO₂ emissions was more pronounced in the control (SL) treatment than in the litter exclusion (BS) treatment at the six sites (Fig. 3). The removal of the litter layer reduced soil CO₂ emissions from all tree species (Fig. 3, Tables 3, 4). CO₂ emissions were significantly higher in the SL treatment than that in the BS treatment ($p < 0.01$) (Table 3). CO₂ emissions from all tree species over the two years showed a significant correlation with soil temperature ($p < 0.01$), soil moisture ($p < 0.01$), and their interaction ($p < 0.01$) (Table 5). CO₂ fluxes at six sites were significantly correlated with SOC and total N when *B. ischcemum* ($p > 0.05$) were excluded (Table 5), and with soil bulk density when *R. pseudoacacia* ($p > 0.05$) were excluded (Table 5). With the exception of *R. pseudoacacia* ($p < 0.01$), soil pH was not correlated with the CO₂ fluxes ($p > 0.05$) (Table 5). The overall balance of net exchange of CO₂, CH₄, and N₂O constitutes the GWP of a tree species. The net GWPs of managed vegetation *R. pseudoacacia*, *P. granatum*, and *Z. jujube* were high (16.69 – 27.63 Mg CO₂-C equivalent ha⁻¹ yr⁻¹) com-

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pared to natural regenerated vegetation *V. negundo* var. *heterophylla*, *L. oblonga*, and *B. ischcemum* (8.44–15.62 Mg CO₂-C equivalent ha⁻¹ yr⁻¹) (Table 6).

3.3 CH₄ fluxes

Average CH₄ flux rates (mean ± S.E.) both in the BS and SL treatment over the two years from *R. pseudoacacia*, *V. negundo* var. *heterophylla*, *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* averaged -151.85 ± 20.16 , -101.28 ± 21.72 , -215.06 ± 74.32 , -131.47 ± 29.97 , -94.95 ± 15.87 , and -99.08 ± 15.83 μg CH₄ m⁻² h⁻¹, respectively (Table 2). Soils in all sites acted as sinks for atmospheric CH₄ (Table 6). Differences in annual mean CH₄ fluxes among tree species were not significant ($p > 0.05$) (Tables 2, 3).

There were no significant seasonal differences in CH₄ fluxes at all six sites over the two years (Fig. 4, Tables 2–4). The litter removal treatment had significant effect on CH₄ flux rates from *R. pseudoacacia* ($p < 0.01$), *V. negundo* var. *heterophylla* ($p < 0.05$), and *Z. jujube* ($p < 0.01$) (Tables 3, 4). With the exception of *L. oblonga* ($p < 0.01$), CH₄ flux rates from all tree species over the two years showed no significant correlation with soil temperature (Table 5). CH₄ flux rates across all tree species over two sampling years showed no significant correlations with soil moisture when *R. pseudoacacia* ($p < 0.01$) and *V. negundo* var. *heterophylla* ($p < 0.01$) were excluded (Table 5). CH₄ fluxes at six sites were not correlated with SOC ($p > 0.05$), total N ($p > 0.05$), soil bulk density ($p > 0.05$), and soil pH ($p > 0.05$) (Table 5).

3.4 N₂O fluxes

Average N₂O flux rates (mean ± S.E.) across the BS and SL treatments over two sampling years from *R. pseudoacacia*, *V. negundo* var. *heterophylla*, *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* averaged -16.76 ± 8.34 , -10.01 ± 5.58 , -34.38 ± 12.00 , -49.45 ± 22.11 , 25.47 ± 9.99 , and 0.60 ± 0.34 μg N₂O m⁻² h⁻¹, respectively (Table 2). Differences in annual mean N₂O emissions between *L. oblonga* ($p < 0.01$), *P. granatum* ($p < 0.01$), and *Z. jujube*, *P. granatum* ($p < 0.05$) and *B. ischce-*

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mum were significant (Table 2). During the dry season, a slightly negative N₂O fluxes at six sites between soil and atmosphere did either increase or decrease from one fortnight to the next (Fig. 5, Table 2). During the rainy season, N₂O fluxes at six sites were negative, while became almost zero and even positive once the rain started (Fig. 5).

5 Soils in all sites acted as sinks for atmospheric N₂O when *Z. jujube* was excluded (Table 6). With the exception of *R. pseudoacacia* ($p < 0.01$), *V. negundo* var. *heterophylla* ($p < 0.05$), and *P. granatum* ($p < 0.01$), litter removal over two years did not have an important effect on N₂O emission ($p > 0.05$) (Tables 3, 4). N₂O flux rates showed no significant correlation with soil temperature when *B. ischcemum* ($p < 0.05$) were excluded (Table 5). Soil N₂O flux rates at all six sites showed no significant correlation with soil moisture (Table 5). N₂O fluxes at six sites were significantly correlated with SOC and total N when *B. ischcemum* ($p > 0.05$) were excluded (Table 5). N₂O fluxes from *L. oblonga* ($p < 0.01$), *P. granatum* ($p < 0.01$), and *Z. jujube* ($p < 0.01$) were significantly correlated with soil bulk density (Table 5). N₂O fluxes at six sites were not
10 correlated with soil pH when *R. pseudoacacia* ($p < 0.01$) were excluded (Table 5).
15

4 Discussion

4.1 CO₂

The average CO₂ flux rates at six sites suggested that soil CO₂ emissions varied with plant species, this is similar to the observations made by Raich and Schlesinger (1992), Raich and Tufekcioglu (2000), Wang et al. (2006), and Iqbal et al. (2009a). Such findings suggested that plant species played a significant role in soil CO₂ fluxes, and therefore changes in plant species had the potential to modify the responses of soils to environmental changes (Wang et al., 2006). The mean CO₂ fluxes in this study ranged from 119.73 mg CO₂ m⁻² h⁻¹ (*L. oblonga*) to 329.19 mg CO₂ m⁻² h⁻¹ (*Z. jujube*). The
20 CO₂ fluxes were consistently low over two years in *L. oblonga* similar to the undisturbed forest, and consistently high in *Z. jujube* similar to the managed forest. In order to quan-
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5 tify the soil CO₂ fluxes between disturbed and natural vegetation in midsubtropical red soil of Southern China, Iqbal et al. (2009a) measured CO₂ emissions from paddy, orchard, upland, and woodland, and found that CO₂ fluxes from orchard were higher compared to woodland soil. Liu et al. (2008) also reported that CO₂ effluxes from orchard were significantly higher than those from pine forest. Differences in soil fluxes of greenhouse gases among natural and managed forest may be attributed to variations in SOC (Young et al., 2005), soil microclimate (Raich and Tufekcioglu, 2000), and below- and aboveground plant metabolism (Campbell and Law, 2005). Iqbal et al. (2009a) attributed the higher CO₂ flux from orchard mainly to the change in the quality of the substrate as compared to woodland, the woodland had the highest resistant carbon pool and lowest active carbon pool. The highest CO₂ fluxes occurred in the *Z. jujube*, which suggested that the large increases in CO₂ fluxes from these soils were the result of weeding, mineral fertilization and manure application, the mineral fertilization and manure application every spring increased C and N contents of soils, changed soil chemical element composition, affected easily-decomposed SOC contents, and thus affected soil respiration (Verburg et al., 2004). CO₂ fluxes in the *R. pseudoacacia* were second highest among the tree species probably because the *R. pseudoacacia* type contains *V. negundo* var. *heterophylla* in the understory, which led to a longer period of active photosynthesis and more root biomass in this type (Campbell and Law, 2005; Wang et al., 2006).

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25 Seasonal changes in CO₂ flux from soils at all sites were correlated with soil temperature – maximum flux rates occurred during the summer months, minimum rates occurred in the winter months, and intermediate rates occurred during the spring and autumn months (Fig. 3). This is similar to the results of Liu et al. (2008) and Tang et al. (2006). The high soil CO₂ flux rates observed during the summer months may have been due to enhanced root respiration resulting from active root growth and increased microbial respiration associated with high soil temperature (Iqbal et al., 2008). Lou et al. (2004) reported that soil CO₂ flux rates coincided with seasonal changes in soil temperature, soil microbial carbon, and dissolved organic carbon. Iqbal et al. (2010)

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also showed soil CO₂ flux rates to be strongly correlated with precipitation, microbial biomass nitrogen, and dissolved organic nitrogen. Yan et al. (2006) and Peichl et al. (2010) found that removal of surface litter reduced soil respiration rates by eliminating CO₂ efflux coming directly from the litter, and also by slowing down belowground biological activities of the soil and roots. In this study, litter removal also reduced CO₂ emission from the forest floor (Fig. 3).

GHG fluxes were related to soil properties, and the relationships varied with site and plant species. Soil temperature influences substrate availability via regulation of daily metabolism and seasonal carbon distributions (Campbell and Law, 2005), soil moisture has numerous physiological and physical effects on ecosystem metabolism (Landsberg and Gower, 1997), and thus are critical factors influencing soil CO₂ fluxes at the ecosystem level (Raich and Schlesinger, 1992). In our study, CO₂ emissions from all tree species over the two years showed a significant correlation with soil temperature, soil moisture, and their interaction (Table 5). The high to moderate CO₂ flux between June and September was observed when soil temperatures and soil moisture were high (Fig. 3). Similarly, low to negligible CO₂ fluxes were observed between October and May, when soil temperatures and soil moisture content were low (Fig. 3). The relationships were comparable to numerous field studies that have documented strong relationships between soil temperature, soil moisture and CO₂ fluxes (e.g., Iqbal et al., 2009a, 2010; Landsberg and Gower, 1997; Liu et al., 2008; Peichl et al., 2010; Raich and Schlesinger, 1992; Saiz et al., 2006; Tang et al., 2006; Xu and Qi, 2001). CO₂ fluxes at six sites were significantly correlated with SOC, total N, and soil bulk density, while soil pH was not correlated with the CO₂ fluxes (Table 5). Similar to our findings, Jacinthe and Lal (2006) found that CO₂ fluxes were significantly correlated with labile C. Saiz et al. (2006) reported that organic carbon concentration in the mineral layers was significantly correlated with soil respiration, and bulk density in the mineral soil layer was negatively correlated to soil respiration. In contrast, Shrestha et al. (2009) observed that soil bulk density and soil pH were significantly correlated with CO₂ fluxes, while Soil C and N concentrations were not correlated with the CO₂ fluxes. Mapanda

et al. (2010) indicated that the variability in GHG emissions from clay soils was to the greatest extent influenced by soil temperature, but soil mineral N and pH were also important.

4.2 CH₄

5 The soils of the six tree species in our study acted as sinks for atmospheric CH₄ on annual basis, and the mean CH₄ flux rates across all of our sites (-139.75 μg CH₄ m⁻² h⁻¹) was similar in magnitude to that of other studies in semi-arid zones (Wang et al., 2005; Yao et al., 2010). We found no significant differences in annual CH₄ fluxes among the different tree species (Tables 2, 3, Fig. 4), and no
10 significant seasonal differences in CH₄ fluxes were observed among the tree species (Tables 3, 4). Previous studies of the effects of plant species on CH₄ fluxes showed varying responses. Liu et al. (2008) and Shrestha et al. (2009) found that land use did not significantly affect either annual or most seasonal CH₄ fluxes. In contrast, Menyailo and Hungate (2003) showed that tree species in Siberian boreal and temperate forests significantly affected potential CH₄ consumption in laboratory microcosms. Wang et al. (2013) considered that plant species in constructed wetland systems had significantly influence on biochemistry of carbon in methane flux to/from
15 the atmosphere. Inubushi et al. (2003) and Iqbal et al. (2009b) found that CH₄ flux was positively correlated with precipitation. With increasing precipitation, 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). Soil CH₄ fluxes at six sites during the second sampling year were highly variable, and did not exhibit any well-defined pattern (Fig. 4). Annual precipitation of 342.92 and 546.85 mm in first and second sampling years respectively (Fig. 2a)
20 may helps explain limited methanogenic activity which may have been insensitive to the small variations in soil moisture observed in this study, a finding similar to that of Chan and Parkin (2001) and Shrestha et al. (2009).

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In our study, there seemed have no obvious factors influencing soil CH₄ consumption. CH₄ fluxes did not display pronounced dependency on soil temperature, moisture, or their interaction (Table 5), and CH₄ fluxes at six sites were not correlated with SOC, total N, soil bulk density, and soil pH (Table 5). The lack of dependence of CH₄ fluxes on environmental factors had been reported frequently (Kato et al., 2011; Menyailo and Hungate, 2003; Peichl et al., 2010; Tang et al., 2006). This possibly indicated that there were environmental factors other than those measured in this study exerting a larger impact on soil CH₄ fluxes and/or that there were not enough samples for these measurements due to their higher spatial and temporal variability (Tang et al., 2006; Vincent et al., 2006). Shrestha et al. (2009) also reported that the spatial pattern of CH₄ fluxes was not significantly influenced by soil moisture, bulk density, pH, and Soil C and N concentrations. This was different from similar studies of Blankinship et al. (2010) and Konda et al. (2010). Blankinship et al. (2010) reported that CH₄ uptake in the colder and wetter ecosystems along the gradient decreased with increasing precipitation, while exhibited less CH₄ uptake in the warmer and drier ecosystems with increasing temperature. Konda et al. (2010) evaluated the spatial structures of GHG in an *Acacia mangium* plantation stand in Sumatra, Indonesia, and observed that CH₄ uptake rates were significantly affected by pH in the drier season, and positively correlated with bulk density and soil NH₄-N in the wetter season. The lack of correlation between CH₄ fluxes and environmental factors in our study was probably due to the reasons explained by Ding and Cai (2007), they observed that the spatial variability of CH₄ emissions were not correlated with abiotic factors, but with biotic factors. Litter removal significantly decreased CH₄ fluxes in our study (Fig. 4) may help prove this phenomenon, a result that is consistent with that of Borken and Beese (2006), who also suggested that litter removal had caused a significant decrease in CH₄ uptake in mixed spruce/beech forests.

4.3 N₂O

Seasonal shifts in N₂O emissions were found to be significant (Fig. 5). N₂O fluxes were low during winter and high through spring until peaking in summer. During the dry season, a slightly negative N₂O fluxes at six sites between soil and atmosphere did either

increase or decrease from one fortnight to the next (Fig. 5). Similar to our findings, Goldberg and Gebauer (2009) and Peichl et al. (2010) found that the soil served as N₂O sink during the drought period, and concluded that soil water status and soil nitrate availability were important driving factors for N₂O sink, long drought led to drastic decreases of soils N₂O fluxes or may even turn forest soils temporarily to N₂O sinks. Rosenkranz et al. (2006) considered that denitrifying bacteria might use atmospheric N₂O as an alternative electron acceptor to nitrate in the case of shortage in nitrate supply. Chapuis-Lardy et al. (2007) observed that low mineral nitrogen and large moisture contents in soil led to N₂O uptake. During the rainy season, N₂O fluxes at six sites were negative, while became almost zero and even positive once the rain started (Fig. 5). Goldberg and Gebauer (2009) also observed that rewetting quickly turned the soil into a source for atmospheric N₂O. Forest soils served as sinks for atmospheric N₂O have been recorded on a broad spectrum (Chapuis-Lardy et al., 2007; Eickenscheidt and Brumme, 2012; Inclán et al., 2012; Kellman and Kavanaugh, 2008; Ma et al., 2012; Peichl et al., 2010; Stewart et al., 2012). Eickenscheidt and Brumme (2012) found that under the reduced deposition roof, net nitrification and nitrate in soil solution were reduced to undetectable levels causing the soil to change from a net source for NO_x into a net sink. However, N₂O sinks have often been overlooked and the driving factors for these sinks are poorly understood (Goldberg and Gebauer, 2009; Stewart et al., 2012).

N₂O fluxes differed significantly among plant species of *L. oblonga*, *P. granatum*, *Z. jujube*, and *B. ischcemum* (Table 2). In general, the annual N₂O fluxes differed significantly among plant species (Table 3), this is similar to the results of Shrestha et al. (2009). When explaining the differences in N₂O emissions from soils under different plant species, SOC and total N had to be considered, as demon-

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strated by Beauchamp (1997) and Dobbie et al. (1999), N availability and SOC affected soil N_2O fluxes. The mean N_2O fluxes observed in this study ranged from $-49.45 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$ in the *P. granatum* to $25.47 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$ in the *Z. jujube*. The average N_2O emission rates, and the total annual emissions recorded across all sites in our study were similar to those reported by Yao et al. (2010) for semi-arid zones. The relatively high annual N_2O emissions we recorded in the *Z. jujube* were similar to the findings of Shrestha et al. (2009), the high N_2O fluxes from the *Z. jujube* forest may be attributed to higher soil N concentrations ($2175.09 \text{ mg kg}^{-1}$ soil in 0–5 cm depth) resulting from the history of fertilization ($150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$). Litter removal for two years did not have an important effect on N_2O emissions (Table 3). The lack of dependency of N_2O flux on litter is similar to observations made by Tang et al. (2006) and Peichl et al. (2010), and suggested that the majority of nitrification and denitrification activities happen in the mineral soil rather than in the surface litter (Tang et al., 2006).

Soil N_2O fluxes were affected by precipitation (Inubushi et al., 2003), temperature (Keeney et al., 1979; Sitaula and Bakken, 1993), SOC (Beauchamp, 1997), N availability (Dobbie et al., 1999), water-filled pore space (Davidson, 1991), and aeration (Firestone, 1982). Our results showed that N_2O fluxes showed no significant correlation with soil temperature (Table 5). In contrast, Sitaula and Bakken (1993) reported increased N_2O fluxes corresponding with increased temperatures. The highly variable and unclear patterns of soil N_2O fluxes at the six sites in our study may help explain why there was no relationship between temperature and N_2O fluxes. Lang et al. (2010) reported that soil temperature did not significantly effect gross and net nitrification rates probably because temperatures did not reach the critical values needed to affect the biological activity of nitrifiers. In contrast, N_2O emission was strongly affected by soil temperature, suggesting that N_2O production through nitrification was more sensitive to temperature changes than nitrate production (Lang et al., 2011). Soil N_2O flux rates at all six sites showed no significant correlation with soil moisture (Table 5). The dependency of N_2O fluxes on soil moisture in our study is similar to other studies (Peichl et al., 2010; Ullah et al., 2009). Limited N availability in some of the plots may have

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prevented a clear relationship between N_2O exchange and soil temperature or soil moisture (Peichl et al., 2010; Tang et al., 2006). It is not uncommon to encounter a lack of relationship between soil temperature, soil moisture and N_2O flux measured at plot scale within the same forest stand (Groffman et al., 2000). N_2O fluxes at six sites were significantly correlated with SOC and total N (Table 5). N_2O fluxes from *L. oblonga*, *P. granatum*, and *Z. jujube* were significantly correlated with soil bulk density (Table 5). This indicated that soil N_2O fluxes were mostly limited by SOC and total N, which was in agreement with results from previous studies (Mapanda et al., 2010; Nishina et al., 2009; Shrestha et al., 2009; Yao et al., 2010). Shrestha et al. (2009) found that SOC and total N were positively correlated with N_2O emissions. Nishina et al. (2009) pointed out that the relationship between soil pH and N_2O emissions in different soils showed little consensus, and considered that other soil properties masked the effect of soil pH on N_2O emissions. Reth et al. (2005) and Mapanda et al. (2010) confirmed the pH as an important factor influencing N_2O emission. Nishina et al. (2009) reported that the N_2O emissions had a weak, but significant positive correlation with pH. In our study, the results showed that the effect of soil pH was not correlated with soil N_2O fluxes (Table 5).

The combine of CO_2 , CH_4 , and N_2O exchanges contribute to the net ecosystem GWP. The average net GWP of natural regenerated and managed forest was 12.88 and 22.45 Mg CO_2 -C equivalent $ha^{-1} yr^{-1}$, respectively (Table 6). Dalal and Allen (2008) reported decrease in GWP in natural forest ecosystems, mostly as CO_2 sinks in plant biomass, microbial biomass, and soil C. The lower net GWPs of natural vegetation suggested that GWP can be minimized though preservation or restoration of existing ecosystems. In terms of GWP, the relative contribution of CO_2 on net GWP was 104.92 %, and the contribution of CH_4 and N_2O was -1.53 and -3.39 %, respectively (Table 6). CO_2 was the overwhelmingly dominant GHG in all tree species studied, and CH_4 and N_2O sinks had limited impacts on each individual GHG and net GWP of the three GHGs together.

5 Conclusions

Soil CO₂ 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 CO₂ emissions demonstrated clear seasonal patterns, with fluxes being significantly higher during the warm rainy season than during the cool dry season. However, soil CH₄ and N₂O fluxes were not significantly correlated with soil temperature, soil moisture, or their interaction, and no significant seasonal differences were detected. Soil CO₂ and N₂O fluxes were significantly correlated with SOC, total N, and soil bulk density, while soil pH was not correlated with CO₂ and N₂O emissions. Soil CH₄ fluxes did not display pronounced dependency on SOC, total N, soil bulk density, and soil pH. Soil surface litter removal resulted in significant decreases in CO₂ emissions and CH₄ uptakes, but had no significant influence on N₂O fluxes.

Soils in six tree species acted as sinks for atmospheric CH₄. With the exception of *B. ischcemum*, soils in all sites acted as sinks for atmospheric N₂O. Tree species difference significantly affected CO₂ and N₂O fluxes but not CH₄ uptakes, with higher rates from managed forests than that from natural regenerated forests. GHG emission potentials evaluated for different tree species indicated the net GWPs were lower in natural regenerated vegetation, suggesting that natural regenerated vegetation were more desirable plant species in reducing global warming. Enhanced GHG fluxes between soils and the atmosphere in managed forests suggested that the soil-atmospheric GHG fluxes in forests on Taihang Mountain may increase in the future if the large areas of secondary forests that are now present were destroyed, so preservation or restoration of existing ecosystems should be the primary goal of carbon sequestration.

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

Site	Elevation (m)	Slope (°)	Slope aspect	Forest type	Age (year)	Height (m)	Understory	Community coverage (%)	Root biomass (g m ⁻²)
<i>Robinia pseudoacacia</i>	469	30	East	Deciduous arbor	20	5.80a	1, 2, 3, 4, 6, 8, 11, 13, 14	91.91	3845a
<i>Vitex negundo</i> var. <i>heterophylla</i>	531	31	South	Deciduous shrub	–	1.60ab	2, 3, 4, 5, 6, 7, 8, 9, 10	95.22b	1266a
<i>Leptodermis oblonga</i>	493	36	North	Deciduous shrub	–	0.59abc	2, 3, 4, 7, 10, 11, 12	93.69c	1200a
<i>Punica granatum</i>	489	32	South	Deciduous small arbor	20	3.25abcd	2, 3, 4, 5, 6, 7, 10, 13	77.00bcd	2420d
<i>Ziziphus jujube</i>	464	30	South	Deciduous small arbor	20	4.63abcde	2, 3, 5, 6, 8, 13, 14, 15, 16	78.33bce	2000e
<i>Bothriochloa ischcemum</i>	635	34	North	Perennial herb	–	0.44abde	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	100.00de	922ade

Site	Soil organic carbon (mg kg ⁻¹)	Total N (mg kg ⁻¹)	Total P (mg kg ⁻¹)	Total K (mg kg ⁻¹)	Soil bulk density (g cm ⁻³)	Soil pH (in water)	Soil capillary water moisture (mm)	Soil saturated water moisture (mm)	Litter biomass (g m ⁻²)
<i>Robinia pseudoacacia</i>	32 779.62a	2822.58a	1147.92a	27 411.11a	1.83a	6.81a	60.00a	68.00a	569
<i>Vitex negundo</i> var. <i>heterophylla</i>	18 597.81a	1697.77ab	642.21ab	26 193.20b	1.60b	6.94b	80.91ab	82.91b	677
<i>Leptodermis oblonga</i>	22 898.46	2007.77ac	563.69ac	22 341.57c	1.53ac	6.90c	89.88ac	90.82a	650
<i>Punica granatum</i>	18 655.96	1560.42ad	371.01abd	13 996.00abc	1.60d	6.39abcd	86.67ad	88.00	488
<i>Ziziphus jujube</i>	26 053.03	2175.09	1334.75bcde	17 299.33acd	1.62e	6.84de	91.50ae	97.50a	466
<i>Bothriochloa ischcemum</i>	27 292.69	1985.79	410.48abcde	18 073.83ace	1.29abcde	6.81df	92.17af	100.00ab	520

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

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

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*

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Table 2. Effects of season, tree species on GHG fluxes, soil temperature, and soil moisture (mean \pm S.E.) of six tree species.

		CO ₂ flux (mg CO ₂ m ⁻² h ⁻¹)	CH ₄ flux (μ g CH ₄ m ⁻² h ⁻¹)	N ₂ O flux (μ g N ₂ O m ⁻² h ⁻¹)	Soil temperature (°C)	Soil moisture (%)
<i>Robinia pseudoacacia</i>	Rainy season	541.32 \pm 61.17 ^a	-177.36 \pm 38.92	-42.58 \pm 22.04 ^b	24.60 \pm 0.81 ^a	11.85 \pm 1.91
	Dry season	139.74 \pm 16.17 ^a	-139.50 \pm 23.31	-2.59 \pm 3.82 ^b	12.82 \pm 1.68 ^a	8.71 \pm 1.31
	Mean	285.57 \pm 31.05 a	-151.85 \pm 20.16	-16.76 \pm 8.34	16.99 \pm 1.38	9.82 \pm 1.09
<i>Vitex negundo</i> var. <i>heterophylla</i>	Rainy season	378.66 \pm 51.56 ^a	-102.01 \pm 52.18	-45.75 \pm 24.49 ^b	25.93 \pm 0.75 ^a	11.93 \pm 1.80
	Dry season	95.68 \pm 17.67 ^a	-100.87 \pm 17.80	9.58 \pm 8.62 ^b	12.67 \pm 1.76 ^a	8.62 \pm 0.92
	Mean	203.85 \pm 25.88 ab	-101.28 \pm 21.72 a	-10.01 \pm 5.58	17.37 \pm 1.48	9.79 \pm 0.89
<i>Leptodermis oblonga</i>	Rainy season	206.93 \pm 25.86 ^a	-184.02 \pm 49.54	-86.43 \pm 29.99 ^a	24.78 \pm 1.24 ^a	12.89 \pm 1.92
	Dry season	66.83 \pm 9.75 ^a	-232.08 \pm 112.15	-5.83 \pm 4.53 ^a	10.76 \pm 2.73 ^a	10.98 \pm 1.76
	Mean	119.73 \pm 13.06 abc	-215.06 \pm 74.32 ab	-34.38 \pm 12.00 a	15.72 \pm 2.05	11.66 \pm 1.32
<i>Punica granatum</i>	Rainy season	401.95 \pm 57.32 ^a	-190.54 \pm 68.79	-77.03 \pm 27.52	27.13 \pm 0.92 ^a	15.95 \pm 2.20 ^a
	Dry season	108.26 \pm 13.10 ^a	-101.94 \pm 28.74	-34.33 \pm 13.66	14.51 \pm 1.66 ^a	9.86 \pm 1.05 ^a
	Mean	212.27 \pm 26.14 cd	-131.47 \pm 29.97	-49.45 \pm 22.11 b	18.98 \pm 1.42	12.02 \pm 1.10
<i>Ziziphus jujube</i>	Rainy season	689.02 \pm 86.47 ^a	-105.88 \pm 37.01	54.92 \pm 27.48 ^b	27.26 \pm 0.94 ^a	9.57 \pm 1.37
	Dry season	137.29 \pm 14.11 ^a	-89.39 \pm 15.06	9.76 \pm 3.57 ^b	11.97 \pm 2.16 ^a	8.66 \pm 1.13
	Mean	329.19 \pm 41.58 bcde	-94.95 \pm 15.87 bc	25.47 \pm 9.99 abc	17.38 \pm 1.78	8.98 \pm 0.87
<i>Bothriochloa ischcemum</i>	Rainy season	322.42 \pm 28.70 ^a	-79.11 \pm 19.04	51.53 \pm 14.82	25.07 \pm 1.08 ^a	19.47 \pm 2.15
	Dry season	89.39 \pm 9.00 ^a	-110.04 \pm 22.16	-27.33 \pm 8.95	10.71 \pm 1.54 ^a	19.14 \pm 1.92
	Mean	171.92 \pm 16.30 ae	-99.08 \pm 15.83 bd	0.60 \pm 0.34 bd	15.80 \pm 1.45	19.26 \pm 1.44

Note: S.E. stands for standard error.

^a Along the columns denote significance of the impacts of season on GHG fluxes, soil temperature, and soil moisture, Significant impact at $\alpha < 0.01$.^b 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.

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Table 3. Significance of the impacts of tree species, litter removal treatment, season on GHG fluxes.

	CO ₂ flux (mg CO ₂ m ⁻² h ⁻¹)	CH ₄ flux (µg CH ₄ m ⁻² h ⁻¹)	N ₂ O flux (µg N ₂ O m ⁻² h ⁻¹)
Tree species	0.000 ^a	0.230	0.000 ^a
Treatment	0.000 ^a	0.000 ^a	0.505
Season	0.000 ^a	0.712	0.219

^a Significant impact at $\alpha < 0.01$.

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Table 4. Significance of the impacts of litter removal treatment and season on GHG fluxes.

		CO ₂ flux (mg CO ₂ m ⁻² h ⁻¹)	CH ₄ flux (µg CH ₄ m ⁻² h ⁻¹)	N ₂ O flux (µg N ₂ O m ⁻² h ⁻¹)
<i>Robinia pseudoacacia</i>	Treatment	0.912	0.011 ^a	0.002 ^a
	Season	0.000 ^a	0.366	0.013 ^b
<i>Vitex negundo</i> var. <i>heterophylla</i>	Treatment	0.000 ^a	0.018 ^b	0.012 ^b
	Season	0.000 ^a	0.965	0.010 ^b
<i>Leptodermis oblonga</i>	Treatment	1.000	0.232	0.090
	Season	0.000 ^a	0.758	0.001 ^a
<i>Punica granatum</i>	Treatment	0.033 ^b	0.228	0.001 ^a
	Season	0.000 ^a	0.166	0.328
<i>Ziziphus jujube</i>	Treatment	0.004 ^a	0.000 ^a	0.051
	Season	0.000 ^a	0.506	0.023 ^b
<i>Bothriochloa ischcemum</i>	Treatment	0.047 ^b	0.024	0.727
	Season	0.000 ^a	0.341	0.087

^a Significant impact at $\alpha < 0.01$.^b Significant impact at $\alpha < 0.05$.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I ◀](#)[▶ I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Table 5. Multiple linear regressions for the relationship between soil properties and GHG fluxes.

		CO ₂ flux (mg CO ₂ m ⁻² h ⁻¹)	CH ₄ flux (μg CH ₄ m ⁻² h ⁻¹)	N ₂ O flux (μg N ₂ O m ⁻² h ⁻¹)
<i>Robinia pseudoacacia</i>	Soil temperature	0.541 ^a	0.006	0.054
	Soil moisture	0.332 ^a	0.165 ^a	0.013
	Soil temperature × soil moisture	0.584 ^a	0.072	0.048
	Soil organic carbon	0.741 ^a	0.064	0.739 ^a
	Total N	0.428 ^b	0.086	0.413 ^b
	Soil bulk density	0.086	0.250	0.184
	Soil pH	0.712 ^a	0.003	0.828 ^a
<i>Vitex negundo</i> var. <i>heterophylla</i>	Soil temperature	0.426 ^a	0.003	0.044
	Soil moisture	0.323 ^a	0.101 ^a	0.004
	Soil temperature × soil moisture	0.534 ^a	0.009	0.038
	Soil organic carbon	0.687 ^a	0.001	0.839 ^a
	Total N	0.531 ^a	0.000	0.640 ^a
	Soil bulk density	0.401 ^b	0.078	0.320
	Soil pH	0.025	0.160	0.052
<i>Leptodermis oblonga</i>	Soil temperature	0.366 ^a	0.492 ^a	0.053
	Soil moisture	0.196 ^a	0.033	0.075
	Soil temperature × soil moisture	0.358 ^a	0.213	0.053
	Soil organic carbon	0.532 ^a	0.131	0.646 ^a
	Total N	0.466 ^b	0.288	0.507 ^a
	Soil bulk density	0.873 ^a	0.103	0.810 ^a
	Soil pH	0.008	0.117	0.008
<i>Punica granatum</i>	Soil temperature	0.388 ^a	0.031	0.051
	Soil moisture	0.462 ^a	0.058	0.052
	Soil temperature × soil moisture	0.451 ^a	0.038	0.020
	Soil organic carbon	0.973 ^a	0.043	0.907 ^a
	Total N	0.533 ^a	0.117	0.675 ^a
	Soil bulk density	0.901 ^a	0.021	0.877 ^a
	Soil pH	0.009	0.068	0.006
<i>Ziziphus jujube</i>	Soil temperature	0.493 ^a	0.016	0.035
	Soil moisture	0.157 ^a	0.078	0.030
	Soil temperature × soil moisture	0.476 ^a	0.076	0.031
	Soil organic carbon	0.815 ^a	0.009	0.793 ^a
	Total N	0.409 ^b	0.004	0.724 ^a
	Soil bulk density	0.927 ^a	0.017	0.742 ^a
	Soil pH	0.218	0.140	0.100
<i>Bothriochloa ischcemum</i>	Soil temperature	0.444 ^a	0.041	0.102 ^b
	Soil moisture	0.242 ^a	0.008	0.010
	Soil temperature × soil moisture	0.513 ^a	0.011	0.016
	Soil organic carbon	0.191	0.218	0.143
	Total N	0.201	0.295	0.164
	Soil bulk density	0.705 ^a	0.002	0.745
	Soil pH	0.034	0.323	0.040

^a Significant correlation at $\alpha < 0.01$.

^b Significant correlation at $\alpha < 0.05$.

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Table 6. Effect of tree species on global warming potential (GWP) and contribution of CO₂, CH₄, and N₂O to GWP.

Tree species	GWP Mg CO ₂ -C equivalent ha ⁻¹ yr ⁻¹	Percent of total contribution to GWP		
		CO ₂	CH ₄	N ₂ O
<i>Robinia pseudoacacia</i>	23.02 ± 0.60 acd	102.94	-1.15	-1.80
<i>Vitex negundo</i> var. <i>heterophylla</i>	15.62 ± 6.49	103.73	-1.15	-2.58
<i>Leptodermis oblonga</i>	8.44 ± 0.46 b	115.23	-3.56	-11.68
<i>Punica granatum</i>	16.69 ± 1.92	107.52	-1.43	-6.09
<i>Ziziphus jujube</i>	27.63 ± 5.13 c	98.54	-0.61	2.08
<i>Bothriochloa ischcemum</i>	14.58 ± 1.82 d	101.56	-1.28	-0.28

The values within a column that are followed by the same letter are not significantly different at an alpha = 0.05.

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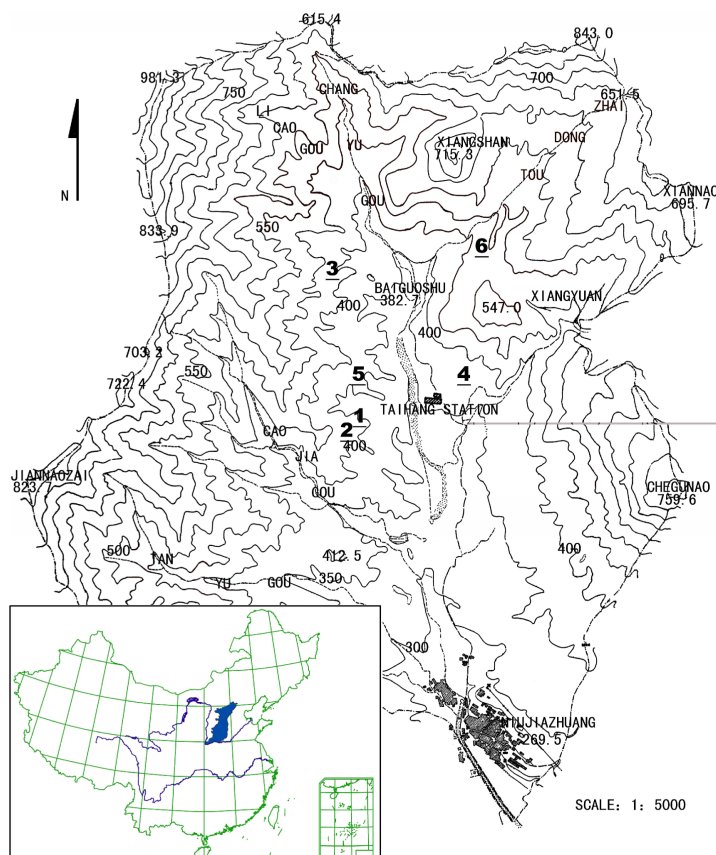


Fig. 1. Locations of six sampling plots in six tree species in Niujiazhuang Catchment on Taihang Mountain in Northern China. 1 is *Robinia pseudoacacia*; 2 is *Vitex negundo* var. *heterophylla*; 3 is *Leptodermis oblonga*; 4 is *Punica granatum*; 5 is *Ziziphus jujube*; and 6 is *Bothriochloa ischcemum*.

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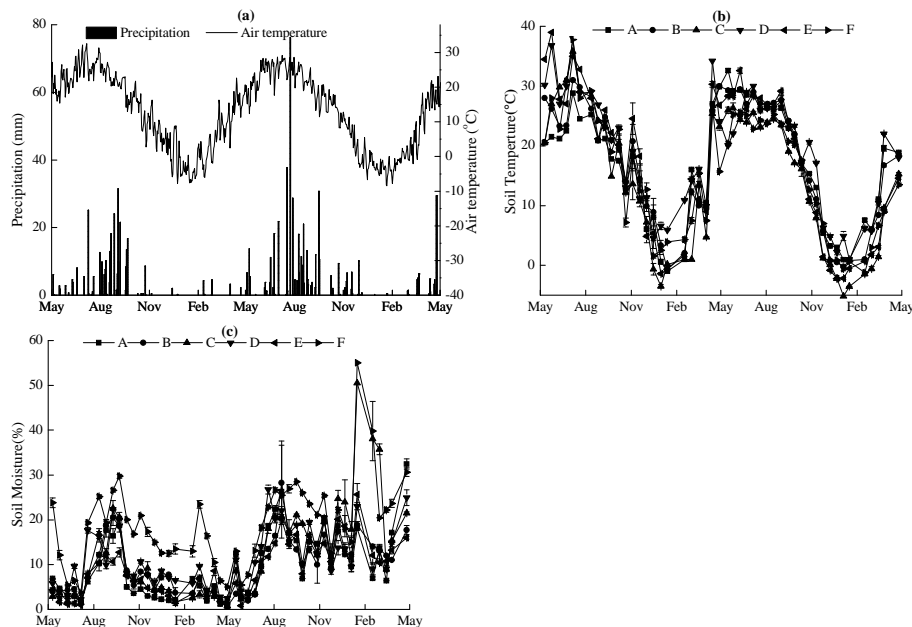


Fig. 2. Seasonal patterns of daily air temperature and precipitation **(a)**, soil temperature at 5 cm depth **(b)**, and soil gravimetric moisture **(c)** measured in six tree species on Taihang Mountain from May 2010 to April 2012. The tree species are (A) *Robinia pseudoacacia*, (B) *Vitex negundo* var. *heterophylla*, (C) *Leptodermis oblonga*, (D) *Punica granatum*, (E) *Ziziphus jujube*, and (F) *Bothriochloa ischcemum*. The error bars represent standard errors ($n = 3$).

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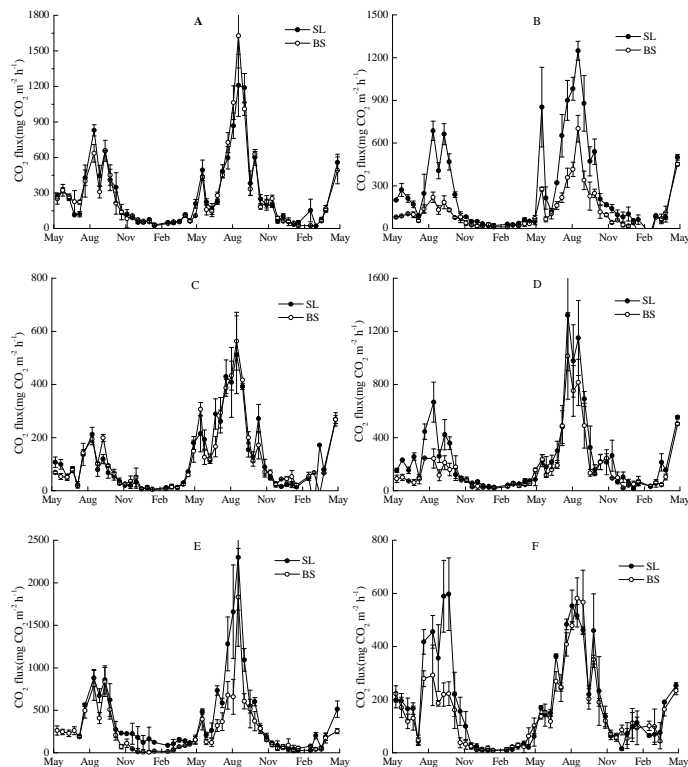


Fig. 3. Seasonal patterns of CO₂ flux rates measured in six tree species on Taihang Mountain with (SL) or without (BS) surface litter from May 2010 to April 2012. The tree species are **(A)** *Robinia pseudoacacia*, **(B)** *Vitex negundo var. heterophylla*, **(C)** *Leptodermis oblonga*, **(D)** *Punica granatum*, **(E)** *Ziziphus jujube*, and **(F)** *Bothriochloa ischcemum*. The error bars represent standard errors ($n = 3$).

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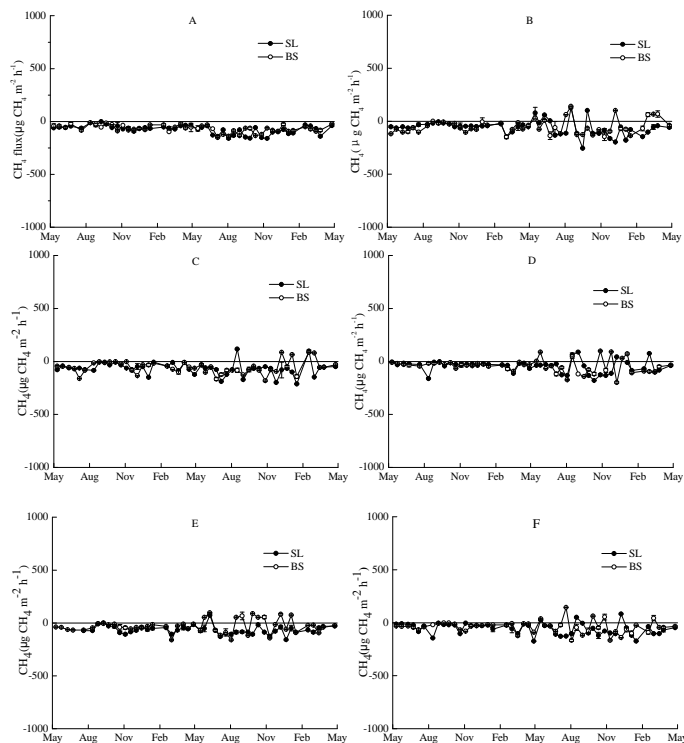


Fig. 4. Seasonal patterns of CH_4 flux rates measured in six tree species on Taihang Mountain with (SL) or without (BS) surface litter from May 2010 to April 2012. The tree species are **(A)** *Robinia pseudoacacia*, **(B)** *Vitex negundo* var. *heterophylla*, **(C)** *Leptodermis oblonga*, **(D)** *Punica granatum*, **(E)** *Ziziphus jujube*, and **(F)** *Bothriochloa ischcemum*. The error bars represent standard errors ($n = 3$).

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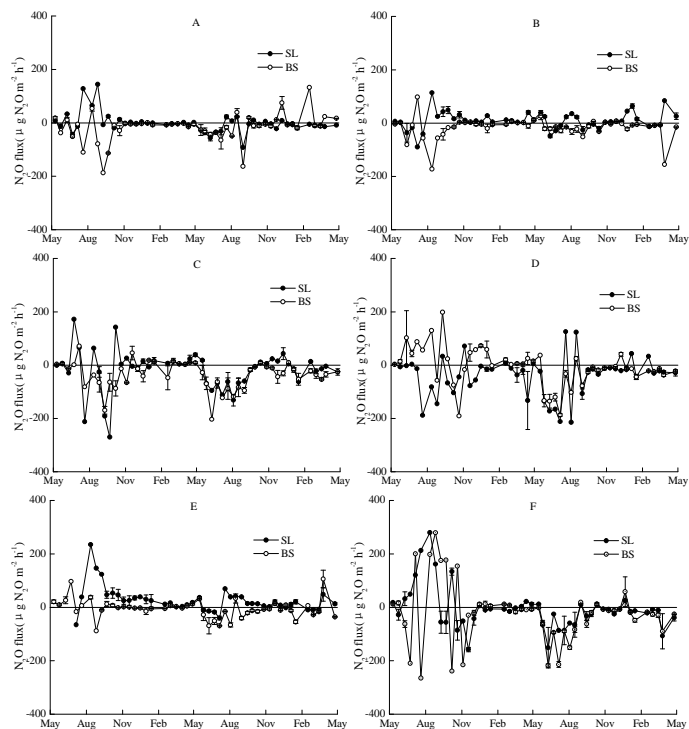


Fig. 5. Seasonal patterns of N_2O flux rates measured in six tree species on Taihang Mountain with (SL) or without (BS) surface litter from May 2010 to April 2012. The tree species are **(A)** *Robinia pseudoacacia*, **(B)** *Vitex negundo* var. *heterophylla*, **(C)** *Leptodermis oblonga*, **(D)** *Punica granatum*, **(E)** *Ziziphus jujube*, and **(F)** *Bothriochloa ischcemum*. The error bars represent standard errors ($n = 3$).

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