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# Effects of compaction by heavy machine traffic on soil fluxes of methane and carbon dioxide in a temperate broadleaved forest

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ABSTRACT

Soil compaction decreases soil aeration and water infiltration, lowering air-filled porosity, which may impact biological processes involved in soil fluxes of carbon dioxide ($F_{CO2}$) and methane ($F_{CH4}$), and decrease the greenhouse gas emissions mitigation potential offered by the forestry sector. We recorded $F_{CO2}$ and $F_{CH4}$ continuously for two years using automated chambers connected to a laser-based gas analyser in an experimental forest site on an acidic ruptic Luvisol that was established to assess the long-term impact of a loaded forwarder. Heavy machine traffic had considerably increased soil surface roughness. Air-filled porosity (*AFP*) in the first 0.1 m was lower in the trafficked plot – especially in hollows – than in the control almost all year long. The temperature sensitivity of $F_{CO2}$ was higher for the control plot than for both mounds and hollows in the trafficked plot. Cumulative $F_{CO2}$ was much higher in the control than in hollows and mounds of the trafficked plot. In contrast, annual $F_{CH4}$ did not significantly differ between the control plot and either the mounds or the hollows in the trafficked plot, but was significantly higher in mounds than in hollows. $F_{CH4}$ was negative all year round indicating a net uptake of $CH_4$, except during winter when a net emission of $CH_4$ was occasionally observed in the hollows on the trafficked plot. While seasonal variations of $F_{CH4}$ were well related to variations in *AFP*, the potential rate of methane uptake at optimal air-filled porosity was higher in the trafficked plot than in the control.

## 1. Introduction

Substituting fuelwood for fossil fuel energy and using wood for the production of manufactured objects are two of the climate change mitigation options that have recently been encouraged in European countries (UNECE and FAO, 2011). However, the resulting more intensive silviculture may have negative impacts on the greenhouse gas budget of the forestry sector. It has recently been shown that intensive biomass harvesting decreases the organic carbon stocks in forest soils resulting in an important transfer of carbon from forests to the atmosphere (Achat et al., 2015). The mechanized forest operations accompanying the intensification of wood production create heavy traffic in managed forests which in turn increases the risk of soil compaction. Soils with a silty-loam texture are very susceptible to compaction, especially when soil water content is high (Horn et al., 1995).

Soil compaction causes a change in soil structure, an increase in bulk density and a decrease in soil macro-porosity and between-pore connectivity (Nawaz et al., 2012; Richard et al., 2001). It decreases soil aeration and water infiltration (Gent et al., 1983; Hamza and Anderson, 2005). The resulting lower porosity and higher soil water content cause lower air-filled porosity, and together with increasing soil strength (Ampoorter et al., 2007; Marchi et al., 2014; Riggert et al., 2016), hinders root growth and activity, impairing tree growth and survival (Gaertig et al., 2002; Goutal et al., 2013a; Jordan et al., 2003; Powers et al., 2005). Compaction also impacts the structure and activity of the soil microbial community (Frey et al., 2009; Ponder and Tadros, 2002; Schnurr-Pütz et al., 2006; Tan et al., 2005) and the soil fauna (Ballard, 2000; Marshall, 2000). In addition, heavy traffic forms rut which create a complex microtopography with a succession of mounds and hollows, and local variations in porosity, all of which affect water circulation, soil water content and air-filled porosity

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*Abbreviations:* $F_{CO2}$, soil $CO_2$ flux; $F_{CH4}$, soil $CH_4$ flux; $T_S$, soil temperature; *SWC*, soil water content; *AFP*, air-filled porosity.
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(Cambi et al., 2015), which may impact biological processes at an infra-metric scale.

Apart from a few exceptions (Ponder, 2005), soil $CO_2$ efflux ($F_{CO2}$) is negatively affected by soil compaction (Fleming et al., 2006; Goutal et al., 2012; Hartmann et al., 2014). Such a reduction may be due to a decrease in carbon mineralisation under less aerobic conditions (Ball et al., 1999) or to a greater physical protection of soil organic matter (Fleming et al., 2006; Gartzia-Bengoetxea et al., 2011), but it is more likely a consequence of reduced tree growth which would decrease root respiration and the amount of litter returning to the soil. While $CO_2$ is the main anthropogenic greenhouse gas (GHG) and $F_{CO2}$ is one of the largest fluxes in the global terrestrial carbon cycle driven by gross primary production (Janssens et al., 2001), the reduction of $F_{CO2}$ in compacted forest soils is likely offset by a reduction in gross primary production. Forest soils are also an important worldwide methane sink (Castro et al., 1993; Ishizuka et al., 2009; Le Mer and Roger, 2001), but the change in soil aeration after compaction reduces methanotrophic activity and may enhance methanogenic activities (Frey et al., 2011; Teepe et al., 2004). Heavy traffic may therefore reduce the net methane uptake by forest soils. Because methane is the second anthropogenic GHG, soil compaction may decrease the GHG emissions mitigation potential offered by the forestry sector.

In the present study, our objectives were to (i) determine the seasonal patterns of soil $CO_2$ and $CH_4$ fluxes, (ii) relate them to changes in soil temperature and air-filled porosity, (iii) evaluate the influence of variations in microtopography on these responses, and (iv) quantify the response to soil compaction of annual cumulative fluxes for both $CO_2$ and $CH_4$. We hypothesized that (i) even six years after compaction, soil $CO_2$ efflux in trafficked areas would not yet have recovered the level observed in undisturbed areas, and (ii) that soil compaction decreases the net soil methane uptake. We recorded soil $CO_2$ and $CH_4$ fluxes continuously for two years using automated chambers connected to a laser-based gas analyser in an experimental forest site that was established to assess the long-term impact of a loaded forwarder.

## 2. Materials and methods

### 2.1. Study site

The study was carried out in a 6-ha experimental site set up in the state-owned forest of "Hauts Bois" (north-eastern France, 48°29′19″N, 6°41′43″E, 300 m asl) in 2007. Mean annual rainfall and air temperature (1981–2010) based on data from the nearest weather station (Essey-les-Nancy, 57 km) are 775 mm and 10.4 °C, respectively. The soil is an acidic a polycyclic ruptic Luvisol (IUSS Working Group WRB, 2015), developed on a 50-cm thick continental quaternary silt loam deposit, lying on heavy clayey material (more than 50% of clay, weathered from Keuper marls) that induces temporary waterlogging. The existing beech (*Fagus sylvatica* L.) stand was harvested in March 2007 with a cable yarding system to prevent soil compaction and the site was divided in three blocks of one hectare each. An eight-wheel-drive forwarder (VALMET 840, Umea, Sweden, 60 cm wide tyres) was used to compact an area of 30 m × 50 m in each block in May, while two 10 m × 50 m strips on each side of these areas remained undisturbed and were used as controls in this study (Fig. 1). The forwarder drove twice on each trafficked area. Sessile oak (*Quercus petraea* (Matt.) Liebl.) was planted in November 2007 at a density of 1600 trees $ha^{-1}$. Ground vegetation was dominated by *Rubus fructicosus* L. and *Anemone nemorosa* L. in the undisturbed areas and by *Juncus* sp. and *Glyceria striata* Lam. in the trafficked areas.

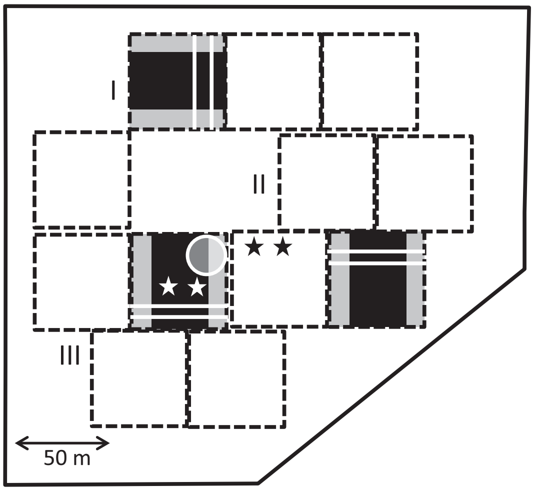

**Fig. 1.** Schematic representation of the 6-ha experimental site with three blocks (1 ha each). Four treatments (square, 0.25 ha) were setup in each block, one being an undisturbed treatment and one being a compacted treatment. The coloured areas represent the compacted treatment. Only the central part was compacted by an eight-wheel-drive forwarder (trafficked area, in black) while the two lateral strips (light grey) remained undisturbed and were used as control in this study. The survey area (twelve chambers connected to one analyser) covers about 300 $m^2$ in the block III (white circle). The white lines indicate transects on which an altimetry survey was conducted in 2007. The stars indicate the position of the piezometers used in this study.

A more detailed description of the experimental site can be found in Goutal et al. (2012, 2013a, 2013c).

### 2.2. Microtopography

Compaction was done in May in order to avoid the formation of large ruts, when the water content of the top soil (0–10 cm) has decreased to 0.33 $m^3\ m^{-3}$ (measured gravimetrically on ten soil cores collected in each block, Goutal et al., 2012).

However, due of the heterogeneity of soil water content and to the presence of tree stumps, the forwarder left a heterogeneous soil surface in the trafficked areas after the second pass, with a succession of mounds and hollows. In May 2007, an altimeter survey was done along two 50-m transects in each block, perpendicular to the direction of the ruts, and including the two undisturbed strips and the central trafficked area (Fig. 1). One measurement was taken every 0.25 m with a tachometer (TC600, Leica, Wild Heerbrugg, Switzerland) at a precision of 0.02 m. In order to account for the slope of the site (0.8–9%), the altitude records for each transect were detrended by fitting a polynomial equation of the distance from the beginning of the transect. The residuals between the predicted and observed altitude values characterized soil surface roughness. We tested the difference in variance between control and trafficked areas with a F-test ("var.test" function in R, R Core Team, 2016).

### 2.3. $CO_2$ and $CH_4$ flux measurements

Twelve home-made automated dynamic closed chambers (20 × 20 × 20 cm), made of acrylic resin, were installed on 5-cm-high bases inserted into the top soil to a depth of 2 cm. Eight chambers (four on mounds and four on hollows) were setup in the central trafficked area of one block (trafficked plot) and four in the undisturbed lateral strips (control plot). They were connected to a gas analyser based on off-axis integrated cavity output spectroscopy (GGA-24EP, Los Gatos Research, Mountain View, CA, USA). Measurements were switched from one chamber to the next