# Impact of forest soil compaction on soil atmosphere composition

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## Abstract

Soil compaction has become an important issue for forest soil sustainability because the increasing timber demand and the mechanization of all silvicultural operations have led to a higher traffic level. Soil compaction causes a physical degradation which in turn disrupts many other functions e.g. wood production, biodiversity, greenhouse gas emission, surface water quality. Two experimental sites were designed in the North-East of France to study the changes of soils subject to heavy traffic by forest machinery, on the short and the long-term. These sites are representative of highly soils sensitive to compaction. They present the same general functioning (neoluvisol), but they differ on some physical (strength, bulk density, clay content) and chemical properties (pH, chemical saturation). The soil atmosphere composition is directly impacted by soil compaction (change of voids volume, size and connection) but also indirectly by change of other soil properties like water content, temperature and biological activity. On the two sites, we observed a decrease in $O_2$ concentration and an increase in $CO_2$ concentration due to traffic, especially during wet periods. The change of soil atmosphere composition will probably impact root growth, gas emissions, microbial and faunal activity and probably have a negative feedback on soil recovery dynamic.

## Key Words

Soil compaction, soil gases.

## Introduction

The general mechanization of forest operations and the increase of wood demand has resulted in an increase in physical damages to soils. Soils subject to heavy traffic will deform until equilibrium between external forces and the counter-forces of the soil is reached which mainly depends on soil intrinsic characteristics determining the soil sensitivity and on soil moisture. Therefore, soil compaction induces changes in the volume, the size and the continuity of voids (Soane and Van Ouwerkerk 1994, Rohand *et al.* 2004; Shestak and Busse 2005; Lamandé *et al.* 2005). These physical modifications will more or less impact transfer processes (water, gas, heat) and consequently soil oxygenation and flooding. Soil flora, fauna and microbial activity will be constrained with a negative feedback on the dynamics of soil restoration. The consequences of heavy traffic on soil are often interdependent and few studies have tackled the issue of the changes of a compacted forest soil on the long-term considering all the functions impacted.

As soil deformation under wheel tracks damages the pore system and increases the volume of soil occupied by water (Shestak and Busse 2005), the aeration status of the soil will be disturbed (Von Wilpert and Schäffer 2005) and soil respiration rate will change. Consequently the composition of its atmosphere may change significantly (Soane and Van Ouwerkerk 1994). Simojoki *et al.* (1991) cited by Soane and Van Ouwerkerk (1994) and Mac Afee *et al.* (1989) cited by Soane and Van Ouwerkerk (1994) observed a significant diminution in $O_2$ concentration due to soil compaction. The presence of gas like $CH_4$, $N_2O$, $H_2S$ or $H_2$, even in low concentration, is an indicator of restricted soil aeration and its oxygenation status (Soane and Van Ouwerkerk 1994). For example, Teepe *et al.* (2004) recorded enhanced $N_2O$ emissions from compacted soils. The aims of this study were to monitor changes in soil atmosphere composition following the traffic of forest machinery on the short and long-term and to determine the relation between the succession of restricted / well-aerated periods with the other parameters influenced by heavy traffic (soil structure, water content, temperature). The underlying questions were –i- how and how much are the functions and functioning of forest soils affected by compaction? and –ii-how long does it take to restore soil functions and functioning after heavy traffic?

## Methods

Two experimental sites have been set up in Lorraine (NE part of France). They are located in the "Hauts-Bois" forest - Azerailles (48° 29′ 19″ N, 6° 41′ 43″ E), Meurthe et Moselle, and in the "Grand Pays" forest - Clermont en Argonne (49° 06′ 23″ N, 5° 04′ 18″ E), Meuse. Each site was clear-cut and timber (*Fagus* *sylvatica*, *Quercus petraea* mainly) were extracted with a cable yarding system to avoid damaging the soil. Afterwards a forwarder drove on the soil only for an equivalent of two travels in spring 2007 in Azerailles (AZ) and in spring 2008 in Clermont en Argonne (CA). The tyres of the forwarder measured 600/55 * 26,5 and were inflated to a pressure of 350 kPa. Its total weight was 21 to 25 tonnes. The sites of Clermont en Argonne and Azerailles have an elevation of 270m and 300m respectively. The climate of the region is characterised by a 30-year mean annual temperature of 9°C (Azerailles) to 9,5 °C (Clermont en Argonne) and a 30-year annual precipitation of 900 mm (Azerailles) to 1000mm (Clermont en Argonne).

The soil of both sites is classified as a neoluvisol (WRB 1990) and is developed on a silt layer of approximately 40-50 cm based on a clayey layer (textural breaking causing a temporary water logging). The soil of both sites is hence considered as highly sensitive to compaction and some chemical and physical differences between the two sites may influence the behaviour and restoration after compaction allowing to identify their main causes. The soil of the Azerailles site has a pH varying between 4.6 and 5.2 along the profile with 22, 56 and 22 % of clay, silt and sand respectively from the surface to a depth of 30-40 cm and with 30 to 60, 32 to 50 and 8 to 18 % of clay, silt and sand from 30-40 cm to 1m depth. Whereas the soil pH of the Clermont en Argonne site varies between 4.4 and 5.1 along the profile, with 13, 72 and 15 % of clay, silt and sand respectively from the surface to a depth of 30-40 cm and with 21 to 33, 54 to 65 and 13 to 14 % of clay, silt and sand from 30-40 cm to 1m depth.

The whole site area (about 5 ha) was split in three blocks to control site variability. The sites were instrumented to monitor numerous parameters, measured at different time and spatial scales to understand how the soil is degraded and how theses parameters interact. One block was equipped for investigations in i-climate (rainfall, air temperature, air saturation index), ii soil climate e.g. Soil moisture using TDR system (Time Domain Reflectometry) and soil temperature using sensors inserted at different soil depth (15, 30 and 60 cm in the undisturbed plot, 10, 25 and 55 cm in the compacted plot, 5 replicates per depth * treatment). The sites were also equipped with piezometers distributed on the whole site area with some of them (10 in CA and 12 in AZ) fitted with sensors recording every 4 hours the water table level and the others being measured once a month. The soil gases were collected once a month in Azerailles from 42 gas collectors (5 depths * 3 blocks * 2 treatments + 2 * 1 depth * 1 treatment * 2 blocks + 5 * 1 depth * 1 block * 2 treatment) and in Clermont en Argonne from 32 gas collectors (5 depths * 3 blocks * 2 treatments + 2 * 1 depth * 1 treatment * 2 blocks). Each collector is composed of a tube that connects a subsurface soil air equilibration port and a sampling port at the soil surface. The gas collectors were inserted into the soil at different depths (10, 25, 35, 50 and 70 cm for the undisturbed plots; 7, 15, 25, 40 and 60 cm for the compacted plots), in the control plot (C) the depth of the gas collector is roughly always 10 cm above the depth of the equivalent one in the compacted plot (T), to account for the volume loss in the compacted one.

## Results

The forwarder traffic led to an increase in bulk density of 26% and 17% compared to the initial values in the first 10 cm in AZ and in CA respectively. This impact decreased with soil depth but was still significant at 60 cm depth. The changes in water content and temperature through the year differed also between treatments, but the effect of compaction on soil moisture and temperature depended on the season, the depth and the site considered.

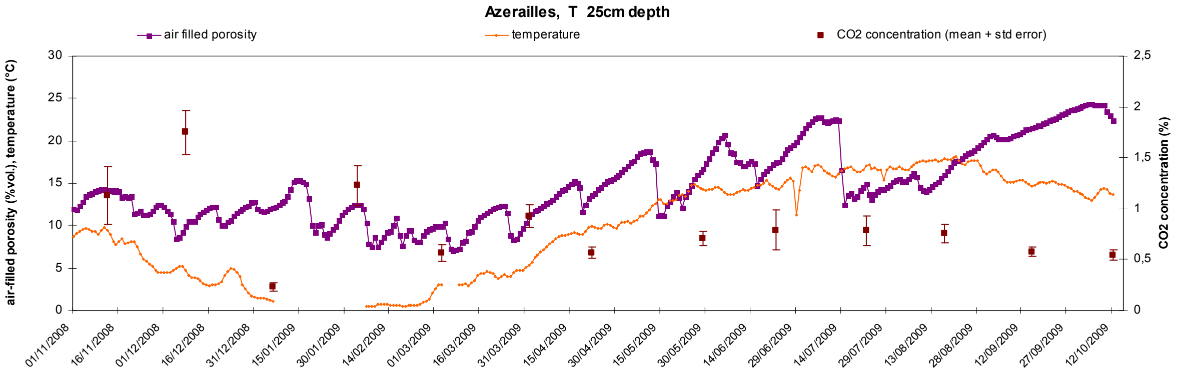
The composition of soil atmosphere was highly variable within the same plot (1 site * 1 block * 1 treatment) probably due the high site variability of water table level, water content and physical parameters (bulk density, hydraulic properties, air permeability). Nevertheless some general patterns could be drawn:

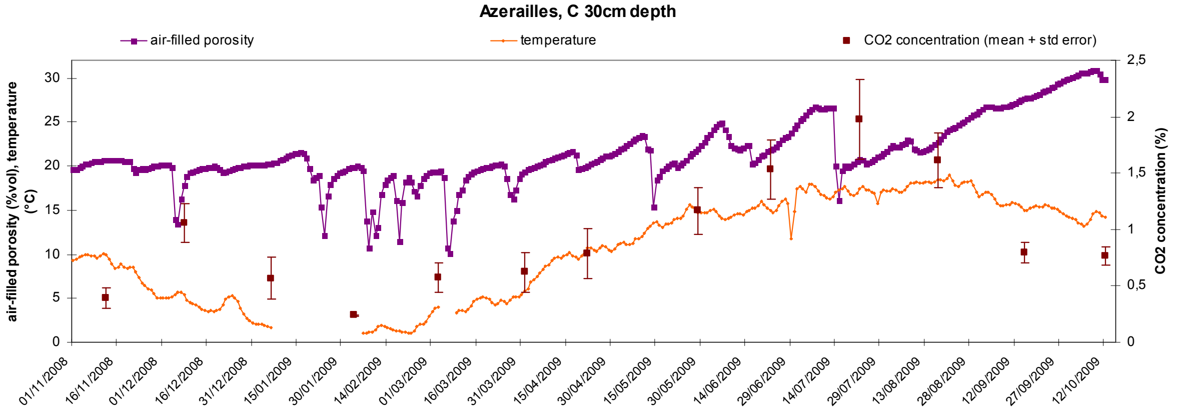
-During wet periods, $O_2$ concentration in the compacted plots was lower than in the undisturbed plots and $CO_2$ concentration was higher in the compacted plots than in the undisturbed ones.
-In CA $CO_2$ concentration was always more important in the compacted plots than in the undisturbed ones, even during dry periods. Besides, the amplitude of the impact of soil compaction on $O_2$ and $CO_2$ concentrations varied among sites, but as they weren't compacted at the same date, it is too early to draw some conclusions from these different amplitudes.

-In AZ no $CH_4$ could be found in the soil atmosphere whereas in CA some $CH_4$ occurred at least during the first year after compaction (in AZ the gas collector were installed one year after compaction, in CA they were installed 2 months after compaction).

-In AZ the atmosphere of the undisturbed soil had a higher $N_2O$ concentration than the one of the compacted soil. In CA it was exactly the opposite situation.

In AZ the 5 gas collectors per treatment inserted at the same depth and near the moisture and temperature sensors, allowed investigations on the relations between soil physical properties affected by compaction and soil atmosphere composition. For example, the two following figures display the data collected from these 10 gas collector. They show that $CO_2$ concentration was lower in the C-treatment only from December 2008 to April 2009, period where the air-filled porosity was far lower in the compacted T-treatment than in the C-treatment. However, even if the air-filled porosity remained more or less lower in the T-treatment from April 2009 to October 2009, the $CO_2$ concentration of the C-treatment became higher than in the T-treatment in that period. Two hypothesis can be made to explain these observations; -i- the respiration was more important in the C-treatment than in the T-treatment where the biological activity was probably most of the year anaerobic and –ii- when the compacted soil dries it cracks more than the undisturbed soil allowing faster gas exchange between the soil and the atmosphere (phenomenon observed when measuring the air permeability of the soil as a function of soil water content, data not shown).





## Conclusions

The traffic of forest machinery has an impact on soil atmosphere composition which depends on many other factors also affected by soil compaction. Consequently it is important to monitor on the long term all the soil properties impacted by soil compaction to understand how soil functions change and interact. For example, in Azerailles $CO_2$ emissions were measured at the same time as the sampling of soil gas and near the gas collectors (F.Parent and D.Epron, EEF, Nancy University). The results show that $CO_2$ emissions throughout the year were lower in the compacted plots than in the control plots although soil atmosphere displayed higher $CO_2$ concentrations in the compacted plots during wet periods and in the undisturbed plots during dry periods.

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