Geoderma 217–218 (2014) 10–17

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

# Impact of heavy traffic on soil macroporosity of two silty forest soils: Initial effect and short-term recovery

N. Bottinelli [a,*], V. Hallaire [b,c], N. Goutal [d], P. Bonnaud [a], J. Ranger [a]

[a] INRA, UR1138 INRA, Biogéochimie des Ecosystèmes Forestiers, F-54280 Champenoux, France
[b] INRA, UMR1069 Sol Agro et Hydrosystème Spatialisation, F-35000 Rennes, France
[c] Agrocampus Ouest, F-35000 Rennes, France
[d] Office National des Forêts (ONF), Direction Technique et Commerciale Bois—Dep. R&D, 14, Rue Girardet, 54000 Nancy, France

## ARTICLE INFO

*Article history:*
Received 16 November 2012
Received in revised form 28 October 2013
Accepted 30 October 2013
Available online 30 November 2013

*Keywords:*
Compaction
Porosity
Micromorphology

## ABSTRACT

Processes and rate of macroporosity changes following heavy traffic in forest ecosystems are seldom studied. The aim of this study was to determine the ability of forest soils to regenerate their macroporosity naturally. The study was performed on 2 silty temperate-forest soils classified as sensitive to compaction located in north-eastern France. Macroporosity was measured in control and trafficked plots at 3 depths (0–7, 15–30 and 30–45 cm) over 2–3 years. Soil macroporosity characteristics (shape, size and orientation) were assessed on polished sections through 2D-image analysis and micromorphic observations. Immediately after heavy traffic, macroporosity decreased by 96 to 49% from 0 to 45 cm in depth. Natural regeneration of macroporosity occurred in the upper 7 cm of soil, while the soil below remained compacted. Small and medium macropores (0.05–0.8 $mm^2$) dominated by rounded and irregular pores regenerated completely. Large macropores (>0.8 $mm^2$) originally dominated by vughs, mammilated vughs and channels rarely regenerated and were gradually replaced by horizontally oriented planar pores. Our results suggest that initial stages of natural macroporosity recovery are likely due to plant-root penetration and physical processes (shrink–swell, freeze–thaw), whereas recovery due to fauna activities appears later.

## 1. Introduction

Compaction is recognised as a major threat to soil fertility in large areas of cultivated land. It is estimated to be responsible for the degradation of $6.8 \times 10^4$ $km^2$ worldwide, of which $3.3 \times 10^4$ $km^2$ is located in Europe (Oldeman et al., 1991). Moreover, approximately 32% of soils in Europe are highly vulnerable to soil compaction, and another 18% are moderately vulnerable (Fraters, 1996). As a result, soil compaction was identified as one of the six main threats to sustained soil quality in Europe (Commission of the European Communities, 2006).

The growing mechanisation of forest operations increases soil compaction, resulting in a decrease in soil macroporosity (i.e., pores $> 30$ μm) (Berli et al., 2004; Frey et al., 2009; Greacen and Sands, 1980; Herbauts et al., 1996; Rab, 2004; Startsev and McNabb, 2001), through which water, solutes, gas through the soil, thereby reducing exchange processes (Greacen and Sands, 1980). Such changes may also modify the soil as a habitat and thus change or reduce biological activity of soil flora and fauna (Beylich et al., 2010; Lipiec and Hatano, 2003). Therefore, the assessment, understanding and prediction of soil compaction and associated changes in macroporosity are important issues in preventing permanent soil degradation and yield losses.

In forests, the remediation of compaction by tillage is rarely used and difficult to apply due to the presence of stumps and large roots. Therefore, compacted forest soils must recover their structure through natural processes (i.e., wetting–drying cycles, freeze–thaw cycles during winter or biological activity, such as root growth and penetration and fauna activities). Most studies based on measurement of bulk density (Brais, 2001; Croke et al., 2001; Goutal et al., 2012; Greacen and Sands, 1980; Page-Dumroese et al., 2006; Rab, 2004) or macropore volume (Rab, 2004) show that, once compacted, initial layers of forest soils recover slowly to undisturbed levels, varying considerably from several years to several decades. Because quantifications based on bulk density or macropore volume do not allow visualisation of structural changes, the inherent processes involved have rarely been identified and rely on assumptions.

Two-dimensional image analysis and micromorphic descriptions on soil sections provide interesting tools for quantifying and qualifying soil macroporosity. For example, channels are associated with plant roots and burrowing fauna, while mammilated vughs are associated with fauna pellets (Brewer, 1964; Vandenbygaart et al., 2000). Shrinkage of drying soil and ice-lens formation in freezing soil generate relatively connected planar pores (Rasa et al., 2012). In contrast, compaction induces thin, horizontal planar pores that rarely interconnect (Pagliai

---

[*] Corresponding author at: UR1138 INRA, Biogéochimie des Ecosystèmes Forestiers, rue d'Amance, 54280 Champenoux, France. Tel.: +33 3 83 39 41 09; fax: +33 3 83 39 40 76.
*E-mail address:* nicobottinelli86@hotmail.com (N. Bottinelli).

0016-7061/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geoderma.2013.10.025

et al., 2003). Both image analysis and micromorphic descriptions have been used in crop ecosystems to investigate processes responsible for macroporosity regeneration after compaction (Alakukku, 1996; Boizard et al., 2013; Bullock et al., 1985; Pagliai, 1987) but not in forest ecosystems. Information about the processes that change soil macroporosity over time could improve understanding of the time necessary to restore forest soil subject to heavy traffic.

The aim of this study was to quantify and interpret the initial and short-term effects of heavy traffic on soil macroporosity of 2 silty forest soils. We assumed that studying shape, size, orientation and origin of the macroporosity would improve understanding of soil macroporosity recovery after compaction by heavy traffic in forests. This was accomplished using 2D-image analysis associated with micromorphic observations on polished soil sections sampled from 0 to 45 cm in depth immediately after heavy traffic and 2–3 years later.

## 2. Materials and methods

### 2.1. Location, climate and soil

This study was conducted in 2 ongoing experiments in Lorraine (north-eastern France). The first experiment was located in the "Haut-bois" forest near Azerailles (AZ) (48°29′19″ N, 6°41′43″ E), Meurthe et Moselle department, and the second was located in the "Grand Pays" forest near Clermont-en-Argonne (CA) (49°06′23″ N, 5° 04′18″ E), Meuse department. The region had a 30-yr mean annual temperature of 9 °C (AZ) to 9.5 °C (CA) and mean annual precipitation of 900 mm (AZ) to 1000 mm (CA). The soil at both sites is classified as neoluvisol (ruptic) (WRB, 2006) and is developed on a silt loam layer approximately 50-cm thick laying on a clay layer (weathering of a Keuper marl at AZ site and weathering of gaize rock at CA). Selected properties presented in Table 1 show differences in clay content, clay mineralogy, swelling index and pH between the two sites.

### 2.2. Experimental plots

Each site was clear-cut over a 5-ha area. Logs were manually felled and were lifted and transported to the landing area using a cable-yarding system to avoid forest-machinery traffic during harvesting. The remaining slash was carried out of the sites by hand or with an Iron Horse to limit heterogeneity of soil-surface cover during subsequent forwarder traffic. Each site was divided into 3 blocks. In each block, the same fully-loaded 8-wheel-drive forwarder (1996 Valmet 840, serial number 9146, Valmet Logging, Sweden) drove on land strips for an equivalent of two passes (one forward and one rearward pass) in May 2007 and March 2008 at AZ and CA, respectively. The tyres of the forwarder were 60 cm wide, had a diameter of 133 cm (600/55 × 26.5) and were inflated to a pressure of 360 kPa for both sites. The empty forwarder weighed 11.4 Mg, with the four front wheels supporting 6.9 Mg and the four rear wheels supporting 4.5 Mg. In AZ, the wood-loaded forwarder weighed 23.3 Mg, with the four front and the four rear wheels supporting 7.56 Mg (i.e. the empty weight on the four front wheels + 5% of the load) and 15.76 Mg (i.e. the unloaded weight on the four rear wheels + 95% of the load), respectively. In CA, we only weighed the wood load and deduced the total weight of the loaded forwarder (16.7 Mg), the loaded weight on the four front wheels (7.17 Mg) and rear wheels (9.57 Mg) according to the measurements taken in AZ. Soil water content at time of traffic was higher at CA than at AZ between 0 and 10 cm depth (0.49 vs. 0.32 g $g^{-1}$) and between 20 and 30 cm depth (0.32 vs. 0.27 g $g^{-1}$), while similar values were found between 30 and 50 cm depth (0.27 g $g^{-1}$). Each plot measured 50 × 50 m, with two undisturbed control (Co) 10 × 50 m land strips on each side of the 30 × 50 m trafficked area (Tr). In autumn 2007 (AZ) and 2008 (CA) the entire site surface area was planted with sessile oak (*Quercus petraea* L.) at a density of 1600 seedlings per ha at each site. At AZ the composition of the vegetation was immediately modified during the summer following the forwarder traffic; the Tr plots consisted mostly of rushes (*Juncus* spp.), and the Co plots were composed mostly of bramble (*Rubus fructicosus* L.). At CA a similar change in vegetation composition was also observed but was slighter than at AZ.

**Table 1**
Selected soil physical and chemical properties before the experiment started in 2007 for Azerailles (AZ) site and 2008 for Clermont-en-Argonne (CA) site.

| Depth | $pH_{water}$ | Sand (%) | Silt (%) | Clay (%) | SOC[a] (g $kg^{-1}$) | XRD[b] | Swelling index[c] |
|---|---|---|---|---|---|---|---|
| *AZ* | | | | | | | |
| 0–10 cm | 4.8 | 22.2 | 55.6 | 22.2 | 3.1 | K, I, Ch, I/C int | 0.18 |
| 10–30 cm | 4.6 | 20.5 | 56.9 | 22.6 | 1.5 | K, I, Ch, I/C int | 0.12 |
| 30–60 cm | 4.7 | 14.6 | 46.5 | 38.9 | 0.1 | K, I, Ch, I/C int | – |
| *CA* | | | | | | | |
| 0–10 cm | 4.4 | 15 | 72.2 | 12.8 | 2.9 | K, I, V, HIC, S | 0.08 |
| 10–30 cm | 4.5 | 15.3 | 70.6 | 14.1 | 0.8 | K, I, V, HIC, S | 0.05 |
| 30–60 cm | 4.7 | 13.3 | 61.9 | 24.8 | 0.8 | K, I, V, HIC, S | – |

[a] Soil organic carbon (SOC) content, determination using a CHN analyser.

[b] Identification of clay minerals using X-ray diffraction (XRD); K, kaolinite; I, illite; Ch, chlorite; I/C int., interstratified illite–chlorite; V, vermiculite; S, smectite; HIC., hydroxy-interlayered clay.

[c] Swelling index = $(V_{-10\ hPa} - V_{air\ dry}) / (W_{-10\ hPa} - W_{air\ dry})$. V and W corresponded to the specific volume (g $cm^{-3}$) and W to the gravimetric water content (g $g^{-1}$) measured from the shrinkage curve (Goutal et al., 2012).

### 2.3. Soil sampling and measures

Considering the possibility of soil macroporosity recovery rate changing according to depth, measurements were made at 0–7 cm, 15–30 cm and 30–45 cm depths. At AZ, soil samples were collected (i) in Co and Tr in June 2007 ($T_0$, 1 month after traffic); (ii) in Tr in April 2009 ($T_{+2}$, 2 years after traffic) and (iii) in Co and Tr in May 2010 ($T_{+3}$, 3 years after traffic). For the CA site, soil samples were collected (i) in Co and Tr plots in April 2008 ($T_0$, 1 month after traffic); (ii) in Tr in April 2009 ($T_{+1}$, 1 year after traffic) and (iii) in Co and Tr in May 2010 ($T_{+2}$, 2 years after traffic).

#### 2.3.1. Soil macroporosity

In total, 90 undisturbed soil blocks from 3 replicate plots per treatment were collected from soil profiles opened across the plots at right angles to the direction of the passage. Blocks were obtained with small cardboard boxes (7 cm high × 5 cm wide × 5 cm deep) inserted vertically at depth of 0–7 cm and large cardboard boxes (15 cm high × 9 cm wide × 5 cm deep) inserted vertically at depths of 15–30 and 30–45 cm. Then, blocks were sealed with plastic film, and put in the fridge to avoid water evaporation. Blocks were impregnated with a polyester resin (Scott Bader Crystic®) containing fluorescent dye (Ciba Uvitex® OB). Each soil block was cut in the horizontal plane to produce a 6-mm-thick polished section. One and two images were captured for small and large sections, respectively. Sections were captured under both reflected natural and ultraviolet (UV) light (in which dark colours indicate the solid phase and light colours indicate macroporosity) with a digital Olympus LC20 camera and digitised in a rectangular grid of 1600 × 1200 pixels with a spatial resolution of 30 μm per pixel.

Macropore-space quantification was performed on binary images created by manipulating these digital images with ImageJ software (Rasband, 2009). First, natural-light and UV images were thresholded to obtain respective binary images. Then, because quartz and feldspar may react under UV light and thereby resemble macropores, binary UV images were subtracted from binary natural-light images. Finally, macropores smaller than 50 pixels (i.e., 0.05 $mm^2$, corresponding to