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Characteristics of Soil Structure and Greenhouse Gas Fluxes on Ten-Year Old Skid Trails with and without Black Alders (*Alnus glutinosa* (L.) Gaertn.)

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Abstract: Forest soil compaction caused by heavy machines can cause ecosystem degradation, reduced site productivity and increased greenhouse gas (GHG) emissions. Recent studies investigating the plant-mediated alleviation of soil compaction with black alder showed promising results (*Alnus glutinosa*). This study aimed to measure soil recovery and GHG fluxes on machine tracks with and without black alders in North-East Switzerland. In 2008, two machine tracks were created under controlled conditions in a European beech (*Fagus sylvatica*) stand with a sandy loam texture. Directly after compaction, soil physical parameters were measured on one track while the other track was planted with alders. Initial topsoil bulk density and porosity on the track without alders were 1.52 g cm^{-3} and 43%, respectively. Ten years later, a decrease in bulk density to 1.23 g cm^{-3} and an increase in porosity to 57% indicated partial structure recovery. Compared with the untreated machine track, alder had no beneficial impact on soil physical parameters. Elevated cumulative N_2O emission (+30%) under alder compared with the untreated track could result from symbiotic nitrogen fixation by alder. Overall, CH_4 fluxes were sensitive to the effects of soil trafficking. We conclude that black alder did not promote the recovery of a compacted sandy loam while it had the potential to deteriorate the GHG balance of the investigated forest stand.

Keywords: soil compaction; soil structure; skid trails; greenhouse gas fluxes; black alder; soil recovery

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1. Introduction

The compaction of forest soils by fully mechanized logging with machine weights of up to 50 tons [1] leads to reduced soil aeration by a loss of macro porosity and the disruption of pore continuity [2]. As a consequence, a decline in site productivity [3] and ecosystem degradation are possible [4]. Furthermore, limited soil aeration reduces the sink function of forest soils for greenhouse gases. Methane, which is consumed by methanotrophic bacteria in upland forest soils, is produced by methanogenic archaea when organic matter is decomposed under anaerobic conditions [5] and N_2O is produced as an intermediate product of denitrification under anoxic conditions [6]. For these reasons, it is necessary to minimize the area affected by compaction and to recover the initial soil structure where no further disturbance is expected. As mechanical soil loosening, e.g., with agricultural techniques in forests is inconvenient [7] and natural soil recovery is slow [8,9], recent studies evaluated the potential of trees and herbs to alleviate soil compaction by root penetration and the promotion of biotic activity.

The recovery of forest soils is frequently studied on skid trails [10], which serve as machine tracks within the forest stand during logging operations. Soil structure formation by plants is commonly linked to root penetration, the promotion of soil fauna by the introduction of organic C and soil shrinkage by water extraction [11]. Carminati et al. [12] demonstrated via X-ray tomography and image analysis that gaps evolve between roots and the surrounding soil at dry conditions. Meyer et al. [13,14] observed that black alder (*Alnus glutinosa* (L.) Gaertn.) planted on skid trails in combination with compost application created air-conducting porosity to a depth of 70 cm after seven years, presumably by root penetration. Additionally, Flores Fernandez et al. [15] found alder species in combination with liming and mulching suitable to improve soil aeration on a skid trail. Apart from physical penetration, roots can promote soil structuring and the stabilization of aggregates by releasing exudates [16]. Vergani and Graf [17] found evidence that roots of grey alder (*Alnus incana* (L.) Moench) improved aggregate stability and water permeability. Furthermore, biotic activity, especially earthworm activity, positively affects soil structure recovery [7]. Ebeling et al. [18] observed the recovery of forest soils with high biological activity within 10–20 years after compaction, while a forest soil with low biological activity was not completely recovered after 40 years. Likewise, superficial soil recovery of a skid trail in a black alder stand reported by Warlo et al. [19] was presumably the result of high biotic activity under alder.

Among the examined studies dealing with the plant-mediated recovery of forest soils, the most promising results were obtained with alder species. Black alder seems to be particularly suitable as its roots are supplied with atmospheric oxygen via an aerenchyma, enabling root growth under anaerobic conditions [20]. With this physiological adaption to waterlogging, black alder naturally occurs on floodplains and riparian areas from mid-Scandinavia to the Mediterranean [21]. Planted on skid trails with often anaerobic soil conditions, black alder could contribute to the recovery of soil structure by root penetration. Additionally, symbiotic N fixation by *Frankia alni* with N inputs of up to 160 kg ha^{-1} yr^{-1} [22] promotes biotic activity under alder, resulting in further positive effects on structure formation. On the other hand, N fixation can cause increased N_2O emissions [23], deteriorating the greenhouse gas balance of forest stands regardless of possibly improved soil aeration.

The primary objective of this study is to quantify the natural and alder-enhanced recovery of soil physical parameters on machine tracks. Long-term studies of forest soil recovery after soil trafficking are scarce and studies providing detailed information on initial conditions and machine configurations are even scarcer. In 2008, a compaction experiment was conducted by the Swiss Federal Research Institute WSL in a beech stand [24]. A treatment with black alders planted in 2008 on compacted soil was included to evaluate the potential of alders to promote soil regeneration. The aim was therefore to evaluate soil recovery based on changes in soil physical parameters acquired directly after compaction compared with the results of a re-analysis in 2018. To assess the possible undesired effects of alders on the greenhouse gas budget, we measured fluxes of CO_2, N_2O and CH_4 on a monthly basis for ten months prior to sampling for soil physical analyses.

2. Materials and Methods

2.1. Site Description

The studied site (9°05′05″ N, 47°38′41″ E, 550 m asl) was located in a beech (*Fagus sylvatica* L.) stand on the Swiss Plateau close to Ermatingen. The terrain was slightly sloped (<5 degrees) and the soil was classified as Luvic Cambisol [25] with an L-mull in humus form. The pH value ($CaCl_2$) in the mineral soil was 4.6 and the texture was a sandy loam. Mean annual temperature was 8.4 °C and mean annual precipitation was 900 mm [24].

In 2008, a soil compaction experiment was conducted by the Swiss Federal Research Institute WSL [24]. Four machine passages with a fully loaded Forwarder (Valmet 840.2) weighing 26 t equipped with 71 cm-wide tires (Trelleborg Twin 428 LS2 710/45 26.5) were applied to create several skid trail-like machine tracks. The skid trails have not been trafficked since 2008. We chose two “moderately compacted” [26] situations: one in the beech stand, and the other one in direct neighborhood to the beech stand, planted with black alder in 2008 (planting depth 15 cm, spacing between alders 120 cm, no addition of fertilizer or compost). Along five replicate transects (each of ca. 30 m length) through both skid trails, three strata were defined according to Schäffer et al. [27] and Teepe et al. [28]: (i) undisturbed control in the middle between both skid trails, (ii) the wheel tracks of both skid trails and (iii) the center bulges between the wheel tracks (Figure 1). The aim of stratification was to provide comparability between sub-plots with equal initial soil disturbance. As forest soil properties and soil–atmosphere greenhouse gas fluxes vary widely between sites but even on a plot scale [29,30], the two skid trails and the five replicate strata were judged as independent from each other.

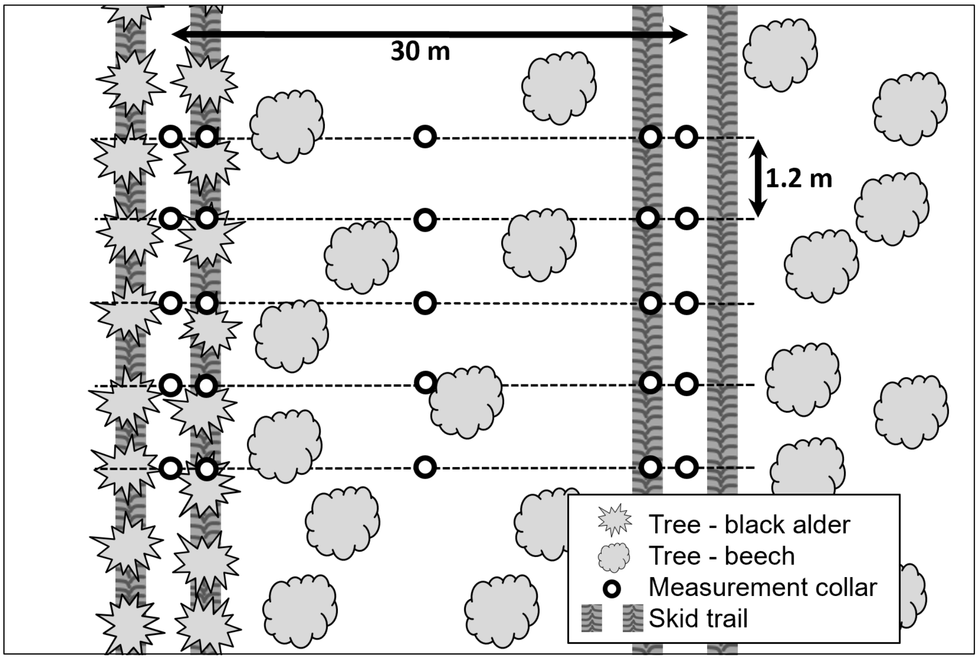

Figure 1. Sketch of the experimental design with the two investigated skid trails. Measurement collars were installed along five replicate transects in the wheel tracks of each skid trail, in the center bulges and in the undisturbed stand between the skid trails.

2.2. Filed Measurements

In 2008 and in 2012, CO_2, N_2O and CH_4 fluxes were measured with static chambers as described in Hartmann et al. [31]. In September 2017, new PVC collars (inner diameter 15.5 cm, height 9 cm) were installed to a depth of 5 cm in every stratum. The collars served as a permanent anchor for monthly measurements of soil gas fluxes (CO_2, CH_4 and N_2O) with closed chambers (closure time 30 min, 6 gas samples in vacutainers) during the period between October 2017 and August 2018. Gas analysis was conducted with a gas chromatograph (8000 series, Fisons PLC, Loughborough, UK) equipped with a flame ionization detector (FID) for CH_4 measurements and an electron capture detector (ECD) for N_2O and CO_2 measurements [32]. Gas fluxes were calculated according to Hutchinson and Livingston [33] using robust linear regressions [34] of gas concentration change over time within the chambers. A Frequency Domain probe (ML1, Delta-T Devices Ltd., Cambridge, United Kingdom) was used to measure volumetric soil moisture θ close to each collar at 5 cm depth. Chamber air temperature and soil temperature at 5 cm depth were recorded.

2.3. Soil Sampling and Laboratory Anayses

Following the compaction experiment in 2008, bulk density, total porosity and macro porosity were measured in 0–10 and 20–35 cm depth. A detailed description of the used methodology is given in Frey et al. [35]. In August 2018, soil rings (200 cm^3) were taken at the positions of the gas measurement collars in 10 cm intervals down to 50 cm depth, after the organic layer was removed (altogether 125 soil rings). Total porosity was determined with vacuum pycnometry. Water retention characteristics and pore size distribution was determined after water saturation and subsequent equilibration to a water potential of -160 hPa (pF 2.2) on a filter bed [36]. Measurement of soil gas diffusivity D_s/D_0 at field fresh moisture state and pF 2.2 was conducted according to Kühne et al. [37]. Topsoil water-filled pore space (WFPS) and air-filled porosity (ε) at the gas sampling dates were calculated based on total porosity Φ (from lab measurements) and soil moisture at field measurements. Topsoil D_s/D_0 at sampling dates was modeled with a transfer function using ε and an empirical model for forest soils proposed by Schack-Kirchner et al. [38]:

$$D_s/D_0 = 0.496 \times [\varepsilon_{calc}/100]^{1.661} \tag{1}$$

The measured D_s/D_0 was fitted well through the used transfer model. Diffusion efficiency E, which aggregates the tortuosity and discontinuity of the pore system [39], was calculated by

$$E = D_s/D_0 \times \varepsilon^{-1} \tag{2}$$

Bulk density of the mineral soil was calculated as the fraction of the soil sample dried at 105 °C and the volume of the soil sample V. Fine root (roots <2 mm diameter) mass density was calculated as the quotient of the mass of fine roots after drying at 105 °C and V. After grinding and drying sample aliquots at 105 °C, carbon (C) and nitrogen (N) contents were quantified with an elemental analyzer (Vario EL cube, Elementar, Langenselbold, Germany).

2.4. Statistical Anayses

Calculations and statistical analyses were performed with R version 3.2.3 (R Foundation for Statistical Computing, Vienna, Austria, 2015). The package “dunn.test” [40] was used to test for significant differences between treatments with Dunn’s test for multiple comparisons. The package “robustbase” [34] was used for robust regression models to determine soil gas fluxes. The 95% confidence intervals of medians were approximated according to McGill et al. [41].

3. Results

3.1. Soil Physical Parameters

Ten years after soil trafficking, bulk density in the wheel tracks of both skid trails was still higher than in the undisturbed stand (Figure 2 left). The highest values were found in a depth of 20–30 cm (1.7 g cm^{-3}) and decreased in the depths below. However, except for the depth of 40–50 cm, no significant differences in bulk density between the skid trail treated with alders and untreated skid trails were evident. Center bulges generally exhibited intermediate behavior between the undisturbed stand and wheel tracks (data not shown).

The general patterns of fine root distribution (Figure 2 right) and measured relative gas diffusivity at pF 2.2 (Figure 3 left) were the reverse of the bulk density trend. This applies generally also for diffusion efficiency (Figure 3 right) but in the wheel tracks the depth gradient was very weak.

3.2. Comparison of Soil Physical Parameters in 2008 and 2018

In Table 1 are listed the soil physical parameters of the control and the skid trails for the sampling in 2008 and 2018. It has to be considered that the sampled depth in 2008 was 5 cm deeper. In 2008, the impact of soil trafficking was most pronounced at 0–15 cm depth, and was less distinct at 20–35 cm depth. Comparing soil physical parameters between 2008 and 2018 reveals decreasing bulk density and increasing macro porosity in all treatments, including the control. As already mentioned, on the skid trail planted with alders, soil physical parameters did not differ significantly from those on the untreated skid trail in 2018.

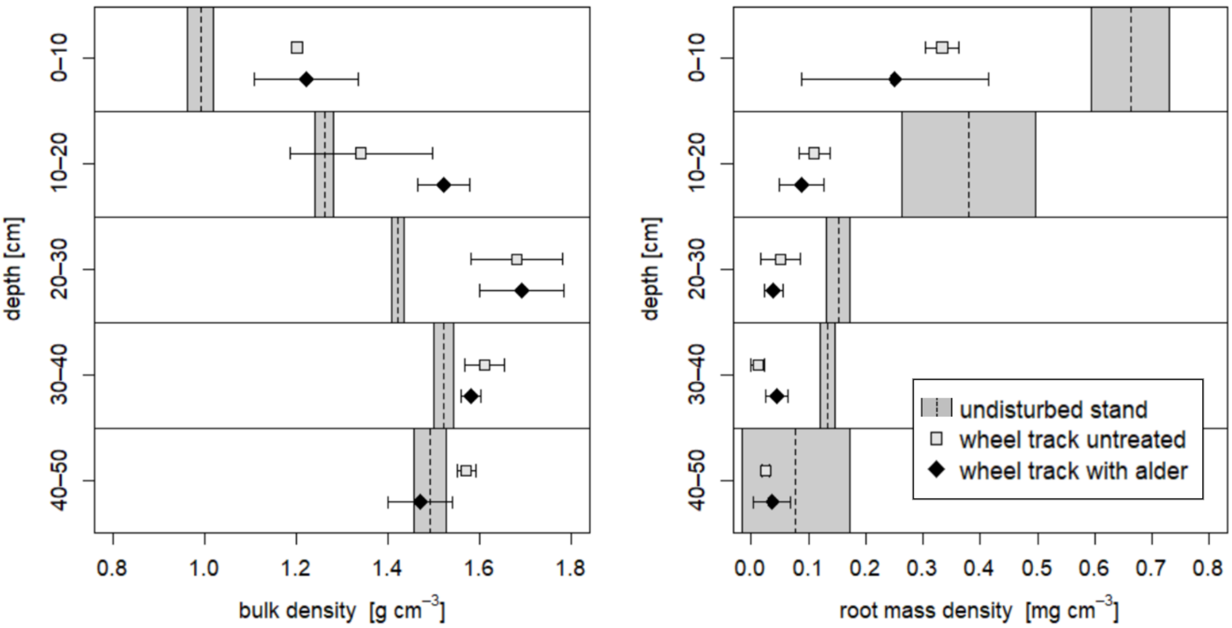

Figure 2. Median values of bulk density (**left**) and fine root mass density (**right**) in the undisturbed beech stand (dashed lines) and on the wheel tracks of the skid trails 10 years after soil trafficking. The grey shading and error bars indicate the 95% confidence intervals of median values.

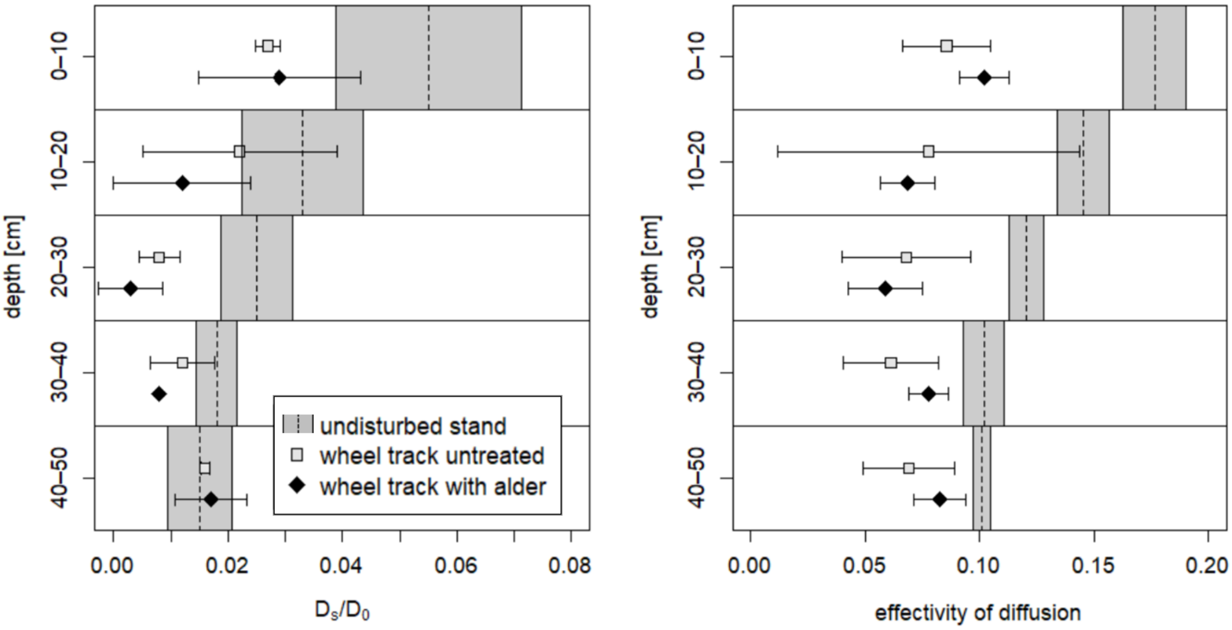

Figure 3. Median values of the relative diffusion coefficient (D_s/D_0) at pF 2.2 (**left**) and efficiency of diffusion at pF 2.2 (**right**) in the undisturbed beech stand (dashed lines) and on the wheel tracks of the skid trails 10 years after soil trafficking. The grey shading and error bars indicate the 95% confidence intervals of median values.

3.3. Soil Carbon and Nitrogen Contents

A tendency towards higher C and N contents was found in 0–10 cm depth on the wheel track of the skid trail with alders (C: 44.6 g kg^{-1}; N: 3.2 g kg^{-1}) compared with the untreated skid trail (C: 29.5 g kg^{-1}; N: 2.3 g kg^{-1}) and the undisturbed stand (C: 38.4 g kg^{-1}; N: 2.8 g kg^{-1}). In the same depth, C/N ratios ranged between 13 and 14 and declined to <10 in the depths below.

Table 1. Median values of bulk density, total porosity and macro porosity and their 95% confidence interval in the undisturbed beech stand (control) and on the wheel track of the untreated skid trail and the skid trail planted with black alders. Different letters indicate significant median differences (Dunn's test) between 2008 and 2018.

	Sampling Depth *	Beech Stand		Skid Trail (Untreated)		Skid Trail (Alder)
		2008	2018	2008	2018	2018
Bulk density [g m^{-3}]	1	1.23 ± 0.04^{a}	0.99 ± 0.03^{b}	1.52 ± 0.04^{a}	1.23 ± 0.01^{b}	1.22 ± 0.11^{b}
	2	1.49 ± 0.03^{a}	1.42 ± 0.01^{b}	1.56 ± 0.04^{a}	1.68 ± 0.10^{a}	1.69 ± 0.10^{a}
Total porosity [%]	1	50.1 ± 0.7^{a}	65.2 ± 1.8^{b}	43.3 ± 2.0^{a}	57.1 ± 3.0^{b}	57.9 ± 8.7^{b}
	2	42.4 ± 1.0^{a}	47.7 ± 0.1^{b}	39.8 ± 0.3^{a}	40.9 ± 4.2^{a}	37.7 ± 2.0^{a}
Macro porosity [%]	1	13.3 ± 2.4^{a}	15.8 ± 1.6^{a}	3.3 ± 0.6^{a}	19.8 ± 3.1^{b}	18.3 ± 8.7^{b}
	2	9.8 ± 1.6^{a}	8.5 ± 0.5^{a}	4.2 ± 0.5^{a}	11.1 ± 3.3^{b}	3.6 ± 7.7^{b}

* sampling depth 1 in 2008 = 0–15 cm; sampling depth 1 in 2018 = 0–10 cm; sampling depth 2 in 2008 = 20–35 cm and sampling depth 2 in 2018 = 20–30 cm.

3.4. Environmental Conditions during Greenhous Gas Measurements

Throughout the field measurements, WFPS was higher and D_s/D_0 was lower on both skid trails compared with the undisturbed stand (Figure 4). No treatment effect of black alder was evident.

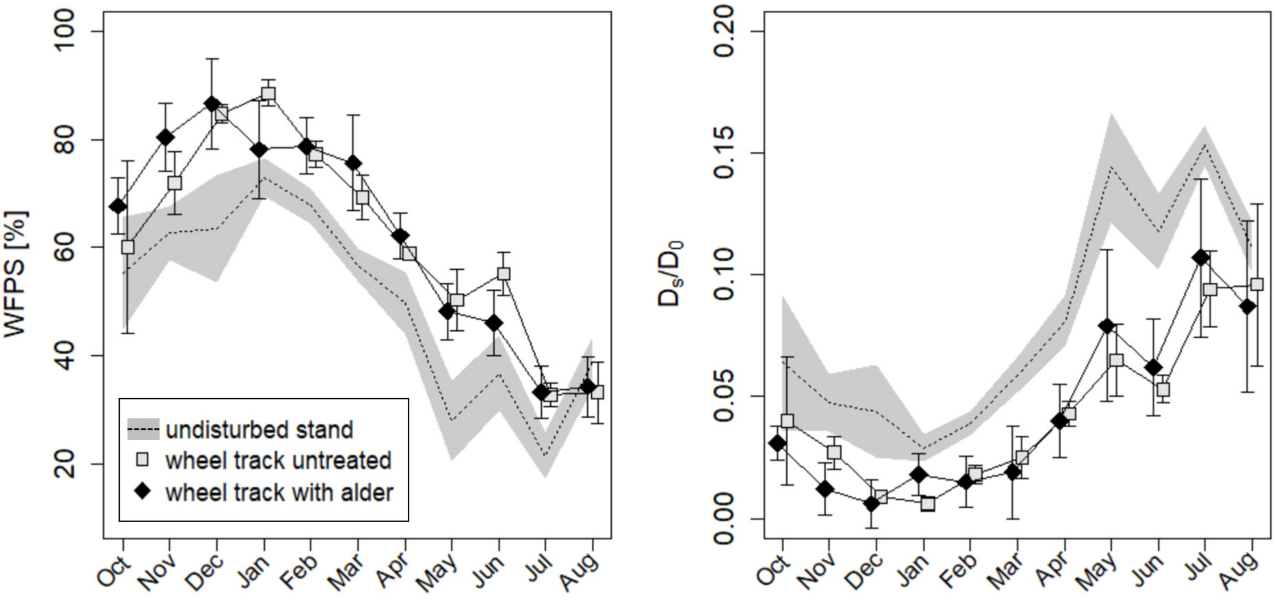

Figure 4. Monthly median values of WFPS (**left**) and modeled relative diffusion coefficient (**right**) in the undisturbed beech stand (dashed line) and on wheel tracks 10 years after soil trafficking (2017/18). The grey shading and error bars indicate the 95% confidence intervals of median values.

3.5. Greenhouse Gas Fluxes

GHG fluxes for the whole skid trail were obtained by weighting gas fluxes on the wheel tracks with 54% (2 times 71 cm tire width) and fluxes on the center bulges with 46% (120 cm width between the tires). Mostly negative CH_4 fluxes (i.e., CH_4 oxidation) were observed, with the lowest values in the undisturbed beech stand (up to -19.4 g ha^{-1} d^{-1}) and the highest values, but mostly still negative, on the skid trail with black alders (up to 0.2 g ha^{-1} d^{-1}; Figure 5). Overall, fluxes did not differ significantly between treatments; however, there was a tendency towards stronger CH_4 uptake in the undisturbed stand than on the skid trails. CH_4 fluxes were positively correlated with WFPS (r^2 = 0.51) and negatively correlated with D_s/D_0 (r^2 = 0.47). Cumulative CH_4 oxidation was strongest in the undisturbed beech stand (Table 2). On the skid trail with alders, cumulative CH_4

oxidation was significantly lower compared with the undisturbed stand but not lower than on the untreated skid trail.

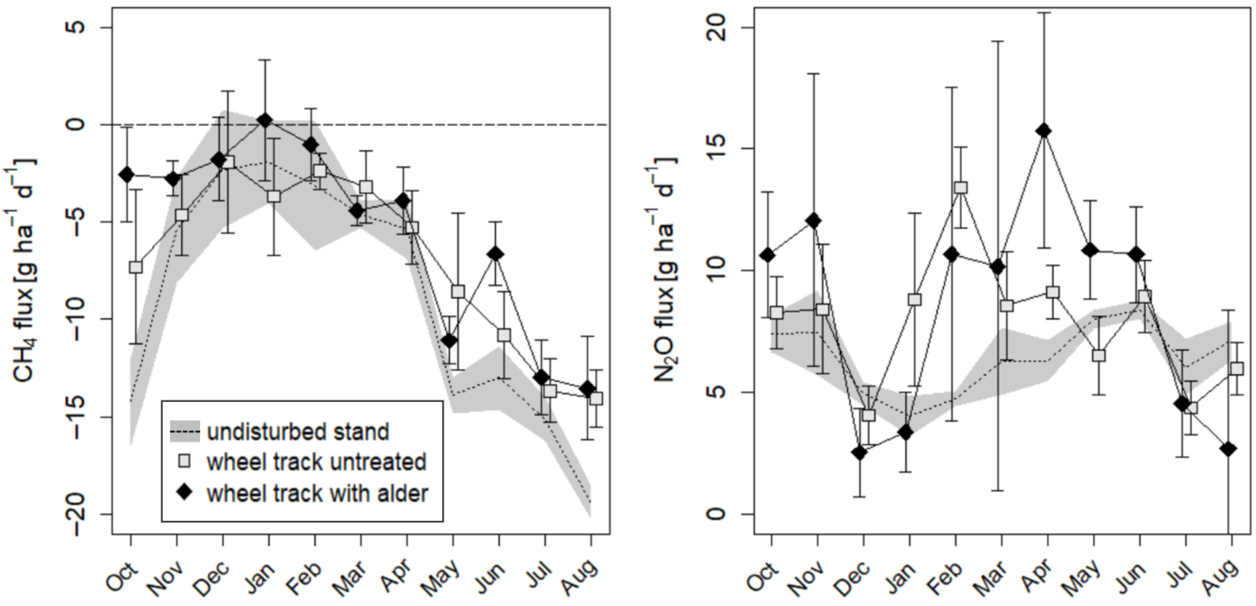

Figure 5. Medians of monthly N_2O and CH_4 flux measurements in the undisturbed beech stand (dashed line) and on wheel tracks 10 years after soil trafficking (2017/18). The grey shading and error bars indicate the 95% confidence intervals of median values.

Table 2. Median values of cumulative CO_2, N_2O and CH_4 fluxes and their 95% confidence interval. Different letters indicate significant differences between treatments.

	Beech Stand	**Skid Trail Untreated**	**Skid Trail Alder**
CH_4 (kg ha^{-1} yr^{-1})	-2.53 ± 0.79 ^{a}	-2.14 ± 0.62 ^{ab}	-1.67 ± 0.56 ^{b}
N_2O (kg ha^{-1} yr^{-1})	2.51 ± 0.23 ^{a}	2.49 ± 0.35 ^{a}	3.23 ± 0.70 ^{b}
CO_2 (Mg ha^{-1} yr^{-1})	26.1 ± 5.5 ^{a}	26.7 ± 5.3 ^{a}	28.0 ± 6.5 ^{a}

Median values of N_2O fluxes throughout the year were positive under all treatments, ranging from 2.5 to 15.8 g ha^{-1} d^{-1} (Figure 5). None of the tested parameters (WFPS, D_s/D_0, soil temperature, C and N contents) were significantly correlated with N_2O fluxes. Temporal variability was high on both skid trails compared with the undisturbed stand. In some cases, significantly higher N_2O emissions were found on the skid trails compared with the uncompacted control. In April and May 2018, the highest N_2O emissions were observed on the skid trail with alders. Cumulative fluxes under alder were significantly higher than in both other treatments (Table 2). CO_2 fluxes were positively correlated with soil temperature (r^2 = 0.43). Annual and cumulative CO_2 fluxes did not differ significantly between treatments.

4. Discussion

4.1. Soil Recovery on the Skid Trail without Treatment

This study of soil recovery after forest machine movement relies on soil physical measurements directly after soil trafficking with a forwarder and 10 years later. To our knowledge, this is unique as vehicle impact on forest soils is mostly studied by space-for-time replacement. This means that soil parameters in wheel tracks at a certain time after soil trafficking are compared with those of supposedly unaffected soil, e.g., [42,43]. What was in theory an advantage of our study turned out to be problematic due to confusion concerning the undisturbed reference which revealed an unexpected increase in macro porosity and a decrease in bulk density. Depending on whether the data from the undisturbed stand in 2008 or in 2018 are chosen as reference, soil recovery is more or less pronounced. In parts this can be an effect of the 5 cm extended depth range in the earlier sampling that brought a stronger part of the natural depth gradient of bulk density into the measurements. Furthermore, in managed forests prior compacting can be barely excluded, which makes the definition of an undisturbed control problematic. Ampoorter et al. [42] found a locally unexpected low impact of soil trafficking on a silt loam and hypothesized that a high degree of initial compaction, caused by historic uncontrolled machine traffic, could have prevented further compaction. Based on a systematic survey at 302 sites in South-West Germany, Schäffer et al. [43] reported compact or platy soil structure in 30% of the forest area outside skid trails, which they attributed to uncontrolled vehicle movement. In order to exclude such an effect, we chose control plots in 2018 explicitly along a transect between trees, inaccessible for vehicles. Because we had no other hypothesis than inherited compaction to explain the reduced bulk densities in 2018, we will hereafter use the data from 2018 as overall reference for the discussion. On the well-defined area of the skid trail itself however, we assume that potential differences in original conditions are equalized by several machine passages, such that data from 2008 and 2018 are considered sufficiently comparable. It should be kept in mind that soil sampling is always destructive, i.e., sampling at exactly the same location is not possible, which inevitably integrates spatial variability as an unknown factor.

Even though the compaction level in our study was classified as only moderate according to Lüscher et al. [26], aeration-relevant macro porosity was dramatically reduced directly after compaction (−79%), while bulk density increased by 54%. Ten years later, bulk density in the topsoil of the skid trail was less than 24% higher than in the reference, and total porosity also indicated recovery. However, a recovery of macro porosity is not enough to recover soil aeration by gas diffusion, which depends also on pore diffusion efficiency. Pore diffusion efficiency is defined as the relative diffusivity of a given volume with straight continuous pores. Deviations from these ideal pores can be caused by three geometric features [37] which can be strongly impacted by soil deformation: pores can be interrupted by shearing (connectivity), diffusion pathways can be lengthened (tortuosity), and cross sections of continuous pores can be reduced (restrictivity). In short, the observed recovery of macro porosity without a respective increase in gas diffusivity indicates a less effective pore system on the skid trails. Considering that fine roots are highly sensitive to the soil aeration status [44], limited soil aeration could explain lower fine root densities on the skid trail compared with the undisturbed stand. However, Hildebrand [45] showed for a loess loam that if bulk density was higher than 1.25 g cm^{-3}, the root growth of beech seedlings was inhibited. In our study, this threshold was exceeded in all depths below 10 cm, potentially representing a mechanical barrier for root growth.

In the literature, the relevance of structure formation by root penetration is controversial. On the one hand, roots are able to create macro pores at high soil densities by widening preexisting cracks and pores [46] and when roots dehydrate, evolving spaces between the root and surrounding soil might enable gas transport [12]. On the other hand, the radial growth pressure of roots can lead to a compaction of the surrounding soil, resulting in the opposite effect [47]. Since we found no correlation between root mass density and macro porosity or D_s/D_0, we argue that roots were not the main driver for the observed soil recovery in the present study. Alternatively, a generally high biotic activity at the site, indicated by soil respiration rates of up to 160 kg CO_2 ha^{-1} d^{-1} in the undisturbed stand and up to 170 kg CO_2 ha^{-1} d^{-1} on the skid trail, could have promoted soil recovery [7,18]. A narrow C/N ratio can be seen as beneficial for biological activity and a pH of 4.6 could offer favorable conditions for anecic and endogeic earth worms [48]. Several studies showed that earthworms are able to penetrate compacted soil with bulk densities of more than 1.7 g cm^{-3} [49,50], creating macro pores and stable soil aggregates [51]. By doing so, soil particles are ingested rather than pushed aside, causing no compaction of the surrounding soil, but instead earthworm casts at the soil surface [52]. Annual soil displacement by the burrowing activity of earthworms can exceed 100 kg m^{-2} yr^{-1} [53], involving great potential for structural restoration.

Abiotic structure formation by the shrinking and swelling of clay particles [54] or by freeze–thaw cycles [55] probably played a minor role in soil structure formation, since clay content was rather low (17%) and soil freezing at the site is rare due to a mild climate.

4.2. Soil Recovery on the Skid Trail Planted with Black Alders

The comparison of soil structure between the untreated skid trail and the skid trail planted with black alders revealed no evidence for a beneficial effect of alder on soil structure. This stands in contrast to other studies, where black alders [13,14] or grey alders [15] alleviated soil compaction, presumably due to root penetration. However, one should bear in mind that besides varying the experimental setups of studies, the interaction of numerous site-specific characteristics makes inter-study comparisons nearly impossible. This said, the results of the present study are valid for a limited area with specific site conditions.

Structure improvement in the above-cited studies was most distinct when planting alders was combined with the application of compost [13] or mulching and liming [15]. A sharp differentiation between root penetration and additional treatment effects on soil structure was therefore not always possible. However, nutrient input and reduced acidity through compost addition or liming could have ameliorated living conditions for soil-structuring biota. In addition, N fixation by alder species is frequently accompanied by an increase in soil C and N contents [56]. This fertilizing effect can additionally increase biological activity and thereby structure formation [57]. In accordance with this, Warlo et al. [19] attributed the full recovery of soil structure in the topsoil of a skid trail located in an alder stand after 17 years to generally increased biological activity due to N fixation rather than to increased root penetration only. Likewise, Ebeling et al. [18] reported the complete recovery of a compacted soil without any additional treatment but with inherent high biological activity, 20 years after compaction. In the present study, there were neither signs of higher fine root mass density under alder compared to the untreated skid trail nor of increased biological activity. The latter might be due to the fact that alders were limited to the area of the skid trail, which might be too marginal to achieve a significant boost of soil biota through N fixation.

The physiological adaption of black alders to oxygen deficiency [20] would have been expected to cause higher root mass density on the skid trail with alders compared with the untreated skid trail. As this was not the case, the above-mentioned hypothesis of root growth suppression by high mechanical impedance as opposed to limited soil aeration seems more likely.

4.3. Greenhouse Gas Fluxes

At the sampling site, Frey et al. [24] measured CH_4 fluxes of -4.2 g ha^{-1} d^{-1} at non-compacted control plots (averaged over 7, 30, 180 and 360 days after soil compaction). This is in the same range of our observations 9–10 years later. In contrast, on the skid trail Frey et al. [24] measured net positive CH_4 emission, whereas 9–10 years later, CH_4 uptake—though lower than at control plots—was observed on the skid trails. This coincides with the observed regeneration of air-conducting porosity (pores > 50 µm), which is critical for the oxygen diffusion into the soil required for CH_4 oxidation [5]. However, a trend towards less CH_4 oxidation on the skid trail planted with alders compared with the skid trail without treatment was surprising, since soil aeration and WFPS were similar throughout the year. CH_4 oxidation was possibly inhibited by elevated contents of nitrate (NO_3) or ammonium (NH_4) under alder as a result of N fixation by *Frankia alni*. Measuring NO_3 and NH_4 contents was, however, out of the scope of the present study.

Significantly elevated cumulative N_2O emissions on the skid trail with alders could likewise be the result of higher N availability under alder, as found by Mogge et al. [23]. Similar cumulative N_2O fluxes between the untreated skid trail and control suggest that soil structure, i.e., soil aeration on the skid trail, was sufficiently recovered to prevent excessive N_2O production due to anaerobic conditions. This was presumably not the case in 2008 and 2012, when N_2O fluxes on the untreated skid trail measured by Hartmann et al. [31] at the same site were 150% (light compaction) and 270% (severe compaction) higher compared with the non-compacted control. A decline in soil respiration resulting from reduced biotic activity after soil compaction [58] was not apparent and further supports the assumption of a well-advanced recovery of soil structure on both skid trails.

5. Conclusions

The main goal of this study was to evaluate the progression of soil structure regeneration on skid trails. The impact of root penetration on soil structure formation was presumably lower than in other studies and the importance of soil organisms should be taken into account for the recovery of soil compaction. This study underlines a general issue concerning the measurement of changes in soil structure over time. The destructive nature of soil physical sampling inevitably introduces uncertainties to the results due to the impossibility of sampling exactly the same point twice. As gas fluxes are sensitive to the aeration status of the soil, it might be applicable to use them as an indicator for soil structural parameters to overcome this problem. Moreover, they are easy to determine compared with soil physical parameters, such that higher area coverage and better temporal resolution of measurements could be achieved.

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