

Initial recovery of compacted soil—planting and technical treatments decrease CO₂ concentrations in soil and promote root growth

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Abstract

• **Key message** The combination of technical treatments and planting of alder trees in a compacted forest soil improves the circulation of air and water through the pore system. This leads to decreases in CO₂ concentrations and increases in root growth in the soil. Both are indicative of an initial recovery of soil structure.

• **Context** The compaction of forest soils, caused by forest machinery, has as a principal consequence: the destruction of soil structure and thus the reduction of the soil aeration

status. Thus, the gas exchange between soil and atmosphere is reduced and the depth propagation of roots is limited, resulting in the shortage of water and nutrient supplies for trees.

• **Aims** This research aimed at detecting the first stages of recovery of soil structure in a compacted forest soil, which was treated with a combination of techniques (i.e., planting tree species, mulching, addition of lime), which could presumably accelerate the regeneration of soil structure.

• **Methods** The variation of CO₂ concentrations and the dynamics of root growth were repeatedly measured. Linear mixed models were developed in order to test the effects of the treatments and the planting of trees on soil aeration, as well as to identify the influence of the different environmental effects on CO₂ concentration in soil.

• **Results** The planting of root-active trees showed significant effects on decreases in CO₂ concentrations. However, during the short-term observation, some negative effects occurred especially for the mulched sites. Nevertheless, all applied technical treatments promoted an improved soil aeration and a higher root growth compared to untreated sites which points to an initial enhanced recovery of soil structure. Pronounced seasonal and interannual variations of soil respiration were highly influenced by soil temperature and soil water content variations.

• **Conclusion** An initial regeneration of soil structure is indicated by distinct changes of the soil aeration status. This regeneration is partially enhanced by the applied treatments. The quantitative potential of the regeneration techniques needs a longer observation period for mid- and long-term soil recoveries.

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Contribution of co-authors Dr. Peter Hartmann: supervised the work, reviewed the paper and discussion. Prof. Dr. Jürgen Schäffer: practical assistance of field campaigns and soil sample analysis. Dr. Heike Puhmann: reviewed the paper and discussion. PD. Dr. Klaus von Wilpert: coordinated the research project, supervised the work, and reviewed the paper.

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1 Introduction

The passage of heavy forest machines on unprotected forest soils causes damages on soil structure due to soil compaction (von Wilpert and Schäffer 2006). The main consequence of soil compaction is the loss of soil pore volume and pore connectivity, which impedes transfer processes between the soil and the atmosphere (Chen and Weil 2010; Hildebrand et al. 2000). The gas exchange between the atmosphere and the soil is essential for the transport of oxygen to the consumption places and for the disposal of the carbon dioxide formed during respiration (Schäffer and von Wilpert 2012). Therefore, O₂ and CO₂ concentrations in compacted soils may reach threshold values beyond which root vitality is drastically reduced, conditions for root propagation degrade, and fine-root growth is largely hampered (Gaertig et al. 2002; Qi et al. 1994).

Natural regeneration of compacted soil is driven by shrinkage and swelling processes due to freeze-thaw and wetting-drying cycles and by the activity of root and soil organisms such as earthworms (Meyer et al. 2014). If compacted soils are solely left to self-regeneration, the recovery of soil functions can be very slow and can take decades. In some cases, natural regeneration may not take place at all. For this reason, there is a need to find technical and/or biological solutions to accelerate the regeneration (Ebeling et al. 2016; von Wilpert and Schäffer 2006).

Several authors observed that various soil treatments can improve the compacted soil structure, like planting of root-active subsidiary tree species, liming, or mulching. Some tree species can penetrate with their root systems compacted soils and consequently create pathways for gas exchange. While Meyer et al. (2014) observed an increasing macroporosity and air conductance in skid trails planted with black alder (*Alnus glutinosa*; (L.) Gaertn.), Gaertig et al. (2002) showed that the ability of oaks (*Quercus petraea*; (Matt.) Liebl.), in contrast, to open up dense subsoils is limited and that they cannot be used for the restoration of sites with compacted soils. Mulching loosens the top soil, mixes it up with organic material, and, thus, enhances soil aggregation and subsequent soil aeration by forming macropores (Jordán et al. 2010; Zribi et al. 2015). Calcium ions from lime act as a flocculation agent for clay minerals, binding clay colloids together and thereby, promoting the creation of soil aggregates (Schack-Kirchner and Hildebrand 1998), enhancing the circulation of air and water through the soil (Haynes and Naidu 1998), and increasing the soil microbial and mesofauna activities (Schäffer et al. 2001).

On the other hand, increased rooting intensities as well as an improved gas exchange may indicate a regeneration of soils from compaction. Rooting processes increase soil porosity and, consequently, improve the aeration status of the soil. Previous studies showed that rooting intensity is directly related to the soil air CO₂ concentrations and soil gas

permeability (Gaertig et al. 2002). However, CO₂ concentrations also depend on other factors like soil temperature, soil water content, and soil water tension. Fründ and Averdick (2016) found lower values of soil water tension at the wheel track situation which corresponded with higher CO₂ concentrations as well as soil temperature variations within the year. Thus, when using CO₂ concentrations as indicator for soil compaction and its regeneration, one necessarily needs to consider the soil water tension and the soil temperature prevailing in the investigated soils.

The focus of this paper is to analyze the variation of CO₂ concentrations and rooting processes among various soil treatments applied in skid trails within the first 3 years after treatment, in order to detect the first stages of recovery of soil structure. Rhizotron windows based on the design of Schäffer and von Wilpert (2012) were used for a monthly in situ monitoring of root growth and soil aeration status in skid trails and in undamaged control plots. Additionally, replications of diffusive gas samplers, soil water tension sensors, and soil temperature sensors were installed in order to observe CO₂ concentrations and their most important influencing environmental factor.

Our working hypotheses are the following:

- (h₁) Compacted forest soils show higher soil air CO₂ concentrations and a reduced root growth of planted trees in comparison to undamaged (untrafficked) forest soils.
- (h₂) Variations of soil CO₂ concentrations depend mainly on the seasonal variations of environmental conditions (e.g., soil temperature, soil water tension), which influence microbial activity and plant activity.
- (h₃) The applied soil treatments are expected to have the following effects:
 - (h_{3,1}) Planting of root-active trees has a substantial regeneration effect like enhancing the soil aeration status.
 - (h_{3,2}) Mulching disturbs the soil structure initially and will enhance the regeneration of soil structure after the first few years.
 - (h_{3,3}) Liming increases the recovery of the soil structure additionally to planting trees as well as mulching.
 - (h_{3,4}) A combined application of mulching and liming further enhances the soil regeneration.

2 Materials and methods

2.1 Study site

A controlled wheeling experiment was conducted at a forest site around 14 km west of Ulm, in the Swabian Alb (Southern

Germany), with an altitude around 680 m.a.s.l. (submontane altitudinal zone). The mean annual temperature is 7.2 °C, and the mean annual precipitation is about 840 mm (average values for the period 1961–1990). The site comprises silty to clayey loams, which are known to be very sensitive to wheeling. Detailed physical and chemical properties before soil compaction are presented in Flores Fernández et al. (2015).

The study site is an old plantation of Norway spruces (*Picea abies*; (L.) H. Karst), which was cleared in 2010. After the harvest, when the skid trail system had been used for the last time prior to our investigations, the area was planted with spruce and Douglas fir (*Pseudotsuga menziesii*; (Mirb.) Franco) in 2011.

For our investigation, new skid trails were generated in April 2012, with high soil moisture conditions. The mean soil water content during the driving was 39.2 vol% from 0- to 5-cm depth and 33 vol% from 10- to 20-cm depth (measurements were done with a FDR sensor). A HSM 208F forwarder with four axes made six passages on three previously marked skid trails (empty weight 14.9 t, payload 9.8 t, total weight 24.7 t). The length of the generated skid trails was approximately 70 m with a mean width of 5 m.

Two weeks after the wheeling, we applied various regeneration techniques, which were expected to accelerate and enhance the soil regeneration. These were (i) the planting of tree species known to be able to root into dense and badly aerated soils; (ii) the mulching of the harvest residues, the humus layer, and the uppermost mineral soil; and (iii) the addition of lime on the soil surface, as well as combinations of these three techniques. The first skid trail was divided in two parts: One of them was not treated, and in the other part, the liming treatment was applied. The second skid trail was treated with mulching, and in the whole third skid trail, mulching was also performed before lime was added (Flores Fernández et al. 2015).

Parts of the skid trails were planted with black alder (*Alnus glutinosa*; (L.) Gaertn.), gray alder (*Alnus incana*; (L.) Moench), alder buckthorn (*Rhamnus frangula*; (L.)), and goat willow (*Salix caprea*; (L.)); some parts were left unplanted. The plant spacing was 1 m × 1 m, creating a grid along the skid trails with 4-m width, so five plants were planted in each transversal transect. Each transect included both margins (right and left) at the outside part of the trail and both wheel tracks and the median strip between them, so the effect of compaction in the skid trails could be detected in an integrated way. Five transversal transects were planted with each of the tree species in the two mulched skid trails, so for each afforested plot, 25 plants were introduced. In addition, the four tree species were planted in a mixed plot. Only four transversal transects were planted for each afforested plot in the non-mulched skid trail since it was smaller than the mulched ones. A mixture of the tree species was planted as a control (control plots) in the undisturbed soil between the skid trails.

Further details of the experimental design are given in Flores Fernández et al. (2015).

Within 2 years after the wheeling experiment, superior tree growth and survival rates were observed for gray alder (Flores Fernández et al. 2015). For this reason, we focused our further research on this tree species and equipped these plots with diffusive gas samplers, rhizotron windows, and sensors to measure soil water tension and soil temperature (Fig. 1).

2.2 Diffusive soil gas samplers

In July 2013, diffusive gas samplers were installed to obtain monthly samples of the soil air. The type of diffusive gas samplers was developed and firstly applied by Schack-Kirchner et al. (1993). Diffusive gas samplers are based upon partial pressure gradients; the air-filled pore volume is connected with a helium-filled sampling vessel, which acts as a diffusive sink. A separable connection between the aerated soil space (represented by an artificial macropore) and the sampling vessel is achieved by a cannula upon which the vessel, closed by a septum seal, is placed. Due to its very high diffusion coefficient, inert helium causes the sampling vessel to fill rapidly with an equilibrium soil atmosphere.

Four diffusive gas samplers were installed in each wheel track, four in each median strip (center of the skid trails), and four in both undisturbed control plots (each in 25-cm depth). Two diffusive gas samplers were installed aboveground (about 2 cm) as reference to analyze the atmospheric air concentration.

2.3 Rhizotron windows

In spring 2014, 16 rhizotron windows were installed at 25-cm soil depth (30-cm lower margin, 20-cm upper margin), 35 cm away from the diffusive gas samplers in the same situations (wheel track, median strip, undisturbed control plot).

The rhizotron system is a multicomponent assembly (Fig. 2), which consists of a stainless steel ring, a plexiglass window, and a polyvinylchloride (PVC) access tube. In order to view and record the root development, a digital camera attached to a container is inserted through the access tube. A diffusive gas sampler is fitted to the structure to measure the gas concentration directly behind the window.

For the installation, a trench of at least 60-cm length, 50-cm width, and 50-cm depth was excavated leaving an undisturbed soil wall on one side. The soil wall was cleaned, and the roots were cut. During installation, the sharp stainless steel ring (inner diameter 16 cm) was pressed into the soil until the plexiglass window (length 25 cm, width 25 cm) tipped the prepared soil wall. Special attention was paid to maintaining the site-characteristic boundary conditions like soil aeration in the artificial space behind the rhizotron windows in order not to induce artificial root growth reactions due to a shifting soil

- Diffusive gas samplers
- Rhizotron windows

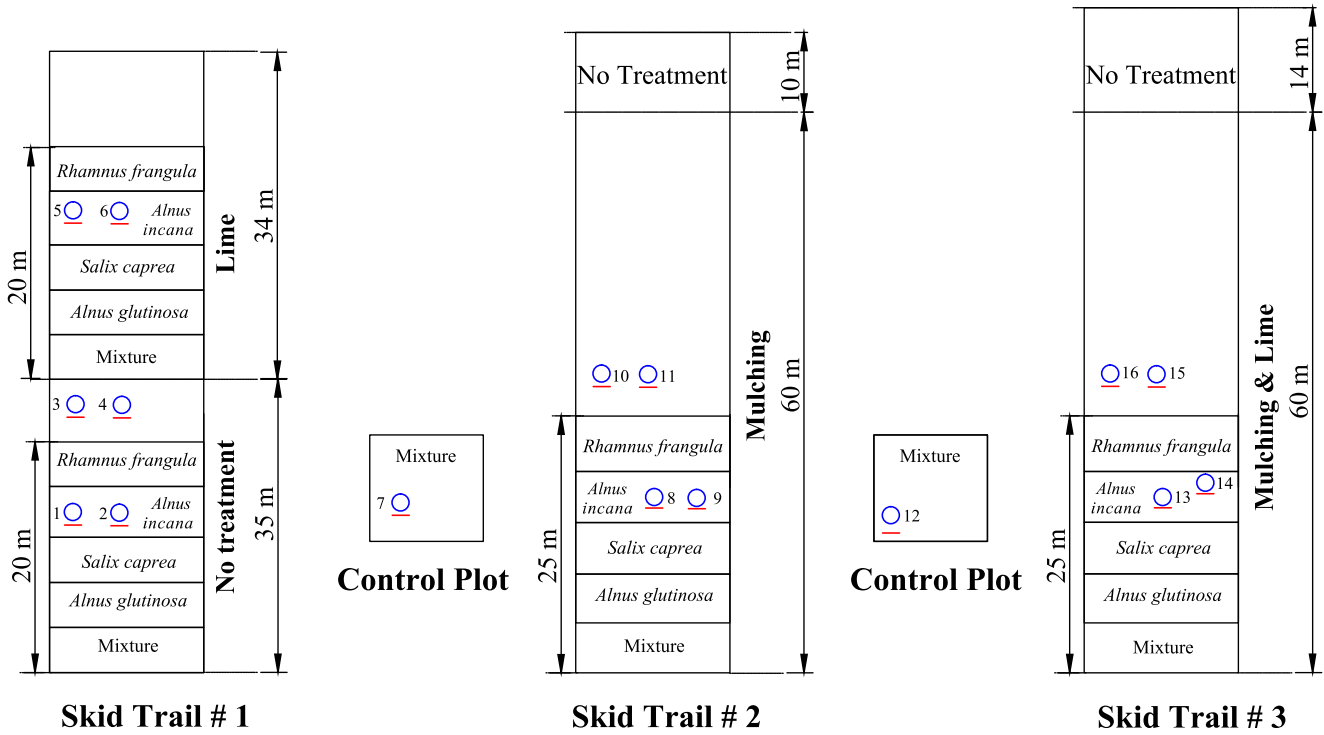


Fig. 1 Overview about the investigation site “Merklingen.” Skid trails (without treatment, limed, mulched, and the combination of mulch and lime), control plots, and location of diffusive gas samplers and rhizotron

windows. Diffusive gas samplers installed in a circular orientation around planted trees are shown as circles; lines show the location of rhizotron windows. Numbers indicate the number of each rhizotron windows installed

aeration status. The steel ring creates an undisturbed space behind the window where no or very few shrinking cracks are expected to appear due to the more homogeneous stress

of a ring compared to a rectangular frame, the latter promoting more irregular stress patterns. To take photographs, the area was lightened using a flexible LED tape, which was placed at

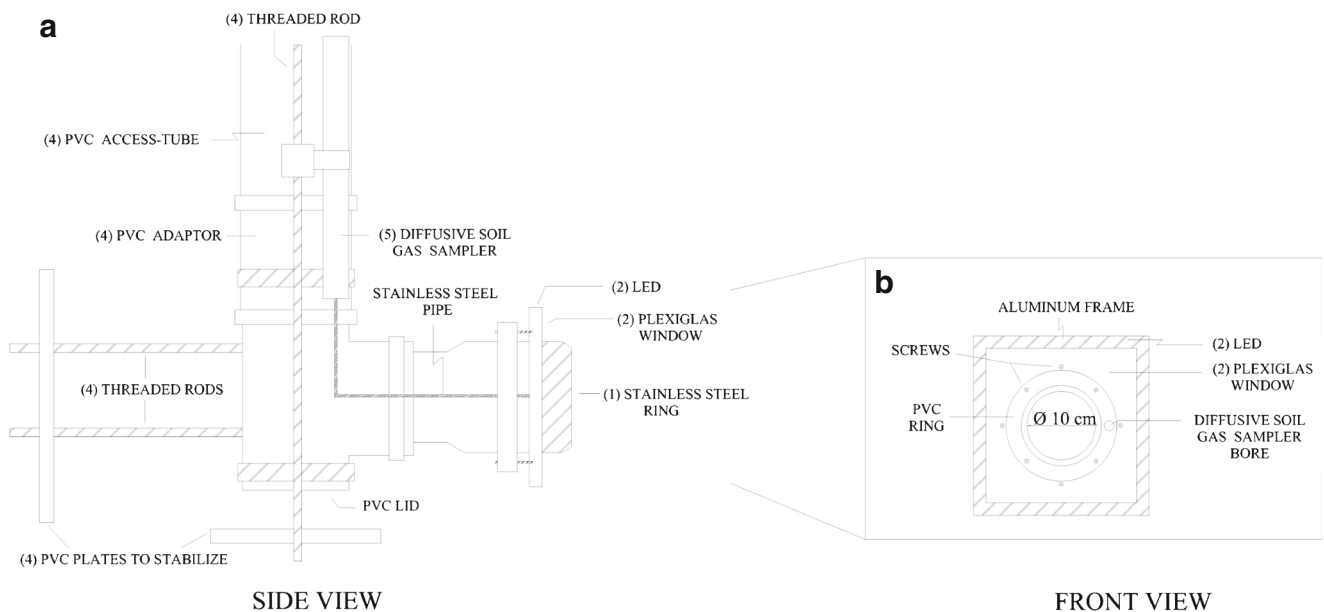


Fig. 2 Sketch of a rhizotron window. (a) Side view and (b) front view of the Plexiglas window. (1) Stainless steel ring, (2) Plexiglas window with flexible LED tape, (4) PVC structure, (5) Diffusive soil gas sampler

the four peripheral sides of the plexiglass, and sealed with silicone. The effect of this light on root growth can be neglected due to the short period of lighting. A scale of 1-cm length was marked in the observation area, in order to facilitate a later scaling of the image to calculate absolute root lengths and growth.

After installing the steel ring and the plexiglass window, the PVC access tube was installed. It consists of a guide tube (diameter 10 cm, length 30 cm), a T connection, and two stabilizing PVC plates. During measurements, the access tube was used to slip down a container with a digital camera (Sony DSC-QX10 Smart Shot, 18.2 Megapixel CMOS sensor). Wi-Fi or NFC connectivity was used to connect the camera with a smartphone or a laptop, and the quality of the image was controlled immediately after the transmission.

Root length was determined by image analysis using AutoCAD 2015, whereby each single root was vectorized by hand-tracking. Root growth was analyzed using the open-source software R version 3.2.2 (R Core Team 2015). The average rooting density (cm/cm²) for each rhizotron window and each sampling time was calculated by dividing the total measured root length by the window size.

The length of the visible roots was measured monthly for the different rhizotron windows between April 2014 and September 2016. No differentiation between herbal and tree roots was possible.

2.4 Soil water tension and soil temperature

Soil water tension and soil temperature were monitored with MPS-6 sensors (Decagon Devices, Inc.). Sensors were installed in the wheel tracks of the planted and untreated plots, the planted and mulched plot, the planted plot treated with the combination of mulching and liming, and the undisturbed control plot. The installation depth (25 cm) corresponds to that of the diffusive gas samplers and the rhizotron windows. Sensors were installed in 2015.

2.5 Statistical analysis

The monthly root growth of each situation was expressed as mean and standard deviation. Student's *t* tests were performed to compare means and standard deviation between the various measuring plots.

Pairwise comparison of the time series of CO₂ concentrations, between values measured by diffusive gas samplers for the skid trail strata (wheel track and the center of skid trails) and the undisturbed control plots, was carried out using the function *stat_smooth* (R software) from the package *ggplot2* and the method *loess*, with a level of confidence interval of 0.95.

2.6 Linear mixed-effect models

In order to test the effects of the soil treatments, the tree planting, and their interactions on soil air CO₂ concentrations measured over the whole observation period (September 2013 to September 2016), a linear mixed-effect model was built using the function *lmer* of the package “lme4” (R software version 3.2.2, (R Core Team 2015)). Models were tested against the respective null model and accepted at a significance level of $p < 0.05$.

A first linear mixed-effect model was developed to describe the relationship between a response variable (CO₂ concentrations [CO₂]) and independent variables. Time span after wheeling (date), treatments (mulch, lime, mulch × lime), and plantation status (yes/no) were considered as fixed effects. The skid trail number was included as random effect:

$$[\text{CO}_2] = f(\text{date} + \text{mulch} + \text{lime} + \text{mulch} \times \text{lime} + \text{plantation} + \text{random effect}) \quad (1)$$

A second linear mixed-effect model was developed to identify the influence of environmental conditions (soil water tension and soil temperature) and root growth on CO₂ concentrations. The observation period used for this model was March 2015 to September 2016. Date, monthly root growth (cm/cm²), soil water tension (log (hPa)), and soil temperature (°C) were considered as fixed effects, and the skid trail number was included as random effect:

$$[\text{CO}_2] = f(\text{date} + \text{root growth} + \text{soil water tension} + \text{temperature}_{\text{soil}} + \text{random effect}) \quad (2)$$

Initially, the different subplots (wheel track and median strip) were also included as random effects in the two models. However, due to the high variability of situations in our study, it reduced the number of data of the individual strata, made it difficult to set up a model, and hence was not considered in the final model versions. This problem was also observed for the fitting of the first linear mixed-effect model (Eq. 1) including the combination between the different treatments and the plantation status; therefore, it was also not considered in the final version.

Percentage increase (or decrease) of CO₂ concentrations related to the different treatments included in Eq. 1, as well as for root growth, the temperature, and the soil water tension in Eq. 2, was calculated by dividing the model estimate by the model intercept and is further on referred to as the “effect.”

3 Results

3.1 CO₂ concentrations

Figure 3 shows the time series of the CO₂ concentrations measured in the skid trails and on the undisturbed control plots (at the diffusive gas samplers and behind the rhizotron windows). Measurements are represented as monthly mean values together with the observed monthly minima and maxima.

Generally, lower CO₂ concentrations were observed at the undisturbed control plots. In contrast, compacted soils presented for most profiles higher CO₂ concentrations, which varied between the different soil treatments (Table 1). Furthermore, all planted plots had lower CO₂ concentrations than the unplanted plots (Fig. 3). The planted and limed plot as well as the planted plot treated with the combination of mulching and liming showed lower values than the unplanted and untreated plot and the unplanted and mulched plot, which

presented the highest CO₂ concentrations. Also, for most of the plots, values measured at the wheel track situations showed higher CO₂ concentrations in contrast to the median strip of skid trails.

The time series followed, with some outliers, a seasonal cycle of CO₂ production and ventilation conditions. During winter, CO₂ concentrations tended to be lower than during late spring and early summer. Extraordinarily high CO₂ concentrations were observed during summer 2014 when values in the diffusive gas samplers reached their overall maxima for most of the plots. Particularly high values were measured in the mulched plots (8.1 vol%). In contrast, during the vegetation period of 2015, CO₂ concentrations decreased remarkably.

CO₂ concentrations in soil air showed a clear tendency to decrease within the observation period for most of the plots (Fig. 3 and Table 1). This tendency was most pronounced for the mulched plots, where values decreased from their maxima of 8.1 vol% in 2014 to 0.8 vol% in 2016. These plots also

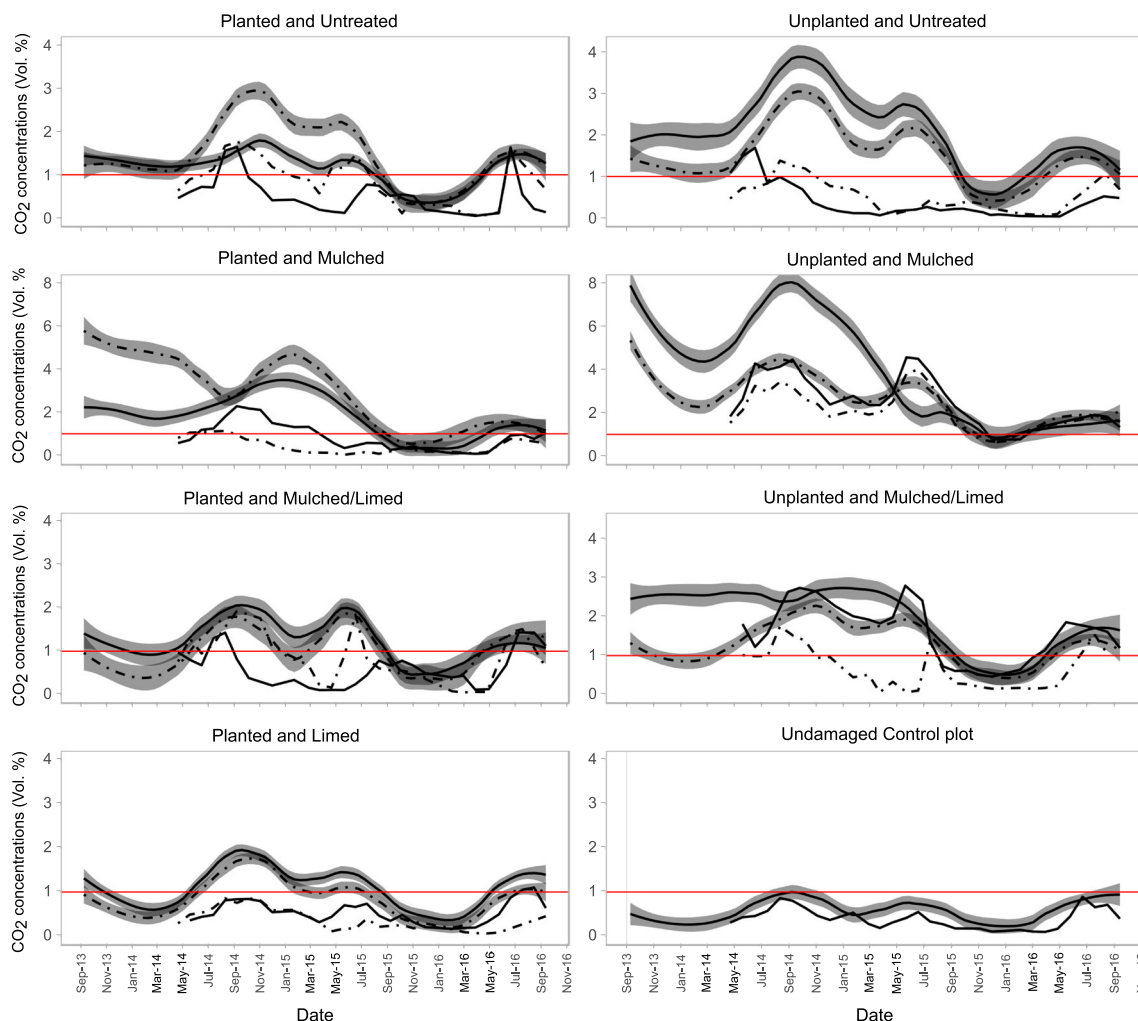


Fig. 3 CO₂ concentrations measured by diffusive gas samplers in the soil matrix and behind the rhizotron windows installed at the wheel track situation (solid shadow line) and the center of the skid trails (dashed shadow line). The horizontal reference line corresponds to 1% CO₂ concentration

Table 1 Mean values, minimum and maximum values of CO₂ concentrations, and linear regression for each situation throughout the measuring period September 2013–September 2016 for diffusive gas samplers (DGS) installed in mineral soil at 25-cm depth and April 2014–September 2016 for rhizotron windows (RWs)

Situation	Location	CO ₂ concentrations (vol%)			ΔCO ₂ concentrations = $a + b \times \text{time}$		
		Min.	Mean	Max.	Intercept, a	Coefficient, b	Signif.
Planted and untreated	DGS wheel track	0.30	1.20	2.10	1.43	−0.010	n.s.
	RWs wheel track	0.10	0.50	1.60	0.82	−0.020	.
	DGS center	0.40	1.50	3.30	1.86	−0.020	n.s.
	RWs center	0.10	0.80	1.70	1.38	−0.040	**
Unplanted and untreated	DGS wheel track	0.50	2.80	4.30	2.91	−0.050	*
	RWs wheel track	0.03	0.30	1.50	0.87	−0.040	***
	DGS center	0.40	2.20	3.10	1.95	−0.020	n.s.
	RWs center	0.10	0.50	1.30	0.08	−0.020	*
Planted and limed	DGS wheel track	0.30	1.10	2.10	1.24	−0.005	n.s.
	RWs wheel track	0.20	0.50	0.90	0.54	0.0001	n.s.
	DGS center	0.20	0.90	1.80	1.02	−0.006	n.s.
	RWs center	0.10	0.40	0.90	0.69	−0.020	***
Planted and mulched	DGS wheel track	0.20	1.80	3.90	2.79	−0.050	**
	RWs wheel track	0.10	1.00	3.60	1.52	−0.040	*
	DGS center	0.02	3.00	6.30	5.37	−0.140	***
	RWs center	0.03	0.30	0.30	0.50	−0.010	n.s.
Unplanted and mulched	DGS wheel track	0.80	4.20	8.10	7.60	−0.200	***
	RWs wheel track	0.03	2.60	4.60	3.85	−0.090	***
	DGS center	0.60	2.80	5.30	4.23	−0.080	***
	RWs center	0.60	2.20	4.00	2.95	−0.060	*
Planted and treated with the combination of mulch and lime	DGS wheel track	0.50	1.30	3.10	2.96	−0.050	***
	RWs wheel track	0.10	0.50	1.40	0.57	0.003	n.s.
	DGS center	0.30	1.00	2.70	0.98	0.005	n.s.
	RWs center	0.10	0.90	1.90	1.30	−0.030	*
Unplanted and treated with the combination of mulch and lime	DGS wheel track	0.40	2.00	4.00	1.57	−0.020	n.s.
	RWs wheel track	0.50	1.70	4.50	2.38	−0.050	*
	DGS center	0.40	1.40	2.60	1.58	−0.010	n.s.
	RWs center	0.10	0.60	1.80	0.95	−0.020	.
Undisturbed control plots	DGS	0.30	0.60	1.30	0.50	0.006	n.s.
	RWs	0.10	0.40	0.90	0.48	−0.005	n.s.

Significance for (.) $p < 0.1$

n.s. no significance

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

presented the highest significance values of the time trend, while the undisturbed control plots and the planted and limed plot showed no significant trend (Table 1).

At the end of the observation period, the lowest CO₂ concentrations were detected at the undisturbed control plots (mean values stayed below 1 vol%). Values at the plot, which was both planted and limed, were also low (Fig. 3). In the unplanted and untreated plot, CO₂ concentrations varied within the observation period in a very narrow range, at comparatively high values between 1.1 and 1.2 vol%. Measurements behind the rhizotron windows

showed lower CO₂ concentrations in soil air in comparison to values measured by diffusive gas samplers, but with comparable seasonal variation.

3.2 Root growth

The monthly root growth averages and the standard deviation for the different areas of investigation during the observation period are presented in Fig. 4.

Root growth followed a seasonal development; most rhizotron windows presented increased root growth during

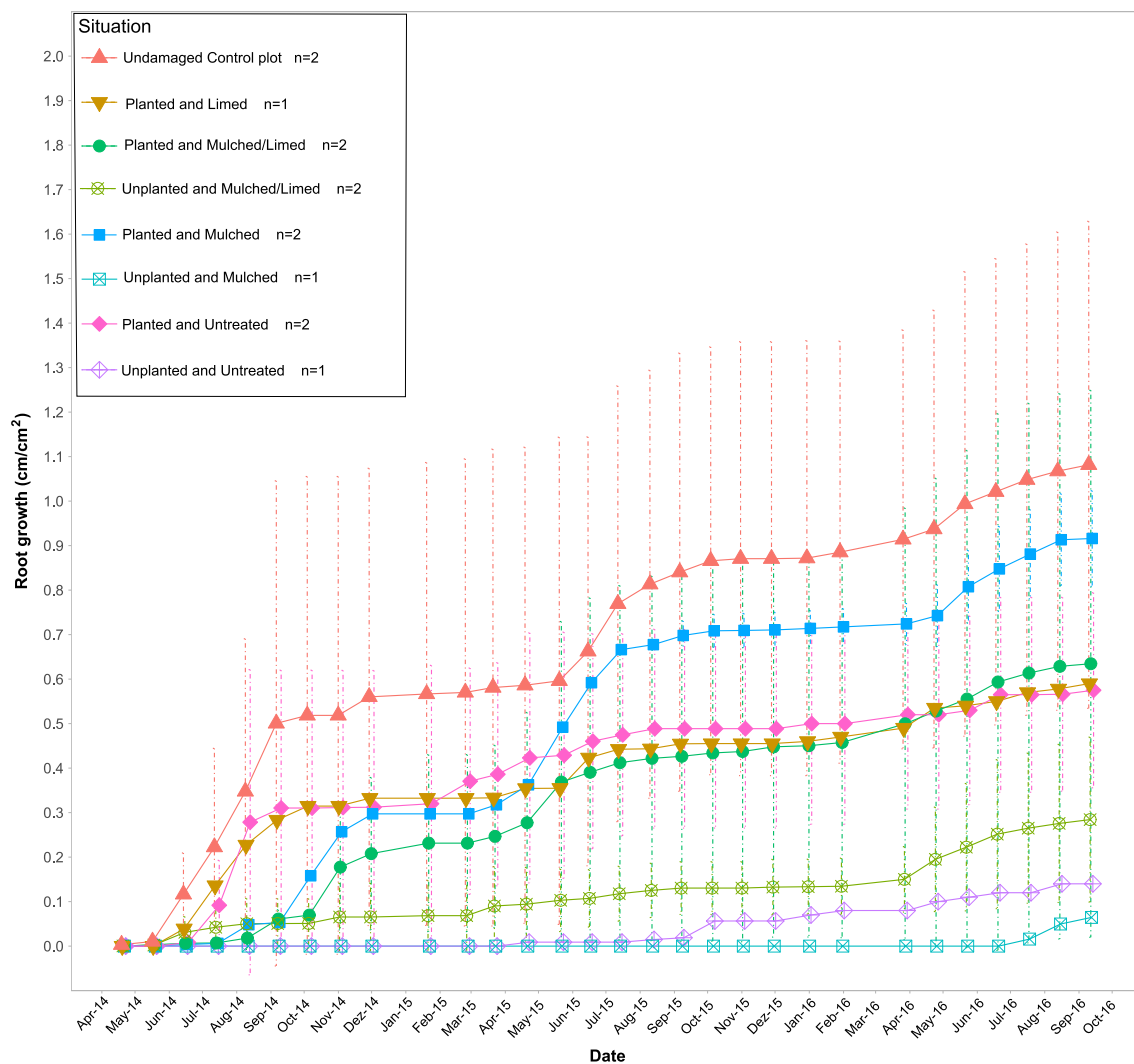


Fig. 4 Root growth (cm/cm^2) observed in the different treatments. n number of rhizotron windows for each situation

the summer period, while during winter months, root growth was almost 0. The development of the rooting system showed significant differences between the treatments as well as between planted and unplanted plots. Planted plots registered higher root growth for the whole observation period than unplanted plots. Only at the end of our observation period, root growth began to increase slightly at the unplanted plots. Root growth for the whole observation period was significantly higher at the undisturbed control plots than in skid trails (Table 2). Root growth was also significantly higher at the planted and mulched plot and at the planted plot treated with the combination of mulching and liming. No significant differences in root growth were found between the planted and limed plot and the planted plot treated with the combination of mulching and liming as well as the planted and untreated plot. The unplanted and mulched plot presented the lowest root growth (Table 2; Fig. 4).

During the first of the three observed vegetation periods, the undisturbed control plots showed the highest root

growth, followed by the planted and untreated plot and the planted and limed plot. In contrast, the planted and mulched plot as well as the planted plot treated with the combination of mulching and liming showed only very little root growth during the first vegetation period. As expected, unplanted plots showed no detectable root growth, with the exception of the plot treated with the combination of mulching and liming.

The planted and mulched plots, which started with very low root growth rates, showed the highest increase in the root growth rate over the whole observation period (Table 2) and in the second vegetation period nearly reached the level of the control. On the other hand, the planted and limed plot and the planted and untreated plot showed at the beginning a comparably high growth rate which decreased during the following two vegetation periods.

It is remarkable that in planted plots, a lower root growth rate was observed in 2016 than in the preceding year. Contradictorily, for unplanted plots, measurements were

Table 2 Mean values of root growth for the different vegetation periods (2014–2016) in the different treatments applied. The number of rhizotron windows for each plot in parentheses. $\Delta_{\text{root growth}}$ represents the difference between root growth measured during each vegetation period (April–September). Root growth represents the values measured

	$\Delta_{\text{root growth}}$ (cm/cm ²)			Root growth (cm/cm ²)
	(April–September)			Total observation period
	2014	2015	2016	(2014–2016)
Undisturbed Control Plots (2)	0.50^a	0.25 ^a	0.14 ^a	1.08^a
Planted and Limed (1)	0.28 ^{ab}	0.10 ^b	0.06 ^{bc}	0.59 ^b
Planted and Mulched (2)	0.05 ^b	0.34^c	0.17 ^d	0.92^c
Planted and treated with Mulch and Limed combined (2)	0.06 ^b	0.15 ^{bc}	0.11 ^c	0.63^b
Planted and Untreated (2)	0.31 ^{ab}	0.07 ^b	0.06 ^b	0.58 ^b
Unplanted and Mulched (1)	0.00 ^b	0.00 ^d	0.06 ^e	0.06 ^e
Unplanted and treated with Mulch and Lime combined (2)	0.02 ^b	0.12 ^e	0.24^g	0.28 ^d
Unplanted and Untreated (1)	0.00 ^b	0.01 ^d	0.04 ^g	0.14 ^{de}

higher in 2016 than in 2014 and 2015, with the unplanted plot treated with the combination of mulching and liming displaying the highest growth rate among the investigated plots (Table 2; Fig. 4).

3.3 Soil water tension and soil temperature

Soil water tension showed a pronounced seasonal variation in all observed plots. From July to November 2015, very dry conditions (−4000 to −9000 hPa) were observed in the planted and mulched plot and in the planted plot treated with the combination of mulching and liming. Also, the control plots showed an intense drought (−2000 to −4500 hPa). The planted and untreated plot showed the highest soil water tension during this period (−1000 to −2500 hPa). Similar differences between the plots were observed from June to September 2016, but measured soil water tensions indicated overall wetter conditions than in 2015.

During winter and spring (December 2015 to May 2016), soil water tension was similar for all plots and indicated near-saturated soil water conditions (−65 to −80 hPa). During 2015, soil temperature was exceptionally high, in particular during summer when monthly mean values reached almost 19 °C. In contrast, soil temperature for summer 2016 presented lower values (16.5 °C).

3.4 Correlation analyses

Tables 3 and 4 present results of the two linear mixed-effect models on the influence of different predictors on the CO₂ concentrations in the soil atmosphere.

throughout the whole observation period. Bold numbers indicate the highest root growth rates for the different vegetation periods. Gray shade indicates the three highest root growth rates for the whole observation period. Lowercase superscripts (a–g) within the same column indicate significant ($p < 0.05$) differences among treatments

In the first linear mixed-effect model (Eq. 1), the planting of trees as well as the time span after wheeling has a highly significant negative effect on CO₂ concentrations. Adding lime and combining liming and mulching also decrease the CO₂ concentrations, but the effect is statistically not significant. In contrast, mulching has a highly positive, but only weakly significant, effect on CO₂ concentrations.

The second linear mixed-effect model (Eq. 2) was developed for a shorter observation period, due to the late installation of the MPS-6 sensors. Results showed, on the one hand, a positive significant correlation of CO₂ concentrations with root growth and soil temperature. On the other hand, a highly negative and significant correlation of CO₂ concentrations with soil water tension was found, which means that CO₂ concentrations are lower in

Table 3 Summary of regression analysis, for the response variable (CO₂), with linear mixed model (Eq. 1) for the time span September 2013–September 2016. Given are the regression coefficients with standard error, the response probabilities from the analysis of variance, and the significance level

	Model 1 ($R^2 = 0.38$)				
	Coeff.	Effect (%)	Std. error	Pr (F)	Significance
Date	−0.041	−1.93	0.004	< 0.000	***
Mulch	1.538	72.60	0.440	0.097	†
Lime	−0.109	−5.14	0.365	0.797	
Mulch × lime	−0.157	−7.41	0.350	0.836	
Plantation	−0.347	−16.38	0.094	0.0002	***

$p < 0.05$; $p < 0.01$; *** $p < 0.001$; † $p < 0.1$

Table 4 Summary of regression analysis, for the response variable [CO_2], with linear mixed model (Eq. 2) for the time span March 2015–September 2016. Given are the regression coefficients with standard error, the response probabilities from the analysis of variance, and the significance level

	Model 2 ($R^2 = 0.56$)				
	Coeff.	Effect (%)	Std. error	Pr (F)	Significance
Date	-0.004	-0.42	0.006	<0.000	***
Root growth	1.398	145	0.625	0.027	*
Temperature _{soil}	0.026	2.70	0.034	<0.000	***
Soil water tension log (hPa)	-0.052	-5.4	0.015	0.0006	***

* $p < 0.05$; $p < 0.01$; *** $p < 0.001$; $p < 0.1$

dry periods and higher in wet periods. Both effects are highly significant in the model. It is difficult to judge which the dominant process is, because the temperature effect may partly contain an autocorrelation since periods with dry soils are simultaneously warm periods.

4 Discussion

Confirming our first hypothesis (h_1), we observed evidences that compaction affects the soil aeration and rootability. Directly after wheeling, higher soil air CO_2 concentrations and lower root growth rates were measured in the wheeled areas compared to the undisturbed plot. This is in accordance with observations made by Fründ and Averdiek (2016) and the findings of von Wilpert and Schäffer (2006). Gaertig et al. (2002) explained this effect by the loss of pore volume and a reduced pore connectivity in compacted soils, which severely interfere with gas exchange between soil and atmosphere, and hence, CO_2 from respiration accumulates in the soil and root density decreases.

Supporting our second hypothesis (h_2), we observed pronounced seasonal variations of soil respiration, which are obviously influenced by changes of environmental variables, such as soil temperature and soil moisture (Fründ and Averdiek 2016), which affect the pore system (Gaertig et al. 2002) and consequently the soil aeration status (Xu and Qi 2001).

The high CO_2 concentrations observed in 2014 can be explained by impeded soil diffusivity due to waterlogging of the pore system (Fründ and Averdiek 2016; Gaertig et al. 2002), which was caused by the extraordinary rainfall at the beginning of the vegetation period. During the vegetation period, soil water was gradually extracted and the porous system emptied, whereby CO_2 concentrations began to decrease. This effect was also observed by Fründ and Averdiek (2016) and was also confirmed by our second linear mixed-effect model (Eq. 2), where CO_2 concentrations decreased with increasing soil water tension. Furthermore, low precipitations and high temperatures led to an extraordinary drought in summer 2015. The soil dried out, which improved soil aeration by opening up pathways for CO_2 disposal (Schäffer and von

Wilpert 2012), and therefore, CO_2 concentrations decreased during the vegetation period. Also, a reduced microbial activity, which was hampered by the drought, may have further reduced the CO_2 concentrations in the soil. A possible formation of shrinkage cracks in the soil, which improves the soil aeration, is a further explanation for the reduced CO_2 concentrations. Although no shrinking cracks were observed through the rhizotron windows (in 25-cm soil depth), cracks have very likely developed in the top soil, in which the wheeling had destroyed the secondary soil structure. As a consequence of the enhanced aeration, a high root growth rate was detected during 2015. This corresponds to observations of a “selective finding capacity of fine root reflexes” made by Hildebrand (1986).

After the drought in 2015, soil water content increased in 2016, inducing a partial waterlogging of the soil pore space and, consequently, a hindered CO_2 discharge to the atmosphere. Remarkably, however, CO_2 concentrations were lower during summer 2016 than in summer 2015. It seems that soil temperature has a higher effect on CO_2 concentrations than soil water tension (Davidson et al. 1998). This is also supported by the linear mixed-effect model (Eq. 2), which showed a highly significant effect of soil temperature, but with a slightly lower effect. Also, the seasonal cycle of CO_2 concentrations showed higher values during summer time, when soil temperature tended to increase and thus stimulate soil microbial activity and the phenological status of trees (Beylich et al. 2010; Davidson et al. 1998; Murach et al. 1993).

CO_2 concentrations tended to decrease over the whole observation period which points to an initial recovery of soil structure by both shrinking crack formation and soil aggregation induced by the drought in 2015 as well as the planting of root-active tree species. This is in line with our second linear mixed model (Eq. 2), which showed a large influence of rooting intensity on CO_2 concentrations. Rooting processes increase soil porosity and, consequently, improve the aeration status of the soil (Gaertig et al. 2002). This mid-term recovery of soil structure, step by step, overlaid the increasing root respiration. Meyer et al. (2014) observed a similar regeneration effect in terms of an enhanced soil aeration by planting black alder. These findings correspond

to results obtained by our first linear mixed-effect model (Eq. 1), where tree planting had a highly and significantly negative effect on CO₂ concentrations and support our third hypothesis (h_{3,1}), which expects a substantial regeneration effect by planting of root-active trees.

In relation to other technical measures applied in order to accelerate the regeneration of soil structure (hypotheses h_{3,2} to h_{3,4}), results obtained by our first linear mixed-effect model (Eq. 1) showed a strong positive effect of mulching on CO₂ concentrations. High CO₂ concentrations, registered on all mulched plots throughout the vegetation periods in 2014 and 2015, support our hypothesis (h_{3,2}) of a soil structure disturbance produced by mulching. This might be related not only to an increase in soil organic matter content (Borken et al. 2002), as a result of mixing shredded woody harvest residues with the upper mineral soil, but also to a compaction of deeper horizons produced by the mulching process due to the weight (10.7 t) and the heavy vibrations of the machine. Therefore, pore volume as well as pore connectivity might have been reduced (Gaertig et al. 2002; Zausig and Horn 1992). Moreover, the mulching destroyed the already existing ground vegetation (Flores Fernández et al. 2015) and consequently, very few roots were present at the beginning of our measurements, which further hampered the CO₂ flux to the atmosphere. However, during the successive years, root growth on the mulched plot, where trees had been planted, reached values close to the undisturbed control plots.

All three observed effects of mulching—the mineralization of woody residues, the increased rooting intensity, and the compaction of the mineral soil below 10–20 cm—should result in increased CO₂ production and CO₂ concentrations in the mineral soil. But obviously, the mechanical overloosening of the upper mineral soil, which gets gradually stabilized by roots and the formation of stable soil aggregates through microbial activity, counteracts the increased respiration rate and, by the time, becomes the dominant process. Our observations give a proof that this surely is the case in the upper mineral soil. How fast or if ever this regeneration process will propagate to the compacted subsoil is, however, still an open question. A final conclusion on this will be crucial for the practical use of mulching as a means to accelerate the regeneration of soil structure.

Adding lime to the soil can improve the diffusion of air between the soil and the atmosphere as a consequence of the stabilization of soil aggregates (Schack-Kirchner and Hildebrand 1998; Schäffer et al. 2001). However, no significant effects between aeration status and rooting on the planted and limed plot were observed yet in our study up to now. This is contradictory to our hypothesis (h_{3,3}), which expects that liming improves the soil structure. Nevertheless, the planted and limed plot had the lowest CO₂ concentrations among the treated plots, which indicates enhanced soil aeration there. Therefore, also, no final

conclusions can be drawn yet with respect to this item, due to the short time span, in comparison to the abovementioned studies. We suppose that an enhanced effect of liming on soil structure may become apparent in later years. This also suggests Schack-Kirchner and Hildebrand (1998), who, only almost 7 years after liming, detected an initial improvement of the soil aeration status on the limed plots.

Our findings do not yet support our hypothesis (h_{3,4}) that the combination of treatments further enhances and accelerates the regeneration of soil structure, even if the planted plot with the combination of mulching and liming showed lower CO₂ concentrations in comparison to other treated plots. This contradictory result can be explained by the acute disturbances produced during mulching and by the short observation period available to detect any effects of the applied treatments.

Our adapted rhizotron window design proved to be a substantial improvement of the original design of Schäffer and von Wilpert (2012). The relation of observed root growth rates among treatments remained stable over the observation period, and shrinking cracks were not observed behind the rhizotron windows, which indicates the maintenance of the site-specific soil aeration at the artificial interface behind the rhizotron windows. Nevertheless, lower CO₂ concentrations measured behind the rhizotron windows were to be expected, due to disturbances produced in the soil during the installation of the rhizotron windows and also because of the larger interface between the soil and the measuring device which is 3.2 cm² for the diffusive gas samplers and roughly 80 cm² for the rhizotron windows. The latter increases the probability that natural and highly continuous macropores were captured by the rhizotron windows but were rarely included in diffusive gas sampler measurements.

5 Conclusion

At the beginning of our observations, the whole skidding trail area showed, due to a damaged soil structure, higher CO₂ concentrations and lower root growth rates in comparison to an undisturbed control plot.

CO₂ concentrations in soil air showed a clear tendency to decrease during the observation period for most of the plots, where some soil treatment had been applied directly after wheeling. The planting of root-active trees showed a substantial regeneration effect. However, no significant differences were observed between the different soil treatments applied (liming, mulching, and a combination of both).

However, a more exhaustive analysis of soil physical properties, e.g., pore size distribution and gas diffusivity, should be carried out in order to analyze the soil structural regeneration, which is the physical base of a better gas exchange between the soil and the atmosphere.

The high variability of impacts of the different treatments in their time-dependent development in combination with the comparably short observation period of 2 to 3 years is the reason that model building and interpretation of model results were rather difficult. Nevertheless, most results support the intended regeneration processes or could be well-explained through the initial, partially opposing effects of treatments like, e.g., compaction of subsoil through mulching. How long the contradictory effects will persist and when, if ever, long-term regeneration will take place cannot be answered after the first 3 years of the experiment. However, it is new and worthwhile to study the switch from short-term, partially not intended impacts of the treatments to long-term regeneration.

We could demonstrate the principle potential of all treatments to accelerate the regeneration of soil functions, based on the results presented in this study.

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