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Electrical conductivity measurements as a proxy for diffusion-limited microbial activity in soils

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Short summary:

Soil microorganisms exist in a highly structured and variably connected environment, in which they play a critical role in organic matter dynamics. To investigate the relationship between soil respiration and the connectivity of the soil pore water phase, we analysed the use of electrical conductivity as a proxy for soil respiration. Our results show that there were non-linear relationships between the two variables, thereby opening up a new approach to better understand soil respiration.

Abstract:

Soils play a highly dynamic role in the carbon cycle, by acting as either a carbon source or sink. Despite their importance in the global carbon cycle, uncertainties surrounding soil-atmosphere interactions remain, due to the many mechanisms that underlie soil carbon dynamics. One of the main mechanisms determining the decomposition of organic C in soil is the access microbial decomposers have to substrates. While not yet formally tested, there is evidence to support the idea that microbial decomposer access to substrates is diffusion-limited. This is underlined by soil respiration rates being strongly dependent on water availability. In recent years, non-destructive geophysical tools, including electrical conductivity measurements, have been used to determine the water content of soils and connectedness of the water phase in the soil pore network. As both respiration and electrical conductivity may depend on water availability and connectivity, our study aimed to determine whether electrical conductivity measurements could be used as a proxy of diffusion-limited microbial activity in soils. This was done by measuring electrical conductivity and respiration rates at different matric potentials. Sieved and undisturbed top and subsoil samples taken from conventional tillage and conservation agriculture management plots were used. Our results revealed an initial increase and consecutive drop in soil respiration associated with a decrease in the matric potential. The electrical conductivity followed a similar decrease throughout the experimental range and these showed a significant non-linear relationship. These results thus suggest that both measured variables depend on the connectedness of the aqueous phase and suggest that they could be used as groundwork for further investigations into soil respiration and electrical conductivity dynamics.

Keywords: Soil respiration, Microbial activity, Carbon cycle, Diffusion limitation, Water availability, Electrical conductivity, Pore connectivity, Soil moisture, Geophysical measurements

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1. Introduction

Natural soils contain the most diverse terrestrial microbial communities as well as terrestrial organic carbon reserves with quantities surpassing that found in both the atmosphere and vegetation combined (Crowther et al., 2019; Dubey et al., 2020). They are part of a highly dynamic cycle associated with a balance between soils acting as a carbon sink or source for atmospheric carbon (Hargreaves et al., 2015; Six et al., 2006). Carbon (C) inputs to soil are processed by microbial communities and either released to the atmosphere (generally in the form of CO_2) or are converted to microbial biomass and ultimately soil organic matter (Al-Maliki & Ebreesum, 2020; Fan et al., 2015; Sandor et al., 2020). A number of factors are believed to modulate the dynamics of C in soil, including the intrinsic resistance of the organic molecules to decomposition, the spatial inaccessibility of organic matter (OM) to microbial decomposers and organo-mineral associations (Lützow et al., 2006). The decomposition of OM occurs when organic molecules encounter microbial decomposers or their extracellular enzymes (Dignac et al., 2017). The spatial separation of OM and decomposers is believed to be a major constraint on decomposition in soils, as both microorganisms and OM are heterogeneously distributed, and only cover a small percentage of the soil pore system (Dignac et al., 2017; Lützow et al., 2006). This means that for decomposition to occur, one or the other, or both, must move.

A relatively small proportion of the soil microbial communities possess the capacity for flagellar motility, most of which is limited to zones with high OM contents (Ramoneda et al., 2024), such as the rhizosphere. This means that microbial decomposition of OM may rely on the diffusion of organic molecules towards decomposers (Nunan et al., 2020). The diffusion-limitation of OM decomposition is supported by the observation that it often varies as a linear function of the square root of time (Stanford & Smith, 1972), a characteristic of diffusion limited processes. As substrate diffusion can only occur in the presence of water, in the context of partially saturated soils, this would correspond to the necessity of the aqueous phase reaching across connected pores (Lang et al., 2007). This reliance on the presence of water is underlined by studies indicating respiration becoming virtually undetectable at very low water contents (Davidson et al., 1998). The availability of water has been identified as the single most important factor affecting microbial processes, including microbial respiration (Kpemoua et al., 2023; Nasiri et al., 2023). Although the relationship between moisture levels and carbon decomposition is well established, the hierarchy of mechanisms underlying the relationship is not certain.

Geophysical tools are fast and cost-effective tools for the measurement of soil moisture contents and also provide insight into the spatial characterization of porous material (e.g., Garre et al., 2021; Hermans et al., 2023; Loiseau et al., 2023). Electrical conductivity measurements are particularly sensitive to the connectivity of the conductive phase; that is the aqueous phase, where charge carriers move thereby enabling the characterization of pore spaces in which solute diffusion takes place (Jougnot

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et al., 2009; Revil & Jougnot, 2008). Consequently, these techniques are increasingly used to monitor the spatial and temporal distribution of water-filled pores in soils (Friedman, 2005; Jougnot et al., 2018; Samouëlian et al., 2005).

With both respiration and electrical conductivity potentially relying on the diffusion of either substrates or charge carriers across the soil systems, this raises the question of whether electrical conductivity measurements could act as a proxy for soil the quantification of soil respiration in the absence of water flow. To answer this question and improve our understanding of the relationship between microbial respiration and diffusion, our study first of all aimed to investigate the relationship between soil respiration and electrical conductivity at different soil matric potentials. The measurements were conducted on both sieved and undisturbed top- and subsoil samples taken from two different treatments of a long-term field trial.

Our primary hypothesis was that in diffusion-limited conditions, microbial respiration rates will be positively correlated with electrical conductivity stemming from a shared dependence on diffusive transport. We further hypothesized that higher initial carbon availability would weaken this correlation, due to the broader distribution of organic substrates reducing diffusion constraints. In the case of our samples we believe this would cause differences between topsoil and subsoil samples to emerge. Finally, we hypothesized that sieving would homogenize the pore network, resulting in more consistent relationships between conductivity and respiration compared to those observed in undisturbed soil samples.

2. Material and Methods

2.1. Study site and sample collection

The soil used in the study was collected from the "La Cage" field experiment on the French National Institute for Agricultural Research (INRAE) campus in Versailles, Ile-de-France (48°45'N; 2°08'E). The climate in the greater Parisian basin can be characterised as temperate, with an average precipitation of 630 mm and an annual average temperature of 10.4 °C (Bellone et al., 2023). The soil is a well-drained Luvisol (Autret et al., 2020). The experimental site was established in 1998 to conduct long-term field studies on the effects of different cultivation methods. This study focused on the conventional tillage and conservation agriculture fields. The conventional tillage site underwent annual ploughing to a depth of 30 cm and systematic pesticide application. In contrast, the conservation agriculture site was not tilled and was maintained with persistent cover crops. Pesticides were only applied in the conservation agriculture site if plant damage was observed. Since sampling occurred during the off-season in early November 2023 between the main crop. The plant cover of the conventional tillage field was mustard, while that of the conservation agriculture was common vetch and black oats. These were in place to protect the soil. The main crops consisted of a wheat-pea-rapeseed crop rotation for the conventional tillage site and pea-wheat-corn-oat rotation for the conservation tillage site. A more detailed description of the plant cover used and field treatment practices can be found in Autret et al. in 2016. The choice to use the conventional tillage and conservation agriculture treatments was based upon the fact that these were likely to have different soil structures and C contents, both key factors influencing carbon dynamics. The selection of these two systems is supported by findings from the LaCage study site, which show that

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conservation agriculture generally sustains higher microbial biomass, total C and significantly greater bound organic carbon content compared to conventional tillage(Henneron et al., 2015; Juarez et al., 2013). Further studies have identified the presence of more stable water soluble aggregates and associated improved porosity in the conservation agriculture fields compared to conventional tillage treatments (Chabert & Sarthou, 2020; Cosentino et al., 2006). This improved aggregate stability is believed to impact the maintenance of pore connectedness across a range of matric potentials (Mondal & Chakraborty, 2022).

In order to have a wide range of pore size distributions, pore connectivity, carbon contents and microbial biomass, we used sieved (<2 mm) and undisturbed samples from the topsoil (0–15 cm) and subsoil (50 cm). The soil microbial biomass and soil C contents are known to decrease with depth down the soil profile (Salomé et al., 2010) and sieving changes the physical structure and water retention properties of soil (Herbst et al., 2016).

Undisturbed samples were obtained by inserting PVC sampling cores (80 mm in length and 58 mm in internal diameter) directly into the soil horizons and extracting them carefully to preserve the soil structure. All undisturbed samples were frozen at -20°C until use. This was done to minimize organic matter decomposition that might occur during the preservation of samples prior to the incubation experiments (Allende-Montalbán et al., 2024). Bulk soil collected for sieving was air-dried, sieved to 2 mm, and stored at 10°C until the experiment began.

2.2. Study approach and incubation set-up

The study analysed the effect of matric potential, corresponding to different crop available soil water contents, on soil respiration rates and electrical conductivity during short term incubations of samples at varying pressure heads (-70, -100, -250, -350, -450 and -630 hPa). Samples were placed in airtight microcosms fitted with a ceramic plate, allowing for adjustments of the pressure head, and a septum for headspace sampling (Poll et al., 2010; Fig.1). Five microcosms at a time were subjected to controlled suctions using a pump, and the drained water was collected in refrigerated bottles at 4°C for subsequent analyses of the ionic strength of the soil solution across matric potentials. One of the microcosms was exclusively used to weigh samples in order to ensure that changes in moisture content were as expected. Each treatment was carried out in triplicate. A schematic description of the laboratory set-up can be found in Fig. S1 of the supplementary materials. The incubations were carried out at 20°C. The samples were held at each pressure head for approximately 24 hours after no more water leaching was observed to achieve hydraulic equilibrium. In total there were 24 microcosms (4 soils x 2 structural treatments x 3 replicates) used during the experiment. The samples were analysed in a randomized fashion, i.e. no replicates from the same sample and treatment combination were measured at the same time.

After measurements at -630 hPa were completed, samples were transferred to mason jars equipped with a septum to allow headspace sampling and containing an oversaturated lithium chloride solution. This induced a suction at the sample surface that is equivalent to a pressure head of -996 hPa (Colas, 2011.; Greenspan, 1977). Sample weights were monitored periodically to determine whether the target pressure head had been reached, with measurements continuing until no further water loss was observed.

2.3 Sample preparation for incubation

Undisturbed samples were thawed gradually by transferring them from a deep freezer to an 8°C refrigerator for 24 hours, then to a 20°C laboratory for five days prior to the beginning of the incubations. Sieved samples were prepared by packing the soil to a bulk density of 1.73 g/cm³, equivalent to the average density of undisturbed samples. Samples were saturated via capillary rise by initially placing them in 1 cm. Water was added gradually over the course of 24 hours until full saturation of the soil samples was achieved. The samples were then transferred into airtight, sealed microcosms and incubated in the dark, in order to reduce algal growth on the surface of the microcosms that could be caused by direct sunlight.

2.4 Analytical data collection

2.4.1 CO_2 flux measurements

Soil respiration rates were determined by measuring the increase in CO_2 concentration in the microcosm headspace three times over a period of 48 to 72 hours, depending on the rate at which CO_2 accumulated, by gas chromatography (Agilent 3000).

2.4.2 Electrical Conductivity Measurements

Sample electrical conductivity was monitored using a PSIP unit (Portable Spectral Induced Polarisation by Ontash and Ermac, ontash.com) in parallel with soil respiration measurements. The PSIP unit was fitted to a custom-made electrode configuration on each sample. A frequency of 1 Hz was used, aligning with the most commonly employed frequency when measuring in electrical conductivity for field studies (e.g., Blanchy et al., 2025).

The PVC cores were equipped with brass screws (1.5 mm thick and 16 mm long), which served as electrodes. The electrode configuration and corresponding geometrical factors were determined using COMSOL Multiphysics 5.0 software and can be found represented in the Supplementary materials (Fig. S2). Each electrode was inserted 6 mm into the soil cores to ensure reproducibility by maintaining optimal soil contact and avoiding minor shrinkage effects caused by moisture loss around the sample edges. The injection electrodes were positioned at the top and bottom of the samples respectively, with three pairs inserted vertically and one pair inserted horizontally to capture a broader distribution of electrical lines throughout the sample. Electrical conductivity values were calculated using the geometric factors outlined in Table S1 of the supplementary materials.

2.4.3. Organic matter and water content data collection

After the measurements had been concluded, the samples were dried at 105°C for 24 hours to obtain the final water content of each sample. A subsample was then ground in order to measure total organic matter content by loss-on-ignition. For this step, we followed the procedure outlined in Hogsteen et al. (2015) where samples were heated at 550°C for 3 hours in a Nabertherm oven.

2.4.4. Statistical analysis and data visualisation

The statistical analysis was conducted in RStudio (v. 4.3.0; R Core Team 2023). The respiration flux was obtained by determining the slope of the regression plots of CO_2 accumulation against time. The CO_2 flux per gram of organic matter equivalent per hour was then used to calculate the CO_2 flux relative to the flux at -70 hPa. Comparison between the relative fluxes and electrical conductivity measurements of each sample across the matric potential range was made using a linear mixed-effect model (fit using the nlme package) to determine differences among depths and field treatments.
Variance across matric potentials was assessed, and pairwise differences were tested using Type III ANOVA with Satterthwaite's method for degrees of freedom, implemented via the "ggstatsplot" package, to account for unbalanced data.
The electrical conductivity data was represented as a relative conductivity compared to the highest value at -70hPa to allow for the comparison of electrode pairs and sample types. Finally, a nonlinear mixed-effects model with a log–log power law form was used to describe the relationship between respiration flux and electrical conductivity, with random effects grouped by sample to account for heterogeneity among soil conditions.

3. Results

3.1. Soil respiration rates across soil matric potential and organic matter quantification

The organic matter content across the treatments showed no statistical difference (F_{Welch}= (7, 10.4) = 1.96, P = 0.16), with a small-to-moderate effect size (ω^2_p = 0.27, 95% *CI* [0.00, 1.00]). The lowest organic matter content was observed for the sieved topsoil conventional tillage samples and the highest amount was observed in the sieved conventional tillage subsoil (Fig. S3). At the highest saturation level, there was a significant increase in total respiration rate between the sieved compared to the undisturbed samples (P<0.03) and the topsoil compared to the subsoil samples (P<0.002) (Table S2).
The relative respiration rate, normalised to the measured values at -70 hPa, showed a near-consistent decrease across the tested matric potentials (Fig. 1). For the sieved samples, this decrease was maintained across all matric potentials, while for the undisturbed samples there was a respiration peak at -250 hPa. This increase was especially prominent for the topsoil conservation agriculture sample. Apart from the undisturbed sample values at this matric potential, no significant difference between sampling depth and field treatments was recorded. This was supported by the linear mixed-effects model results (REML, Satterthwaite's method), which showed a significant effect of applied matric potential on respiration flux (P = 0.0008), but no significant effect of sample type (P = 0.178), field treatment (P = 0.436), or their interactions. Additionally, it should be mentioned that no significant difference in the relative respiration flux at -996 hPa and at -630 hPa was found (P > 0.618;

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Type III ANOVA, Satterthwaite's method). This finding was further supported by post hoc analysis confirming no significant difference after -450 hPa (P=0.311; estimate marginal means with Kenward-Roger degrees of freedom).

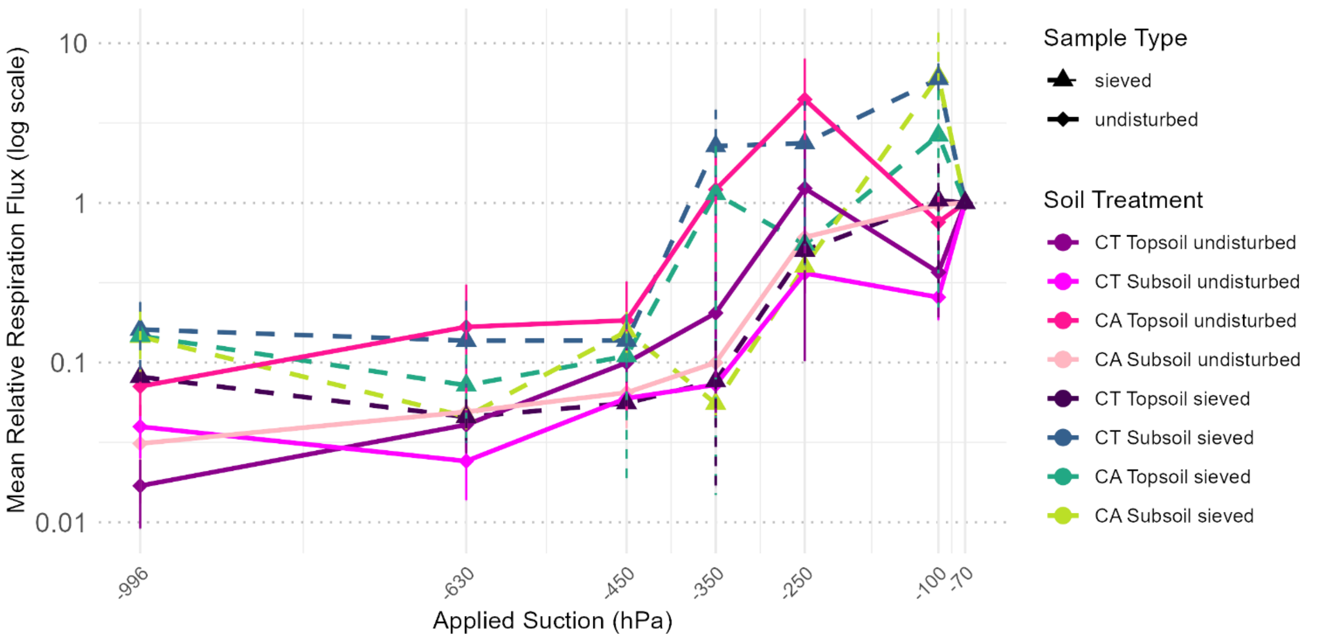

Figure 1: Mean relative soil respiration flux obtained from the triplicate of each treatment measured at a range different Applied Suctions (hPa). The different suctions represent different soil matric potentials analysed over the course of the study. The sample abbreviation CA stands for conservation agriculture field treatment and CT stands for conventional tillage. The solid lines represent undisturbed soil cores while the dashed line corresponds to sieved samples. The relative respiration rate is normalised to the respiration rate observed at -70 hPa corresponding to our highest tested saturation and are represented in a log scale. The error bars exceeding the marker size point are shown. For more details on averages and standard deviation of the mean please consult Table S3 of our supplementary materials.

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3.2. Soil electrical conductivity across soil matric potential

There was a difference in pore water electrical conductivity (supplementary materials, Table S1) with most values ranging between 413 and 637 µS/cm, with the exception of the sieved conventional tillage top- and subsoil which had values of 1052 and 742 µS/cm, respectively. To allow an easier comparison between samples given these differences, we chose to use the relative conductivity of each sampling depth and field trial to improve the comparability between samples.

The majority of the electrode pairs show a consistent decrease as the matric potential decreased (Fig. 2). Exceptions to this relationship were recorded for the conventional tillage subsurface samples at -630 hPa for the electrode pairs 1 and 3 of the sieved samples and electrode pair 4 of the undisturbed samples. The measurements at -996 hPa for the sieved conventional tillage subsoil samples did not work and these results are excluded from our principal analysis. (Full range in Supplementary, Fig. S4) For the conventional tillage topsoil samples, the electrode pair 4 showed a high fluctuation across the measured matric potentials, as well as some small increases between -70 and -100 hPa. However, these were not statistically significant (P = 0.9703). Finally, electrode pair 2 of the sieved conservation agriculture samples decreased more steeply than the other measurements. Besides these fluctuations, no difference between sampling depths nor differences between sieved and undisturbed samples were observed (P = 0.7).

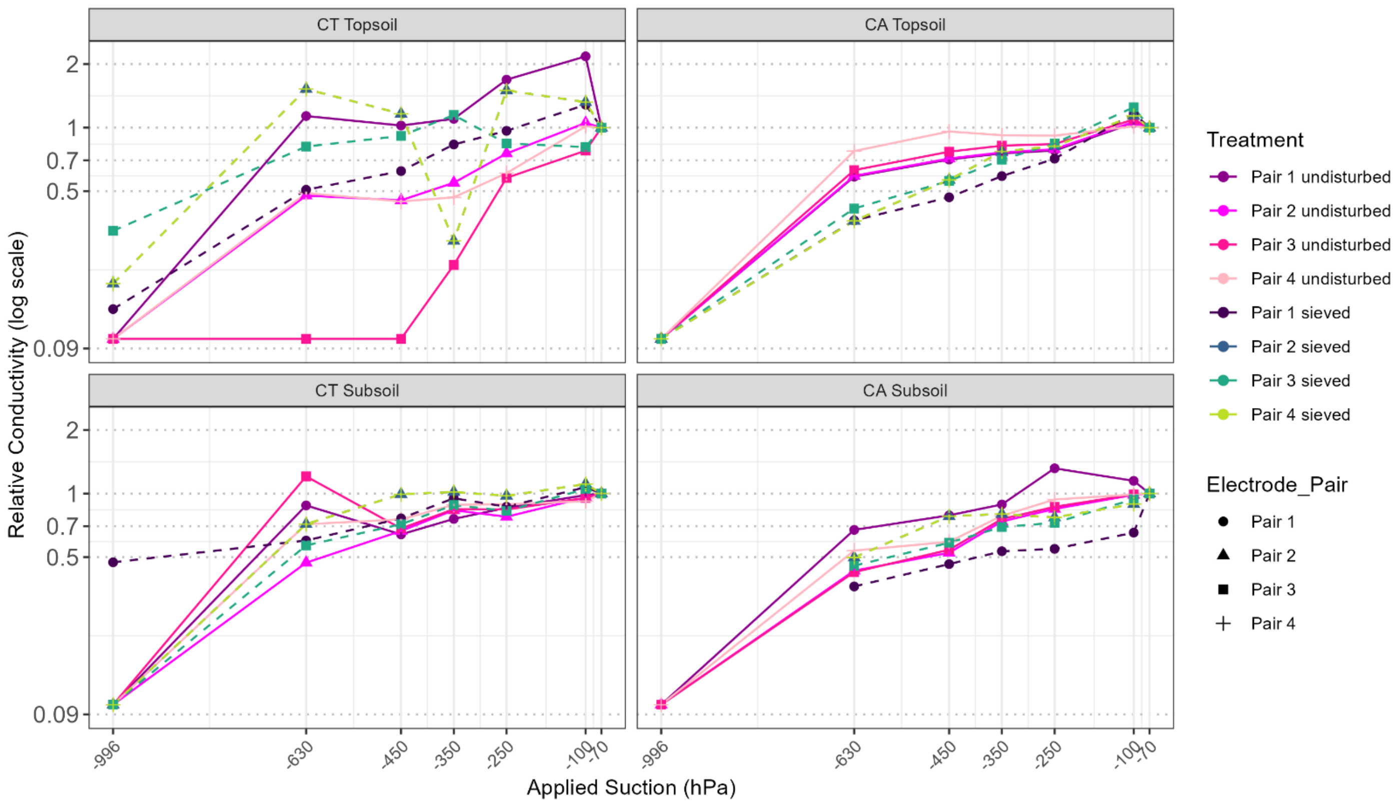

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Figure 2: Mean relative electrical conductivity (n=3), normalised to the rate observed at -70 hPa, is shown for the sieved samples (dashed line) and undisturbed (solid line) for the two different sample depths of the two field treatment types across a range of applied suctions (hPa). The applied suctions correspond to the associated soil matric potentials. The field treatment abbreviation CA stands for conservation tillage, while CT stands for conventional tillage. The averages are composed of three measurements of a triplicate of each Treatment type at each Applied Suction. The included standard deviation is not visible given its size did not exceed the size of the symbols. For more information on the associated averages and standard deviations of the means please consult Table S4-Table S8 of the supplementary materials.

3.3. Relationship between relative respiration rate and relative electrical conductivity

The relationships between respiration rates and electrical conductivity were established after excluding the data at matric potentials above -250hPa because respiration rates in the undisturbed samples decreased between -250 and -70hPa (Fig. 1). This increase has been recorded in past studies and is caused by limitations in oxygen availabilities rather than substrate access (Moyano et al., 2013). Additionally, for improved visualization we selected to present only the electrode pairs 1 and 2. However, the entire data range is presented in the supplementary material (Supplementary, Fig. S5).

Our results showed a decrease in the respiration and electrical conductivity with a decrease in soil matric potential which resulted in non-linear relationships between the two over the range of matric potentials studied (Fig. 3). Generally, the slopes of the relationships between the relative respiration rates and electrical conductivity revealed a steeper slope for the undisturbed samples compared to the sieved samples. The relationships were all statistically significant ($P < 0.02$), with the exception of the undisturbed conventional tillage top- and subsoil and sieved conservation agriculture subsoil measurements ($P > 0.1$). The R^2 values across treatments ranged from 0.07 to 0.84, with stronger relationships observed for undisturbed samples (e.g., CT topsoil $R^2 = 0.84$, $P = 0.028$) and weaker or nonsignificant relationships for sieved samples (e.g., CA subsoil $R^2 = 0.28$, $P = 0.474$) (Table S9). Comparison of nested nonlinear mixed-effects models showed a statistically significant effect of the soil matric potential was found to be statistically significant ($P = 3.14 \times 10^{-16}$) supporting a strong effect of the water content on the soil respiration flux and electrical conductivity rate.

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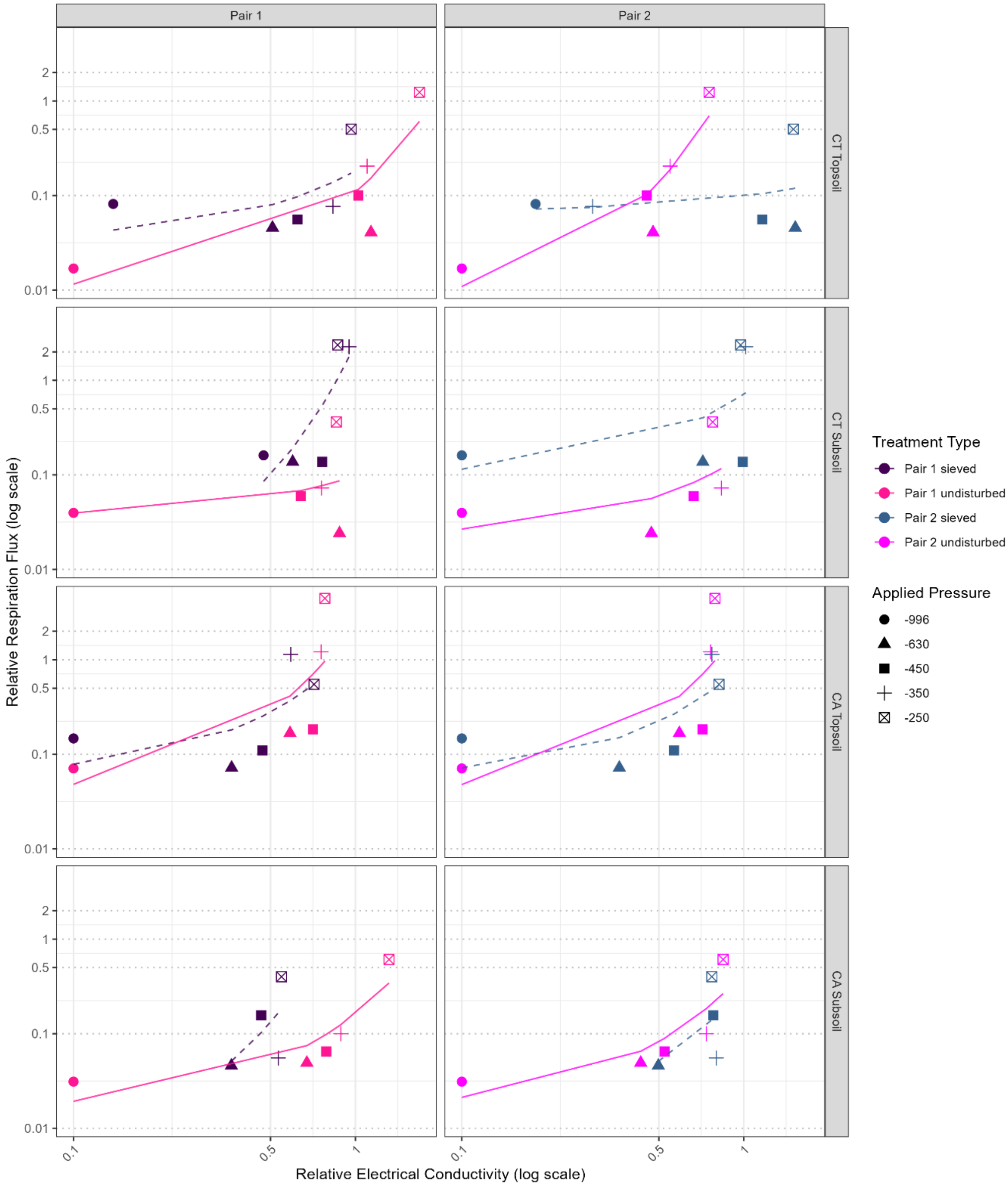

240 **Figure 3: Mean relative respiration flux (n=3) in relation to the mean relative electrical conductivity, normalised to the rate observed at the value observed at -70 hPa, is shown for the sieved samples (dashed line) and undisturbed (solid line) for the two sample depths of the two different field treatments across a range of applied suctions (hPa) illustrated by different marker points for the electrode pair 1 and 2. The average respiration was calculated based on triplicate respiration flux measurements of each treatment and the electrical conductivity represents the average of three measurements of each triplicates of each treatment at each applied suction.**
245 **Additional information on the average respiration and average electrical conductivity as well as their associated standard deviations**

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are presented graphically in Fig. 1 and Fig. 2 and in the supplementary materials in Table S2 and Table S3. The relationship between the two parameters is visualized in the form of an exponential model. The field treatment abbreviation CA stands for conservation tillage, while CT stands for conventional tillage. The measurements at -996 hPa for CA Subsoil has been excluded. Note that both axes have log scales.

4. Discussion

4.1. Electrical conductivity as a proxy of soil respiration

We hypothesised that as matric potential decreases, CO_2 flux and electrical conductivity would decrease due to reduced pore connectivity of the aqueous phase in the pore network of the samples (Fig. 4). This loss of water availability increases hydraulic and electrical tortuosity, leading to a reduction in diffusion rates (Ghanbarian et al., 2013; Revil & Jougnot, 2008). Our results tend to confirm this hypothesis, showing a decrease in both measured parameters as the soils dry, associated with a higher applied matric potential.

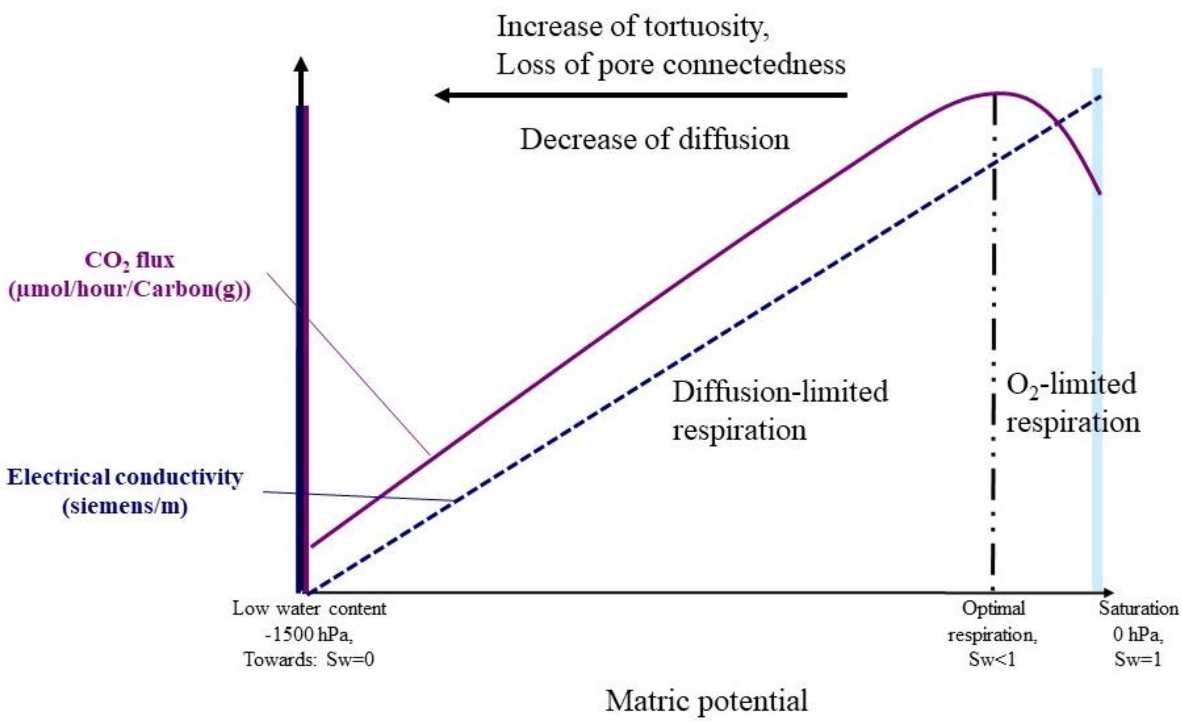

Figure 4: Conceptual sketch of the links between respiration rate and electrical conductivity in soils associated with a decreasing saturation. The key difference between oxygen limited and diffusion limited respiration are indicated across the applied matric potentials.

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However, the undisturbed samples showed a respiration peak at -250 hPa while the sieved samples showed a small increase in respiration rate at -100 hPa (Fig. 1). This flux increase is due to an optimal matric potential required for effective microbial carbon mineralisation first being reached at that potential. Above this optimal matric potential (i.e., -250 to 0 hPa for undisturbed and -100 to 0 hPa for sieved samples), the air phase is poorly connected in the soil porosity. As oxygen diffuses more slowly through water than air, microbial activity is limited, potentially leading to anoxic conditions at the microbial scale (Moyano et al., 2013). This reduction in respiration at high saturation has been extensively documented across various soil types, supporting the validity of our measurements. It also highlights an optimal matric potential where oxygen availability and pore connectivity are balanced (Ebrahimi & Or, 2015; Moyano et al., 2013). As the respiration rates close to saturation in the undisturbed samples were likely limited by oxygen availability up until -250 hPa rather than the diffusion of substrates, the measurements close to saturation were excluded for the comparison between relative respiration rates and relative electrical conductivity. For the sieved samples only a minor increase at -100 hPa was recorded, but for comparability the two highest saturations are also excluded of the correlation plots for our sieved samples (Fig. 3).

A general decrease in electrical conductivity was observed in most samples, linked to a reduced connectivity of the water phase in the pore system (Fig. 2). This reduction in connected water phases increases electrical tortuosity (i.e., a proxy for diffusion tortuosity), lengthening the diffusion path of charge carrier ions until the water phase becomes disconnected (Ghanbarian et al., 2013; Jougnot et al., 2018). In unsaturated porous materials, ion movement depends on water quantity and connectedness but is also influenced by the type of ions and electrical charges at the mineral surface (Revil & Jougnot, 2008). This concept of increased tortuosity is also further reflected in soil respiration in the form of the tortuosity of diffusion pathways of the substrates having to diffuse across a lengthened pathway to reach the microbial communities and thus consecutively decreasing at our highest tested matric potential.

Interestingly, at -630 hPa in the conventional tillage subsoil samples, electrical conductivity showed an unexpected increase. While a clear physical explanation is lacking, we observed mould fungi on the sample surfaces between -250 and -350 hPa, suggesting a potential link. Previous studies (Ameen et al., 2019; Sun et al., 2022) describe fungal-induced changes in microenvironment conductivity, possibly due to phosphate transformation or aggregate formation (Hartmann & Six, 2022). This feature was not observed for the other sampling depths and field treatments, suggesting that increased electrical conductivity could be linked to the presence of fungi. This assumption is supported by past studies describing physical and chemical changes in the microenvironment around fungal hyphae (Ameen et al., 2019; Sun et al., 2022). Regarding ionic changes in soil samples, these studies reported an increase in the conductivity of the microenvironment surrounding fungal hyphae, attributed to the transformation of phosphates from bound forms into free ions. In our study, this effect solely impacting the final pump measurement could be explained by the need for the fungal hyphae to have spread sufficiently between electrodes before their effect can be detected. Alternatively, fungi have been associated with aggregate growth and associated changes in porosity due to the clay particle encrusting of hyphae (Hartmann & Six, 2022). However, for the conservation tillage subsoil samples the electrical conductivity fell back down at -996 hPa which could mean that the loss of water content became too significant to maintain any increases associated with fungal presence.

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In several cases the decrease in the respiration rate was not significant between -630 and -996 hPa (Fig. 1). These findings are supported by studies identifying a more sigmoidal decrease in respiration in relation to water availability meaning that between certain matric potentials the decrease will be more gradual (Curiel Yuste et al., 2007; Ghezzehei et al., 2019).

4.2. Impact of soil structure on the observed correlation

We hypothesized that sieving would significantly impact our results by forming a more homogenous distribution of pore sizes in the pore network, leading to a more uniform decrease of the electrical conductivity and respiration rate compared to the undisturbed samples. However, while sieving did have a significant impact on the respiration rate, this was not the case for the electrical conductivity values. In the case of soil respiration, the hourly flux of the sieved samples at saturation was significantly higher than that of the undisturbed samples (Fig.1). Our findings align with a study by Herbst et al. (2016) comparing sieved and undisturbed soil cores across a broad water content range. Two mechanisms can explain the differences between sieved and undisturbed samples. Firstly, sieving alters pore size distribution, affecting the wetting process and allowing hydraulic pore connectivity to persist for longer (Castellini & Ventrella, 2012; Shaxson, 2006). This change in pore structure could also help reduce nutrient leaching rate during the drying cycle, with smaller pore sizes taking longer to drain, thereby reinforcing the contrast between sieved and undisturbed samples at mid-range soil matric potential (Çelik et al., 2021; Gupta Choudhury et al., 2014). Secondly, sieving can affect carbon availability to microbial decomposers. The physical protection of organic C from microbial decomposition is believed to be a major mechanism leading to organic C persisting in soil (Moyano et al., 2013; Six et al., 2006). Sieving may disrupt the physical protection, by breaking down soil aggregates and mixing, thus bringing organic substrate and microbial decomposers into close proximity, which is necessary for decomposition to occur. Improved aeration and substrate availability in sieved samples may explain why soil respiration remains elevated even close to complete saturation. The steady decrease in respiration after reaching the optimal matric potential underlines that water availability is an important restricting factor for organic matter decomposition (Crawford, 2005; Fan et al., 2015). The finding that there was no difference in relative electrical conductivities between sieved and undisturbed samples suggests that the difference in soil structure becomes the most evident for soil respiration while not being as important of an influence for the electrical conductivity. This finding can be explained by the fact that while particle shape and orientation are important factors influencing conductive pathway lengths, Nadler (1991) found that when bulk densities and water contents remain similar, the effect of particle size is negligible.

4.3. Impact of agricultural treatment

Although there were no significant differences in either relative respiration rate or relative electrical conductivity between the field treatments, the relationships between the two differed significantly. The undisturbed conventional tillage samples exhibited a generally weaker correlation compared to the conservation agriculture samples, particularly for the topsoil samples caused by higher respiration rates still being maintained at higher matric potentials. These observations could be explained by past studies underlining conventional tillage promoting soil organic matter oxidation in the topsoil through the breakdown of

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large soil aggregates and consecutively distributing organic matter throughout the soil profile (Franco-Luesma et al., 2020; Zsolt et al., 2020). In our measurements, this reasoning is further supported by this observed trend in the sieved samples being reversed, further underlining that breaking down big aggregates and consecutively mixing the liberated stored carbon across the samples can lead to higher respiration rates even at lower matric potentials.

4.4. Effects of topsoil compared to subsoil

Finally, we hypothesized that the relationships between respiration and electrical conductivity in the topsoil would not be as strong as the relationships in the subsoil due to the more ubiquitous distribution of OM across the pore system and therefore a reduced dependence on diffusion in the topsoil. However, no significant difference was found. This does not mean that the hypothesis should be rejected, because the OM contents of the topsoil and subsoil were not significantly different either, suggesting that OM was equally available to decomposers in both. This means that the dependence of OM decomposition on diffusion as a function of OM availability could not be tested with these soils. Nevertheless, the organic matter in the topsoil was significantly more mineralisable compared to the subsoil at higher moisture levels, which may be related to the nature of the OM. As the soils dried, the respiration rates in the topsoil and subsoil were similar, suggesting that the impact of the diffusion limitation became more limiting and masked any depth effect. This relationship between top- and subsoil respiration rates is not maintained for the sieved soil samples. This discrepancy could be explained by the substrates being homogenized across the sample, which allowed better microbial access and, consequently, increased carbon mineralization (Salomé et al., 2010).

5. Conclusion

The present study investigated whether electrical conductivity measurements in soils can be used as a proxy of soil respiration quantification given the reliance of both parameters on the availability of a connected water phase. This investigation tested both sieved and natural soils from two long-term agricultural study fields and two different depths. Throughout our experiment, we applied different suctions before measuring the increase in CO_2 content over 72 hours, as well as the electrical conductivity. The analysis of the relationship between the two variables revealed a strong relationship across the tested soil matric potentials confirming a similar effect in both parameters with loss of water availability. This leads us to conclude that electrical conductivity could be used as a proxy to measure diffusion-limited microbial activity in the form of soil respiration rates. Additionally, we observed a difference between the sieved and undisturbed samples showing an overall steeper decrease in the undisturbed samples compared to the sieved ones. Our results are in support of the spatial distribution of organic matter having a significant impact on soil respiration rates, therefore confirming that respiration in soils is, at least partly, diffusion-limited in absence of significant water flow (i.e., rain events or important water table changes). This study paves the way to use electrical conductivity as a proxy for these diffusion processes though water connectedness and tortuosity. Future works

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will be carried out to test this hypothesis further and provide a more quantitative framework to mechanistically relate soil respiration and electrical conductivity in soils.

-Author contribution

The experimental conceptualization was a collaboration between all co-authors. Funding acquisition, project management and supervision: DJ and NN; initial methodology development and validation: MG, OF; Investigation, Formal analysis: OF; Visualization: OF, DJ, NN; Writing: First draft: OF; Rewriting and editing: NN, DJ, OF

Competing interests

The authors declare that they have no conflict of interest.

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