Responses to Reviewers' Comments (manuscript # soil-2018-35)

"On-farm study reveals positive relationship between gas transport capacity and organic carbon content in arable soil"

Tino Colombi, Florian Walder, Lucie Büchi, Marlies Sommer, Kexing Liu, Johan Six, Marcel G. A. van der Heijden, Raphaël Charles and Thomas Keller

Dear Editor,

We herewith submit the response to the comments by the Editor and the two Reviewers to our manuscript (soil-2018-35). First we address the points raised by the Editor. Following that, we provide point-by-point answers to the comments and suggestions provided by the two Reviewers. Major changes to which we refer to in our responses are marked in yellow in the attached manuscript file.

At this point we would also like to thank the Editor and the two Reviewers for constructive and insightful comments, which helped tremendously to improve the manuscript. We hope that our adjustments are satisfactory and that the manuscript is suitable for publication in SOIL.

Sincerely,
Tino Colombi, Florian Walder, Lucie Büchi, Marlies Sommer, Kexing Liu, Johan Six, Marcel G. A. van der Heijden, Raphaël Charles and Thomas Keller

Responses to comments by Editor

Editor comment: The authors found a positive correlation between soil properties that are related to soil aeration and the soil organic carbon content. Since soil organic matter plays an important role in soil structure formation and hence on soil physical properties like soil hydraulic conductivity, bulk density, gas diffusivity and permeability, this relation is not unexpected neither really novel. Many studies have already made the link between soil physical properties and soil organic matter. What is however novel is that the authors invert the causality of the relation. Their hypothesis is that an increase in soil aeration in arable soils leads to an increase in soil organic matter, rather than that an increase in soil organic matter leads to a better soil aeration. This inversion is interesting and opposite to other causal relations between soil aeration status and soil organic matter content that go in the other direction and that suggest an accumulation of soil organic carbon when organic matter turn-over is hindered by a lack of oxygen. The authors' argument is that with increasing aeration, not only the respiration of organic matter is enhanced but also the input of fresh organic matter via an increased root development. When growth increases more than respiration, then there will be more accumulation and the equilibrium soil organic matter content will shift to higher levels. The crux is that growth should increase more at higher O2 levels than respiration does. Or opposite, the oxygen levels at which growth starts to decline are higher than the oxygen levels at which respiration starts to decline. The authors included references to studies that show that root growth is already limited at higher oxygen concentrations. It would be important to put that against limiting values that are reported for soil respiration.

Response: *We are aware that the effects of soil aeration on both root growth and microbial respiration are extremely difficult to disentangle. One particular difficulty is that the effects of decreasing soil oxygen concentrations in soil air on root growth (i.e. the susceptibility to decreasing oxygen concentrations) may differ substantially among species and between varieties. The physiological reasons for that are manifold. For example, the initiation of root cortical aerenchyma and the development of barriers avoiding oxygen loss are known to differ between species and varieties. These differences in stress tolerance have ultimate implications for root growth and thus soil organic matter input. Hence, we think it would be very speculative to make a comparison between plants and heterotrophic soil life with regard to limiting oxygen concentration in soil air.*
Reviewer #1 raised similar questions (e.g. soil organic carbon content is defined by balance between organic matter input and decomposition). We hope that by answering the comments from Reviewer #1 it became clearer that we "suggest" (rather than "prove") that the positive relationship between soil organic carbon content in gas transport capability resulted from increased root growth. Please refer to our responses below for page and line number references of the adjustments made.

Editor comment: The question is therefore whether better aeration corresponds with higher root development. Unfortunately, no root mass data are available. But, data on carbon inputs have been included and indicate that there is not a large variability in carbon inputs in the different fields. This suggests that larger soil organic matter contents must be due to higher input from roots. A question I have is whether yield data could be included. Higher root biomasses could be related to higher aboveground biomass and a positive relation between biomass production (or yield) and soil organic carbon could support the hypothesis. However, the question still remains whether this positive correlation (if it exists) is due to the effect of soil organic matter on soil aeration. Root growth and biomass could also be affected by other effects of soil organic matter like the release of plant nutrients or a reduction of drought stress by a better water holding capacity of soils with a higher soil organic carbon content. Or, higher nutrient concentrations can be related to a higher clay content, which is also related to a higher soil organic carbon content. Or, higher soil aeration could correspond with more drought stress and lower soil organic degradation. But, this hypothesis would go along with a decrease in plant growth and root carbon input with higher soil aeration. Including alternative hypothesis in the discussion than the main one that is brought forward is therefore important. The issue of several alternative hypotheses goes along with multicollinearity of different parameters that could be responsible for the observed variability of the soil organic carbon content in the different soils. I did not find a clear statement in the authors' responses on how to deal with this issue. Maybe a principal component analyses could be helpful to identify correlated properties. A principal component regression (which by definition does not suffer from multicollinearity) could be useful to identify which (correlated) parameter groups explain the variation in soil organic matter.

Response 1) Including above-ground biomass/yield data: *Unfortunately we only have yield data from the year when the sites were sampled (2016). Having data from only one year does not allow us to make reliable statements about possible correlations between productivity and root-derived organic matter input. Furthermore, as the study was carried out on-farm a whole range of crops and/or varieties have been cultivated over the past years. Given this diversity, root-shoot ratios were most likely not constant – both between species (e.g. Hirte et al., 2018, Agric Ecosyst Environ) and between varieties (e.g. Colombi and Walter, 2017, Front Plant Sci). This makes correlations between aboveground plant growth/productivity and organic matter inputs even more difficult and speculative.*
Response 2) Alternative hypothesis and collinearity: *We hope that the adjustments made at various points in the text (see responses to reviewer comments for more details) make it now clear that our results suggest (and not prove) that higher soil organic carbon contents resulted from root growth, which was facilitated by higher gas transport capability. Throughout the manuscript we emphasize that we see soil aeration as one of many drivers for soil organic carbon dynamics, not the only or the most important one (pg 1 L19, pg2 L5-L7, pg11 L32-pg12 L1). Furthermore, in the conceptual model shown in Figure 5, we also highlight the fact that higher gas transport capability might fuel microbial activity and thus the decomposition of soil organic carbon. We think that by doing so, alterative hypothesis and interpretations of our results should be adequately represented in the manuscript.*
We thank the Editor for raising the aspect of collinearity between different predictor variables. Accordingly, we checked for collinearity between the different predictors (clay content and gas transport properties/water holding capacity) used in Eq. 3 (results are displayed in Supplemental Figure S4 and S6) and a clear statement is provided in the response to the comment given by Reviewer #2 (see below).

Editor comment: Furthermore, soil aeration status like soil water status are defined by state variables like oxygen concentration, water content and water potential which vary considerably over time due to the dynamic meteorological boundary conditions and the dynamic respiration. How these state variables change over time and depth in response to external drivers depends on the soil properties. In their study, the authors focus on the soil properties, which influence of course the state variables. But it is important to keep in mind that microbial turnover processes and root groth depend on the state variables (temperature, soil water potential, soil water content, and oxygen concentration) and only indirectly on the physical soil properties

Response: *It is true that we use soil properties that relate to state variables and not state variables per-se in order to make statements about relationships between physical properties and soil organic carbon content. We think that we point out now much clearer that the properties we measured (e.g. gas transport properties) are related to/define potential aeration (pg2 L18-24, pg11 L14-17).*

Responses to comments by Reviewer #1

Reviewer comment: General comments: The authors present an empirical anaylsis of the relation between soil organic carbon contents measured under no-till, conventional and organic farming practice and static soil physical properties. The manuscript is well-structured and written in a concise style. However, there are major methodological concerns. There is no evidence that the differences in SOC are releated to the farming practice. 10 sites were chosen for each farming practice. Since SOC measurements prior to the change in farming practice are not availble it is not clear whether the SOC changed as a result of the farming practice or whether this is just a result of a random selection of 30 sites. This is corroborated by p<0.1 for a significant difference in SOC according to management (table 2).

Response: *From this very first comment we draw the conclusion that our main findings were not communicated clear enough in the original submission. We therefore made numerous changes throughout the manuscript (cf. responses to the other comments) in order to better emphasize the aims and major findings/conclusions of our study. In very general terms: The primary aim of the study was not to evaluate whether farming practice affects soil organic carbon content and/or sequestration but to "investigate relationships between gas transport capability and organic carbon content in arable soil covering a range of textural compositions" (cf. last paragraph of the Introduction pg3, L21-27). We chose this focus since soil aeration/gas transport properties is often not included into assessments of soil quality (cf. Figure 2 and Figure 4 in Bühnemann et al., 2018, Soil Biol Biochem), even though it is known that gas transport properties of soil control soil-atmosphere gas exchange and hence oxygen concentration in soil air, which greatly matter for all kinds of biological activity. We address this issue more specifically in the comments below.*
Further on in the manuscript we present the effects of the different soil management systems on soil organic carbon content as well as soil physical properties including gas transport properties, of which certain were significant (LSD-test at $p < 0.05$ and < 0.01, Figure 2 and 3, Table 3, Supplemental Figure S1 and S2). However, we now clearly state at multiple occasions that there was considerable overlap between the management systems (pg1 L23-24, pg8 L12-13, L21-23, pg8 L33-pg9 L1, pg10 L25-26) as well as large variation between individual fields for most soil properties assessed (pg7 L18, pg8 L1-2, L23, L32, pg10 L22-25, pg11 L5-6, summarized in Table 1 and Table 2). As the presented study was carried out on-farm, the management systems are likely not as contrasting as in field plot experiments, where typically one or two factors are altered while the rest of the management is the same for the different treatments. Furthermore, variability in soil texture among sites (cf. Table 1), which occurred here but usually does not occur in field plot experiments, showed a significant effect on a range of soil properties (Table 3, Figure 2 and 3, Supplemental Figure S1). Therefore, the effects of soil management on different soil properties (e.g. soil organic carbon content, gas transport capability, etc.) will not be as pronounced as in field plot experiments.
Moreover, we did not aim to make statements about carbon sequestration, i.e. comparing organic carbon content before and after conversion from one to another soil management system. In fact, all the investigated farms established their current management more than five years ago (this is why we also state that "The fields were managed following three different management systems: conventional (integrated) farming with no-till practice since at least five years, conventional (integrated) farming with tillage since five or more years, and organic farming with tillage since at least five years", pg3 L30-pg4 L2).

Reviewer comment: The topic given in the title and the hypothesis stated in the introduction could not be tested with the data set presented in this study since most relevant factors are not included. The SOC content is in equilibrium between the C inputs (not measured) and the decomposition of C. The decomposition process strongly depends on soil temperature. The second most relevant variable is water stress (often experessed by effective saturation or water-filled pore space WFP, e.g. Manzoni et al., 2012, Ecology 93). Even if the same temperature regime is assumed, the soil water status probably differs considerably between the sites and treatments investigated in this study. Both factors, carbon inputs and soil water status are not included in the data-set presented in this study. The third most relevant factor might be soil aeration. Of course, when the most relveant factors were excluded from the statistical analyses, soil aeration appears to matter...

Response: *To address this, we rephrased the original hypothesis in a more conservative way that –we think– takes into account the uncertainties associated with our study (pg3, L21-22). We emphasize at multiple occasions the "equilibrium" between carbon inputs and decomposition (pg2, L3-5, pg3 L6-15, pg11 L32-pg12 L7, pg12 L16-17, pg12 L29-pg13 L1, Figure 5). Hence, we acknowledge the important role of both carbon inputs (from amendments, crop residues, aboveground litter and roots) as well as decomposition for soil carbon dynamics. Even more importantly, with the current paper we did not aim to state that soil aeration (and hence gas transport properties) is more important than other phenomena for soil organic carbon content, but to show that it matters. We hope that our adjustments in the text (pg 1 L19-20, pg2 L5-L7, pg11 L32-pg12 L1) could clarify this.*

Reviewer comment: And soil water content at sampling or water holding capacity are surely not sufficient to account for the effect of water stress on microbial SOC decomposition. Soil aeration deficits in agricultural topsoils are very unlikely. Strong effects of oxygen deficits were observed at O_2 concetrations < 0.04 cm3/cm3, e.g Glinski Stepniewski, 1985, Soil aeration and its role for plants. This indicates that the topsoil has to be saturated almost entirely with water, what rarely happens. This is related to very high precipitation events only, and even then in a structured topsoil with macropores oxygen supply could be sufficient due to the diffusion of oxygen into watersaturated aggregates (Hojberg et al., 1994, Soil Sci. Soc. Am. J. Diffusion coefficients in near-saturated, structured soils are high, see Kristensen et al., 2010, J. Contam. Hydrol. 115. Soil aeration is a complex and temporally and spatially highly variable process. In order to test the hypothesis stated in the introduction a data set comprising carbon contents at the beginning and the end of the experiment, time-series of soil temperature, time-series of soil water contents, time-series of soil CO2 concentrations, time-sereis of O2 concentrations or at least redox potentials and time-series of soil heterotrophic respiration are required.

Response: *Yes, soil aeration is a highly complex process and is difficult to quantify. This is also why we did not use proxy values (i.e. air-filled porosity, water-filled porosity, degree of saturation) to assess soil aeration but measurements of gas transport properties (i.e. gas diffusivity and air permeability). In doing so, we account for the effects of pore connectivity and pore tortuosity on gas exchange dynamics in soil, which cannot be accounted for when using measurements of air-filled (or water-filled) porosity (pg2 L18-24, and pg9 L18-21).*
Regarding the comment about limiting O_2 concentrations for root growth: Here, we disagree with the comments provided by the Reviewer #1. There are numerous studies from the plant science community (ranging from ecophysiology to agronomy and plant biochemistry), which show that root metabolism undergoes drastic changes and root growth rates decrease at relatively moderated levels of soil hypoxia (O_2 > 10%) and/or very short periods of anoxia (flooding for a couple of hours). Other studies showed that this happens on a regular basis in arable soils. We emphasized on that in the text and provided a number of references (pg. 3 L9-12, pg11 L16-19).

Reviewer comment: I suggest to re-analyse the present dataset with a new focus.

Response: *Following this comment and the comments raised by Reviewer #2, we made numerous changes in the analysis of the data. We now included data on exogenous carbon inputs, both from crop residues and organic amendments, of the last five years (methodology is explained in pg5 L22-31 and pg7 L5-7). In doing so we could show that the amount of exogenous carbon input was similar across the three management systems (pg9 L5-6, Figure 3). Even more importantly, we observed no significant relationship between these inputs and soil organic carbon content (Supplemental Table S9-S13), which is highlighted in the Results (pg10 L5-8), Discussion (pg11 L26-28) and Conclusion (pg12 L26-27) sections. Based on these results we suggest that differences in root growth significantly contributed to differences in soil organic carbon contents among fields* ***(not between management systems)****, (pg10 L11-12 and pg11 L14-24, L26-30).*

Specific comments

Reviewer comment: p2 25 there are approaches that account for macropore tortuosity and thir effects on gas diffusion, e.g. Kristensen et al., 2010, J. Contam. Hydrol.

Response: *We agree with that and emphasize on the need to measure gas transport properties directly in the Introduction (pg2 L18-24) and the Results (and pg9 L18-21) in order to account for pore tortuosity and connectivity.*

Reviewer comment: p2 29-31 yes, but this means that increaed aeration will lead to lower SOC, since decomposition rates would be higher. This is a clear contradiction to what is hypothesized in the abstract: '...that improved soil aeration, which is strongly controlled by soil structure, leads to higher soil organic carbon content.'

Response: *As emphasized in an earlier comment by Reviewer #1 soil organic carbon content results from the balance between input and decomposition of soil organic matter. With the statement given here (now on pg3 L13-15) we try to make it clear that increased soil aeration might also fuel microbial activity and therefore lead to decomposition of soil organic carbon.*

Reviewer comment: p3 13-15 I strongly disagree. There is a bunch of literature (actually an entire community) that found soil temperature and secondly soil water content to be the most relvant drivers of carbon turnover in soils.

Response: *Please refer to our response above, in which we try to make clear that we did not aim to state that aeration is the only, or the most important property regulating carbon cycling in soil, but to show that it matters (pg 1 L19, pg2 L5-L7, pg11 L32-pg12 L1). However, plants represent the only possible source for soil organic carbon besides amendments. Plants are highly responsive to changes in soil oxygen (pg1 L19-20, pg3 L9-13, pg11 L16-19), hence soil aeration is of importance. The same applies of course also for the effects of oxygen concentrations in soil air on microbial growth and activity and thus the decomposition of soil organic carbon (pg1 L19-20, pg3 L13-15, pg11 L32-pg 12 L5, pg12 L29-30). Our empirical data together with existing literature provide evidence that soil aeration is an important factor (but not the only one) for soil carbon cycling.*

Reviewer comment: p3 23 but how will you separate the confounding effects of increased aeration and limited water ability for decomposition? Both are highly inter-related. Low water contents, leading to decreased SOC decomposition, are inherently linked to increased soil aeration and vice versa.

Response: *We hope that our rephrased last paragraph of the Introduction addresses this comment (pg3 L21-27). As stated above, we did not aim to play soil aeration as a driver for soil organic carbon content off against other drivers, but to provide empirical and conceptual evidence that soil gas transport properties have an effect.*

Reviewer comment: p3 16-28 a clear mechanistic description of the processes and the status variables that affect soil aeration and its consequences on SOC decomposition is missing

Response: *We see this comment related to one of the comments provided by Reviewer #2. Therefore, we adjusted the Introduction in order to make it clearer how soil aeration, biological (both auto- and heterotrophic) activity and soil organic carbon content (both inputs and outputs) are related (pg3 L6-15).*

Reviewer comment: p4 1-2 do you really expect measurable and significant differences in SOC after 5 years? There is a clear lack of data on C inputs.

Response: *No we do not and this was not the aim of the study. Please see our responses to the general comments. We completely agree on the need for data on exogenous carbon inputs (was also raised by Reviewer #2) and we included this into the manuscripts as stated above.*

Reviewer comment: p6 1-2 water holding capacity is not a good proxy for he dynamics of soil water content or water-filled pore space

Response: *We completely agree with this but we did not use it for that. We used it as an additional soil physical property that has implications for root growth and is associated with soil structure (pg2 L15-18, pg11 L28-32)*

Reviewer comment: p8 13 exacly, there is considerable overlap, which also causes a rather higher error probability ($p<0.1$) ...

Response: *Please refer to the responses to the general comments and our adjustments made that emphasize on the overlap between management systems (pg1 L23-24, pg8 L12-13, L21-23, pg8 L33-pg9 L1, pg10 L25-26). As stated above, we present results from an on-farm study (not experimental field plots) covering a wide range of soil textures, in which contrasts in management between systems might be less pronounced as in filed plot experiments.*

Reviewer comment: p8 24-15 What would be the effect of increased porosity/water holding capacity? The same amount of water (precipitation) infiltrating into a larger volume will cause less water-filled porosity. This in turn will cause less SOC decomposition, which subsequently leads to higher SOC contents. I suspect a spurious relationship between air permebility/gas diffusivity and SOC. I assume the true correlation is between waterfilled porosity and SOC content.

Response: *Water-filled porosity (which we see as the complementary of the pore space to air-filled porosity) does not account for pore connectivity/tortuosity (pg2 L19-24). Furthermore, our regression analysis showed that air-filled porosity (and thus water-filled porosity) is less suited as a predictor for soil organic carbon content than gas transport properties (pg9 L18-21, Figure 4, Supplemental Tables S1-S3 and Supplemental Figure S3 and S5).*

Reviewer comment: p10 9-10 I strongly disagree. The effect of soil aeration on SOC decomposition is well documented in literature. This is text book knowledge, see Glinski Stepniewski, 1985, Soil aeration and its role for plants, chapter I, section II, A.4 and A.5

Response: *As stated above, numerous previous studies showed that even decreases of just a few percentages of oxygen in soil air might significantly reduce root growth and thus soil organic carbon inputs (pg. 3 L9-12, pg11 L16-17).*

Reviewer comment: p11 5-6 This is highly deculative. Neither organic matter inputs nor the main drivers of decomposition were included in the data-set. p11 28-30 This statement is probably one of the main conclusions of this study. However, neither carbon inputs nor the stimulation of carbon decomposition was measured in this study. This conclusion is specultive at this point and not related to results presented in this study.

Response: *We agree that the initial submission of the manuscript contained a number of possibly too speculative statements, which was also remarked by Reviewer #2. Following these suggestions we made numerous changes in order to better address possible uncertainties of our study, i.e. by clearly stating that we propose a positive relationship between gas transport capability and soil organic carbon content, which most likely resulted from increased root growth (pg 1 L26-29, pg 10 L4-8, pg11 L14-19, L21-26, pg 12 L22-25). Furthermore, we clearly state on pg12 L33-pg13 L1 that opposite relationships may occur in different land-use systems and/or climates.*

Responses to comments by Reviewer #2

Reviewer comment: All in all, the present study could be a valuable contribution worth being published in soil, provided that multi-collinearity is taken into account and that relations between SOC or Cmic and soil physical parameters are also looked at for the individual management groups. A revised discussion needs to be more conservative. Ideally also more information is provided on C-inputs. The present conclusion heavily depends on the assumption that root C-inputs were lifted by better soil physical traits. But no proof is provided. Also no proof is given that root-C in these systems forms the single most important precursor of SOC. The consequence is that many of the proposed causal relationships are really tentative. This uncertainty needs to be better echoed into the discussion and title. Having said that, the topic is really pertinent, all texts are well written and results have been well presented, and all is based on an impressive volume of work.

Response: *We appreciate these critical and highly constructive general comments. In accordance to the suggestion, we changed the title of the manuscript to "On-farm study reveals positive relationship between gas transport capacity and organic carbon content in arable soil". In doing so we believe the mentioned uncertainties (e.g. no data on root biomass) are now better reflected in the title of the manuscript without losing its main finding, which is the positive relationship between soil gas transport capability and soil organic carbon content. Furthermore, we adapted the Abstract following the same line of thoughts, i.e. being more conservative in our conclusions (pg1 L18-30). Regarding the other general comments, please refer to the comments below (i.e. Influence of exogenous inputs of soil organic matter, regressions in individual management groups, collinearity of predictors).*

Reviewer comment: The introduction in principle reads well but should be condensed a bit further. To my impression the article really starts with p1L16. The preceding part could in fact be entirely omitted.

Response: *We shortened the first part of the introduction (pg2 L2-12) but did not entirely delete it as we believe that a brief general introduction to organic carbon content of arable soils and its relationship to soil management is needed. Furthermore, we addressed in this very first paragraph some of the comments raised by Reviewer #1.*

Reviewer comment: It would also be better to place the research hypothesis (p3L23) closer to mention of mechanisms that would explain why better aeration should lead to more C in soil.

Response: *According to the suggestion, we moved the "aims" of the study closer to the explanation of the mechanisms underlying the relationships between soil gas transport properties, root growth and soil organic carbon content (pg3 L6-27).*

Reviewer comment: M&M P4L9 samples were collected in spring: across a single whole season soil environmental conditions could have evolved: e.g. in April drought and in late May a wet period. As a consequence variables like microbial biomass, respiration and soil penetration resistance are also depending on time of sampling. Was the impact of actual sampling date investigated on the studied soil parameters? Or is this effect negligible? I could assume so for microbial biomass given that the substrate-induced respiration method was used. In other words, was the effect of a covariate sample timing required in the ANOVAs?

Response: *The soil samples were collected within a period of ~40 days between late April and the end of May (information is now included in the Material and Methods section, pg4 L8). In the study we followed a specific sampling design: The different fields were allocated as triplets, which means that one field of each management system (conventional, no-till and organic) were geographically close to each other. Sampling was done following this layout, i.e. one triplet was sampled per day (information is now included in the Material and Methods section, pg4 L9-11). This was done to avoid confounding effects of location/sampling date on the differences between management systems. However, due to this design we are unfortunately not able to disentangle effects of the location from effects of the sampling time with the presented statistical approach (linear mixed model followed by ANCOVA). Nevertheless, we introduced sampling time as an additional predictor variable into the multiple-linear regression models (Eq. 3, pg7 L5-7). This analysis showed that sampling date had no significant influence on soil organic carbon content (pg10 L4-5, Supplemental Tables S5-S8).*

Reviewer comment: The statistical approach is very clearly described: really helpful. The approach to cover a wide range in soil texture complicates the analysis but on the other hand promotes representativeness of this work. The authors have done well in accounting for variation caused merely by soil texture. The outcome of the ANOVA is also well presented in the figures. One question though: In the ANOVA of non-texture variables a factor clay content was included, but interactions with the other factors were disregarded. On what basis did you decide to do so? Could we assume the impact of clay% on SOC, Cmic etc. is independent from depth and management?

Response: *This choice was made due to the absence of significant management-depth interactions on clay content (Table 1). A statement addressing this is now included in the Material and Methods section (pg6 L21-23).*

Reviewer comment: Also, why clay and not silt or sand%? Please comment.

Response: *We chose clay content because it is commonly seen as the textural fraction that is most closely associated with soil structure and soil physical properties as well as with soil organic carbon content. In addition, clay was suitable as it showed the highest variability (expressed as coefficient of variation) among sites. Two sentences motivating this choice are now included in the Material and Methods section (pg6 L19-21).*

Reviewer comment: I am missing the point why significance of Eq. 4 is introduced as well. Any relations between SOC content and soil physical variables were already investigated by Eq3. The regression analysis with soil physical traits as dependent variable are apparently redundant.

Response: *As suggested we have removed Eq. 4 and all associated statements in the Results and Discussion section.*

Reviewer comment: Results: Results have been well presented, just one remark: L11-12 seems to be in contradiction with Fig. 2: total porosity of the subsoil did significantly differ between management systems.

Response: *Thank you for this. We have changed the respective statement (pg7 L29-30).*

Reviewer comment: Otherwise a well written and clear section. Generally though, no account was made of multi-collinearity among explored predictor variables. In 3.4 the positive relation between clay content, air permeability and gas diffusivity and microbial biomass was discussed. But at the same time we know that SOC content dominantly explains 'micC' and 'Resp' (Table 5). It cannot be excluded that mutual positive correlations exist between 1 SOC and 2 clay content, 3 air permeability or gas diffusivity. From the regression models presented in Table 4 it is then not possible to conclude that air permeability or gas diffusivity have a direct significant impact on micC. Their relation may very well be indirectly manifested through SOC content. More conservative regression models that exclude redundant variables are needed here. In any case the authors should more carefully draw conclusions in this study and leave room for alternative explanations than the currently forwarded main conclusion.

Response 1) Collinearity in multiple linear regression models: *We performed linear regressions between the different predictor variables in the multilinear regressions models (i.e. clay content and gas diffusivity/air permeability/water holding capacity, cf. Eq 3) in order to check for possible collinearity. In brief, we did not find significant correlations* *between gas transport properties and clay content (0.00 < R^2 <0.11). Hence, we suggest that there was no collinearity between clay content and gas transport properties (pg9 L17-18, Supplemental Fig. S4). Water holding capacity in contrast was correlated with clay content (0.61 < R^2 < 0.67). Due to this collinearity we additionally performed simple regressions between water holding capacity and soil organic carbon content. As observed in the multiple regression models (Figure 4), higher water holding capacity was related to increased soil organic carbon (Supplemental Figure S6, pg9 L24-26).*

Response 2) Relationship between gas transport properties and microbial biomass/respiration: *We agree with this comment. Therefore, we removed the regressions formerly presented in Table 4 and present more conservative regression models, i.e. microbial carbon/respiration as a function of soil organic carbon content/microbial carbon. This is mentioned in the Material and Methods section (pg7 L8-13, Eq. 4, Table 5). The results are also presented/discussed in a more conservative way in order to emphasize that soil aeration might have an indirect effect on microbial biomass and activity by increasing soil organic carbon content (pg10 L13-18, pg11 L32-pg12 L3).*

Reviewer comment: Discussion: The current study's main conclusion, viz. aeration, here represented by gas diffusivity and air permeability, significantly controls SOC levels in soils seems premature. This conclusion is drawn from positive linear relations between SOC level an these soil physical variables based on a set of organic and conventionally managed agricultural fields. SOC levels were significantly larger in topsoil of the fields under organic management vs. under conventional management, as could be expected (only organic nutrient sources, cover crops, ley). Obviously a larger SOC level also increases soil strength and lowers soil bulk density, with then also improved aeration. It is then not warranted to immediately conclude that vice versa improved aeration leads to higher SOC levels. Such could only be said if inputs of exogenous OM was more or less constant (aside C inputs from roots) in the investigates set of fields. Separate regressions for on the one hand CT and NT fields and OR fields on the other also need to be presented. If similar trends are found as in the full (n=30) set then indeed the conclusion seems viable. Looking at Fig. 4, with 4 of the OR fields with highest SOC levels, this may not be the case. The assumption that root-derived C-inputs are superior sources of native SOC in comparison to above-ground plant parts has indeed been demonstrated by several researches. Indeed the so-termed 'relative-contribution factor' of root-C is 2-3x that of above-ground plant parts. But to evaluate if indeed roots form the dominant source of native SOC in the studied fields, the readers need to get more insight into the crop rotations and exogenous OM input management. If in case of OR, exogenous OC input by far exceeds that from roots (more than a factor 2-3) than it seems much less likely that any relation could exist between SOC level and gas diffusivity and air permeability.

Response 1) Exogenous soil organic carbon inputs vs. inputs from roots: *We consider this as a very valuable comment. Therefore, we present now data on inputs of soil organic carbon (both crop residues and organic amendments such as slurry, manure and compost) over the last five years before fields were sampled. The calculations are based on information we obtained from the farmers (data was available for 29 of the 30 fields, pg5 L22-31). Interestingly, there was no significant difference ($p > 0.50$, Figure 3) between the three management systems with regard to the amount of exogenous organic carbon input (pg9 L5-6). To evaluate whether exogenous inputs of organic matter influenced soil organic carbon content, we included the total amount of organic carbon input (i.e. sum of residues and amendments) as an additional predictor into the regression models (pg7 L5-7). The results of these regressions are presented as supplementary tables (Supplemental Tables S9-S13) and in the Results (pg10 L5-7), Discussion (pg11 L26-28) and Conclusion (pg12 L26-29) sections. In summary, we did not find any significant correlation between exogenous inputs of organic matter and soil organic carbon content (topsoil and subsoil). Hence, we propose that the differences in soil organic carbon content were caused by difference in root derived carbon. We elaborate on that in more detail (and in a more conservative way as in the original submission) in the Results (pg10 L10-12), the Discussion (pg11 L26-31) and the Conclusion (pg12 L26-29) section.*

Response 2) Regressions for individual management groups: *We agree that such an analysis is of value, especially if the aim is to evaluate whether relationships between soil gas transport properties and soil organic carbon content change with soil management. However, in the current study we did not aim to explore this aspect (pg3 L21-27) but to investigate links between soil aeration and soil organic carbon content per-se. Nevertheless, we performed the following additional regression analyses, which are similar to those suggested by Reviewer #2: Instead of performing the regressions for the organic management system on the one hand and the no-till and conventional on the other hand, we did the analysis for the no-till on the one hand and the conventional and organic on the other hand. We chose to do so, i) since the predictor variables (i.e. gas diffusivity, air permeability, air-filled porosity and water holding capacity) were mainly affected by tillage rather than organic farming practice (pg9 L27-32, pg11, L3-4, Figure 2) and ii) since the amount of exogenous organic carbon input was not higher in the organic system than in the two systems that also receive mineral fertilizer (pg9 L5-6, Figure 3). These separate regressions are summarized in the Results section (pg9 L27-32) and included in the Supplement (Supplemental Tables S1-S4). More importantly, these regressions support our main conclusion of the study ("positive relationship between soil gas transport capability and soil organic carbon content") since this positive relationship also occurred when looking at tilled and untilled fields separately.*

Reviewer comment: No root biomass data were supplied to back p11 L5s sub conclusion.

Response: *We unfortunately do not have data on root biomass over the last five years (would be an incredible sampling effort to sample 30 fields at multiple locations for five years). In order to address the comment we rephrased statements on root growth in a way that makes clear that we "propose" or "suggest" a positive relationship between certain soil physical properties, root growth and soil organic carbon content (pg 1 L27-29, pg 10 L4-8, pg11 L26-31, pg12 L9-11, pg12 L26-29).*

Reviewer comment: At the same time the authors best recognize that at present also other views exist: several recent studies have highlighted that the aboveground residues are more important for long-term SOM stabilization (HF-SOM) as compared to belowground. This has been often linked with the relatively high decomposability of aboveground residues which generate more microbial by-products, which are actually the precursor of the long-term stabilized SOM, associated with HF e.g. Cotrufo et al., 2013 (GCB), 2015 (nature geosci); Lavallee et al., 2018 (BG).

Response: *Thank you for this remark and the link to the references. We addressed it in the Discussion section (pg11 L 7-12).*

On-farm study reveals positive relationship between gas transport capacity and organic carbon content in arable soil

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Abstract. Arable soils may act as a sink in the global carbon cycle but the prediction of their potential for carbon sequestration remains challenging. Amongst others, soil aeration is known to influence root growth and microbial activity, and thus inputs and decomposition of soil organic carbon. However, the influence of soil aeration on soil organic carbon content has been only little explored, especially at the farm level. Here, we investigated relationships between gas transport properties and organic carbon content in the topsoil and subsoil of 30 fields of individual farms covering a wide range of textural composition. The fields were managed either conventionally, organically or according to no-till practice. Despite considerable overlap between the management systems, we found that tillage increased soil gas transport capability, while organic farming resulted in higher soil organic carbon content in the topsoil. Remarkably, higher gas transport capability was associated with higher soil organic carbon content, both in the topsoil and subsoil ($0.53 < R^2 < 0.71$). Exogenous organic carbon inputs in the form of crop residues and organic amendments in contrast were not related to soil organic carbon content. Based on this, we conjecture that higher gas transport capability resulted in improved conditions for root growth, which eventually led to increased input of soil organic carbon. Our findings show the importance of soil aeration for carbon storage in soil, and highlight the need to consider aeration in the evaluation of carbon sequestration strategies in cropping systems.

1 Introduction

Arable soils play a crucial role in the global carbon cycle because they can act both as a terrestrial carbon sink and source (Lal, 2004; Smith et al., 2008; Zomer et al., 2017). The balance between carbon inputs from plant roots, aboveground litter and organic amendments, and the decomposition of soil organic matter by heterotrophic soil organisms ultimately determines soil organic carbon content. Soil carbon dynamics are highly dependent on a range of environmental factors ranging from soil mineralogy and chemical properties, soil structure and related physical conditions, to local climatic conditions and their effects on soil temperature and moisture (Manzoni et al., 2012; Rasmussen et al., 2018; Young et al., 1998). Soil management including crop rotations, tillage, cover crops, and the application of organic amendments is known to affect soil organic carbon content. However, discordant results on the effects of specific soil management approaches on carbon contents have been reported (Chan et al., 2003; Gattinger et al., 2012; Govaerts et al., 2009; Leifeld et al., 2009; Powlson et al., 2014; Smith et al., 2008), which merits further investigation to better understand factors and processes that control soil organic carbon content in arable soils.

Plants convert carbon dioxide into organic carbon through photosynthesis. A range of studies showed that up to 70% of the total organic carbon in arable soil derives from roots in the form of root biomass and root exudates (Balesdent and Balabane, 1996; Kätterer et al., 2011; Kong and Six, 2010; Rasse et al., 2005). Root growth is greatly affected by soil structure and related physical properties and processes such as soil aeration, water holding capacity, and soil penetration resistance. High penetration resistance, low water holding capacity as well as poor soil aeration and the resulting hypoxic conditions result in decreased root growth (Bengough et al., 2011; Jin et al., 2013; Rich and Watt, 2013; Valentine et al., 2012). Soil aeration is controlled by gas diffusivity through diffusive transport and air permeability through advective transport. Both gas diffusivity and air permeability are key properties that constitute the soil physical constraints on soil aeration (Horn and Smucker, 2005). Gas transport properties are often estimated from proxy values such as total and air-filled porosity. However, because these proxies do not account for pore connectivity and tortuosity, which is crucial for air circulation and thus oxygen concentration in soil air, they do not accurately describe gas transport in soil. Therefore, relative gas diffusion coefficients and air permeability need to be quantified to assess the gas transport capability of soil.

Soil structure and associated soil physical properties are greatly affected by soil management. Tillage has been shown to improve penetrability and aeration of the topsoil (Colombi et al., 2018; Dal Ferro et al., 2014; Martínez et al., 2016b, 2016a; Schjonning and Rasmussen, 2000). However, long-term tillage can also lead to decreased gas transport capability and high penetration resistance both in the topsoil (Kahlon et al., 2013) and the subsoil (Martínez et al., 2016b, 2016a). Diverse crop rotations that include ley and deep rooting species such as rapeseed and oil-seed radish increase soil macro porosity (Chen et al., 2014; Lesturgez et al., 2004; Stewart et al., 2014; Young et al., 1998), which results in better aeration, increased water holding capacity and decreased penetration resistance. Permanent soil cover and organic amendments have been shown to increase water infiltration and soil water retention and to improve soil aeration and penetrability (Albizua et al., 2015; Bronick and Lal, 2005; Kahlon et al., 2013). Several studies showed that high soil organic carbon content coincides with good soil aeration, high water holding capacity and low penetration resistance (Albizua et al., 2015; Celik, 2005; Diacono and Montemurro, 2010; Kahlon et al., 2013; Martínez et al., 2016b, 2016a; Rasool et al., 2007; Reynolds et al., 2008; da Silva et al., 2014). These studies were however limited to one or a few field sites and thus covered only a small diversity of soil textures, which makes it difficult to link soil physical properties to soil organic carbon content. Moreover, the results were obtained from field plot studies where agricultural management may differ substantially from the conditions on commercial farms.

Soil physical properties in general and soil aeration in particular were proposed to play a key role in the regulation of carbon cycling in arable soil (Qi et al., 1994). This is strongly supported by the close interrelation between soil aeration, the resulting concentrations of oxygen in soil air, and root development (Dresbøll et al., 2013; Porterfield and Musgrave, 1998; Thomson et al., 1992; Watkin et al., 1998; Young et al., 1998). It is known that root growth slows down upon decreasing oxygen concentrations in soil air of just a few percentages (Eavis, 1972; Garnczarska and Bednarski, 2004; Grable and Siemer, 1968; Qi et al., 1994). Such reductions in the concentration of oxygen in soil air occur regularly in arable soils (Buyanovsky and Wagner, 1983; Cannell et al., 1984; Weisskopf et al., 2010). Furthermore, roots tend to grow preferably towards well aerated compartments in soil (Colombi et al., 2017; Porterfield and Musgrave, 1998). Besides promoting organic carbon input through root growth, high gas transport capacity of soil may also fuel microbial growth and activity and therefore decomposition rates of soil organic matter (Balesdent et al., 2000; Keiluweit et al., 2016, 2017; Young et al., 1998). Quantitative information about the relationships between soil gas transport capability and soil organic carbon contents in cropping systems is however limited, and soil aeration is typically not included in soil quality assessments (Bünemann et al., 2018). To gain a better understanding about the potential of soil management approaches to contribute to carbon sequestration in arable soils, the role of soil aeration has to be investigated. To understand the interrelations between soil management, aeration and organic carbon content at relevant scales and under realistic management conditions, on-farm studies carried out at multiple sites are needed.

Here, we investigated relationships between gas transport capability and organic carbon content in arable soil on-farm covering a range of textural compositions. The study was conducted on 30 fields of individual farms in the eastern part of Switzerland. The fields were managed according to three different management systems: i) conventional farming without tillage, ii) conventional farming with tillage and iii) organic farming with tillage. Gas diffusivity, air permeability and soil organic carbon content were quantified in the topsoil and the subsoil in order to evaluate whether soil organic carbon content is related to soil gas transport properties. Additionally, soil penetration resistance, total and air-filled porosity, soil textural composition, water holding capacity, and microbial biomass and respiration were assessed.

2 Material and Methods

2.1 Study design

The study was performed on 30 separate fields of at least 1 ha in size each belonging to individual farms in the eastern part of Switzerland. The fields were managed following three different management systems: conventional (integrated) farming with no-till practice since at least five years, conventional (integrated) farming with tillage since five or more years, and organic farming with tillage since at least five years. In the remainder of this paper, we refer to the three different management systems as “no-till”, “conventional” and “organic”, respectively. The system of integrated farming in Switzerland includes a number of practices aiming to enhance the sustainability of cropping systems, which are summarized as the “Proof of Ecological Performance”. Farmers need to comply with the “Proof of Ecological Performance” in order to receive full state subsidies. It includes an even nutrient balance, a diverse crop rotation including crops from different botanical families like small grain cereals, maize, rapeseed, and grain and forage legumes, as well as the avoidance of bare fallow soil and targeted use of plant protection products (Swiss Federal Council, 2014). Ten farms per management system were selected in order to keep a balanced study design. Soil samples were collected in spring 2016 between 20 April and 27 May and winter wheat (*Triticum aestivum*, L.) sown in autumn 2015 was grown in all fields. The different fields were arranged as triplets, i.e., one field of each management system was in proximate location to one field of the two other management systems. Soil samples were taken for each triplet at the same day.

2.2 Soil sampling

Soil samples were collected in a circular sampling area of around 300 m^2. Wheel tracks were excluded for sampling. Undisturbed cylindrical soil core samples of 100 ml volume and 5.1 cm diameter were taken for different soil physical measurements including gas transport properties and water holding capacity. Composite samples were used for the determination of soil texture, soil organic carbon content, and microbial biomass and respiration. Samples were taken from two different depths representing the topsoil and the subsoil of each field. Undisturbed cylinder samples were sampled from 10-15 cm, and 35-40 cm depth, while composite samples were taken from 5-20 cm and 25-50 cm depth. Hence, the mean sampling depths for both types of samples were 12.5 cm and 37.5 cm (Fig. 1). Five undisturbed cylinder samples were collected per depth and field. The composite samples consisted of 15-20 separate auger samples. Both, undisturbed cylinder and composite samples were taken evenly spaced along two transects crossing the sampling area of 300 m^2.

2.3 Measurements on undisturbed cylinder samples

The samples were closed at the bottom and the top and stored in the dark at 4 °C until processing. The soil samples were weighed to determine soil moisture at sampling. The soil cylinders were slowly saturated from below, and equilibrated on a ceramic suction plate to 30 hPa and 100 hPa matric suction. By weighing at saturation and at both matric suctions the respective gravimetric water contents were calculated. Gravimetric water content at 100 hPa matric suction, which is typically seen to represent field capacity (Schjonning and Rasmussen, 2000), is defined in this paper as the soil water holding capacity. The relative gas diffusion coefficient and air permeability were measured at 30 hPa and 100 hPa matric suction as described by Martínez et al., (2016a). To obtain soil bulk density, the soil samples were dried at 105 °C for at least 72 h before weighing. Volumetric water content was calculated from bulk density and gravimetric water content. Total porosity was determined based on soil bulk density and particle density. Particle density was measured for each field and sampling depth. Finally, air-filled porosity (εa) at 30 hPa and 100 hPa matric suction was calculated from total porosity and the respective volumetric water content.

2.4 Measurements on composite samples

Composite samples were processed following the reference method of the Swiss Agricultural Research Stations (Swiss Federal Research Stations, 1996). Before measurements were performed, the composite samples were cleaned from animal and plant debris and then sieved at a mesh width of 2 mm. Soil texture was determined with the pipette method, while soil organic carbon content was quantified by the dry combustion method according to ISO 10694. Soil microbial biomass was estimated from substrate induced respiration measurements as described by Anderson and Domsch, (1978). An equivalent of 50 g soil dry matter was amended with 150 mg glucose before incubation at 22 °C for seven days. Following Heinemeyer et al., (1989), an infrared gas analyser was used to measure initial CO_2 release. Soil microbial biomass (Cmic) was then calculated from these initial respiration rates according to Kaiser et al., (1992) assuming 1 µl CO_2 g^{-1} dry soil h^{-1} to be equivalent to 30 µg Cmic g^{-1} dry soil. Furthermore, soil basal respiration (microbial respiration) was measured in pre-incubated samples (7 days at 22 °C, equivalent of 20 g dry soil) as CO_2 released over a period of 48 h, starting at the second day of the incubation (Swiss Federal Research Stations, 1996).

2.5 Soil penetration resistance

Additional soil physical information was obtained from cone penetrometer measurements. Ten penetrometer insertions were performed in each field across the 300 m^2 sampling area down to a depth of 50 cm (Fig. 1) using an Eijkelkamp penetrologger (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). The cone had a base are of 1 cm^2 and a full apex angle of 60°, and penetration resistance values were obtained in 1 cm steps. To represent the same soil depths as for composite and cylinder samples, average values were calculated for 5 cm to 20 cm depth and 25 to 50 cm depth. Soil water content at the time of penetrometer measurements was obtained from the undisturbed soil cylinder samples.

2.6 Estimation of exogenous organic carbon inputs

As described by Büchi et al., (2019), we followed the French 'Indigo' method (Bockstaller et al., 1997) and used farmer interviews to calculate the amount of exogenous organic carbon inputs during the five years prior to the study. Data on exogenous organic carbon inputs was available for 29 of the 30 fields that were included in the current study. Using information on crop rotation and residue management allowed to estimate the amount of organic matter input that derived from crop residues. Organic matter inputs from organic amendments were estimated based on the number and amount of applications, and the form of the amendment (e.g. compost, slurry, manure) using isohumic coefficients for the different types of organic fertilizers (CSICM, 2010; CTACF, 2006; Sinaj and Richner, 2017). The total amount of exogenous input of organic matter was calculated as the sum of organic carbon derived from crop residues and organic amendments. Organic matter was converted into organic carbon assuming an organic matter-organic carbon ratio of 1.724 (Soil Survey Staff, 2011).

2.7 Data analysis and statistics

Data analysis and statistics were performed in R version 3.4.1 (R Core Team, 2017). The effects of soil management and sampling depth on the different soil properties were evaluated with linear mixed models using the nlme package (Pinheiro et al., 2013). The following model, which was followed by analysis of variance (ANOVA), was used to evaluate whether soil texture significantly differed among management systems and sampling depths:

$$Y_{ijk} = \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + \varepsilon_{ijk} \ , \qquad (1)$$

where Y represents the clay, slit or sand content in the i^{th} management treatment (i = conventional, no-till, organic) of the j^{th} depth (j = 12.5 cm, 37.5 cm) and the k^{th} field (k = 1, 2,…, 29, 30); α denotes the effect of the management treatment, β denotes the effect of the depth, $\alpha\beta$ represents the interaction between management and depth and ε represents the residual error. The effects of the management system, the depth and their interaction were treated as fixed effects. To account for possible autocorrelation of soil properties taken at different depths in the same field, the effect of the field (γ) was included into the model as a random factor. The following model was used to evaluate whether total and air-filled porosity, gas transport properties, water holding capacity, soil organic carbon content, microbial biomass and respiration, were affected by the management system and the soil depth:

$$Y_{ijk} = \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + \delta + \varepsilon_{ijk} \ , \qquad (2)$$

As in Eq. 1, the effects of soil management, depth and their interaction are denoted by α, β and $\alpha\beta$, respectively, and were set as fixed effects while the field (γ) was set as a random effect. The effects of clay content (δ) was included as a fixed co-variable into the model. This allowed to account for the variability of soil texture among sites and thus to account for effects related to the site-specific soil texture. Clay content was chosen due to its known association with soil organic carbon content (e.g. Rasmussen et al., 2018), and soil structure and related soil physical properties (e.g. Dexter, 1991). Furthermore, clay content showed the highest variability among sites of all texture fractions (Table 1). Since no significant effect of the management system and the interaction between management system and sampling depth on clay content was found (Table 1), interactions between clay content, depth and management system were not tested for in the analysis. For soil penetration resistance, the gravimetric water content at sampling was added as an additional fixed co-variable to the model, due to known influence of soil moisture on penetration resistance (Bengough et al., 2011; W. J. Busscher, 1990). Analysis of covariance (ANCOVA) was then used to test for significant effects of fixed factors. Air permeability was transformed to base 10 logarithm for linear mixed model analysis. Pairwise comparison of group mean values within one sampled depth were performed using least significant difference tests (LSD) at $p < 0.01$ and $p < 0.05$, respectively, using the "agricolae" package for R (Mendiburu, 2015).

The following multiple linear regression model was applied to explain soil organic carbon content as a function of soil physical properties:

$$SOC\ [g\ C\ kg^{-1}\ soil] = a * x_1 + b * Clay\ [\%] + c \ , \qquad (3)$$

where *SOC* represents soil organic carbon content and the first explanatory variable (x_1) represents either gas diffusivity, air permeability, air-filled porosity, soil penetration resistance or water holding capacity. As done in Eq. 2, clay content was included as a second explanatory variable into the regression model, which allowed to account for the site specific soil textural composition. Regressions were carried out separately for both levels of matric suction at which gas diffusivity, air permeability and air-filled porosity were determined. To evaluate the influence of sampling date (expressed as the day of the year) and the amount of exogenous organic carbon input on soil organic carbon content, both were included as additional predicting variables into the regression model presented in Eq. 3.

A similar regression model was used to explain soil microbial biomass and soil respiration as a function of soil organic carbon content and as above clay content. The same regression model was also used to explain soil respiration as a function of soil microbial biomass and clay content:

$$Y = a * x_1 + b * Clay\,[\%] + c\,, \qquad (4)$$

where Y represents soil microbial biomass and soil respiration, respectively, whereas and the first explanatory variable (x_1) denotes either soil organic carbon content or soil microbial biomass, respectively. Due to strong effects of the sampling depth on all soil properties assessed, all multiple linear regressions were performed separately for each soil depth. The regression models were evaluated with the linear least square method (lm), which is implemented into the R package "stats" (R Core Team, 2017).

3 Results

Considerable variability in soil textural composition was observed among the 30 fields that were part of the study. Clay, silt and sand contents varied from 11.0% to 48.4%, 19.7% to 43.9% and 16.5% to 60.4%, respectively. Soil texture did not differ significantly between the three different soil management systems. Slightly lower clay and higher sand contents were observed in the topsoil in comparison to the subsoil (Table 1).

3.1 Effects of management system on soil physical properties

The overall variability in total porosity among the investigated fields was relatively low (coefficient of variation (CV) < 10%; Table 2). Nevertheless, total porosity significantly differed between management systems. In the topsoil it was significantly lower in the no-till system than in the two management systems that include regular tillage (LSD test: $p < 0.01$). In the no-till system, mean total porosity at 12.5 cm depth was 48.6% (± 3.1% standard deviation (SD)). Total topsoil porosity of the conventional and organic management system was 54.5% (± 3.6% SD) and 56.1% (± 4.8% SD), respectively (Fig. 2). Consequently, soil bulk density at 12.5 cm depth was higher in the no-till system than in the two management systems that include regular tillage. In the subsoil, i.e. at 37.5 cm depth, total porosity was significantly higher (LSD test: $p < 0.05$) in the organic management system than in the no-till system (Fig. 2).

Gas transport properties (47% < CV < 102%) and to a lesser extent air-filled porosity (21% < CV < 25%) showed much higher variability among the investigated sites than total porosity (Table 2). Compared to the no-till system, air-filled porosity in the topsoil at 100 hPa matric suction was significantly higher (LSD test: $p < 0.01$) in the organic and conventional management system, which include regular tillage (Fig. 2). Similar effects of the management system were found for soil gas transport properties, i.e. relative gas diffusion coefficients and air permeability. Compared to the no-till system, gas diffusion coefficients at 100 hPa matric suction were higher by more than 70% in the organic and conventional system (least significant difference (LSD) test: $p < 0.05$). Similar differences between management systems were measured for air permeability at 100 hPa, which was significantly higher (LSD test: $p < 0.01$) in the organic and conventional systems than in the no-till system (Fig. 2). At matric suction of 30 hPa, similar but less pronounced differences of air-filled porosity and gas transport properties between management systems occurred as under drier conditions at 100 hPa matric suction (Supplemental Fig. S1). In the subsoil however, air-filled porosity, gas diffusion coefficients and air permeability did not differ significantly between the three management systems (Fig. 2 and Supplemental Fig. S1). Despite significant effects of the management system, considerable overlap between the systems was found for gas transport properties and air-filled porosity (Fig. 2 and Supplemental Fig. S1).

Water holding capacity was higher in the organically managed system than in the no-till system both in the topsoil and the subsoil (LSD test: $p < 0.01$). In the topsoil, water holding capacity in the conventional system was significantly higher (LSD test: $p < 0.05$) than in the no-till system, while water holding capacity of the subsoil did not differ between the two systems (Fig. 2). Soil penetration resistance also significantly differed between the management systems. Mean penetration resistance between 5 cm and 20 cm depth was more than 35% lower in the organically and conventionally managed system than in the no-till system. In the subsoil the differences in soil penetration resistance between management systems were not significant. Most likely because of the relatively low variation in soil moisture at the time of measurement, no significant ($p = 0.28$) effects of soil moisture on penetration resistance was found (Supplemental Fig. S2). As found for soil gas transport properties, overlap between management systems occurred for water holding capacity (Fig. 2) and soil penetration resistance (Supplemental Fig. S2) and the variability among sites was comparable to that observed for air-filled porosity (24% < CV < 49%; Table 2).

Significant effects of the soil depth were observed for all soil physical properties. Total and air- filled porosity, gas transport capacities, and water holding capacity (Fig. 2; Supplemental Fig. S1) were lower in the subsoil than the topsoil. Penetration resistance was higher in the subsoil than in the topsoil (Supplemental Fig. S2). Clay content and thus the site-specific soil texture affected total and air-filled porosity, air permeability, and water holding capacity, indicating the influence of texture on soil structure and related physical properties. For gas diffusion coefficients and penetration resistance, no significant effect of clay content ($p > 0.05$) was observed (Fig. 2; Supplemental Fig. S1 and Fig. S2).

3.2 Soil organic carbon content, exogenous carbon inputs, microbial biomass and respiration across management systems

The overall variability in soil organic carbon content among sites was comparable to that of gas transport properties (Table 2). Similar to the results obtained for soil physical properties, considerable overlap in soil organic carbon content between management systems occurred (Fig. 3). Nevertheless, significant differences in soil organic carbon content were observed between management systems. Soil organic carbon content from 5 to 20 cm depth was significantly (LSD test: $p < 0.05$) higher in the organic management system than in the conventional system. Furthermore, soil organic carbon content in the subsoil of the no-till and conventional system was significantly lower (LSD test: $p < 0.05$) than in the organically managed fields (Fig. 3). Exogenous organic carbon inputs in the form of crop residues and organic fertilizers were very similar ($p > 0.50$) between management systems (Fig. 3). Besides soil organic carbon content, significant effects of the management system were found for soil microbial biomass, which was the highest under organic management in both soil layers (LSD test: $p < 0.05$). Microbial respiration did not differ significantly among the three management systems (Table 3). Soil organic carbon content (Fig. 3) as well as microbial biomass and respiration (Table 3) significantly decreased with soil depth and were affected by clay content.

3.3 Interrelations between soil physical properties and soil organic carbon content

Multiple linear regression models (Eq. 3) were used to relate soil physical properties to soil organic carbon content. Soil organic carbon content significantly increased with increasing gas diffusion coefficients and air permeability. For the topsoil, multiple R^2 values were in the range 0.60 to 0.68, and the regression coefficients for gas diffusivity and air permeability measured at 100 hPa matric suction were highly significant ($p < 0.01$). As in the topsoil, increased gas diffusivity ($p < 0.05$, $R^2 = 0.53$) and air permeability ($p < 0.01$, $R^2 = 0.65$) were also related to higher soil organic carbon content in the subsoil (Fig. 4). Similar results were obtained when using gas transport properties measured at 30 hPa instead of the transport properties obtained at 100 hPa to explain organic carbon content (Supplemental Fig. S3). Collinearities between gas transport properties and clay content did not occur (Supplemental Fig. S4). In contrast, no clear relationship between air-filled porosity and soil organic carbon content was observed since the regression coefficients for air-filled porosity were mostly not significant (Supplemental Fig. S5). Given these contrasting results, we suggests that direct measurements of gas transport properties such as gas diffusivity and air permeability are better predictors for soil organic carbon content that proxy values such as air-filled porosity. In addition to gas transport properties, soil organic carbon content was significantly ($p < 0.01$) associated with water holding capacity. Increased water holding capacity was related to higher soil organic carbon content in the topsoil and the subsoil ($0.57 < R^2 < 0.64$; Fig. 4). Due to collinearity between water holding capacity and clay content simple linear regressions between water holding capacity and soil organic carbon content were performed additionally. As observed for multiple linear regressions, water holding capacity and soil organic carbon content were positively related (Supplemental Fig. S6)

Due to significant effects of tillage on gas transport properties and water holding capacity (Fig. 2), regressions were also performed separately for the fields that were regularly tilled (i.e. conventional and organic) and remained untilled (i.e. no-till). Both in tilled and untilled fields, higher soil gas transport capacity was positively associated with increased soil organic carbon content (Supplemental Table S1 and S2), while no such relationship was found for air-filled porosity (Supplemental Table S3). When considering tilled and untilled soils separately, the positive association between water holding capacity and soil organic carbon content was limited to the fields that were subjected to regular tillage (Supplemental Table S4).

Despite trends towards lower soil organic carbon content with increased soil penetration resistance in the topsoil, no significant ($p > 0.05$) relationships between penetration resistance and soil organic carbon content were found (Table 4). Across sampling depths, clay content was positively ($p < 0.01$) related to soil organic carbon content (Fig. 4, Supplemental Fig. S3 and S5). Introducing sampling time as an additional predictor into the regression models, showed that day at which soil samples were taken had no significant effect on soil organic carbon content (Supplemental Table S5 to S8). Furthermore, the amount of exogenous carbon input derived from crop residues and organic fertilizers was not related to soil organic carbon content (Supplemental Table S9 to S13).

The results obtained from the regressions analyses (Eq. 3) show that soil organic carbon content in the current study was positively associated with soil physical conditions facilitating root growth, namely high gas transport capability and water holding capacity. Exogenous inputs of organic carbon in contrast showed no significant influence on the organic carbon content in the soil. This suggests a positive association between soil physical conditions that facilitate root growth and soil organic carbon content (Fig. 5).

3.4 Relationships between soil organic carbon content, soil microbial biomass and respiration

In both soil layers, higher soil organic carbon content significantly ($p < 0.01$) increased soil microbial biomass ($0.75 < R^2 < 0.76$) and soil respiration ($0.64 < R^2 < 0.69$). Furthermore, higher soil microbial biomass was strongly associated ($p < 0.01$; $0.85 < R^2 < 0.86$) with increased soil respiration. Except for microbial respiration in the subsoil, no significant influence of clay content on microbial biomass and respiration was found (Table 3). These results indicate that microbial biomass and activity, and thus potential decomposition of soil organic carbon in the investigated soils, were at best only partially related to soil texture.

4 Discussion

Here, we investigated interrelations between and soil gas transport properties and soil organic carbon content in arable soils. Other than in most field plot studies where different management treatments are compared on the same soil, the current on-farm study included 30 fields with substantial variation in soil texture (Table 1). In addition to soil texture, soil gas transport properties as well as soil organic carbon content were highly variable among the investigated fields both in the topsoil and the subsoil (Table 2). Despite this large variation, significant effects of the soil management system on gas transport properties and soil organic carbon were found, mainly in the top 20 cm of the soil. Our results show that tillage increased gas transport capability and water holding capacity in the topsoil (Fig. 2), while penetration resistance in the topsoil decreased due to tillage (Supplemental Fig. S2). Thus, physical conditions for root growth (Bengough et al., 2011; Rich and Watt, 2013) were improved in the topsoil of the conventional and organic management system compared to the no-till system. Similar findings were obtained from field plot experiments, where tillage resulted in increased gas transport capability and water holding capacity, and lower penetration resistance in the topsoil and occasionally also in the subsoil (Azooz et al., 1996; Dal Ferro et al., 2014;

Kahlon et al., 2013; Martínez et al., 2016a, 2016b; Pires et al., 2017; Schjonning and Rasmussen, 2000). As shown previously (Birkhofer et al., 2008; Gattinger et al., 2012; Mäder et al., 2002), soil organic carbon content was higher under organic management than in the no-till and conventional system (Fig. 3). Hence, differences in soil physical properties were mainly caused by the tillage system, while soil organic carbon content was more related to organic farming.

The large variation in soil texture, gas transport properties and soil organic carbon content among sites enabled us to relate soil organic carbon content to soil gas transport capability and clay content (Eq. 3). Soil organic carbon content significantly increased with higher gas transport capability in the topsoil and the subsoil (Fig. 4). In agro-ecosystems, soil organic carbon derives from roots in the form of root biomass and root exudates as well as from crop residues and organic amendments such as slurry, manure and compost. Recently it was reported that the contribution of aboveground litter to soil organic carbon content might exceed that of roots. This is due to higher decomposability of aboveground residues compared to roots, resulting in more microbial by-products and eventually higher amounts of long-term stabilized soil organic carbon (Cotrufo et al., 2013, 2015; Lavallee et al., 2018). However, numerous other studies showed that 60-70% of soil organic carbon in arable soil derives from roots, suggesting that roots are the dominant input source for soil organic carbon (Balesdent and Balabane, 1996; Kätterer et al., 2011; Kong and Six, 2010; Rasse et al., 2005). Therefore, soil physical properties fostering root growth such as high soil gas transport capability will lead to increased organic matter input and eventually higher soil organic carbon content (Fig. 5). This is supported by previous studies, which showed that impeded soil aeration and the resulting decrease of oxygen concentrations in soil air slows down metabolic activity of roots and reduces root growth (Bengough et al., 2011; Dresbøll et al., 2013; Eavis, 1972; Garnczarska and Bednarski, 2004; Grable and Siemer, 1968; Qi et al., 1994; Thomson et al., 1992; Watkin et al., 1998). Root growth may also be facilitated by high water holding capacity and low soil penetration resistance (Bengough et al., 2011; Rich and Watt, 2013), which consequently also increases soil organic matter inputs. We observed a strong positive relationship between water holding capacity and soil organic carbon content (Fig. 4, Supplemental Fig S6), while soil penetration resistance and organic carbon content were not related (Table 4). This can most likely be explained by the relatively moist conditions at the time of measurements (Supplemental Fig. S2) as relationships between organic carbon content and penetration resistance are stronger under dry conditions (Soane, 1990).

Based on the presented results and existing literature, we propose a positive feedback cycle between soil structure and related soil physical properties, root growth and thus organic matter input and soil organic carbon content (Fig. 5). Since no significant influence of exogenous carbon inputs on soil organic carbon content was found (Supplemental Table S9 to S13), we suggest that the differences in soil organic carbon content among the investigated sites were caused by differences in root growth. It is known that good soil aeration, high water holding capacity and low penetration resistance increase root growth (Bengough et al., 2011; Jin et al., 2013; Rich and Watt, 2013) and therefore the input of soil organic matter. In turn, higher soil organic carbon content improves soil structure, and thus increases soil aeration, water holding capacity and soil penetrability (Carter et al., 2007; Martínez et al., 2016b; Young et al., 1998), which further facilitate root growth (Fig. 5). Young et al., (1998) discussed these interrelations between soil physical properties, soil life and soil organic carbon. Amongst other soil physical functions, soil aeration is of particular importance because it is not only important for root growth but also for microbial biomass and thus the decomposition of organic matter (Balesdent et al., 2000). In the current study, higher soil organic carbon content was related to increased microbial biomass and activity (Table 5). Hence, there might have been an indirect relationship between soil aeration and the decomposition of soil organic carbon (Fig. 5). It is known that anaerobic microsites in soil, which are characterized by minimal microbial activity, are important regulators for the stabilisation of organic carbon (Keiluweit et al., 2016, 2017). Due to root respiration and local carbon dioxide accumulation, such anaerobic microsites are likely to form around roots (Koop-Jakobsen et al., 2018). For the build-up of soil organic carbon at larger scales however, aerobic conditions are needed as they promote root growth (Dresbøll et al., 2013; Grzesiak et al., 2014; Thomson et al., 1992; Watkin et al., 1998). Furthermore, roots are known to grow towards well aerated soil compartments (Colombi et al., 2017; Porterfield and Musgrave, 1998). Hence, aerobic parts of the soil are likely to be enriched with new organic matter. The positive relationship between gas transport properties and soil organic carbon content obtained here (Fig. 4) suggests that in our study, effects of soil aeration on organic matter inputs were more pronounced than eventual stimulation of decomposition.

It has been emphasized that the close interactions between physical, chemical and biological processes need to be accounted for when evaluating the carbon storage potential of arable systems (Qi et al., 1994; Rasmussen et al., 2018; Young et al., 1998). Despite the knowledge about the influence of soil gas transport capability and oxygen concentration in soil air on root growth, the effects of soil aeration on soil organic carbon content have received only little attention. Unlike water and mineral nutrients, oxygen is not directly acquired by soil inhabiting organisms including plants, soil fauna and microbes. However, oxygen largely regulates the growth and metabolism of these organisms and thus plays a crucial role in carbon cycling. As shown here and in previous studies (Albizua et al., 2015; Azooz et al., 1996; Carter et al., 2007; Dal Ferro et al., 2014; Kahlon et al., 2013; Martínez et al., 2016b; Pires et al., 2017; Schjonning and Rasmussen, 2000), agricultural management affects soil structure and therefore soil gas transport properties. Ultimately, this has consequences for root growth (Thomson et al., 1992; Watkin et al., 1998; Dresbøll et al., 2013; Grzesiak et al., 2014) and thus affects the input of soil organic matter through roots. The results presented here, which were obtained on-farm and therefore represent relevant scales and management conditions, reveal that increased organic carbon content in arable soil are related to high gas transport capability.

5 Conclusions

Based on results obtained from 30 fields of commercial farms, we found a positive relationship between gas transport capability and organic carbon content of arable soil. As exogenous organic carbon inputs were not related to soil organic carbon content, differences in soil organic carbon content among the investigated sites were most likely caused by differences in root growth. We therefore propose that higher soil organic carbon content in well aerated soils resulted from enhanced root growth, which was facilitated by increased soil gas transport capability. Good soil aeration might also fuel microbial growth and activity leading to accelerated decomposition of soil organic carbon. The results obtained here indicate that for the current study the effects of aeration on carbon inputs were more pronounced than stimulation of carbon decomposition by heterotrophic soil life. However, opposite relationships between soil aeration and organic carbon content may occur in different land use systems or under different climatic conditions. We suggest that aeration plays a crucial yet underestimated role for the potential of arable soils to act as a terrestrial carbon sink. Future research and policy measures that aim to increase carbon content in arable land use systems need to account for the effects of soil management on soil aeration, and the associations between soil gas transport capability and soil carbon dynamics.

Author contributions

TK, JS, MvdH, RC, FW and LB conceived the study; FW, MS, and KL conducted the sampling; FW and MS carried out laboratory measurements; Data analysis and interpretation was performed mainly by TC with contribution from FW, TK and LB; TC prepared the manuscript with contribution from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Tables

Table 1: Effects of management system (M), sampling depth (D) and their interaction (M:D) on soil texture analysed with linear mixed models (Eq. 1) followed by analysis of variance (ANOVA). ** denotes significant effects at $p < 0.01$. Average values for the different depths represent means of three management systems (no-till, conventional, organic, n=10).

	ANOVA			Average (±SD)			CV [%]		
Soil property	**M**	**D**	**M:D**	**- 12.5**	**- 37.5**	**overall**	**- 12.5**	**- 37.5**	**overall**
Clay [%]	p = 0.41	**	p = 0.33	22.7 (±8.0)	24.1 (±7.7)	23.4 (±7.8)	35.1	32.0	33.3
Silt [%]	p = 0.70	p = 0.33	p = 0.50	34.7 (±4.3)	34.3 (±4.8)	34.5 (±4.5)	12.4	14.2	13.0
Sand [%]	p = 0.37	p = 0.08	p = 0.22	42.6 (±9.2)	41.7 (±10.0)	42.1 (±9.6)	21.6	24.1	22.8

Abbreviation: SD = Standard deviation, CV = coefficient of variation

Table 2: Descriptive statistics on soil physical properties and soil organic carbon content across all three management systems. Mean, SD and CV represent average value, standard deviation and coefficient of variation, respectively, (n=30).

Soil property	Ψ [hPa]	Depth [cm]	Mean	SD	CV [%]
ε [cm^3 cm^{-3}]		-12.5	0.53	0.050	9.5
		-37.5	0.45	0.044	9.8
εa [cm^3 cm^{-3}]	30	-12.5	0.16	0.036	23.4
		-37.5	0.11	0.028	25.0
	100	-12.5	0.18	0.039	21.1
		-37.5	0.13	0.032	24.1
Dp/D0 [-]	30	-12.5	0.017	0.0098	59.1
		-37.5	0.008	0.0039	47.6
	100	-12.5	0.033	0.0171	51.8
		-37.5	0.014	0.0068	49.5
Ka [μm^2]	30	-12.5	32.1	21.54	67.1
		-37.5	15.1	15.37	101.8
	100	-12.5	76.0	45.89	60.4
		-37.5	23.6	21.79	92.4
WHC [g g^{-1}]		-12.5	0.29	0.071	24.1
		-37.5	0.23	0.061	27.2
Q [MPa]		-12.5	1.30	0.635	48.9
		-37.5	2.42	0.725	30.0
SOC [g C kg^{-1} soil]		-12.5	20.0	10.02	50.1
		-37.5	12.1	7.67	63.5

Abbreviations: ε = total porosity, εa = air-filled porosity, Dp/D0, gas diffusion coefficient, Ka = air permeability, WHC = water holding capacity, Q = soil penetration resistance, SOC = soil organic carbon content, Ψ = soil matric suction

Table 3: Effects of management system (M), sampling depth (D), their interaction (M:D) and clay content on soil organic carbon, microbial biomass and microbial respiration analysed with linear mixed models (Eq. 2) followed by analysis of covariance (ANCOVA). ** and * denotes significant effects at $p < 0.01$ and < 0.05, respectively. Average values for the different depths represent means for no-till (NT), conventional (CON) and organic (ORG) soil management system. Different letters indicate significant differences between management systems at individual depths using least significant difference (LSD) tests at $p < 0.05$ (n=10).

	ACNOVA					Average (±SD)			
Soil property	**M**	**D**	**M:D**	**Clay [%]**	**Depth [cm]**	**NT**	**CON**	**ORG**	**LSD**
micC [mg C kg^{-1} soil]	*	**	p = 0.39	**	-12.5	607a (± 355)	573a (± 185)	861b (± 417)	247
					-37.5	261a (± 149)	317ab (± 212)	467b (± 301)	170
Resp [µg CO_2–C g^{-1} soil h^{-1}]	p = 0.21	**	p = 0.29	**	-12.5	0.72 (± 0.44)	0.60 (± 0.19)	0.87 (± 0.39)	0.29
					-37.5	0.35 (± 0.24)	0.40 (± 0.26)	0.51 (± 0.36)	0.20

Abbreviations: SD = Standard deviation, micC = soil microbial carbon, Resp = soil microbial respiration

Table 4: Summary statistics of multiple linear regression models to explain soil organic carbon content as a function of penetration resistance and clay content (Eq. 3). ** indicates significant regression coefficients at $p < 0.01$, ns indicates nonsignificant regression coefficients. R^2 represents multiple r-squared.

Response variable	Depth [cm]	Q [MPa]	Clay [%]	Int	R^2
SOC [g C kg^{-1} soil]	-12.5 cm	-3.936 ns	0.867**	5.416 ns	0.53
	-37.5 cm	-1.655 ns	0.682**	-0.340 ns	0.45

Abbreviations: SOC = soil organic carbon content, Q = soil penetration resistance, Clay = clay content, Int = intercept

Table 5: Summary statistics of multiple linear regression models to explain microbial biomass and soil microbial respiration as a function of soil organic carbon content, microbial biomass, and clay content (Eq. 4). ** and * significant regression coefficients at p < 0.01 and p < 0.05, ns indicates nonsignificant regression coefficients. R^2 represents multiple r-squared.

Response variable	Depth [cm]	SOC [g C kg^{-1} soil]	Clay [%]	Int	R^2
micC [mg C kg^{-1} soil]	-12.5 cm	27.35**	4.882 ns	23.24 ns	0.75
	-37.5 cm	24.33**	3.965 ns	-40.01 ns	0.76
Resp [µg CO_2–C g^{-1} soil h^{-1}]	-12.5 cm	0.030**	-0.003 ns	0.190 ns	0.64
	-37.5 cm	0.021**	0.129**	-0.146 ns	0.69
		micC [mg C kg^{-1} soil]	**Clay [%]**	**Int**	**R^2**
Resp [µg CO_2–C g^{-1} soil h^{-1}]	-12.5 cm	0.001**	-0.006 ns	0.167 ns	0.85
	-37.5 cm	0.001**	0.008*	-0.102 ns	0.86

Abbreviations: micC = soil microbial carbon, Resp = microbial respiration, SOC = soil organic carbon content, Clay = clay content, Int = intercept

Figures

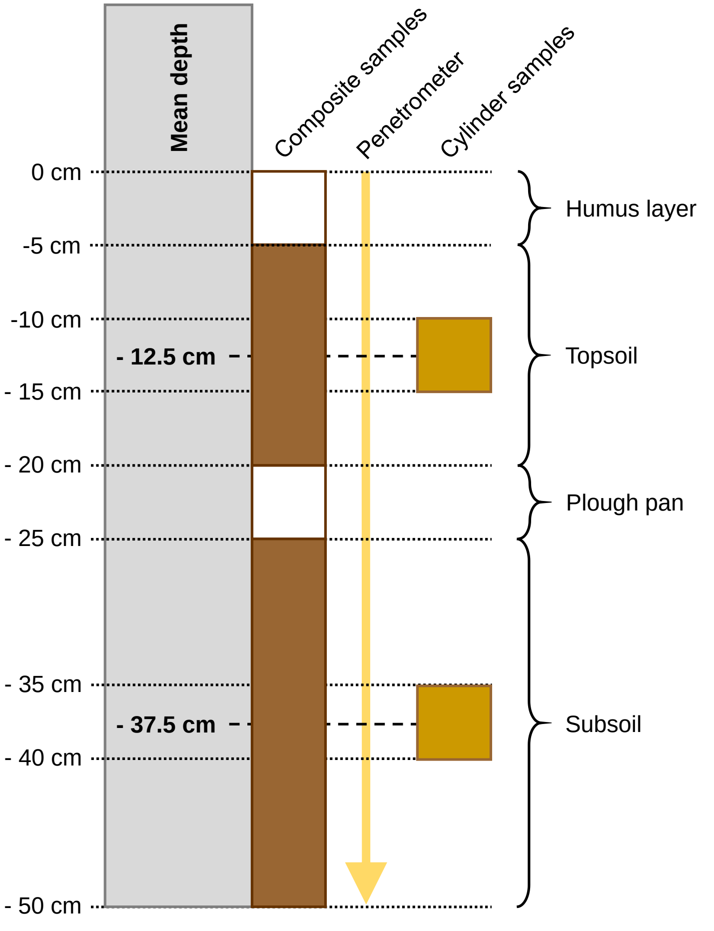

Figure 1: Schematic overview indicating soil layers and respective depths used for composite samples, penetrometer insertions and cylindrical soil core samples.

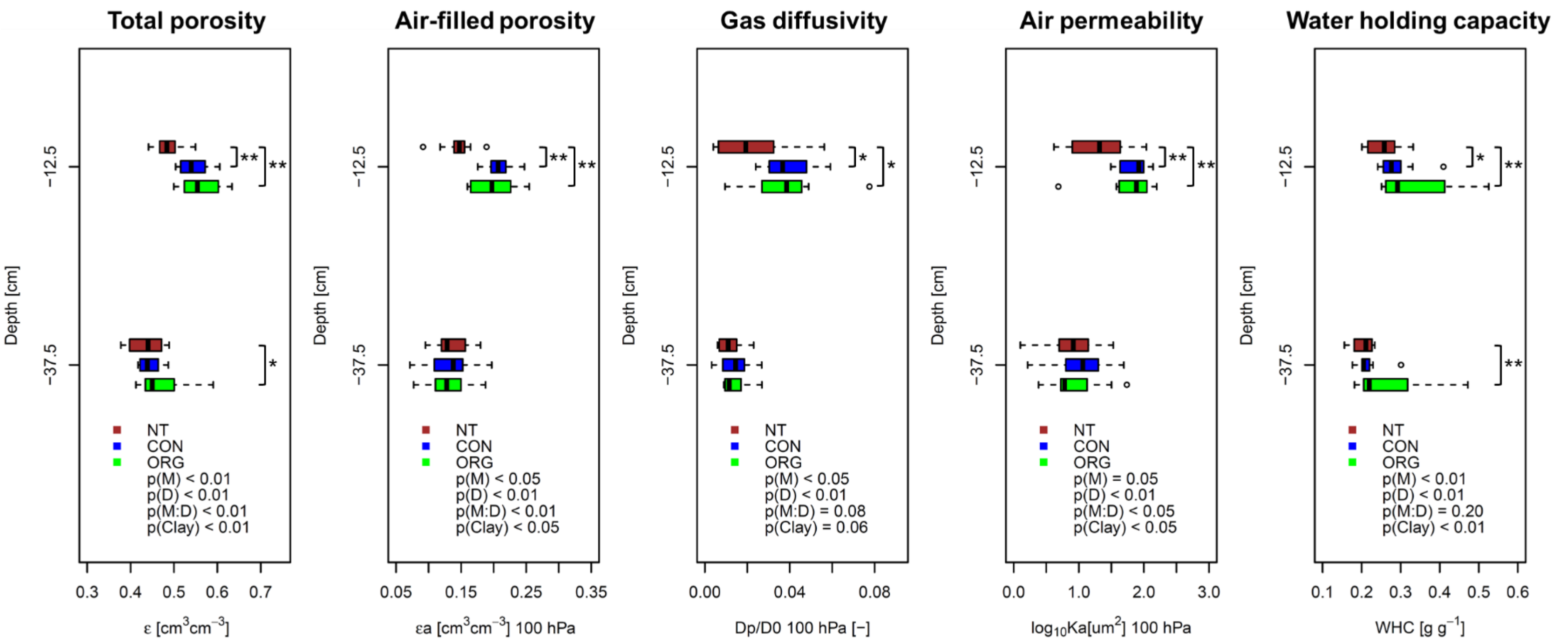

Figure 2: Effects of soil management (M), sampling depth (D), their interaction (M:D) and clay content (Clay) on total soil porosity, air-filled porosity, gas diffusivity and air permeability (all measured at 100 hPa matric suction) and water holding capacity analysed with linear mixed models (Eq. 2) followed by analysis of covariance. NT (red), CON (blue) and ORG (green) denote no-till, conventional and organic management system, respectively. ** and * indicate significant differences between management systems at individual depths using least significant difference (LSD) tests at $p < 0.01$ and $p < 0.05$, respectively (n = 10).

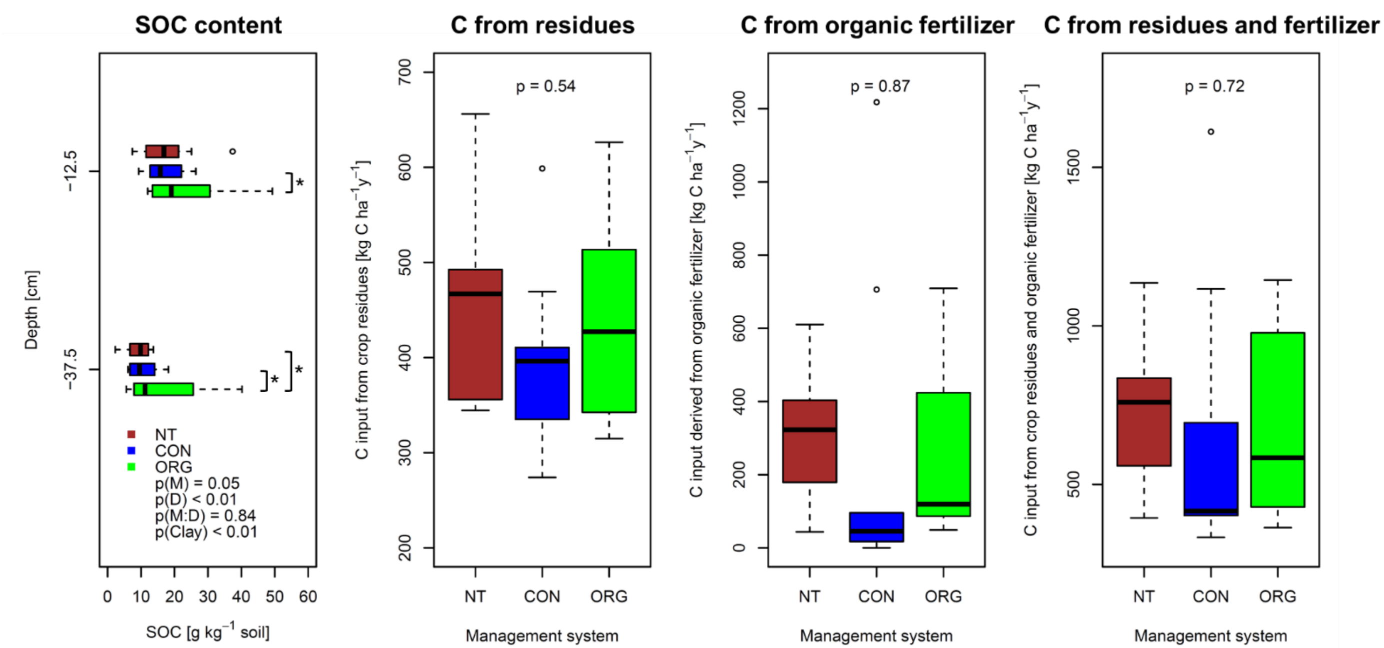

Figure 3: Effects of soil management (M), sampling depth (D), their interaction (M:D) and clay content (Clay) on soil organic carbon content analysed with linear mixed models (Eq. 2) followed by analysis of covariance (n = 10) and effects of management on exogenous carbon inputs calculated as described in Büchi et al., (2019) using analysis of variance (NT: n = 10, CON: n = 9, ORG: n= 10). NT (red), CON (blue) and ORG (green) denote no-till, conventional and organic management system, respectively. * indicates significant difference between management systems at individual depths using least significant difference (LSD) tests at $p < 0.05$.

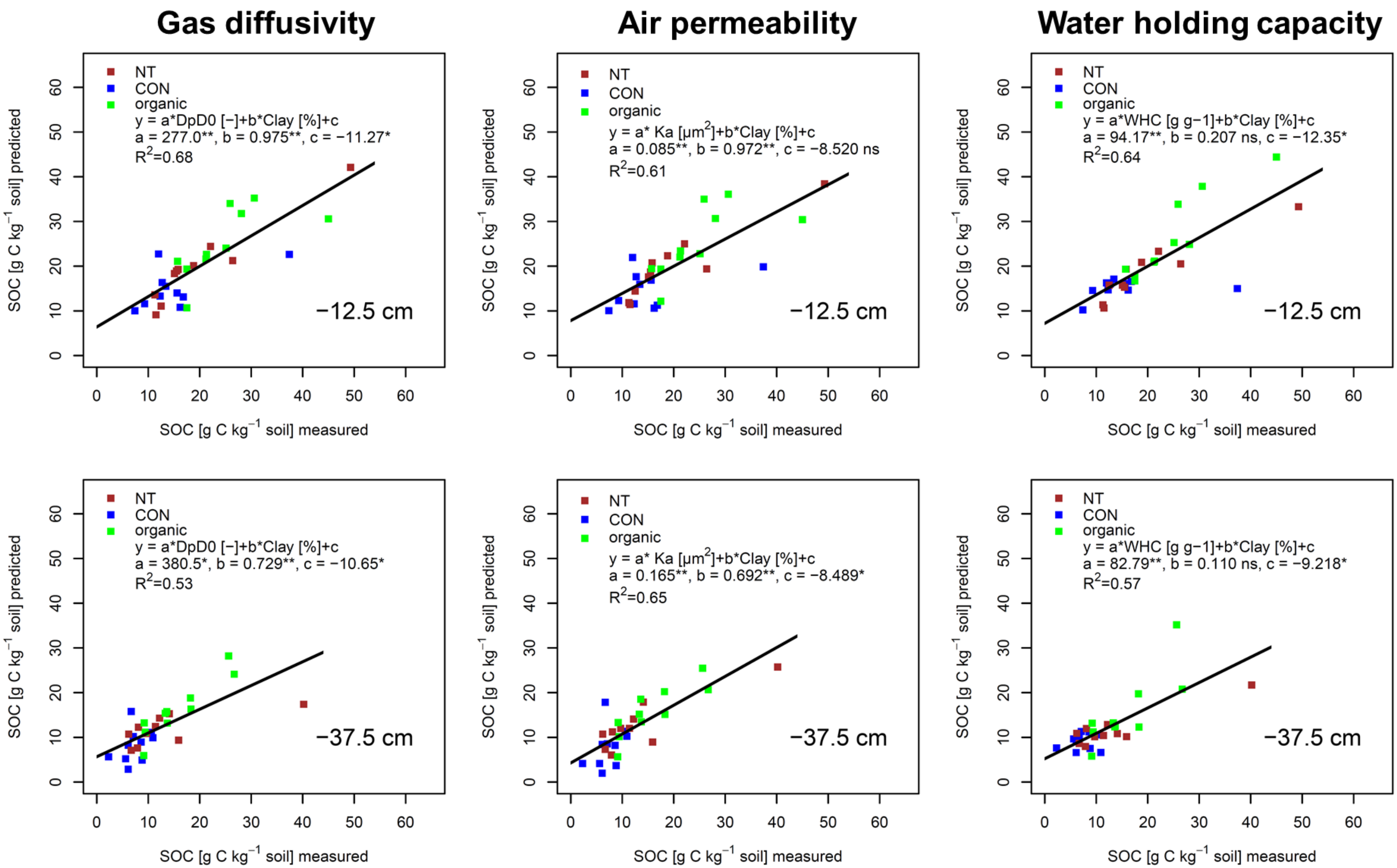

Figure 4: Multiple linear regression models (Eq. 3) to explain soil organic carbon content as a function of gas diffusion coefficients (Dp/D0 [-], air permeability (Ka [μm^2]) measured at 100 hPa matric suction, water holding capacity (WHC [g^3 g^{-3}]), and clay content (Clay [%]). NT (red), CON (blue) and ORG (green) denote no-till, conventional and organic management system, respectively. ** and * indicates significant regression coefficients at $p <$ 0.01 and $p < 0.05$, respectively, ns indicates nonsignificant regression coefficients. R^2 represents multiple r-squared.

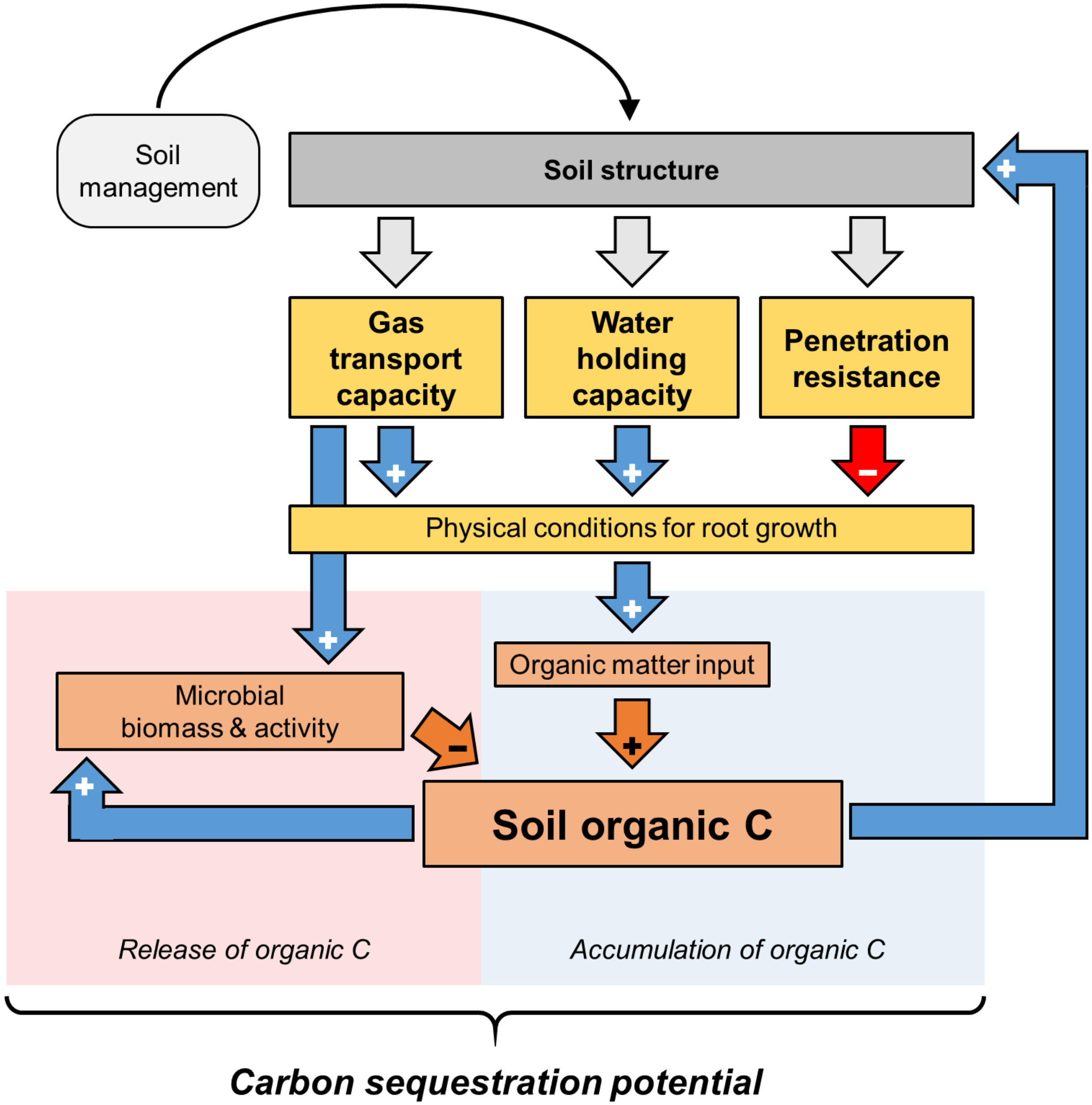

Figure 5: Conceptual model illustrating the influence of soil structure and related soil physical properties on soil organic carbon content. Improved soil aeration, water holding capacity and soil penetrability leads to better physical conditions for root growth, which fuels soil organic matter input and increases soil organic carbon content. In turn, soil structure and related physical properties are further improved. Improved soil aeration and high soil organic carbon content may also fuel microbial growth and activity and thus accelerate soil organic matter decomposition.