

Aggregates versus pores? A survey among soil scientists about their perspectives on soil structure

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Aggregates versus pores? A survey among soil scientists about their perspectives on soil structure

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Abstract. Despite mostly uniform definitions of soil structure, two perspectives on it have been juxtaposed in the past: the “aggregate perspective” and the “pore perspective”. The debate as represented in the literature appears to be polarised. To test whether this is also the case in the wider soil science community, an online survey was conducted asking about soil scientists’ view on these perspectives. There was a strong bias towards participants from Germany (139 of 251) but all career stages and different sub-disciplines were well-represented, so the results are assumed to be representative at least for the German soil science community. As expected, the largest group of participants (49 %) equally agreed with both perspectives and both concepts were judged as important to understand soil structure. A clear correlation between career stage and strength of opinion could not be found. The survey is not meant to decide democratically on these questions but to give an impression of the status quo of the debate in the wider community. This snapshot is by far not complete. To make best use of research resources, it may be helpful to identify potential barriers to effective communication, like misunderstandings or irrational belief perseverance, in further studies.

1 Introduction

Soil structure has been defined as “the spatial arrangement of primary particles and pores” (Koestel et al., 2021) and many earlier definitions are similar to this one (e.g., Dexter, 1988; Lal, 1991). Despite this apparent agreement, there is a debate going on between soil scientists taking different perspectives on soil structure. The two main viewpoints have been called “aggregate perspective” and “pore perspective”. Proponents of the aggregate perspective view the structure of most soils as consisting of aggregates, i.e. clusters of particles cohering more strongly with each other than with neighbouring particles (Yudina and Kuzyakov, 2019). This usually includes a distinction between regions at the surface and the inside of aggregates, and between inter- and intra-aggregate pores (Kladivko, 2017). A further feature of this perspective is that aggregation is thought to have distinct hierarchical levels with smaller aggregates being more stable and being contained within larger ones (Tisdall and Oades, 1982). The organisation of soil into aggregates is thought to drive important soil functions like carbon turnover according to this perspective. Studies using this approach in most cases include the separation of soil clods into smaller pieces either by mechanical force or by use of water.

Proponents of the pore perspective are mostly skeptical of the fragmentation of soils into aggregates both in terms of actual methods and in terms of concepts. They consider the aggregate approach to not be useful for many soils and in most use

cases, for example when soil functions like fluxes of matter or energy are quantified, particularly if these are upscaled to whole soil profiles or landscapes (Kravchenko et al., 2019; Vogel et al., 2022). Instead, they state that the pore system as a whole drives most soil functions. Therefore, they emphasize that soils should be studied in a more intact state to include processes occurring at larger scales and to maintain more spatial information. The aggregate concept is not needed for the explanation of soil functions according to this perspective.

Occasional criticism of studying fragmented soil dates back as far as 1938, when Kubiěna compared a “crushed or pulverized soil” to a “demolished building” (Kubiěna, 1938). Many years later, this criticism was refined (Letey, 1991; Young et al., 2001) and recently, the debate has intensified with numerous papers and letters to the editor dealing with this issue (Rabot et al., 2018; Kravchenko et al., 2019; Yudina and Kuzyakov, 2019; Vogel et al., 2022; Yudina and Kuzyakov, 2023; Garland et al., 2024).

When I came across this debate during my Master’s thesis on the stability and structure of aggregates from a field experiment, it appeared to me that the soil science community was divided into two camps. Also some authors described this debate between the two “fundamentally different” (Vogel et al., 2022) perspectives as “controversial” (Yudina and Kuzyakov, 2019), leading to “a rift in the soil science community” (Garland et al., 2024). However, the impression of two distinct camps could be misleading because only scientists with strong opinions about that matter are likely to make the effort to write a paper about it. Therefore, it is unclear how the wider soil science community relates to that issue, which leads to two questions: (1) *How is the intensity of agreement with aggregate and pore perspective distributed among soil scientists?* And, regarding the supposed fundamental difference between them, (2) *how many soil scientists see the two main perspectives as compatible or mutually exclusive?*

Despite its long history, the problem has not been solved yet. In fact, involved scientists do not even always agree on what the core of the conflict is (Kravchenko, 2023) and even on whether there is – or should be – any conflict at all (Garland et al., 2024). Quite frequently, scientists write that their point of view has been misrepresented by others (e.g., see comments in the open review of Garland et al. (2024)). This raises the question whether there are external, i.e. non-argumentative factors that affect the communication on this matter.

Proponents of the aggregate perspective have been criticised for not letting go of the aggregate concept simply because they were used to it (Baveye, 2023). Belief perseverance in spite of contradicting experimental data can in fact occur also in natural scientists (Nissani and Hoefler-Nissani, 1992). Notably, this applies to all scientists involved in that debate, irrespective of their opinion on the matter. Moreover, scientists who have used either approach in their work can feel they wasted their time if they abandon the underlying concept (sunk cost effect, Arkes and Blumer, 1985). The longer they have worked with it, the more is potentially at stake for these researchers. This raises the question whether scientists develop stronger opinions about that matter as they reach later career stages. This correlation could also have rational reasons. During their career, scientists may have found more and more evidence for the usefulness of their concept of soil structure. Disentangling the causes would be interesting but the before that, it is necessary to find out: (3) *Does the strength of opinion increase with increasing career stage?*

Referring to the three questions named above, this study aims to test the following hypotheses:

1. The positions in the soil science community are not as polarised as the literature suggests.

2. Most soil scientists judge the two perspectives to be compatible.
3. The strength of opinions increases with increasing career stage.

The approach taken here was to have a look at this debate from a social sciences' perspective, doing a survey among soil scientists. The aim was to get a clearer picture of social aspects of the status quo of the debate.

65 **2 Methods**

The design of the survey was guided by two main goals: a) include as many scientists as possible and b) introduce as little bias as possible. To enable and motivate as many soil scientists as possible to participate in the survey, the following aspects were considered in its design: 1. accessibility, potential barriers and additional motivation to participate, 2. frustration as a barrier to completing the survey.

70 Accessibility was supported by conducting the survey online, published via the mailing list of the German Soil Science Society (Deutsche Bodenkundliche Gesellschaft (DBG), on 17th February 2023) and posted on Twitter (today "X", on 6th April 2023). It was formulated in English to reach an international audience. Participation was anonymous by default.

To avoid frustration and thus abortion of filling out the online form, the questionnaire was kept short (18 questions including subquestions) and only little personal information was asked for (Table A1 in the Appendix). Most of the questions were closed
75 type, i.e. offering a limited set of answers to choose from, and only ten questions were mandatory. In a pre-test among three colleagues from my institute, the questionnaire took ca. 5-10 minutes to fill out. When asking for (dis)agreement with different statements, the scale from strong disagreement to strong agreement had an even number of answer options to avoid the effect that (especially weakly motivated) participants tend to choose the option in the middle (Bishop, 1987; Masuda et al., 2017).

People who are interested in a topic are more likely to participate in a related survey, which is a case of self-selection bias
80 (Whitehead, 1991). Overcoming this bias was critical regarding the first hypothesis. As a motivation for scientists not involved or particularly interested in the debate, they were given the option to participate in a lottery at the end of the questionnaire by entering their email address. This compromised their anonymity and participants were made aware of that both on the welcome page of the survey and in the additional information to the free text field. Participants could win one of eight prizes (stickers, magnets, a T-shirt) with a soil-related printing.

85 Definitions of the "aggregate perspective" and "pore perspective" are most likely contested themselves. An inadequate definition of a perspective might make it seem less appropriate. Therefore, to not introduce any bias, no definitions were given and participants were asked to use their own understanding of the terms.

The questionnaire consisted of five question blocks, each presented on a separate browser page (Table A1 in the Appendix). Mandatory questions were marked with an asterisk (*). The first two blocks covered details regarding the participants' scientific
90 career and working place, and their self-estimated level of expertise on the matter. Then followed an array of statements with a six-point scale from "strongly disagree" to "strongly agree" plus the options "not enough knowledge" and "no answer". In the fourth block, participants were explicitly asked for their preference for the aggregate or the pore perspective, with the additional

options “equally agree with both”, “no opinion”, and “do not have enough knowledge to judge”. If one of the two perspectives was favoured, an additional question opened asking them for the strength of their opinion. Additionally, participants were asked to rate the relevance of the debate to their own research and to soil science in general. The last question block gave the opportunity to elaborate on any thoughts on that topic in a free-text field and to give feedback on the questionnaire.

Data analysis and figure plotting was done with R (Pedersen and Cramer, 2023; R Core Team, 2023; Wickham, 2016; Wickham et al., 2022).

3 Results

3.1 Characteristics of the participants

In total, 350 people started the survey (via DBG mailing list, called “DBG” from here on: 228; via Twitter: 122) and 280 completed it (DBG: 189, Twitter: 91). Of these, 251 stated that they were academic researchers (DBG: 171, Twitter: 80). Since the target group was academic soil scientists, only these 251 complete questionnaires were analysed. The answers from both sub-surveys were very similar, so pooled results are presented here.

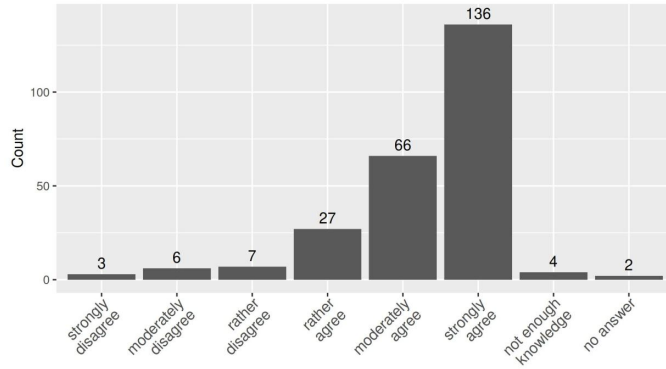
More than half of the participants (139) had their workplace in Germany, followed by the USA (29), Switzerland (21) and 1 to 6 scientists each from 30 countries on all continents (Table A2 in the Appendix). All career stages were represented in the participants, namely PhD students (69), PostDocs (76), (assistant/associate/full) professors (56), retired (10), and other (40). In a multiple choice question about the research focus area, the three main soil science sub-disciplines were almost equally frequent (soil (micro)biology/ecology: 95, soil chemistry: 110, soil physics: 93), with markedly fewer scientists working in hydrology (28), mineralogy (16) and other sub-disciplines (64). The self-estimated expertise on the debate was moderate to high with most people rating their expertise as “rather low” (54), “rather high” (87), or “high” (66). Only few people judged their expertise as “very high” (22), “low” (14), “very low” (7), or gave no answer (1).

3.2 Polarisation (Hypothesis 1)

The answers on a scale from “strongly disagree” to “strongly agree” (questions C1a-f) all had unimodal distributions (Fig. 1). The two opposing phrases regarding the (non)existence of aggregates got very different reactions (Fig. 1 a,b). Most participants strongly (136), moderately (66), or rather agreed (27) with the statement that aggregates exist and have characteristics that are typical of different soils (a phrase cited from Kravchenko et al. (2019)). In contrast, the phrase stating that “aggregates are merely artifacts and do not exist in soils in their natural state”, rephrased from a – supposedly rhetorical – question in Yudina and Kuzyakov (2019), mostly got negative reactions from “strongly disagree” (128) over “moderately disagree” (45) to “rather disagree” (43).

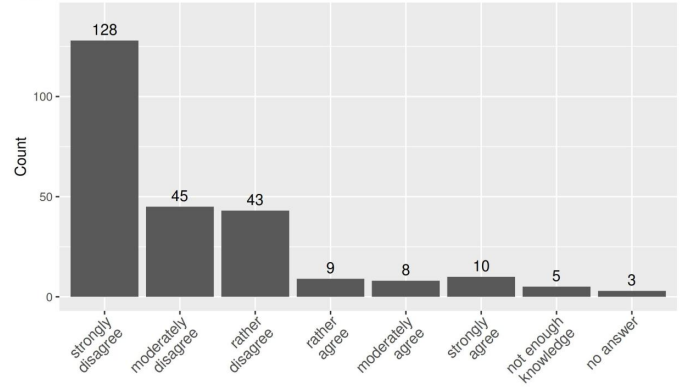
The agreement with the phrase “In order to understand soils, the concept of aggregates is important” was high with 142 participants agreeing strongly (Fig. 1 c). The same statement referring to pore systems instead of aggregates got even higher agreement with 187 participants agreeing strongly (Fig. 1 d).

a 'Aggregates do exist and have a size, form and stability that is typical for individual soils.**'



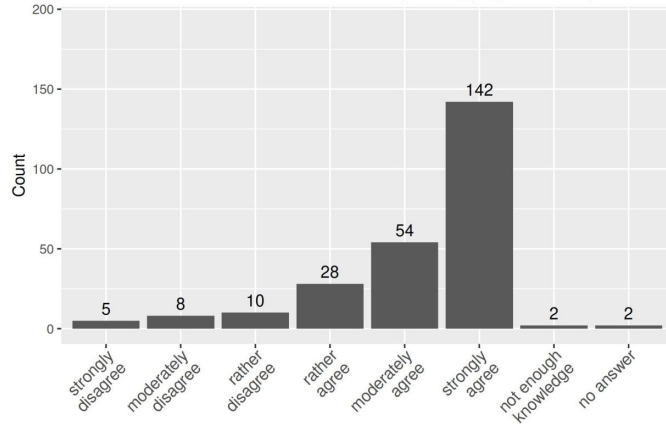
*) Kravchenko et al. 2019

b 'Aggregates are merely artifacts and do not exist in soils in their natural state.***'

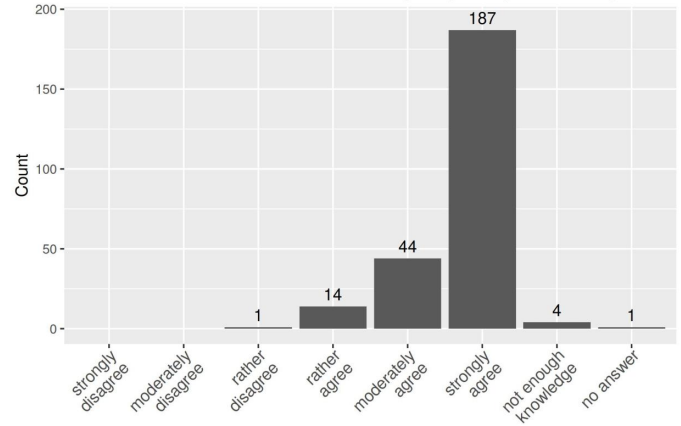


**) rephrased from Yudina/Kuzyakov 2019

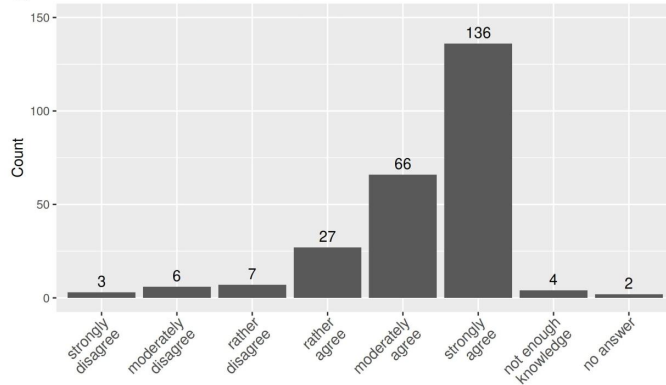
c 'In order to understand soils, the concept of aggregates is important.'



d 'In order to understand soils, the concept of pore systems is important.'



e 'The pore and aggregate perspective are conflicting.'



f 'The aggregate and pore perspective are two sides of one coin.'

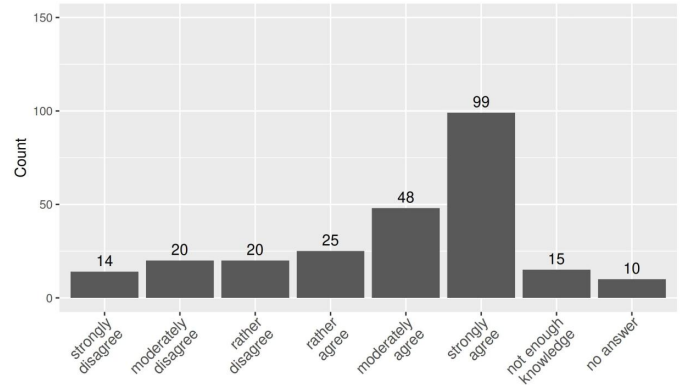


Figure 1. Survey results: Reactions to the statements given in the title of each sub-figure (absolute numbers, both sub-surveys combined, only academic researchers and complete questionnaires).

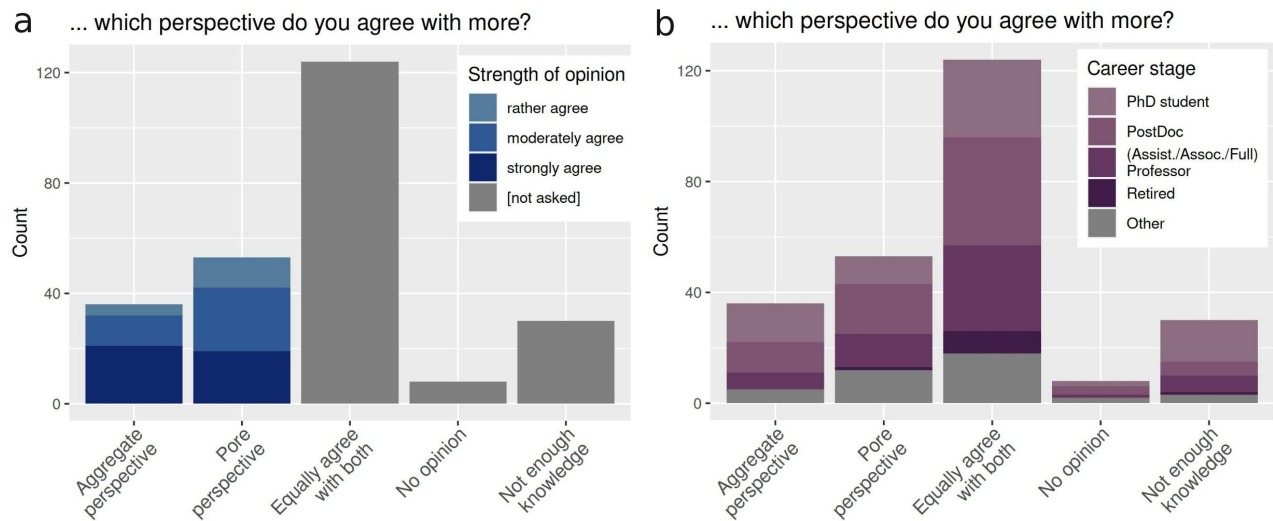


Figure 2. Reactions when explicitly asked for a preference for aggregate or pore perspective (absolute numbers, both participant pools (“DBG” and “Twitter”) combined, only academic researchers and complete questionnaires). a) Columns sub-divided by strength of opinion. Only those who agreed with one of the perspectives were asked for that. b) The same graph as a) with columns sub-divided by career stage of the participants.

When directly asked to position themselves regarding the pore and aggregate perspective, a simple majority (124 of 251; 49%) equally agreed with both perspectives (Fig. 2 a). Eighty-nine participants (35%) agreed more with either perspective and 40 participants (16%) strongly agreed with one of them.

3.3 Complementary or exclusive? (Hypothesis 2)

Two statements were presented to participants to ask them whether they deemed the aggregate and the pore perspective to be complementary or conflicting (Fig. 1 e,f). The phrase stating that they are conflicting got mostly strong agreement (136), followed by moderate agreement (66). The other phrase saying that the two perspectives were “two sides of one coin” got weaker agreement with 99 participants agreeing strongly and 48 moderately. Thus, although these phrases were meant to express opposite views, both were mainly agreed with.

3.4 Correlation of polarisation with career stage (Hypothesis 3)

From the visual impression in Fig. 2 b, all career stages contribute equally to the different answers regarding the question which perspective they prefer. The statistical tests support this impression. Spearman’s rank correlations between career stage and the strength of opinions regarding the different statements (questions C1a-f, see Table A1) and regarding the explicit preference for one perspective (question D2) were all positive but generally low (Spearman’s rho 0.02–0.17, Table A3 in the Appendix).

Only one of the correlation coefficients was significant at an alpha level of 0.05 (one-sided test). Note that the true p-value was uncertain because the data set contained many ties (participants sharing the same rank).

140 Results were similar but more variable when correlating self-estimated expertise with strength of opinion. Spearman's rho in these cases ranged from 0.07 to 0.34 and four of the correlation coefficients were significantly positive at an alpha level of 0.05 (one-sided test; Table A4 in the Appendix). Again, due to many ties in the data set, the true p-value could not be calculated exactly.

4 Discussion

145 4.1 Representativeness

As presented in Sect. 3.1, 139 of 251 participants (55 %) worked in Germany. I therefore strongly doubt that the results are representative of the world-wide soil science community. The German soil science community, however, is likely to be represented well because of the balanced mixture of career stages and sub-disciplines.

4.2 Low polarisation and no correlation with career stage

150 Participants by majority strongly agreed with the importance of the aggregate concept and, consistently, disagreed with the statement that they do not exist in natural soils. At the same time, they strongly agreed with the importance of the pore concept to understanding soils. This is also reflected by 124 participants (49 %) stating that they equally agree with both perspectives. Among the 89 participants (35 %) who favoured one of the perspectives, a large group (40 participants) had a strong opinion about that matter, which may explain the controversial debate. However, these 40 scientists only represented a minority (16 %) of all participants.

155 None of the statements (C1a-f) had a bimodal distribution of answers, which could have hinted at two groups with opposing views. These results are consistent with the assumption that the (German) soil science community as a whole is not as polarised regarding the debate around perspectives on soil structure as a reading of the literature might suggest. Admittedly, it is difficult to compare these data to the polarisation of views represented in the literature because the latter is hard to quantify. Nevertheless, a majority of participants equally agreeing with both perspectives is not compatible with a view of "fundamentally different" (Vogel et al., 2022) perspectives, so I consider my first hypothesis confirmed. Note that this is not a statement about the validity of either viewpoint but only about their representation within the scientific community.

160 Given such a low degree of polarisation, it is not very surprising to not find any strong correlations of strength of opinion with career stage. Thus, the second hypothesis could not be confirmed. Correlations of self-estimated expertise with strength of opinion tended to be stronger but were not consistently significant ($p < 0.05$), either. Thus, in this group, no hint to irrational belief perseverance could be found. It may nevertheless be effective in individuals or groups in the soil science community but in this study, we found no sign of it.

4.3 Complementary or exclusive?

The opposing statements that the two main perspectives in the debate are either “conflicting” or “two sides of one coin” both got much agreement. This contradiction may be explained with misunderstandings. Firstly, “two sides of one coin” might have been misunderstood as “opposing sides” instead of “two parts of the same thing”, especially in countries where there is no equivalent to this English saying. Secondly, “The pore and aggregate perspective are conflicting” may have been misunderstood as “There is a conflict between *scientists* preferring either the pore or the aggregate perspective”. Nevertheless, it is reasonable to assume that the vast majority of scientists who deem both perspectives to be important to understand soils (questions C1a and f) and who do not prefer one perspective over the other (question D1) will consider them complementary.

5 Conclusions

The survey presented here is not meant to decide democratically whether the different positions really are compatible or which one is the better one. Rather, it is a first peek into social and psychological aspects and the status quo of the debate. The survey showed that perspectives of soil scientists are more moderate than what the literature makes it seem. Moreover, many participants mentioned in the free-text field that they had not been aware of the debate and many also had doubts about its relevance. These results may serve as a starting point for further investigations and debates. As part of the debates, it should apparently be made clearer which consequences arise from following one or the other perspective. Further investigations, preferably done by researchers in psychology, may be helpful to identify potential barriers to effective communication. If non-argumentative factors such as misunderstandings or irrational belief perseverance were found to hinder the debate, this could inform the design of communication techniques that alleviate these barriers.

For example, misunderstandings did not only affect parts of the survey but also the debate itself, as mentioned in the introduction. To improve the efficiency of the debate, communication techniques that help avoid misunderstandings should be employed (e.g., clear definition of terms, being specific and careful with generalisations).

Moreover, debate participants should strive to create a constructive atmosphere to not provoke unnecessary emotional resistance. As an example, criticism of other peoples’ work could be oriented towards rules like these: Firstly, reproduce your counterpart’s position in a way that they approve of this description; secondly, list any points of agreement; thirdly, mention what you have learned from your counterpart’s work and only then criticise their work (Dennett, 2013). Additionally, irony and sarcasm should be used sparingly when confronting scientists with criticism of their approach.

Despite the formal texts being written about that matter, the debate partly appears fuzzy and confusing. With this study, I tried to get a clearer picture of its social environment. Researchers interested in understanding and structuring this debate better, both in terms of its social dynamics and its content, are very welcome to reach out to me.

Data availability. The data set cannot be made publicly available due to protection of privacy of the survey participants. However, I explicitly encourage any interested researcher to contact me for access to the data.

200 *Author contributions.* SR did everything, from the research idea over conducting the survey and data analysis to writing and revising the manuscript. The help that I had in doing so is mentioned in the Acknowledgements.

Competing interests. I am part of a research group that focuses on microaggregates (see Acknowledgements), which could be perceived as a bias.

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Appendix

Table A1: List of questions asked in the survey and their answer options. Closed questions were single choice except B1 and B2, which were multiple choice. Mandatory questions are marked with an asterisk (*), like it was done in the survey.

Question Nr.	Answer options	
Section A: About you (1)		
A1*	Are you an academic researcher?	Yes / no
A2	What type of institution do you work at (mainly)?	University / Other research institution / Other
A3*	What is your career stage?	PhD student / PostDoc / (Assistant/Associate/Full) Professor / Retired / Other
A4	Which country is your (main) research institution located in?	[drop-down menu with list of countries]
Section B: About you (2)		
B1	Which areas were you educated in?	Geology / Agriculture / Forestry / Biology / Hydrology / Other
B2	In which field is your research focus area?	Soil (micro-)biology/ecology / Soil chemistry / Soil Physics / Hydrology / Other
B3	How do you rate your expertise about different perspectives on soil structure?	very low / low / rather low / rather high / high / very high
Section C: Your view on soil structure (1)		
C1*	There are (at least) two broad perspectives on soil structure, the aggregate perspective and the pore perspective. Please indicate how much you agree or disagree with the following phrases. If you feel you do not have enough knowledge to judge a statement, choose “not enough knowledge”.	
C1a*	“In order to understand soils, the concept of pore systems is important.”	strongly disagree / moderately disagree / rather disagree / rather agree / moderately agree / strongly agree / not enough knowledge / no answer
C1b*	“Aggregates do exist and have a size, form and stability that is typical for individual soils.” ^a	[see above]
C1c*	“The pore and aggregate perspective are conflicting.”	[see above]
C1d*	“Aggregates are merely artifacts and do not exist in soils in their natural state.” ^b	[see above]

Continued on next page

Table A1– continued

Nr.	Question	Answer options
C1e*	“In order to understand soils, the concept of aggregates is important.”	[see above]
C1f*	“The aggregate and pore perspective are two sides of one coin.”	[see above]
Section D: Your view on soil structure (2)		
D1*	As mentioned, there are (at least) two broad perspectives on soil structure, the aggregate perspective and the pore perspective. Using your own definitions/understandings of them, which perspective do you agree with more? If you do not know what these terms mean, choose “Do not have enough knowledge to judge”.	aggregate perspective / pore perspective / equally agree with both / no opinion / do not have enough knowledge to judge
D2*	If you chose either “aggregate perspective” or “pore perspective”, please mark how strongly you agree with the chosen perspective.	strongly agree / moderately agree / rather agree
D3	The adequacy of aggregate and pore perspective is a matter of scientific debate. How do you rate the relevance of this debate to ...	
D3a	... your personal research?	very low / low / rather low / rather high / high / very high
D3b	... soil science in general?	[see above]
Section E: Closing questions		
E1	If you want, you are welcome to share some additional thoughts on this topic	[free text field]
E2	Do you have any feedback on this questionnaire?	[free text field]

Annotations:

a) Literal quote of Yudina & Kuzyakov (2019),

b) Re-phrased from a rhetorical question in Kravchenko et al. (2019)

Table A2. Answers to question A4, “Which country is your (main) research institution located in?”. Absolute numbers, only academic researchers and complete surveys, both participant pools (“DBG” and “Twitter”) combined.

Country	Nr of participants	Country (continued)	Nr of participants (continued)
Germany	139	Finland	2
USA	29	Indonesia	2
Switzerland	21	Spain	2
Sweden	6	Czech Republic	1
Brazil	4	Georgia	1
India	4	France	1
Italy	4	Japan	1
Slovenia	4	Luxembourg	1
Australia	3	Malawi	1
Chile	3	Mexico	1
South Africa	3	Netherlands	1
Argentina	2	Nigeria	1
Austria	2	Portugal	1
Canada	2	Russia	1
China	2	Tanzania	1
Colombia	2	Ukraine	1
Ethiopia	2		

Table A3. Rank correlations of *career stage* with different measures of strength of opinion. The test mode was always one-sided with the alternative hypothesis being: true rho > 0.

Measure of strenght of opinion	Spearman’s rho	P-value *
Answer to question D2, sorted from weak to strong agreement	0.021	0.45
Answer to question C1a, converted	0.140	0.06
Answer to question C1b, converted	0.149	0.05
Answer to question C1c, converted	0.175	0.03
Answer to question C1d, converted	0.096	0.14
Answer to question C1e, converted	0.070	0.22
Answer to question C1f, converted	0.104	0.13

Answers to questions C1a-f were converted to levels of strength of opinion as follows, sorted from low to high level: (1) not enough knowledge – no opinion, (2) rather (dis)agree – weak opinion, (3) moderately (dis)agree – moderate opinion, (4) strongly (dis)agree – strong opinion, (-) no answer – NA.

*) P-values < 0.05 in **bold**. Note that p-values could not be calculated exactly because the data set contained ties.

Table A4. Rank correlations of *self-estimated knowledge* with different measures of strength of opinion. Answers to questions C1a-f converted as described for Table A2. The test mode was always one-sided with the alternative hypothesis being: true rho > 0.

Measure of strenght of opinion	Spearman's rho	P-value *
Answer to question D2, sorted from weak to strong agreement	0.263	< 0.01
Answer to question C1a, converted	0.237	< 0.01
Answer to question C1b, converted	0.090	0.07
Answer to question C1c, converted	0.338	< 0.01
Answer to question C1d, converted	0.085	0.08
Answer to question C1e, converted	0.070	0.12
Answer to question C1f, converted	0.159	< 0.01

Answers to questions C1a-f were converted to levels of strength of opinion as follows, sorted from low to high level: (1) not enough knowledge – no opinion, (2) rather (dis)agree – weak opinion, (3) moderately (dis)agree – moderate opinion, (4) strongly (dis)agree – strong opinion, (-) no answer – NA.

*) P-values < 0.05 in **bold**. Note that p-values could not be calculated exactly because the data set contained ties.