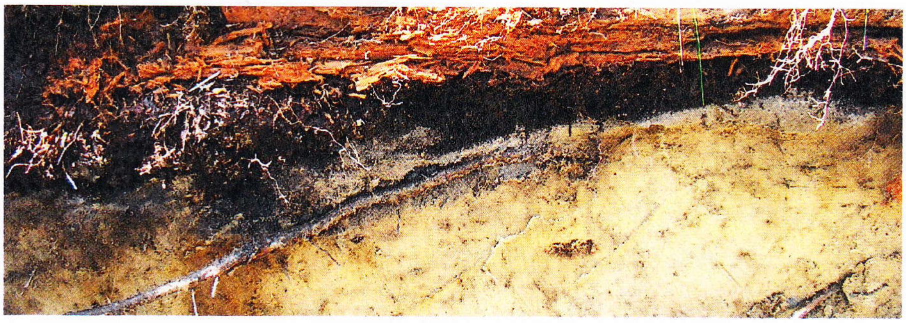

ΠΕΔΟΜΕΤΡΟΝ

Newsletter of the Pedometrics Commission of the IUSS Issue 48, April 2024

From the Chair

Welcome to the 48th edition of the Pedometron. It was great to see many of you a few weeks ago at the New Mexico Pedometrics conference. The conference was a success with a good number of participants and a wide range of topics presented. We had two field excursions and perfectly organized sessions by our local organizers. For those who could unfortunately not attend, we included a report with the highlights from the conference written by one attendee. You will also find feedback from the organizer, with the hope that this will be useful for future organizers.

In this issue, we have prepared the regular items with some scientific items on Frontier-line analysis and Bottom-up digital soil mapping, a cartoon, and the pedomathemagica. We also proposed the regular item "in conversation with" to Dr. Ma, who is the recipient of this year's Margaret Oliver Award.

Pedometrics is one of the most active commissions of the IUSS. In the last weeks, Division 1 has examined the requests for closure and extensions of several IUSS working groups that fall under the umbrella of Pedometrics. All active WGs that requested extensions seemed to be approved. This is certainly good news but also expected given the upcoming conferences in digital soil mapping and Global Soil Map and IUSS centennial with so many Pedometrics-related scientific sessions.

Another important announcement is the opening of a Special Issue on addressing the 10 pedometrics challenges. This issue is open in the European Journal of Soil Science. It was open to receive contributions from the presenters of the recent Pedometrics conference but is open to anyone who wishes to send an outstanding pedometric paper addressing one or several of the challenges.

Alexandre Wadoux
April 2024, Montpellier, France

In this issue

Announcements 2
Upcoming conferences 4
Frontier-line analysis 6
Looking back at Pedometrics 2024 in New Mexico 12
Conference report 22
A cartoon 24
In conversation with 25
Pedomathemagica 28
Bottom-up digital soil mapping 30
A survey 36

Delivered by

Chair
Alexandre Wadoux
Vice-chair
Simone Priori
Editor
Lei Zhang

Frontier-line analysis: a novel pedometric technique for estimating potential carbon sequestration

R.A. Viscarra Rossel [1] and R. Webster [2]

[1] Soil Landscape Science, School of Molecular Life Sciences, Faculty of Science Engineering, Curtin University, GPO Box U1987, Perth WA 6845, Australia.

[2] Rothamsted Research, Harpenden AL5 2JQ, United Kingdom.

E-mail: raphael.viscarra-rossel@curtin.edu.au; richard.webster@rothamsted.ac.uk

Maximum carbon storage

The globe is warming, and scientists are now agreed that the cause is the increased concentration of CO_2 in the atmosphere in the last 100 years or so. Much of that extra CO_2 has come from our burning fossil fuels to heat our buildings and generate electricity. Manufacturing industry and transport have played their parts. So too has agriculture. The clearance of forests, land drainage and cultivation for arable crops have led to the oxidation of carbon in the soil and the release of huge quantities of C as CO_2. The International Panel on Climate Change (IPCC) reckons that the globe will soon be 1.5°C warmer than before industrialization. Delegates at the recent meeting COP27 wished to limit that increase by 2050, but they failed to agree on cuts to emissions to achieve it. Worse, if emissions continue at the current rate then an increase to 2°C is likely sometime this century. Such warming is predicted to have dire consequences: a rise in sea level globally, submergence of island nations and coastal settlements, increased flooding in some regions and drought in others, more wild fires, ... If we are to avoid such ills and prevent global warming's exceeding 1.5°C then we need to limit the net increase in CO_2 in the atmosphere to zero. Scientists, stake-holders and politicians are therefore turning their attention to the capture and storage of gases and sequestration of C; their aim is 'net zero' emissions.

The capture and storage of CO_2 at source from factories and power stations are matters of technology. Those from the atmosphere must depend on Nature—by photosynthesis, and on land by storage of C in the soil. The soil could store more C than it does by more judicious land use and sound management. In that way the soil would provide a more long-lasting store of C than that in the vegetation; and it would also improve the soil as a medium for plant growth and ecosystems services such as greater storage of water and reduced run-off, erosion and flooding. The question then is: could the soil store in the long term more C than it does at present while at the same time sustaining its productive use?

We know from long-term field experiments that for any given form of land management the amount of C in the soil reaches an equilibrium in which gains balance losses, and some experiments seem to show that there is a maximum amount that the soil can store (West & Six, 2007). The soil gains C initially as organic residues or manure, largely as only partly decomposed particles. Those are mineralized rapidly by soil organisms, and approximately 90% of the C is lost within 30 years (Basile-Doelsch *et al.*, 2020). Much of the rest decomposes more slowly into smaller molecules that bind to mineral surfaces where they are protected against microbial attack and thereby stabilized in the soil, i.e. sequestered (Lehmann & Kleber, 2015). We call this material mineral-associated organic carbon, abbreviated to MAOC, and it is this form that we consider when we assess the soil's ability to store more C.

Given the above, we might expect that the larger is the soil's specific surface area of the mineral fraction the greater is the soil's potential to sequester C, and we might expect the relation to be linear. Following this line of reasoning Hassink (1997) obtained data from several sets of experiments and by simple linear regression he found that the MAOC depended on the soil's clay+silt <20-μm fraction. The fit was reasonable. Of course, the regression line does not express the maximum amounts of C that the soil could store: it passes through the means of the data. However, Hassink also found less than half as much C in the samples of Australian soil as in samples from other parts of the world for the same proportions of the <20-μm fraction, the significance of which we return to below.

Hassink & Whitmore (1997) modelled the interaction between C and the soil's fine fraction as one of adsorption–desorption kinetics. They showed that the rate at which any new C could be captured depended on the capacity already occupied by C; the closer the soil was to full capacity, the slower was any further accumulation of C. Six *et al.* (2002) pursued these ideas. They too regressed the MAOC on the fine-particle fractions of soil, and ones with various mineralogies. They nevertheless postulated asymptotic increases in the soil's organic C with increases in carbon inputs, with an asymptote's being the soil's storage capacity. Feng *et al.* (2013) recognized that a linear regression inevitably underestimates the maximum amounts of C that soil with given proportions of clay+silt. So instead they fitted boundary lines to the scatter of the upper tenth percentile of organic C and its corresponding proportion of clay+silt. This still left some values of C above the boundary line. Since then several groups of scientists have fitted regressions, boundary lines and other functions to estimate the potential of the soil to store C; we list them elsewhere (Viscarra Rossel *et al.*, 2024). Among the most recent are Georgiou *et al.* (2022); they estimated the stocks of MAOC and maximum storage capacity of the soil at 1044 sites around the world by fitting a quantile regression to the data and treating the upper 95% bound on the regression as the maximum capacities of the soil to store MAOC. Boundary lines and quantile methods are undoubtedly better than ordinary least-squares regression for finding the storage capacities of the soil. They do not estimate the maxima, however, because they fit through data, and there are always values of MAOC that lie above the fitted upper bounds.

The alternative which we believe serves to determine the maxima is to fit frontier lines. It is a technique which as far we know has not been used by soil scientists before. We illustrate its application with data from Australia.

Data and their frontier lines

The data that we (Viscarra Rossel *et al.*, 2024) have recently rigorously analysed and to which we have fitted frontier lines comprise estimated stocks of MAOC (in t ha^{-1}) and proportions of sand, silt and clay in the topsoil (0–30 cm) at 5089 sites. These are essentially the data used by Viscarra Rossel *et al.* (2019) to derive understanding of the composition of organic carbon of Australian soil.

Frontier-line analysis

The frequency distribution of the MAOC is strongly positively skewed. To stabilize the variances for statistical analysis we transformed the estimates to common logarithms, though for illustration we graph the results on the original scale.

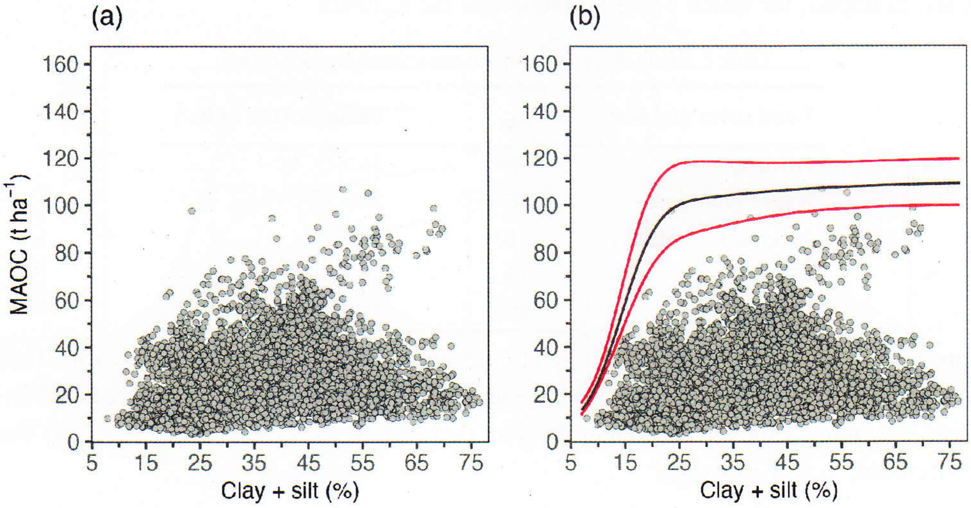

Figure 1. MAOC plotted against the percentage of clay+silt: (a) simply showing the data; (b) with the fitted frontier line in black and the 95% confidence bounds in red.

Figure 1(a) shows the MAOC plotted against the percentage of clay+silt. Clearly, there is a wide range of MAOC for any give percentage of clay+silt. The lower bound on the scatter appears to be approximately linear for the range 25% to 75% clay+silt. The apparent upper bound is certainly not linear: it increases sharply from its value at about 10% clay+silt, and then its gradient decreases steadily until it is almost negligible. This upper bound connects the maximum values of the MAOC in the data, and we can regard it as representing the potential carbon storage capacity of the soil over the range of percentage clay+silt. Finding a mathematical expression for the bound is problematic. To make sense of the physical chemistry of carbon stabilization we want a line that is smooth, monotonic non-decreasing and ideally differentiable. The solution to the problem lies in economic theory and practice where production outputs are related to inputs. Economists aim to find the most efficient practices and companies by fitting frontier lines to data (Parmeter & Racine, 2013). By analogy, our aim is to estimate the soil's maximum storage capacity for MAOC for any given proportion of clay+silt.

Several forms of frontier-line analysis have been proposed. The details are complex and are described by Parmeter & Racine (2013). We have chosen the smooth non-parametric analysis with the above desirable qualities as implemented in the R library SNFA (McKenzie, 2022). The method finds a locally weighted average of the non-linear relation between $\log_{10}$MAOC, the dependent variable, and the percentage of clay+silt as predictor. It does so with a smoothing kernel and optimal weights determined for a Nadaraya–Watson estimator. To ensure that the estimated frontier lines were robust we took 100 bootstrap samples, fitted a frontier line to each in turn and computed the averages of the lines to obtain our final frontier estimates. This also enabled us to place 95% bounds on the lines.

Frontier-line analysis

Selected results

We have fitted frontier lines to the data for all 5089 soil samples, to subsets for various forms of land cover, and separately for all classes of the Australian Soil Classification (ASC) (Isbell, 2016). Here we present a few examples, for which Table 1 summarizes the statistics.

Table 1 Mean stocks of mineral-associated organic carbon

Land cover and Soil	N_{obs}	Mean MAOC / t ha^{-1}
All data	5089	26.2
Native grassland	876	19.9
Improved grassland	2420	31.5
Vertosols	829	21.0
Chromosols	509	34.3

In Figure 1(b) we show the frontier line fitted to the whole set of data. Figure 2 shows the frontier lines for MAOC in (a) native grassland and alongside it (b) shows the frontier line for MAOC in improved pastures. Figure 3 shows the frontier lines for two widespread classes of the ASC, (a) Vertosol and (b) Chromosol.

All five graphs have the same general form: an initial steep rise in the frontier lines to 20–25% clay+silt, a fairly tight curve for clay+silt in the range approximately 25 to 35%, and thereafter a gentle increase, or for the Vertosol, Figure 3(a), no further increase.

Interpretation

What should we infer from these results? Clearly the maximum MAOC does not increase linearly with increases over the whole range of the fine fraction. Our interpretation is that in coarse-textured soil containing less than ≈20% clay+silt, i.e. in the range within which the relation appears to be linear, the mineral surfaces are saturated with organic C. In contrast, once the clay+silt fraction exceeds 35% the mineral surfaces are no longer saturated. The reason, we believe, is that there is not enough organic C in the soil to be sequestered in this way. There is too little vegetation to produce the organic residues to decompose to MAOC. There are two reasons for that. One is that even in the most favourable conditions of ample soil water and plant nutrients photosynthesis limits plant production, as Janzen *et al.* (2022) remark. Further, Powlson *et al.* (2022) point out that arable cropping leaves the ground bare for some time, and so even less organic matter is produced than under natural systems. The second reason is that dry weather, shortage of plant nutrients and other soil conditions such as strong acidity, salinity and alkalinity seriously stunt plant growth.

The latter constraint can to some extent be alleviated by land management: by irrigation, the application of fertilizers, by liming to counter acidity and gypsum to limit the effects of salt in the soil. The contrast between the native grassland and the improved pasture in Australia, displayed in Figure 2, illustrates what can be achieved. There is more MAOC in the soil of the improved pasture than in the soil of the native grassland. Fertilizers have been applied, and legumes such as clover have been incorporated in the swards to produce more plant growth. Perhaps surprisingly, the frontier lines are little different. There are evidently local patches of relatively fertile soil in otherwise oligotrophic grassland. There plant growth matches that in the improved pasture, and so roughly the same amounts of MAOC are available to give similar maxima on the mineral surfaces.

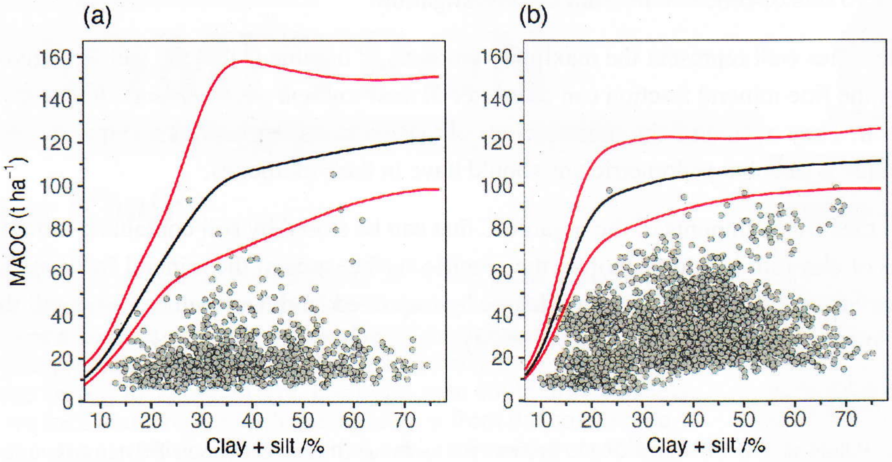

Figure 2. Frontier lines in black and their 95% confidence bounds in red fitted to MAOC against the percentage of clay+silt: (a) for native grassland; (b) for improved pasture.

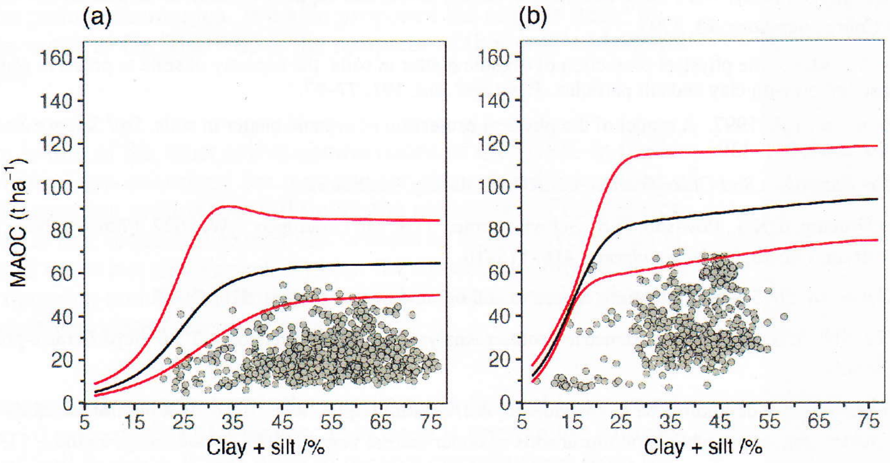

Figure 3. Frontier lines in black and their 95% confidence bounds in red fitted to MAOC against the percentage of clay+silt: (a) for Vertosols; (b) for Chromosols.

Perhaps even more surprising is the graph for the Vertosol, Figure 3(a). Contrast it with the graph for the Chromosol, Figure 3(b), which is a fairly typical for example of the relations between MAOC and the fine fraction. The samples of the Vertosol have the largest proportions of clay+silt, and one might expect them to store the most C. In fact they do not; they store almost the least, and certainly their maxima on the frontier line are the smallest of all the soil types recorded. The reason is that they occur in the arid and semi-arid parts of Australia where the climate severely restricts plant growth.

Conclusion

We may draw two sets of conclusions from the investigation.

1. The frontier lines well represent the maximum amounts of organic C that the soil with given proportions of the fine mineral fraction can sequester *in their current environment, climate and land management*. They overcome the shortcomings of least-squares regressions and quantile estimates. The technique is one that pedometricians should have in their toolboxes.

2. The actual maximum amounts of the organic C that can be stored by soil containing more than about 20% of clay+silt is limited, not by the specific surface area of the mineral fraction, but largely by the environment and only to small degree by improved land management—we call these their *attainable maxima* (Viscarra Rossel *et al.*, 2024).

References

Basile-Doelsch, I., Balesdent, J. & Pellerin, S. 2020. Reviews and syntheses: the mechanisms underlying carbon storage in soil. *Biogeosciences*, **17**, 5223–5242.

Feng, W., Plante, A.F. & Six, J. 2013. Improving estimates of maximal organic carbon stabilization by fine soil particles. *Biogeochemistry*, **112**, 81–93.

Georgiou, K., Jackson, R.B., Vindušková, O., Abramoff, R.Z., Ahlström, A., Feng, W., Harden, J.W., Pellegrini, A.F.A., Polley, H.W., Soong, J.L., Riley, W.J., Torn, M.S., 2022. Global stocks and capacity of mineral-associated soil organic carbon. *Nature Communications*, **13**, 3797.

Hassink, J. 1997. A model of the physical protection of organic matter in soils: the capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil*, **191**, 77–87.

Hassink, J. & Whitmore, A.P. 1997. A model of the physical protection of organic matter in soils. *Soil Science Society of America Journal*, **61**, 131–139.

Isbell, R. 2016. *The Australian Soil Classification*. CSIRO Publishing, Melbourne.

Janzen, H.H., van Groenigen, K.J., Powlson, D.S., Schwinghamer, T. & van Groenigen, J.W. 2022. Photosynthetic limits on carbon sequestration in croplands. *Geoderma*, **416**, 115810.

Lehmann, J. & Kleber, M. 2015. The contentious nature of soil organic matter. Nature, **528**, 60–68.

McKenzie, T. 2022. SNFA: Smooth Non-Parametric Frontier Analysis. R package version ≥ 3.5.0. https://cran.r-project.org/web/packages/snfa

Powlson, D.S., Poulton, P.R., Glendining, M.J., Macdonald, A.J. & Goulding, K.W.T. 2022. Is it possible to attain the same soil organic matter content in arable agricultural soils as under natural vegetation? *Outlook on Agriculture*, **51**, 91–104.

Six, J., Conant, R.T., Paul, E.A. & Paustian, K. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and Soil*, **241**, 155–176.

Viscarra Rossel, R.A., Webster, R., Zhang, M., Shen, Z., Dixon, K., Wang, Y.-P. & Walden, L. 2024. How much organic carbon could the soil store? The carbon sequestration potential of Australian soil. *Global Change Biology*, **30**, e17053.

Viscarra Rossel, R.A., Lee, J., Behrens, T., Luo, Z., Baldock, J. & Richards, A. 2019. Continental-scale soil carbon composition and vulnerability modulated by regional environmental controls. *Nature Geoscience*, **12**, 547–552.

West, T.O. & Six, J. 2007. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. *Climatic Change*, **80**, 25–41.