PNNL-35030

# Investigating carbon stabilization in soils via mineral adsorption

## What are we missing when we define mineral associated organic matter.

September 2023

Qian Zhao
Odeta Qafoku,
Kenton Rod

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Richland, Washington 99354

# Abstract

Understanding carbon (C) fluxes released from soil to atmosphere is critical to regulating global climate change. Soil minerals play a crucial role in stabilizing C, based on recent studies which have found that mineral associated C can be stored in soils for decades to centuries longer than non-mineral associated C. We aim to maximize C sequestration via mineral adsorption in soils. To achieve this objective, it is important to understand the potential impacts of C stabilization via adsorption to mineral surfaces. Particularly, investigating the quantitative impacts of C sorption to minerals is novel to understanding and implementing multi-scale biogeochemical processes of C stabilization in soils. We will conduct a literature review on potential impacts of C sorption to minerals, thereby contributing to the net C storage in soils. Our findings will allow us to quantitatively understand soil C changes and durability at molecular and ecosystem scales, fulfilling existing scientific gaps in the community as well as interests of sponsors, such as DOE-BER.

# Summary

This project provides insights into the role of minerals on soil carbon (C) storage, sequestration, and contribution to the global C cycle. The outcomes of this study demonstrated how mineral adsorption processes might enhance C storage in terrestrial ecosystems. We have conducted an outline of a manuscript that focuses on the diverge quantification methods of mineral associated organic matter (MAOM) pool in soil could lead to an uncertain estimation of global mineral associated C stock in models. Meanwhile, we also build up a body of literatures as well as a dataset of MAOM-C stock and the fraction of MAOM-C to total soil organic carbon (SOC) across different ecosystems from literatures. Along with MAOM pool size data, this dataset also includes site metadata, including mean annual temperature (MAT), mean annual precipitation (MAP), soil moisture, soil pH, etc. We are continuously building this dataset by synthesize data from literatures. Information from this LDRD project will be used to develop a literature review manuscript and potential DOE BER proposals.

# Acknowledgments

This research was supported by the **EBSD Mission Seed**, under the Laboratory Directed Research and Development (LDRD) Program at Pacific Northwest National Laboratory (PNNL). PNNL is a multi-program national laboratory operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830.

# Acronyms and Abbreviations

soil organic matter (SOM)
mineral associated organic matter (MAOM)
carbon (C)
soil organic carbon (SOC)
mean annual temperature (MAT)
mean annual precipitation (MAP)

# Contents

# Figures

# Tables

# 1.0 Introduction

Understanding carbon (C) fluxes released from soil to atmosphere is critical to regulating global climate change. Soil minerals play a crucial role in stabilizing C, based on recent studies which have found that mineral associated C can be stored in soils for decades to centuries longer than non-mineral associated C (Lützow et al 2006, Mikutta et al. 2019, Schmidt et al. 2011). For example, microbial-derived C can be stabilized in soil over years through adsorption to amorphous Fe hydroxides (e.g., ferrihydrite), Al oxides, and Ca-bearing minerals (e.g., calcite), due to their high surface areas, the prevalence of surface hydroxyl groups, and bridging capacities. This project probes the impact of organo-mineral and microbe-mineral interactions on C assimilation and protection in soil to guide soil C sequestration. Thus, our findings allow us to quantitatively understand the persistent soil C that associates with soil minerals at molecular and ecosystem scales, fulfilling existing scientific gaps in the community as well as interests of sponsors, such as the U.S. Department of Energy (DOE)-Biological and Environmental Research (BER). This effort aligns well with the directorate objectives of PNNL Earth and Biological Sciences Directorate (EBSD) on Durable Soil Carbon Storage for Atmospheric Carbon Dioxide Removal.

# 2.0 Current understanding of C budget in the MAOM pools

Second State of the Carbon Cycle Report (SOCCR2) has identified the soil C stock in top 1m soil from North American is 400 PgC (Lajtha et al. 2018). Estimates of global soil organic carbon (SOC) stocks vary from 684 to 724 Pg in the surface 0.3 m (Batjes 1996), the Intergovernmental Panel of Climate Change (IPCC) standard sampling depth (Aalde et al. 2006), and (Sokol et al., 2019)1462 to 1548 Pg in the top meter and 2,060 ± 220 Pg C to 2 m (Batjes 1996). Diverse C inputs result in heterogeneity of the SOM pool. Studies showed both microbial-derived C and plant-derived C are major sources of mineral-associated organi matter (MAOM). The formation and accumulation of SOC are primarily derived from plant- and microbial C (Angst et al., 2021; Ma et al., 2018; Sokol & Bradford, 2019). While the significance of plant residues to SOM persistence is well recognized due to the slow cycling of plant debris (e.g., lignin and phenols) (Angst et al., 2021; Schmidt et al., 2011), the importance of microbial products and residues (hereafter ‘microbial necromass’) in the slowly cycling SOC pool has only recently been appreciated (Fan et al., 2021; Kallenbach et al., 2016; Liang et al., 2019; Wang et al., 2021; Wu et al., 2023). Microbial necromass contributes to 33-62% of total SOC in various types of ecosystems (measured as amino sugars) (Liang et al., 2019; Wang et al., 2021). However, the long-term persistence of microbial necromass in the SOM pool depends on the associations with soil minerals (Kästner et al. 2021), even though the specific necromass-mineral interactive mechanisms are still unclear.

The estimations of MAOM pool in soils have been largely studied in the last decade. Studies showed the proportion of MAOM to total SOM varies significantly, ranging from 25%-90% (Table 1). The proportion of the MAOM pool varies across different ecosystem types with 60% in forest, 72% in grassland, and 79% in cropland. Lugato et al (2021) did size fractionation on 400 soils and quantified MAOM with a machine learning (ML) approach.  The model was then used to predict the C and N in the MAOM fraction for the 9,229. The average mineral associated C stocks in European grasslands and forest soils varied between 15 and 38 g C $kg^{-1}$ soil (Figure 1).

Table 1. Percentage of Fe-OC to total OC in natural soil and sediment environments.

| Site or ecosystem type | Proportion of MAOM to total SOM | Methods | Reference |
|---|---|---|---|
| 14 Forest soils in the USA | 0.6-57.8% (average 37.8%) | Dithionite extraction | Zhao et al. 2016 |
| 4 wetland soils in China | 7-91% | Size and density | Liu et al. 2023 |
| Mangrove soils in the Philippines | ~15 % | Dithionite extraction | Dicen et al., 2019 |
| Arable soils in China | 6.2–31.2 %<br>Agriculture soils – grassland and arid | Dithionite extraction | Wan et al., 2019 |
| 10 Peatlands in China | 1.64–5.94 % | Dithionite extraction | Huang et al., 2021a |
| 186 grassland and forest soils in European | 25-85% (60% in forest, 72% in grassland, 79% in cropland) | Size | Cotrufo et al., 2019 |
| 1451 all ecosystem types | 65% | Size | Georgiou et al. 2022 |

| | | | |
|---|---|---|---|
| Grasslands | | | |
| Tibetan alpine grasslands in China | 15.8 ± 12.0 % | Dithionite extraction | Fang et al., 2019 |
| Meadow soils in the Qinghai-Tibetan Plateau | 4.1–25.6 % | Dithionite extraction | Mu et al., 2020 |
| Sediments | | | |
| Marine sediments in Mexican and Indian margins, the Southern Ocean, the St. Lawrence estuary and gulf, and the Black Sea | 21.5 ± 8.6 % | Dithionite extraction | Lalonde et al., 2012 |
| East China Sea sediments | 2.77–31.5 % | Dithionite extraction | Ma et al., 2018 |
| Changjiang estuary sediments in China | 7.4 ± 3.5 % | Dithionite extraction | Zhao et al., 2018 |
| Wax Lake Delta sediments in the USA | ~15.0 % | Dithionite extraction | Shields et al., 2016 |
| Sediments in Eurasian Arctic Shelf | 0.5-22% | Dithionite extraction | Salvadó et al., 2015 |
| Saanich, Arabian Sea, Mexican margin, and St. Lawrence estuary | 25.7–62.6 % | Dithionite extraction | Barber et al., 2017 |
| Permafrost | | | |
| Permafrost soils in northern Alaska | 13.68±2.31 % | Dithionite extraction | Joss et al., 2022 |
| Permafrost soils in the Qinghai-Tibetan Plateau | 19.5 ± 12.3 % | Dithionite extraction | Mu et al., 2016 |
| Discontinuous permafrost region in Sweden | 9.9–14.8% | Dithionite extraction | Patzner et al., 2020 |

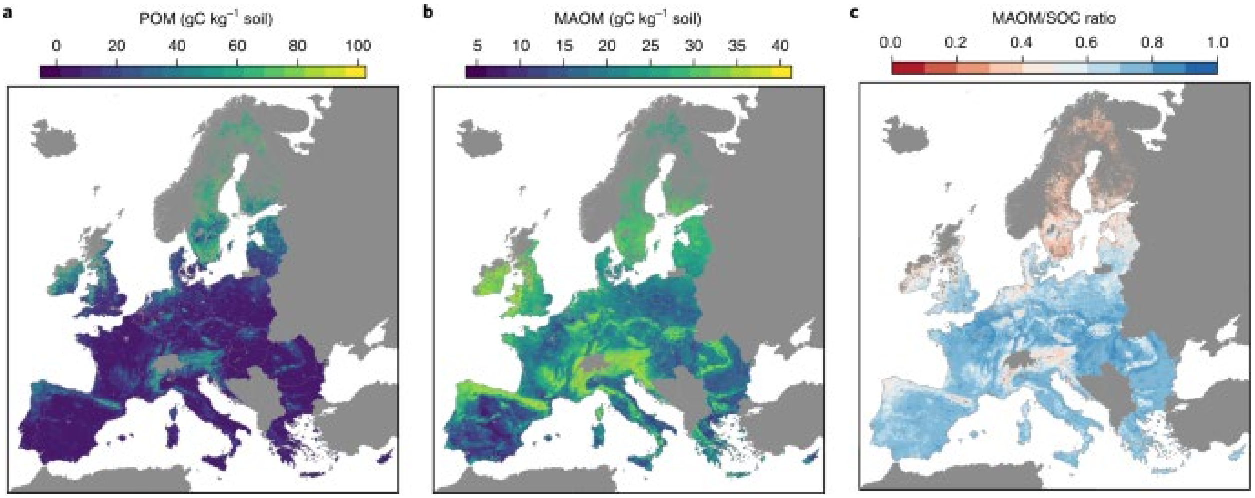


Figure 1. **a**–**c**, Carbon content (gC kg$^{-1}$ soil) in POM (**a**) and MAOM (**b**), and ratio between MAOM carbon and total SOC (**c**) from Lugato et al (2021).

# 3.0 Different parameters impact on MAOM pool size

## 3.1 Quantification methods

There are diverse methodologies for quantifying the MAOM pool in soil. Abramoff et al (2021) compiled 402 laboratory sorption experiments and quantified, for the first time, the sorption capacity of mineral soils to DOC for six soil orders. They find that mid- and low-latitude soils and subsoils have a greater capacity to store DOC by sorption compared to high-latitude soils and topsoils. The global additional DOC sorption is estimated to be 107 ± 13 Pg C to 1 m depth, projecting a 7% increase in the existing total carbon stock.

Another two major MAOM quantification methods are chemical extraction and size fractionation. Chemical extraction includes sodium pyrophosphate, sodium dithionite, oxalate acid, and HCl. These solvents target to dissolve specific minerals from soils, thereby releasing OC that associates with these minerals. Among these solvents, sodium dithionite has been widely used to quantify mineral bound OC in addition to quantify extracted Fe, Al, and other metals (Lalonde et al 2012, Zhao et al. 2016). Meanwhile, size fractionation separates the MAOM pool by less than 53μm particle size. This approach is easy and high throughput so that can be applied to a large number of sample sites. Dithionite extraction could underestimate the MAOM pool as it only extracts a portion of minerals from soils but not all, whereas size fractionation most likely overestimates the pool as there could be non-mineral bound C within particles less than 53μm. These different quantification approaches result in large variations in estimating the MAOM pool size in soils. For instance, dithionite extraction estimates about 25% of total SOC as MAOM C, whereas size fractionation estimates an average of 65% of total SOC as MAOM C pool. Such different estimations on MAOM pool result in diverge projections in continental scale MAOM pool. Given the total C stock, we estimated 60-260PgC in the MAOM pool in top 1m soil in North America. This diverge estimations on the MAOM pool size will impact on the accuracy of C cycling predictions by biogeochemical process-based models.

## 3.2 Other factors

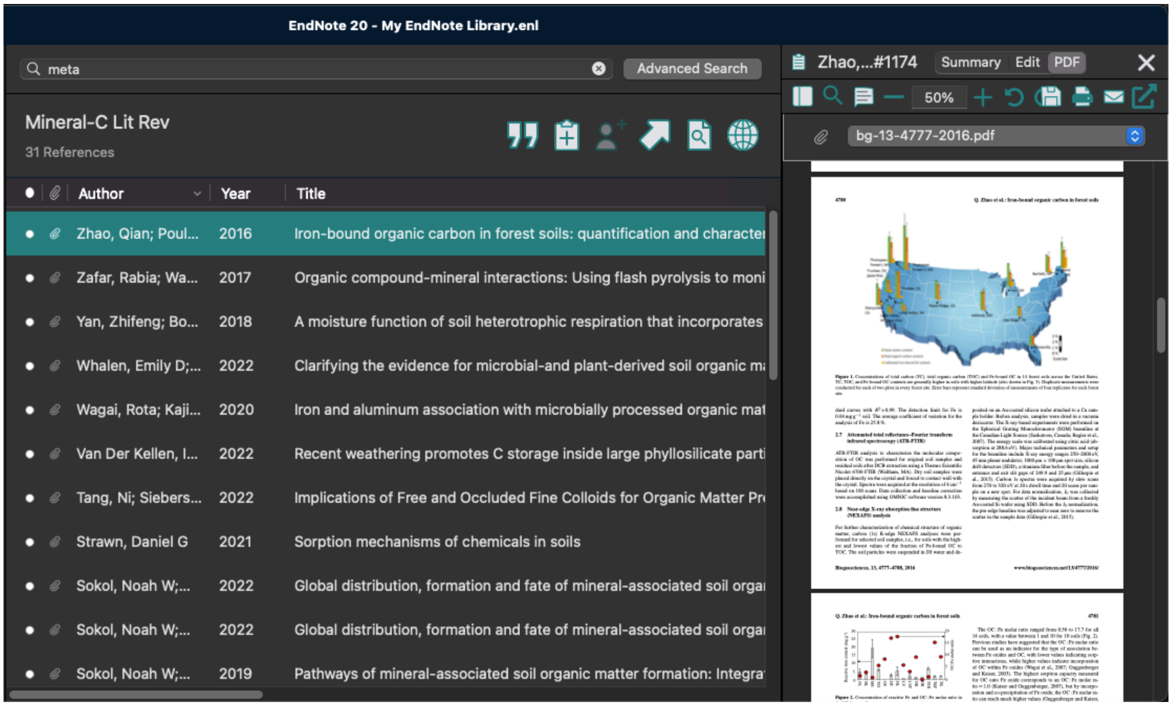
MAOC to reactive Fe ratios (OC:Fe) can indicate the mechanism of Fe-OC interactions. A mass ratio over 0.22 is indicative for Fe-OC associations predominantly formed by co-precipitation or chelation (Wagai and Mayer, 2007). Below an OC:Fe mass ratio of 0.22, OC is mainly assumed to be sorbed onto Fe minerals. Around 86% of the permafrost samples exceed an OC:Fe mass ratios of 0.22 (Joss et al. 2022). Other soil parameters, such as the bulk density, pH, and moisture content, were correlated with MAOM-C (Mu et al. 2022). Soil with higher pH results in higher fraction of MAOM-C, whereas higher soil moisture contents result in lower MAOM-C due to high microbial activities and consumption of available C.

## 4.0 Implications and discussion on C cycling modeling

Ungeneralizable MAOM fractionation approach results in a large uncertainty to the estimation of MAOM pool, thereby impacting the estimation of C persistence in soil. Consensus on the experimental method of defining MAOM pool is necessary to the soil community. The lab-scale quantification of C storage via minerals is applicable to ecosystem scale and global scale. Soil mineralogy is a major factor to predict ecosystem-C behavior in terms of microbe-mineral interactions and nutrient-mineral interactions. The quantitative data from this project can be incorporated into process-based models, such as Earth and Environmental Systems (ESS), and/or artificial intelligence and machine learning (AI/ML) based models to improve model prediction on C storage by considering organo-mineral protection.

# 5.0 Conclusion

This project provides insights into the role of minerals on soil carbon (C) storage, sequestration, and contribution to the global C cycle. The outcomes of this study demonstrated how mineral adsorption processes might enhance C storage in terrestrial ecosystems. We have conducted an outline of a manuscript that focuses on the diverge quantification methods of MAOM pool in soil could lead to an uncertain estimation of global mineral associated C stock in models. Meanwhile, we also build up a body of literatures (Figure 2) as well as a dataset of MAOM-C stock and the fraction of MAOM-C to total SOC across different ecosystems from literatures (Appendix A). Along with MAOM pool size data, this dataset also includes site metadata, including MAT, MAP, soil moisture, soil pH, etc. We are continuously building this dataset by synthesize data from literatures. Information from this LDRD project will be used to develop a literature review manuscript and potential DOE BER proposals.



| Author | Year | Title |
|---|---|---|
| Zhao, Qian; Poul... | 2016 | Iron-bound organic carbon in forest soils: quantification and characte |
| Zafar, Rabia; Wa... | 2017 | Organic compound-mineral interactions: Using flash pyrolysis to moni |
| Yan, Zhifeng; Bo... | 2018 | A moisture function of soil heterotrophic respiration that incorporates |
| Whalen, Emily D;... | 2022 | Clarifying the evidence for microbial-and plant-derived soil organic m |
| Wagai, Rota; Kaji... | 2020 | Iron and aluminum association with microbially processed organic mat |
| Van Der Kellen, I... | 2022 | Recent weathering promotes C storage inside large phyllosilicate parti |
| Tang, Ni; Siebers... | 2022 | Implications of Free and Occluded Fine Colloids for Organic Matter Pr |
| Strawn, Daniel G | 2021 | Sorption mechanisms of chemicals in soils |
| Sokol, Noah W;... | 2022 | Global distribution, formation and fate of mineral-associated soil orga |
| Sokol, Noah W;... | 2022 | Global distribution, formation and fate of mineral-associated soil orga |
| Sokol, Noah W;... | 2019 | Pathways of mineral-associated soil organic matter formation: Integra |

Figure 2. The list of literatures of quantifying mineral-associated OC in soil.

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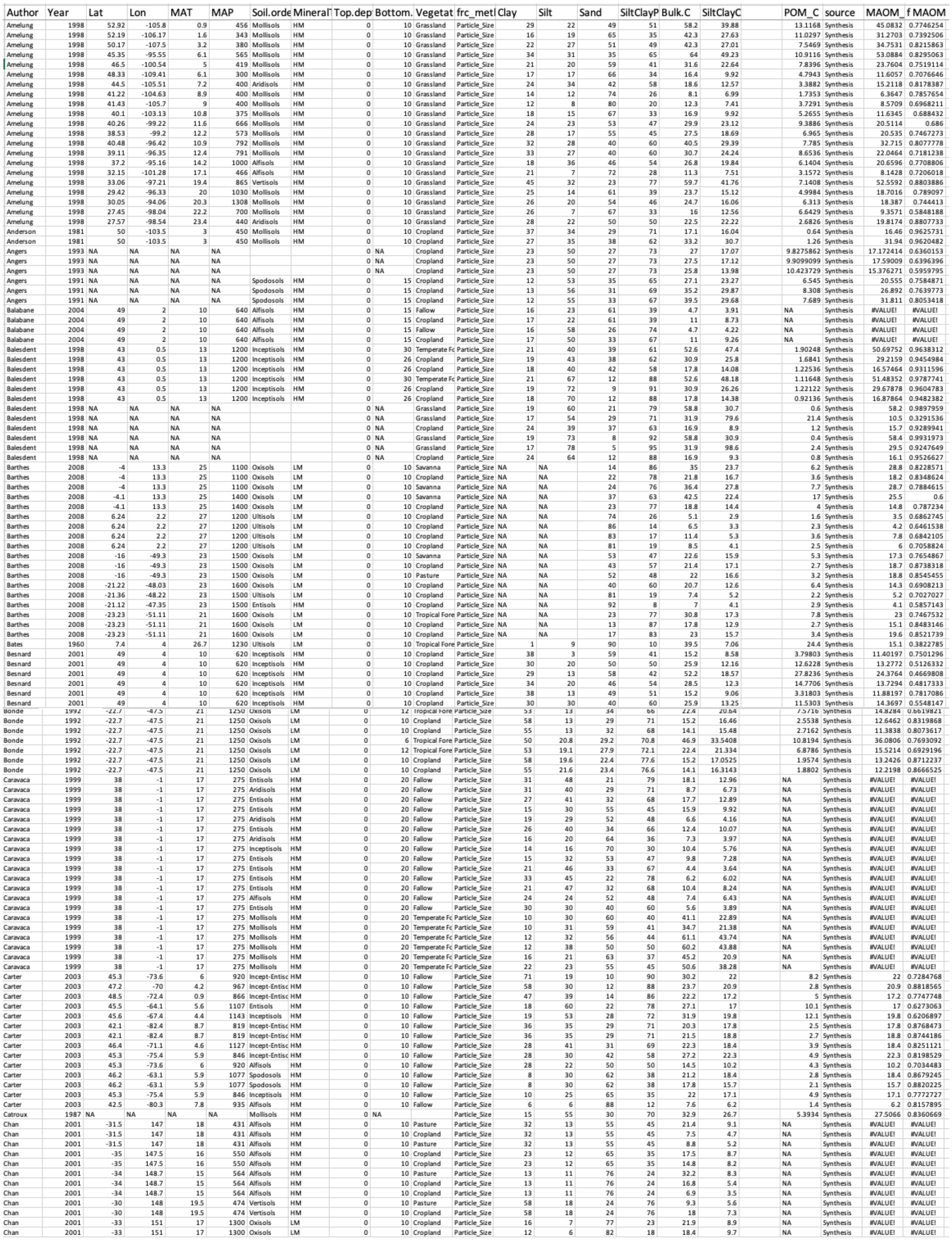
# Appendix A – A working dataset of MAOM-C



| Author | Year | Lat | Lon | MAT | MAP | Soil.orde | MineralT | Top.dep | Bottom. | Vegetat | frc_metl | Clay | Silt | Sand | SiltClayP | Bulk.C | SiltClayC | | POM_C | source | MAOM_ | f MAOM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Amelung | 1998 | 52.92 | -105.8 | 0.9 | 456 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 29 | 22 | 49 | 51 | 58.2 | 39.88 | | 13.1168 | Synthesis | 45.0832 | 0.7746254 |
| Amelung | 1998 | 52.19 | -106.17 | 1.6 | 343 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 16 | 19 | 65 | 35 | 42.3 | 27.63 | | 11.0297 | Synthesis | 31.2703 | 0.7392506 |
| Amelung | 1998 | 50.17 | -107.5 | 3.2 | 380 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 22 | 27 | 51 | 49 | 42.3 | 27.01 | | 7.5469 | Synthesis | 34.7531 | 0.8215863 |
| Amelung | 1998 | 45.35 | -95.55 | 6.1 | 565 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 34 | 31 | 35 | 65 | 64 | 49.23 | | 10.9116 | Synthesis | 53.0884 | 0.8295063 |
| Amelung | 1998 | 46.5 | -100.54 | 5 | 419 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 21 | 20 | 59 | 41 | 31.6 | 22.64 | | 7.8396 | Synthesis | 23.7604 | 0.7519114 |
| Amelung | 1998 | 48.33 | -109.41 | 6.1 | 300 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 17 | 17 | 66 | 34 | 16.4 | 9.92 | | 4.7943 | Synthesis | 11.6057 | 0.7076646 |
| Amelung | 1998 | 44.5 | -105.51 | 7.2 | 400 | Aridisols | HM | 0 | 10 | Grassland | Particle_Size | 24 | 34 | 42 | 58 | 18.6 | 12.57 | | 3.3882 | Synthesis | 15.2118 | 0.8178387 |
| Amelung | 1998 | 41.22 | -104.63 | 8.9 | 400 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 14 | 12 | 74 | 26 | 8.1 | 6.99 | | 1.7353 | Synthesis | 6.3647 | 0.7857654 |
| Amelung | 1998 | 41.43 | -105.7 | 9 | 400 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 12 | 8 | 80 | 20 | 12.3 | 7.41 | | 3.7291 | Synthesis | 8.5709 | 0.6968211 |
| Amelung | 1998 | 40.1 | -103.13 | 10.8 | 375 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 18 | 15 | 67 | 33 | 16.9 | 9.92 | | 5.2655 | Synthesis | 11.6345 | 0.688432 |
| Amelung | 1998 | 40.26 | -99.22 | 11.6 | 666 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 24 | 23 | 53 | 47 | 29.9 | 23.12 | | 9.3886 | Synthesis | 20.5114 | 0.686 |
| Amelung | 1998 | 38.53 | -99.2 | 12.2 | 573 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 28 | 17 | 55 | 45 | 27.5 | 18.69 | | 6.965 | Synthesis | 20.535 | 0.7467273 |
| Amelung | 1998 | 40.48 | -96.42 | 10.9 | 792 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 32 | 28 | 40 | 60 | 40.5 | 29.39 | | 7.785 | Synthesis | 32.715 | 0.8077778 |
| Amelung | 1998 | 39.11 | -96.35 | 12.4 | 791 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 33 | 27 | 40 | 60 | 30.7 | 24.24 | | 8.6536 | Synthesis | 22.0464 | 0.7181238 |
| Amelung | 1998 | 37.2 | -95.16 | 14.2 | 1000 | Alfisols | HM | 0 | 10 | Grassland | Particle_Size | 18 | 36 | 46 | 54 | 26.8 | 19.84 | | 6.1404 | Synthesis | 20.6596 | 0.7708806 |
| Amelung | 1998 | 32.15 | -101.28 | 17.1 | 466 | Alfisols | HM | 0 | 10 | Grassland | Particle_Size | 21 | 7 | 72 | 28 | 11.3 | 7.51 | | 3.1572 | Synthesis | 8.1428 | 0.7206018 |
| Amelung | 1998 | 33.06 | -97.21 | 19.4 | 865 | Vertisols | HM | 0 | 10 | Grassland | Particle_Size | 45 | 32 | 23 | 77 | 59.7 | 41.76 | | 7.1408 | Synthesis | 52.5592 | 0.8803886 |
| Amelung | 1998 | 29.42 | -96.33 | 20 | 1030 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 25 | 14 | 61 | 39 | 23.7 | 15.12 | | 4.9984 | Synthesis | 18.7016 | 0.789097 |
| Amelung | 1998 | 30.05 | -94.06 | 20.3 | 1308 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 26 | 20 | 54 | 46 | 24.7 | 16.06 | | 6.313 | Synthesis | 18.387 | 0.744413 |
| Amelung | 1998 | 27.45 | -98.04 | 22.2 | 700 | Mollisols | HM | 0 | 10 | Grassland | Particle_Size | 26 | 7 | 67 | 33 | 16 | 12.56 | | 6.6429 | Synthesis | 9.3571 | 0.5848188 |
| Amelung | 1998 | 27.57 | -98.54 | 23.4 | 440 | Aridisols | HM | 0 | 10 | Grassland | Particle_Size | 28 | 22 | 50 | 50 | 22.5 | 22.22 | | 2.6826 | Synthesis | 19.8174 | 0.8807733 |
| Anderson | 1981 | 50 | -103.5 | 3 | 450 | Mollisols | HM | 0 | 10 | Cropland | Particle_Size | 37 | 34 | 29 | 71 | 17.1 | 16.04 | | 0.64 | Synthesis | 16.46 | 0.9625731 |
| Anderson | 1981 | 50 | -103.5 | 3 | 450 | Mollisols | HM | 0 | 10 | Cropland | Particle_Size | 27 | 35 | 38 | 62 | 33.2 | 30.7 | | 1.26 | Synthesis | 31.94 | 0.9620482 |
| Angers | 1993 | NA | NA | NA | NA | | | 0 | NA | Cropland | Particle_Size | 23 | 50 | 27 | 73 | 27 | 17.07 | | 9.8275862 | Synthesis | 17.172414 | 0.6360153 |
| Angers | 1993 | NA | NA | NA | NA | | | 0 | NA | Cropland | Particle_Size | 23 | 50 | 27 | 73 | 27.5 | 17.12 | | 9.9099099 | Synthesis | 17.59009 | 0.6396396 |
| Angers | 1993 | NA | NA | NA | NA | | | 0 | NA | Cropland | Particle_Size | 23 | 50 | 27 | 73 | 25.8 | 13.98 | | 10.423729 | Synthesis | 15.376271 | 0.5959795 |
| Angers | 1991 | NA | NA | NA | NA | Spodosols | HM | 0 | 15 | Cropland | Particle_Size | 12 | 53 | 35 | 65 | 27.1 | 23.27 | | 6.545 | Synthesis | 20.555 | 0.7584871 |
| Angers | 1991 | NA | NA | NA | NA | Spodosols | HM | 0 | 15 | Cropland | Particle_Size | 13 | 56 | 31 | 69 | 35.2 | 29.87 | | 8.308 | Synthesis | 26.892 | 0.7639773 |
| Angers | 1991 | NA | NA | NA | NA | Spodosols | HM | 0 | 15 | Cropland | Particle_Size | 12 | 55 | 33 | 67 | 39.5 | 29.68 | | 7.689 | Synthesis | 31.811 | 0.8053418 |
| Balabane | 2004 | 49 | 2 | 10 | 640 | Alfisols | HM | 0 | 15 | Fallow | Particle_Size | 16 | 23 | 61 | 39 | 4.7 | 3.91 | | NA | Synthesis | #VALUE! | #VALUE! |
| Balabane | 2004 | 49 | 2 | 10 | 640 | Alfisols | HM | 0 | 15 | Cropland | Particle_Size | 17 | 22 | 61 | 39 | 11 | 8.73 | | NA | Synthesis | #VALUE! | #VALUE! |
| Balabane | 2004 | 49 | 2 | 10 | 640 | Alfisols | HM | 0 | 15 | Fallow | Particle_Size | 16 | 58 | 26 | 74 | 4.7 | 4.22 | | NA | Synthesis | #VALUE! | #VALUE! |
| Balabane | 2004 | 49 | 2 | 10 | 640 | Alfisols | HM | 0 | 15 | Cropland | Particle_Size | 17 | 50 | 33 | 67 | 11 | 9.26 | | NA | Synthesis | #VALUE! | #VALUE! |
| Balesdent | 1998 | 43 | 0.5 | 13 | 1200 | Inceptisols | HM | 0 | 30 | Temperate Fc | Particle_Size | 21 | 40 | 39 | 61 | 52.6 | 47.4 | | 1.90248 | Synthesis | 50.69752 | 0.9638312 |
| Balesdent | 1998 | 43 | 0.5 | 13 | 1200 | Inceptisols | HM | 0 | 26 | Cropland | Particle_Size | 19 | 43 | 38 | 62 | 30.9 | 25.8 | | 1.6841 | Synthesis | 29.2159 | 0.9454984 |
| Balesdent | 1998 | 43 | 0.5 | 13 | 1200 | Inceptisols | HM | 0 | 26 | Cropland | Particle_Size | 18 | 40 | 42 | 58 | 17.8 | 14.08 | | 1.22536 | Synthesis | 16.57464 | 0.9311596 |
| Balesdent | 1998 | 43 | 0.5 | 13 | 1200 | Inceptisols | HM | 0 | 30 | Temperate Fc | Particle_Size | 21 | 67 | 12 | 88 | 52.6 | 48.18 | | 1.11648 | Synthesis | 51.48352 | 0.9787741 |
| Balesdent | 1998 | 43 | 0.5 | 13 | 1200 | Inceptisols | HM | 0 | 26 | Cropland | Particle_Size | 19 | 72 | 9 | 91 | 30.9 | 26.26 | | 1.22122 | Synthesis | 29.67878 | 0.9604783 |
| Balesdent | 1998 | 43 | 0.5 | 13 | 1200 | Inceptisols | HM | 0 | 26 | Cropland | Particle_Size | 18 | 70 | 12 | 88 | 17.8 | 14.38 | | 0.92136 | Synthesis | 16.87864 | 0.9482382 |
| Balesdent | 1998 | NA | NA | NA | NA | | | 0 | NA | Grassland | Particle_Size | 19 | 60 | 21 | 79 | 58.8 | 30.7 | | 0.6 | Synthesis | 58.2 | 0.9897959 |
| Balesdent | 1998 | NA | NA | NA | NA | | | 0 | NA | Grassland | Particle_Size | 17 | 54 | 29 | 71 | 31.9 | 79.6 | | 21.4 | Synthesis | 10.5 | 0.3291536 |
| Balesdent | 1998 | NA | NA | NA | NA | | | 0 | NA | Cropland | Particle_Size | 24 | 39 | 37 | 63 | 16.9 | 8.9 | | 1.2 | Synthesis | 15.7 | 0.9289941 |
| Balesdent | 1998 | NA | NA | NA | NA | | | 0 | NA | Grassland | Particle_Size | 19 | 73 | 8 | 92 | 58.8 | 30.9 | | 0.4 | Synthesis | 58.4 | 0.9931973 |
| Balesdent | 1998 | NA | NA | NA | NA | | | 0 | NA | Grassland | Particle_Size | 17 | 78 | 5 | 95 | 31.9 | 98.6 | | 2.4 | Synthesis | 29.5 | 0.9247649 |
| Balesdent | 1998 | NA | NA | NA | NA | | | 0 | NA | Cropland | Particle_Size | 24 | 64 | 12 | 88 | 16.9 | 9.3 | | 0.8 | Synthesis | 16.1 | 0.9526627 |
| Barthes | 2008 | -4 | 13.3 | 25 | 1100 | Oxisols | LM | 0 | 10 | Savanna | Particle_Size | NA | NA | 14 | 86 | 35 | 23.7 | | 6.2 | Synthesis | 28.8 | 0.8228571 |
| Barthes | 2008 | -4 | 13.3 | 25 | 1100 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 22 | 78 | 21.8 | 16.7 | | 3.6 | Synthesis | 18.2 | 0.8348624 |
| Barthes | 2008 | -4 | 13.3 | 25 | 1100 | Oxisols | LM | 0 | 10 | Savanna | Particle_Size | NA | NA | 24 | 76 | 36.4 | 27.8 | | 7.7 | Synthesis | 28.7 | 0.7884615 |
| Barthes | 2008 | -4.1 | 13.3 | 25 | 1400 | Oxisols | LM | 0 | 10 | Savanna | Particle_Size | NA | NA | 37 | 63 | 42.5 | 22.4 | | 17 | Synthesis | 25.5 | 0.6 |
| Barthes | 2008 | -4.1 | 13.3 | 25 | 1400 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 23 | 77 | 18.8 | 14.4 | | 4 | Synthesis | 14.8 | 0.787234 |
| Barthes | 2008 | 6.24 | 2.2 | 27 | 1200 | Ultisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 74 | 26 | 5.1 | 2.9 | | 1.6 | Synthesis | 3.5 | 0.6862745 |
| Barthes | 2008 | 6.24 | 2.2 | 27 | 1200 | Ultisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 86 | 14 | 6.5 | 3.3 | | 2.3 | Synthesis | 4.2 | 0.6461538 |
| Barthes | 2008 | 6.24 | 2.2 | 27 | 1200 | Ultisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 83 | 17 | 11.4 | 5.3 | | 3.6 | Synthesis | 7.8 | 0.6842105 |
| Barthes | 2008 | 6.24 | 2.2 | 27 | 1200 | Ultisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 81 | 19 | 8.5 | 4.1 | | 2.5 | Synthesis | 6 | 0.7058824 |
| Barthes | 2008 | -16 | -49.3 | 23 | 1500 | Oxisols | LM | 0 | 10 | Savanna | Particle_Size | NA | NA | 53 | 47 | 22.6 | 15.9 | | 5.3 | Synthesis | 17.3 | 0.7654867 |
| Barthes | 2008 | -16 | -49.3 | 23 | 1500 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 43 | 57 | 21.4 | 17.1 | | 2.7 | Synthesis | 18.7 | 0.8738318 |
| Barthes | 2008 | -16 | -49.3 | 23 | 1500 | Oxisols | LM | 0 | 10 | Pasture | Particle_Size | NA | NA | 52 | 48 | 22 | 16.6 | | 3.2 | Synthesis | 18.8 | 0.8545455 |
| Barthes | 2008 | -21.22 | -48.03 | 23 | 1600 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 40 | 60 | 20.7 | 12.6 | | 6.4 | Synthesis | 14.3 | 0.6908213 |
| Barthes | 2008 | -21.36 | -48.22 | 23 | 1500 | Ultisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 81 | 19 | 7.4 | 5.2 | | 2.2 | Synthesis | 5.2 | 0.7027027 |
| Barthes | 2008 | -21.12 | -47.35 | 23 | 1500 | Entisols | HM | 0 | 10 | Cropland | Particle_Size | NA | NA | 92 | 8 | 7 | 4.1 | | 2.9 | Synthesis | 4.1 | 0.5857143 |
| Barthes | 2008 | -23.23 | -51.11 | 21 | 1600 | Oxisols | LM | 0 | 10 | Tropical Fore | Particle_Size | NA | NA | 23 | 77 | 30.8 | 17.3 | | 7.8 | Synthesis | 23 | 0.7467532 |
| Barthes | 2008 | -23.23 | -51.11 | 21 | 1600 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 13 | 87 | 17.8 | 12.9 | | 2.7 | Synthesis | 15.1 | 0.8483146 |
| Barthes | 2008 | -23.23 | -51.11 | 21 | 1600 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | NA | NA | 17 | 83 | 23 | 15.7 | | 3.4 | Synthesis | 19.6 | 0.8521739 |
| Bates | 1960 | 7.4 | 4 | 26.7 | 1230 | Ultisols | LM | 0 | 10 | Tropical Fore | Particle_Size | 1 | 9 | 90 | 10 | 39.5 | 7.06 | | 24.4 | Synthesis | 15.1 | 0.3822785 |
| Besnard | 2001 | 49 | 4 | 10 | 620 | Inceptisols | HM | 0 | 10 | Cropland | Particle_Size | 38 | 3 | 59 | 41 | 15.2 | 8.58 | | 3.79803 | Synthesis | 11.40197 | 0.7501296 |
| Besnard | 2001 | 49 | 4 | 10 | 620 | Inceptisols | HM | 0 | 10 | Cropland | Particle_Size | 30 | 20 | 50 | 50 | 25.9 | 12.16 | | 12.6228 | Synthesis | 13.2772 | 0.5126332 |
| Besnard | 2001 | 49 | 4 | 10 | 620 | Inceptisols | HM | 0 | 10 | Cropland | Particle_Size | 29 | 13 | 58 | 42 | 52.2 | 18.57 | | 27.8236 | Synthesis | 24.3764 | 0.4669808 |
| Besnard | 2001 | 49 | 4 | 10 | 620 | Inceptisols | HM | 0 | 10 | Cropland | Particle_Size | 34 | 20 | 46 | 54 | 28.5 | 12.3 | | 14.7706 | Synthesis | 13.7294 | 0.4817333 |
| Besnard | 2001 | 49 | 4 | 10 | 620 | Inceptisols | HM | 0 | 10 | Cropland | Particle_Size | 38 | 13 | 49 | 51 | 15.2 | 9.06 | | 3.31803 | Synthesis | 11.88197 | 0.7817086 |
| Besnard | 2001 | 49 | 4 | 10 | 620 | Inceptisols | HM | 0 | 10 | Cropland | Particle_Size | 30 | 30 | 40 | 60 | 25.9 | 13.25 | | 11.5303 | Synthesis | 14.3697 | 0.5548147 |
| Bonde | 1992 | -22.7 | -47.5 | 21 | 1250 | Oxisols | LM | 0 | 12 | Tropical Fore | Particle_Size | 53 | 13 | 34 | 66 | 22.4 | 20.64 | | 7.5716 | Synthesis | 14.8284 | 0.6619821 |
| Bonde | 1992 | -22.7 | -47.5 | 21 | 1250 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | 58 | 13 | 29 | 71 | 15.2 | 16.46 | | 2.5538 | Synthesis | 12.6462 | 0.8319868 |
| Bonde | 1992 | -22.7 | -47.5 | 21 | 1250 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | 55 | 13 | 32 | 68 | 14.1 | 15.48 | | 2.7162 | Synthesis | 11.3838 | 0.8073617 |
| Bonde | 1992 | -22.7 | -47.5 | 21 | 1250 | Oxisols | LM | 0 | 6 | Tropical Fore | Particle_Size | 50 | 20.8 | 29.2 | 70.8 | 46.9 | 33.5408 | | 10.8194 | Synthesis | 36.0806 | 0.7693092 |
| Bonde | 1992 | -22.7 | -47.5 | 21 | 1250 | Oxisols | LM | 0 | 12 | Tropical Fore | Particle_Size | 53 | 19.1 | 27.9 | 72.1 | 22.4 | 21.334 | | 6.8786 | Synthesis | 15.5214 | 0.6929196 |
| Bonde | 1992 | -22.7 | -47.5 | 21 | 1250 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | 58 | 19.6 | 22.4 | 77.6 | 15.2 | 17.0525 | | 1.9574 | Synthesis | 13.2426 | 0.8712237 |
| Bonde | 1992 | -22.7 | -47.5 | 21 | 1250 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | 55 | 21.6 | 23.4 | 76.6 | 14.1 | 16.3143 | | 1.8802 | Synthesis | 12.2198 | 0.8666525 |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 31 | 48 | 21 | 79 | 18.1 | 12.96 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Aridisols | HM | 0 | 20 | Fallow | Particle_Size | 31 | 40 | 29 | 71 | 8.7 | 6.73 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 27 | 41 | 32 | 68 | 17.7 | 12.89 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 15 | 30 | 55 | 45 | 15.9 | 9.92 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Aridisols | HM | 0 | 20 | Fallow | Particle_Size | 19 | 29 | 52 | 48 | 6.6 | 4.16 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 26 | 40 | 34 | 66 | 12.4 | 10.07 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Aridisols | HM | 0 | 20 | Fallow | Particle_Size | 16 | 20 | 64 | 36 | 7.3 | 3.97 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Inceptisols | HM | 0 | 20 | Fallow | Particle_Size | 14 | 16 | 70 | 30 | 10.4 | 5.76 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 15 | 32 | 53 | 47 | 9.8 | 7.28 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 21 | 46 | 33 | 67 | 4.4 | 3.64 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 33 | 45 | 22 | 78 | 6.2 | 6.02 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 21 | 47 | 32 | 68 | 10.4 | 8.24 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Alfisols | HM | 0 | 20 | Fallow | Particle_Size | 24 | 24 | 52 | 48 | 7.4 | 6.43 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Entisols | HM | 0 | 20 | Fallow | Particle_Size | 30 | 30 | 40 | 60 | 5.6 | 3.89 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Mollisols | HM | 0 | 20 | Temperate Fc | Particle_Size | 10 | 30 | 60 | 40 | 41.1 | 22.89 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Mollisols | HM | 0 | 20 | Temperate Fc | Particle_Size | 10 | 31 | 59 | 41 | 34.7 | 21.38 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Mollisols | HM | 0 | 20 | Temperate Fc | Particle_Size | 12 | 32 | 56 | 44 | 61.1 | 43.74 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Mollisols | HM | 0 | 20 | Temperate Fc | Particle_Size | 12 | 38 | 50 | 50 | 60.2 | 43.88 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Mollisols | HM | 0 | 20 | Temperate Fc | Particle_Size | 16 | 21 | 63 | 37 | 45.2 | 20.9 | | NA | Synthesis | #VALUE! | #VALUE! |
| Caravaca | 1999 | 38 | -1 | 17 | 275 | Mollisols | HM | 0 | 20 | Temperate Fc | Particle_Size | 22 | 23 | 55 | 45 | 50.6 | 38.28 | | NA | Synthesis | #VALUE! | #VALUE! |
| Carter | 2003 | 45.3 | -73.6 | 6 | 920 | Incept-Entisc | HM | 0 | 10 | Fallow | Particle_Size | 71 | 19 | 10 | 90 | 30.2 | 22 | | 8.2 | Synthesis | 22 | 0.7284768 |
| Carter | 2003 | 47.2 | -70 | 4.2 | 967 | Incept-Entisc | HM | 0 | 10 | Fallow | Particle_Size | 58 | 30 | 12 | 88 | 23.7 | 20.9 | | 2.8 | Synthesis | 20.9 | 0.8818565 |
| Carter | 2003 | 48.5 | -72.4 | 0.9 | 866 | Incept-Entisc | HM | 0 | 10 | Fallow | Particle_Size | 47 | 39 | 14 | 86 | 22.2 | 17.2 | | 5 | Synthesis | 17.2 | 0.7747748 |
| Carter | 2003 | 45.5 | -64.1 | 5.6 | 1107 | Entisols | HM | 0 | 10 | Fallow | Particle_Size | 18 | 60 | 22 | 78 | 27.1 | 17 | | 10.1 | Synthesis | 17 | 0.6273063 |
| Carter | 2003 | 45.6 | -67.4 | 4.4 | 1143 | Inceptisols | HM | 0 | 10 | Fallow | Particle_Size | 19 | 53 | 28 | 72 | 31.9 | 19.8 | | 12.1 | Synthesis | 19.8 | 0.6206897 |
| Carter | 2003 | 42.1 | -82.4 | 8.7 | 819 | Incept-Entisc | HM | 0 | 10 | Fallow | Particle_Size | 36 | 35 | 29 | 71 | 20.3 | 17.8 | | 2.5 | Synthesis | 17.8 | 0.8768473 |
| Carter | 2003 | 42.1 | -82.4 | 8.7 | 819 | Incept-Entisc | HM | 0 | 10 | Fallow | Particle_Size | 36 | 35 | 29 | 71 | 21.5 | 18.8 | | 2.7 | Synthesis | 18.8 | 0.8744186 |
| Carter | 2003 | 46.4 | -71.1 | 4.6 | 1127 | Incept-Entisc | HM | 0 | 10 | Fallow | Particle_Size | 28 | 41 | 31 | 69 | 22.3 | 18.4 | | 3.9 | Synthesis | 18.4 | 0.8251121 |
| Carter | 2003 | 45.3 | -75.4 | 5.9 | 846 | Incept-Entisc | HM | 0 | 10 | Fallow | Particle_Size | 28 | 30 | 42 | 58 | 27.2 | 22.3 | | 4.9 | Synthesis | 22.3 | 0.8198529 |
| Carter | 2003 | 45.3 | -73.6 | 6 | 920 | Alfisols | HM | 0 | 10 | Fallow | Particle_Size | 28 | 22 | 50 | 50 | 14.5 | 10.2 | | 4.3 | Synthesis | 10.2 | 0.7034483 |
| Carter | 2003 | 46.2 | -63.1 | 5.9 | 1077 | Spodosols | HM | 0 | 10 | Fallow | Particle_Size | 8 | 30 | 62 | 38 | 21.2 | 18.4 | | 2.8 | Synthesis | 18.4 | 0.8679245 |
| Carter | 2003 | 46.2 | -63.1 | 5.9 | 1077 | Spodosols | HM | 0 | 10 | Fallow | Particle_Size | 8 | 30 | 62 | 38 | 17.8 | 15.7 | | 2.1 | Synthesis | 15.7 | 0.8820225 |
| Carter | 2003 | 45.3 | -75.4 | 5.9 | 846 | Inceptisols | HM | 0 | 10 | Fallow | Particle_Size | 10 | 25 | 65 | 35 | 22 | 17.1 | | 4.9 | Synthesis | 17.1 | 0.7772727 |
| Carter | 2003 | 42.5 | -80.3 | 7.8 | 935 | Alfisols | HM | 0 | 10 | Fallow | Particle_Size | 6 | 6 | 88 | 12 | 7.6 | 6.2 | | 1.4 | Synthesis | 6.2 | 0.8157895 |
| Catroux | 1987 | NA | NA | NA | NA | Mollisols | HM | 0 | NA | | Particle_Size | 15 | 55 | 30 | 70 | 32.9 | 26.7 | | 5.3934 | Synthesis | 27.5066 | 0.8360669 |
| Chan | 2001 | -31.5 | 147 | 18 | 431 | Alfisols | HM | 0 | 10 | Pasture | Particle_Size | 32 | 13 | 55 | 45 | 21.4 | 9.1 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -31.5 | 147 | 18 | 431 | Alfisols | HM | 0 | 10 | Cropland | Particle_Size | 32 | 13 | 55 | 45 | 7.5 | 4.7 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -31.5 | 147 | 18 | 431 | Alfisols | HM | 0 | 10 | Pasture | Particle_Size | 32 | 13 | 55 | 45 | 8.8 | 5.2 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -35 | 147.5 | 16 | 550 | Alfisols | HM | 0 | 10 | Cropland | Particle_Size | 23 | 12 | 65 | 35 | 17.5 | 8.7 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -35 | 147.5 | 16 | 550 | Alfisols | HM | 0 | 10 | Cropland | Particle_Size | 23 | 12 | 65 | 35 | 14.8 | 8.2 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -34 | 148.7 | 15 | 564 | Alfisols | HM | 0 | 10 | Pasture | Particle_Size | 13 | 11 | 76 | 24 | 32.2 | 8.3 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -34 | 148.7 | 15 | 564 | Alfisols | HM | 0 | 10 | Cropland | Particle_Size | 13 | 11 | 76 | 24 | 16.8 | 5.4 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -34 | 148.7 | 15 | 564 | Alfisols | HM | 0 | 10 | Cropland | Particle_Size | 13 | 11 | 76 | 24 | 6.9 | 3.5 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -30 | 148 | 19.5 | 474 | Vertisols | HM | 0 | 10 | Pasture | Particle_Size | 58 | 18 | 24 | 76 | 9.3 | 5.6 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -30 | 148 | 19.5 | 474 | Vertisols | HM | 0 | 10 | Cropland | Particle_Size | 58 | 18 | 24 | 76 | 18 | 7.3 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -33 | 151 | 17 | 1300 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | 16 | 7 | 77 | 23 | 21.9 | 8.9 | | NA | Synthesis | #VALUE! | #VALUE! |
| Chan | 2001 | -33 | 151 | 17 | 1300 | Oxisols | LM | 0 | 10 | Cropland | Particle_Size | 12 | 6 | 82 | 18 | 18.4 | 9.7 | | NA | Synthesis | #VALUE! | #VALUE! |

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