Pacific Northwest
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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

U.S. DEPARTMENT OF ENERGY

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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)

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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 % 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

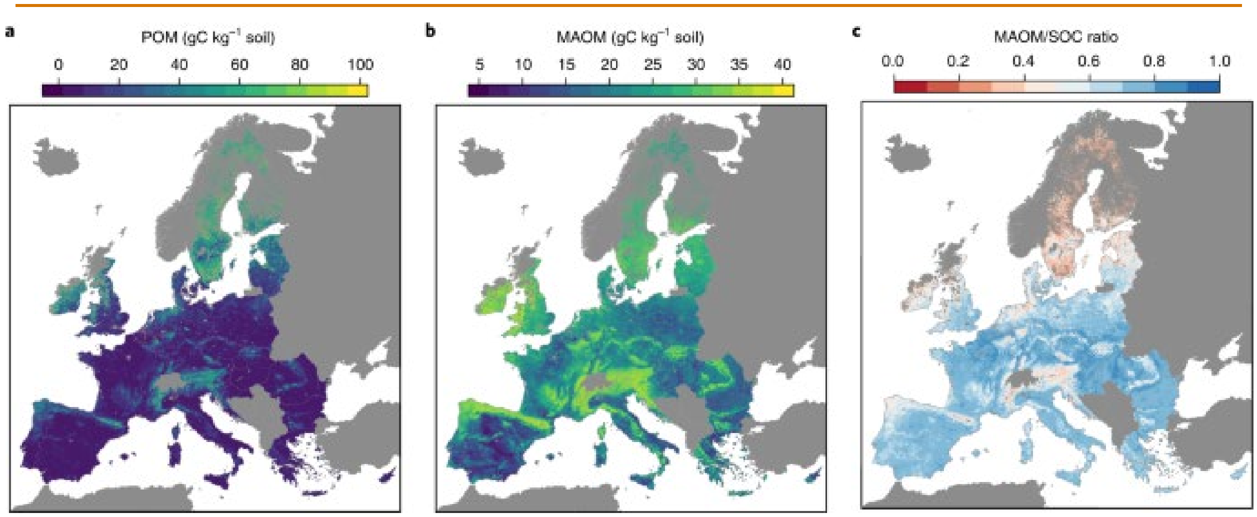

Figure 1. **a–c**, Carbon content (gC kg^{-1} soil) in POM (**a**) and MAOM (**b**), and ratio between MAOM carbon and total SOC (**c**) from Lugato et al (2021).

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.

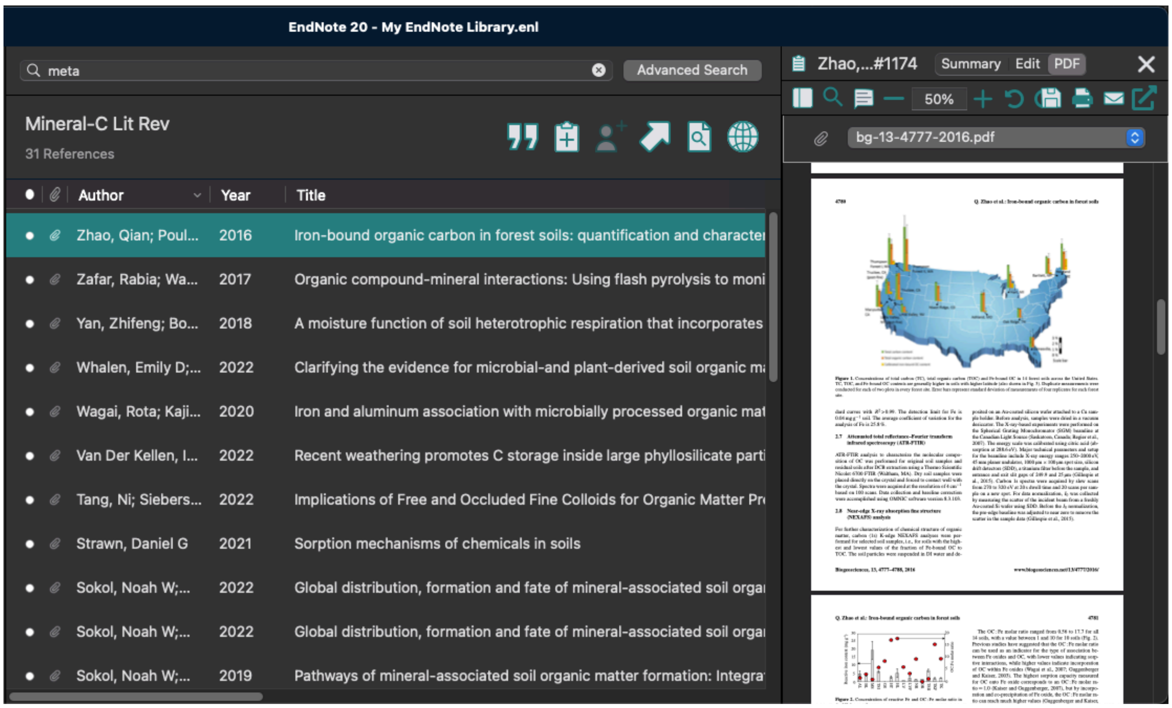

Figure 2. The list of literatures of quantifying mineral-associated OC in soil.

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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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