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Maximum Potentially Dispersible and Stabilizable Clays under Cropping in Soils with Inherent Textural Differences

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Abstract

Physical and mechanical stresses induced changes in clay dispersion is a major sustainability and environmental issue, particularly in large-scale intensive agricultural production systems. However, the dispersed clay may re-stabilize when the stresses are reduced or minimized/removed. The objectives of this study are to (i) quantify the maximum potentially dispersible (DC_{max}) and stabilizable clay (SC_{max}) in soils with textural differences when the stresses were introduced and reduced, respectively, and (ii) identify the role of inherent soil variable(s) on DC_{max} and SC_{max}. Dispersible clay measurements were conducted at monthly intervals for 3 years on seven soil types under different cropping treatments. The cropping treatments used in this study were conventionally tilled continuous corn (CTCC) and forages, which were established in 1989 on plot that were previously under CTCC for more than 10 years. The CTCC represents stress imposed and the forages the stress reduced system. The DC_{max} in the stress imposed system across soils ranged from 3.2 to 16.6% compared to 6.4 to 33.8%, the total clay (TC) content. The DC_{max} increased with increasing TC and decreasing soil organic matter (SOM) content. The SC_{max} in the stress reduced system across soils ranged from 1.2 to 4.5% and it increased with increasing TC and SOM. Eleven to 37% of the DC_{max} was re-stabilized during the 3-year period under forages, i.e. stress reduced system. The amount of SOM in the soil at the time of switchover from CTCC played a significant role in the re-stabilization of dispersed clay, particularly in soils with similar TC. The results show the stabilization of dispersed clay under reduced stresses depended on DC_{max} and SOM.

Key words : Dispersible clay, Stabilizable clay, Soil texture, Soil organic matter, Physical and mechanical stresses.

1. Introduction

Dispersed clays in soils under cropping, can be a major sustainability and environmental issue, because of its association with runoff and erosion. In the highly mechanized intensive agricultural production systems the physical and mechanical stresses induced by multiple tillage, heavy machinery wheel traffic, and water impact energy from over-head sprinklers are, at least partially, responsible for increases in clay dispersion. Number of environmental factors, such as freezing and thawing (Rasiah and Kay, 1994) and wetting and drying cycles also play a role in clay dispersion (Caron and Kay, 1992a & b). Weakening and breaking of '＜clay＞-＜soil organic matter (SOM)＞-＜clay＞' bonds during SOM mineralization, removal of polyvalent cations, particularly Ca^{2+}, from ‘＜clay＞-＜Ca^{2+}＞-＜clay＞’ bonds, and Ca^{2+} displacement by Na^{+}, under saline condition, are examples of chemical stress induced clay dispersion (Baldock and Oades, 1990).

Dispersed clays in soils have impact on soil physical, chemical and biological processes. Clay dispersion induced aggregate bond weakening enhances aggregate breakdown when soils were subjected to further physical and mechanical stresses (Rasiah and Kay, 1995a ; Shanumuganathan and Oades, 1982). Clay dispersion increased sediment load in runoff (Rasiah and Kay, 1995b ; Isensee and Sadeghi, 1986 ; Miller and Baharuddin, 1986), decreased water infiltration and conductivity in soil profiles (Collis-George and Greene, 1979), and may decrease the proportion of habitable pores for microbes through pore clogging.

The dispersed clay (DC) in a given non-saline soil under cropping increased with increasing gravimetric soil water content (θ) (Rasiah *et al.*, 1992). On the other hand, the DC in texturally different soils increased with increasing total clay content (TC), soil pH, and θ, and decreasing SOM (Rasiah *et al.*, 1992). When θ increased to a potential maximum value, θ_{max}, then potential existed for the dispersed clay to approach a potential maximum value, DC_{max} (Rasiah, 1994). In texturally different soils, the DC_{max} and θ_{max} depended on TC and SOM (Rasiah, 1994). Though it is known that under field conditions, at least a small proportion of DC_{max} may re-stabilize during soil drying, the major proportion would remain dispersed or weakly bonded (Caron and Kay, 1992a & b). The weakly bonded sites are points of potential failure zones, which are responsible for aggregate breakdown under physical and mechanical stresses.

When the physical and mechanical stresses inducing clay dispersion under conventional corn were reduced, through switch over to forage-corn rotation, the dispersed clay re-stabilized during the forage phase (Rasiah and Kay, 1994). Furthermore, inclusion of forages in rotations or as legume covers increased water infiltration (Cassman and Rains, 1986), improved porosity (Disparte, 1987), and protected soil surface from rain and sprinkler drop impact, thereby preventing crust formation (Disparte, 1987). Though re-stabilization of dispersed clay might have had several beneficial effects on soil water processes, limited information, however, exists on maximum potentially stabilizable clay (SC_{max}) under forages of corn-forage rotation. Thus, quantitative information on physical and mechanical stresses induced clay dispersion under stressed systems and that on stabilization under reduced stresses are essential. Therefore, the objectives of this study are to (i) to provide quantitative information on DC_{max} and SC_{max} when the stresses were imposed and reduced, respectively, in soils with textural differences and (ii) identify the role played by inherent soil variable(s) on DC_{max} and SC_{max}.

2. Materials and methods

1) General

The data used in this study is from crop rotation and tillage experiments established in 7 sites (Table 1) in Ontario province, Canada, in 1989 and continued until 1991. Before 1989, the experimental sites, in farmers' field, were under conventionally tilled continuous corn (*Zea mays* L.), CTCC, for at least 10 years. Conventional tillage involved plowing in the fall, followed by secondary tillage in the spring. The CTCC treatment represents the physical and mechanical stresses imposed system, and the forage phase in corn-forage rotation the stress reduced system. Crop rotations at the sites included cereal-forage or soybean-forage rotation. In this study, however, we will present the data relating to CTCC and corn-forage rotation only. During the sampling period the corn-forage rotation plots were in the forage phase. The forages included in the rotation were alfalfa (*Medicago sativa* L.) in soil 4, bromegrass (*Bromus inermis* L.) in soils 1, 2, 3, and 6, and red clover (*Trifolium pratense* L.) in

Table 1 Soil description and selected properties

Soil type	Soil description: Series name (US classification)	Caly	Silt	Soil organic matter	$CaCO_3$	pH
		(…………… g/ 100 g soil … or % ……………)				
1	Brookston clay (Typic Haplaquept)	33.8	27.3	3.3	0.00	5.77
2	Brookston clay (Typic Haplaquept)	21.1	42.3	3.1	0.79	7.33
3	Tuscola silt loam (Aquic Hapludalf)	18.5	56.9	3.9	0.16	6.60
4	Conestoga silt loam (Aquic Eutrochrept)	18.3	52.0	3.9	1.50	7.2
5	Conestoga silt loam (Aquic Eutrochrept)	17.9	53.4	3.4	2.04	7.17
6	Wattford loamy sand (Arenic Hapludalf)	6.4	10.4	2.9	0.00	6.40
7	Fox loamy sand (Arenic Hapludalf)	6.4	15.7	2.2	0.10	5.84

soil 5 and 7. The experimental design at each site was a randomized complete block with four replications. Crop, fertilizer, weed, pest, and disease managements were carried out according to the recommendations of the Ontario Ministry of Food and Agriculture (1988a and b). For further experimental details and other related information, the readers are referred to Rasiah and Kay (1994 and 1995a, b) and Rasiah *et al.* (1992).

2) Soil sample collection and laboratory analyses

Soil cores (7 cm diameter and 7 cm length) were collected from the surface 0 to 7-cm layer at four randomly selected locations from each replicate at monthly intervals from May through September in 1989, 1990, and 1991. The soil cores from each replicate were thoroughly mixed, and approximately one-quarter of the mixed moist soil sieved, on a mechanical shaker, using a nest of sieves with mesh openings of 10, 2, and 1 mm, respectively, and a shaking time of one minute. The aggregates retained on the 1-mm sieve, i.e. 1 to 2-mm aggregates, were used for the dispersible clay (DC) and field soil water content (θ g/g) determinations. The 1 to 2-mm aggregates from the 1989 soil samples were also used for particle-size, soil organic matter content, SOM, pH in a 1 : 1 soil : water mixture, and calcium carbonate content (Page, 1986) determinations. The results of the analyses are reported in Table 1.

Dispersible clay measurements on the field moist 1 to 2-mm aggregates were conducted using the procedure described by Pojasok and Kay (1990). In brief, three 5-g subsamples of the field moist 1 to 2-mm aggregates from each replicate were prewetted on a wetting table at 1 cm suction for 90-min using deionized water. The prewetted sample was transferred to a 50-ml test tube using 40-ml of deionized water. The suspension was shaken in a mechanical shaker for 10-min and then transferred to a 250-ml conical flask using another 80-ml of deionized water. After a 40-min settling time (calculated using Stakes Law), the DC in the suspension was determined, using a colorimeter previously calibrated for each soil. The DC is expressed as a percent of total oven-dry soil mass. The θ in the 1 to 2-mm aggregates was

Table 2 The maximum gravimetric soil water content (θ_{max}) and the maximum potentially dispersible clay (DC_{max})

Soil property	Soil type						
	1	2	3	4	5	6	7
θ_{max}(g/g soil)	0.46	0.44	0.48	0.45	0.40	0.37	0.40
DC_{max} (g/100 g soil)	16.6	12.8	6.0	5.7	7.8	3.2	5.4

Table 3 The dispersible clay at average water content and that at maximum water content expressed as a fraction of other variables

Dispersible clay type and its relationship with other variables							
Soil type	†DC ($\tilde{\theta}$)	DC_{max}/TC	[DC_{max}− DC ($\tilde{\theta}$)]=A	A/DC_{max}	A/TC	DC ($\tilde{\theta}$)/DC_{max}	DC ($\tilde{\theta}$)/TC
1	5.86	0.50	10.77	0.65	0.32	0.36	0.18
2	5.12	0.61	7.64	0.60	0.37	0.41	0.24
3	2.69	0.33	3.28	0.55	0.18	0.45	0.15
4	2.77	0.32	2.97	0.52	0.17	0.49	0.16
5	3.40	0.44	4.38	0.57	0.25	0.44	0.19
6	2.06	0.51	1.16	0.36	0.18	0.64	0.33
7	1.22	0.84	4.19	0.79	0.66	0.22	0.19

† DC ($\tilde{\theta}$)=dispersible clay at average water content ($\tilde{\theta}$), DC_{max}=maximum potentially dispersible clay, TC =total clay in soil.

determined gravimetrically and expressed as a fraction of the oven-dry soil mass (g/g).

3) Computations

According to Rasiah *et al.* (1992) the dispersed clay (DC) across soil types increased with increasing soil-water content (θ),

$$DC_i = p_i + q_i \theta_i \qquad [1]$$

where the subscript 'i' refers to a given soil. When θ_i in Eq. [1] approaches a finite maximum value (θ_{max}), then clay dispersion is at its potential maximum and this is defined as DC_{max}. The DC_{max} was computed using Eq. [1], for $\theta = \theta_{max}$, and the computed values are provided in Table 2. The θ_{max} used in the DC_{max} computations are also provided in Table 2. The values for p_i and q_i, for each soil, used in the computation of θ_{max} and DC_{max} are provided by Rasiah *et al.* (1992) in their table 2.

Rasiah and Kay (1994) developed a model, to predict the net amount of clay re-stabilized by forages, in corn-forage rotation, and they defined this as SC_{net},

$$SC_{net} = (\Delta p - \Delta q \theta_f)(1 - e^{-kt}) + q_c(\theta_c - \theta_f) \qquad [2]$$

where SC_{net} is the difference in DC between that under CTCC and the corresponding forage treatment. In Eq. [2] the Δp, Δq, k, and q_c are model parameters, which were estimated using experimental data. In Eq. [2] Δq is equal to the difference between q of forage and corn and similarly for Δp. The subscript 'c' refers to corn, 'f' to forage, the superscript 'k' a rate constant, and 't' is time, in months, after the introduction of forages in corn-forage rotation. The values for the parameters in Eq. [2] are provided by Rasiah and Kay (1994) in their table 3. The amount of dispersed clay that can be re-stabilized by forages, i.e. under reduced stresses, as 't' approaches infinity has been defined by Rasiah and Kay (1994) as maximum potentially stabilizable clay SC_{max} and they

Table 4 The stabilized clay expressed as a fraction of dispersed clay

Soil type	Stabilized clay and its relationship with dispersed clay types				
	†$\Delta SC(\tilde{\theta})$	$\Delta SC(\tilde{\theta})/TC$	$\Delta SC(\tilde{\theta})/DC(\tilde{\theta})$	$\Delta SC(\tilde{\theta})/[DC_{max}-DC(\tilde{\theta})]$	$\Delta SC(\tilde{\theta})/DC_{max}$
1	4.51	0.14	0.77	0.42	0.28
2	3.02	0.14	0.59	0.40	0.24
3	1.77	0.10	0.66	0.54	0.30
4	1.80	0.10	0.65	0.61	0.32
5	2.09	0.12	0.61	0.48	0.27
6	1.17	0.19	0.57	1.01	0.37
7	0.55	0.09	0.47	0.14	0.11

†$\Delta SC(\tilde{\theta})$=stabilized clay at average water content $(\tilde{\theta})$, DCmax=maximum potentially dispersible clay, TC=total clay in soil, and $\Delta DC(\tilde{\theta})$=stabilized clay at average water content $(\tilde{\theta})$.

showed, through appropriate re-arrangement of Eq. [2], that SC_{max} can be computed using the following equation,

$$\Delta SC(\tilde{\theta})=(\Delta p-\Delta q\tilde{\theta}) \quad [3]$$

where $\tilde{\theta}$ is the average soil water content over the growing season in a given soil. The $\Delta SC(\tilde{\theta})$, computed using Eq. [3], for the 7 soils are provided in Table 4.

3. Results and Discussion

1) General

The total clay content (TC) in the soils ranged from 6.4% to 33.8%, the texture from loamy sand to silty clay, and the soil organic matter content (SOM) from 2.2 to 3.9% (Table 1). The clay mineralogy is dominated by illite, with subordinate amounts of chlorite, vermiculite, and hydroxy-interlayered vermiculite (Baldock and Kay, 1987 ; Evans and Cameron, 1983).

Depending on the length of time (t) after the introduction of forages, in corn-forage rotation, soil moisture content (θ) at sampling, and the soil type the amount of dispersed clay (DC) in the soils ranged from 0.05% to 12% (Rasiah *et al.*, 1992 ; and Rasiah and Kay, 1994). In general, the DC was high in soils with high TC, suggesting that source strength played an important role on the amount of DC in soil under field conditions. The DC in the 7 soils increased with increasing TC and θ, but decreased with increasing SOM and soil pH (Rasiah *et al.* 1992).

The DC in the 7 soils decreased with time after the introduction of forages and subsequent to change over from conventional to no-till system (Rasiah and Kay, 1994). Rasiah and Kay (1995b) showed that runoff and sediment load, from soil 5, increased with increasing DC, regardless of the cropping treatment. Though runoff simulations were not conducted at the other sites, we anticipate similar trends from these sites. Indirect evidence for swelling, during wetting, induced structural destabilization and reduction in infiltration rate was derived positive associations that existed between DC and runoff (Rasiah and Kay, 1995b). From the foregoing, it is evident that DC in the 7 soils played important roles in surface and subsurface soil water flow, and the spatio-temporal changes in DC depended on inherent soil variables, θ, and cropping and tillage management practices.

2) Maximum potentially dispersible clay

The maximum potentially dispersible clay (DC_{max}) in the soils ranged from 3.2 to 16.6-g clay/100-g soil (Table 2). Rasiah (1994) showed that DC_{max} increased with increasing TC and decreasing SOM, but was determined largely by the source strength, i.e. TC. The DC_{max} estimates, computed using the equation provided by Raisah (1994, Eq. 7) show that 14.1-g clay/100-g soil was potentially dispersible in soil 1, at 3.5% SOM, and the estimated DC_{max} increased to 15.6 g clay 100 g^{-1} soil when the SOM decreased to 3.0%. This suggests that 10% increase in clay dispersion was associated with 0.5% loss in SOM, possibly through C-mineralization. Similar estimations for soil 6 show that only 6% increase in clay dispersion for 0.5% reduction in SOM, suggesting the impact of C-mineralization on clay dispersion was higher in clay soil than in loamy sand.

The clay dispersed at maximum soil water content (θ_{max}) is also potentially available for transport in surface and subsurface flow (Table 2). Because, the clay dispersed at θ_{max} is free from soil aggregates, it can be transported in infiltrating water and may clog soil pores during soil drying. The soil water status favorable for maximum clay dispersion to occur usually arises after rain or irrigation events. Thus, in soils with high TC, potential existed for large quantities of the clay to be dispersed at θ_{max} and transported in surface and subsurface flow. In soil 1, with 33.8% TC, the DC_{max} was 16.6%, implying that ≈ 50% of the TC was potentially available for transport in flow compared to ≈84% of the TC in soil 7 (Tables 2 and 3). Even though the absolute amount of the DC_{max} was higher in soil 1 than in soil 7, a larger proportion of it in relation to TC was potentially available for transport in runoff from soil 7. The least amount of DC_{max} was found in soil 3 and 4 that are characterized by high SOM, indicating the importance of SOM in decreasing clay dispersion at maximum soil water content.

Even though Rasiah and Kay (1995) showed that runoff or sediment load and DC(θ) was positively correlated, in reality though it seems that DC_{max} should have been correlated with runoff and sediment load.

During dry-spells that follow rain or irrigation events, the amount of dispersed clay in soils will decrease with decreasing θ, i.e. a corollary of the positive empirical relation between dispersed clay and θ (Rasiah *et al.*, 1992). Thus, the obvious question now is what is the fate of this DC_{max} during soil drying? During soil drying the DC_{max}, at least a small proportion of it may re-stabilize, temporarily, through weak ＜clay＞-＜clay＞ bonding or be deposited on aggregate surfaces and/or pore walls. During re-wetting the temporary bonds may break and release free clay. Evidences for temporary weak bonding and for the release of free clay have been provided by Caron and Kay (1992a). Thus, we suggest the clay that is potentially available for re-stabilization through changes in cropping and tillage practices is that present at θ_{max}, i.e. DC_{max}. On the other hand, Rasiah and Kay (1994) used the amount clay dispersed at average field water content [DC($\tilde{\theta}$)] as that available for re-stabilization through changes in cropping and tillage systems.

Because, the θ_{max} soil water status (Table 2) is short lived, we computed DC($\tilde{\theta}$), for each soil, as a fraction of DC_{max} [DC($\tilde{\theta}$)/DC_{max}] and TC [DC($\tilde{\theta}$)/TC] (Table 3). The difference between DC_{max} and DC($\tilde{\theta}$) is the amount that was dislodged from soil aggregates through saturation and is in a relatively dynamic or in an un-aggregated state and readily available for transport. Thirty six to 79% of the DC_{max} or 18 to 65% of the TC was in dynamic or un-aggregated state. Exclusive of the loamy sand 7, 52 to 65% of the DC_{max} in silt loam and clay soils were in un-aggregated or dynamic state and we suggest that this fraction of the DC_{max} need immediate re-stabilization attention.

The DC($\tilde{\theta}$) is the amount of dispersed clay that is in a weakly bonded state due to soil drying, but may disperse or disaggregate during saturation. When DC($\tilde{\theta}$) was expressed as a fraction of DC_{max} (Table 3), it showed that 22 to 64% of the DC_{max} was DC($\tilde{\theta}$), suggesting that soil drying played an important role in reducing the amount of clay available for transport in water. In clay and silt loam soils, 36 to 49% of the DC_{max} was DC($\tilde{\theta}$), The highest and lowest percents were associated with loamy sands, suggesting inherent soil variables other TC playing a temporary role in the stabilization of dispersed clay during soil drying.

The major emphasis on clay dispersion in this paper is that induced by mechanical and physical stresses and dynamics of the dispersed clay in relation to soil water status. However, it is important to recognize here that dispersion induced by salinity, particularly that arising from saline water use, may be a major issue in arid, semi-arid, and tropical environments. Several studies have shown the impact of salinity on decreases in soil hydraulic conductivity through pore clogging by the dispersed clay (Sumner, 1993). Gypsum application was effective in restoring, at least partially, conductivity under saline condition. This suggests, the pore clogging clay particles were transported or translocated away from pore walls after gypsum application and were probably re-stabilized in aggregates. Limited quantitative information, however, exists on the fate of dispersed clay under forages in forage-cereal rotations in saline soils.

3) Maximum potentially stabilizable clay

The amount of dispersed clay (DC) under forages in forage-corn rotations decreased with time, during the 3 yr period, in the 7 soil types and the DC under forages were always less the corresponding continuous conventional corn treatment (Rasiah and Kay, 1994). The aforementioned provides evidence for the forage-phase induced stabilization of clay that was in dispersed status under corn. As time approaches infinity, the DC under forages may decrease to near zero and the amount of clay stabilized would be at its potential maximum, SC_{max}. The SC_{max} at growing season average water content, $\tilde{\theta}$, is defined as $\Delta SC(\tilde{\theta})$. The $\Delta SC(\tilde{\theta})$ is the difference in dispersed clay between the corn and forage treatment. During the 3-year period, the $\Delta SC(\tilde{\theta})$ ranged from 1.17 g clay $100\,g^{-1}$ soil to 4.51 g clay $100\,g^{-1}$ soil (Table 4). The $\Delta SC(\tilde{\theta})$ had been shown to increase with increasing TC, SOM, and soil pH (Rasiah and Kay, 1994).

The clay stabilized by forages ranged from 9 to 19% of TC (Table 4). According Rasiah and Kay (1994), the fraction of the dispersed clay that was stabilized by forage is $\Delta SC(\tilde{\theta})/DC(\tilde{\theta})$. Thus, according to them 47 to 77% of the dispersed clay was stabilized by forages in 3 years (Table 4). However, in reality though, as mentioned elsewhere in the text, the total dispersed clay in a given soil is DC_{max}. Thus, $\Delta SC(\tilde{\theta})$ was expressed as a fraction of DC_{max} (Table 4). This form of expression revealed that only 11 to 37% of the DC_{max} was stabilized by forages. We also indicated elsewhere in the text the difference between DC_{max} and $DC(\tilde{\theta})$ is the amount that was in a relatively free or dynamic state. Therefore, we expressed $\Delta SC(\tilde{\theta})$ as a fraction of this difference (Table 4). This computation indicated that 14 to almost all the so-called free state clay was stabilized by forages. Ironically, the highest and lowest stabilization of the clay in dynamic state occurred in the loamy sands. The highest stabilization occurred in the loam with the high SOM and the lowest in the loam with low SOM. This suggests the SOM present at the time of introduction of forage probably played an important in enhancing the stabilization of the clay in dynamic state.

The maximum amount of clay that can be stabilized by forages depended on the dispersed clay pool and we have shown this pool is DC_{max} and not $DC(\tilde{\theta})$ as indicated by Rasiah and Kay (1994). The DC_{max} is a much larger pool than $DC(\tilde{\theta})$ in a given soil (Tables 2 and 3), and $DC(\tilde{\theta})$ is only 22 to 64% of DC_{max}. The DC_{max} increased with increasing TC and decreasing SOM (Rasiah, 1994). The $\Delta SC(\tilde{\theta})$ showed a trend to increase with increasing TC or DC_{max} or $\Delta DC(\tilde{\theta})$ and/or SOM (Fig. 1 and Table 4). Therefore, we explored $\Delta SC(\tilde{\theta})$ as a function of TC and SOM, or DC_{max} and SOM, or $\Delta DC(\tilde{\theta})$ and SOM using the stepwise variable selection procedure. The analyses produced a significant relation only with DC_{max} and SOM independent variables,

$$\Delta SC(\tilde{\theta}) = -1.75 + 0.25\,DC_{max} + 0.56\,SOM \quad \{R^2 = 0.96 \text{ and } P < 0.01\} \qquad [4]$$

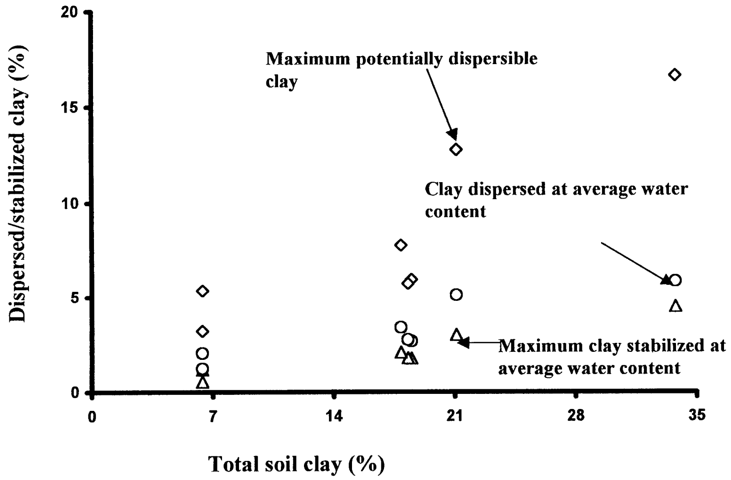

Fig. 1 The relationship between maximum potentially stabilizable, [$\Delta SC(\tilde{\theta})$], or dispersible, [$\Delta DC(\tilde{\theta})$], and total clay (TC).

Equation [4] indicates that $\Delta SC(\tilde{\theta})$ increased with increasing DC_{max} and SOM. However, the role played by DC_{max} is different from that of SOM. The amount of clay that can be stabilized by forages depends largely on the dispersed clay pool. This pool could be either TC or DC_{max} or $\Delta DC(\tilde{\theta})$. The aforementioned analyses, i.e. using TC or $\Delta DC(\tilde{\theta})$ or DC_{max} as the clay pool, indicate that DC_{max} is the pool that determined $\Delta SC(\tilde{\theta})$ and not TC or $\Delta DC(\tilde{\theta})$. Equation [4] also indicates that SOM enhanced clay stabilization when the dispersed pool was not a limiting factor. For example, in the loamy sands (soils 6 and 7) with 6.4% clay content, the influence of SOM on clay stabilization is higher in soil 6, with 2.9% SOM, than in soil 7, with 2.2% SOM. The SOM clay stabilization enhancement role was significant only when DC_{max} was used as the dispersed clay pool and not TC or $\Delta DC(\tilde{\theta})$. This provides further support to our hypothesis that DC_{max} is pool that determined the maximum potentially stabilizable clay.

The enhanced effectiveness of SOM in clay stabilization under forages, suggests the binding materials arising from short-term forages were more effective under high initial SOM and is consistent with the results reported by other workers (Nadler and Letey, 1989 ; Swift, 1991). The results are also compatible with the observation made by Baldock and Oades (1990) that Ca^{2+} addition during straw decomposition resulted in increased structural stabilization through synergistic effects.

We suggest that in soils with high DC_{max} the organic binding materials produced by short-term forages were more effectively utilized during clay stabilization. This probably led to the immobilization of the organic materials in the stabilized aggregates, thereby leading to gradual increases in SOM. The aforementioned hypothesis is consistent with the findings of by Dormaar and Foster (1991).

As mentioned elsewhere in the text, quantitative information on the stabilization of dispersed clay in saline soils under forages is scarce. Recently, however, Mitchell *et al.* (2000) showed that soil aggregation under legume winter cover crops, followed by summer cereals using saline water for irrigation, was higher than without cover crop treatment. Further, the stability of soil with gypsum treatment and saline water use was less than cover crop. However, surface soil salinity was higher under winter cover than the gypsum treatment. Unfortunately, the changes in clay dispersion after saline water irrigation and winter cover crop treatment were not measured in this study. Nevertheless, the results indirectly show that clay dispersion might decreased after the introduction of winter cover crops according to Rasiah *et al.* (1992), who showed negative correlations existed between aggregate stability and dispersed clay (Rasiah *et al.* 1992).

Even though the forage phase in forage-corn rotation was effective in stabilizing dispersed clay, the practical applicability of this rotation is limited, because, such rotations may not be economically feasible or acceptable. Further, if animal husbandry is not incorporated in the farming systems then efficient utilization of forages is limited. Thus, it seems winter cover cropping or under-seeding green manure legumes in cereals, particularly under corn, more appropriate than forage-corn rotations.

4. Conclusions

In previous studies, the dispersed clay at average field water content [DC($\tilde{\theta}$)] was considered amount that was available for stabilization when forages were introduced (unstressed system) in forage-corn rotation. In this study, we show the maximum potentially dispersible clay (DC_{max}) is the pool that was available for stabilization when the forages were introduced. The DC_{max} is much larger than DC($\tilde{\theta}$), which ranged from 22 to 49 % of DC_{max} across soil types. The DC_{max} under conventional corn (stressed system) ranged from 32 to 84 % of the total clay (TC) across soil types. This indicates that substantial quantities of TC were in dispersed state in the stressed system. When the impact of the stresses were reduced, through the introduction of forages, the dispersed clay re-stabilized and the amount stabilized ranged from 11 to 37 % of the DC_{max} across soil types. The sources strength, the total clay content (TC), determined DC_{max} pool and consequently SC_{max}. Soil organic matter (SOM) had opposing effects on SC_{max} and DC_{max}. The SC_{max} increased with increasing SOM in a given soil and across soil types. Thus, we suggest SOM conservation and management not only enhances clay stabilization, it may contribute towards C-sequestration in soil, particularly under reduced tillage systems. C-sequestration in soil may help in reducing the concentration of green house gases in atmosphere.

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References

Baldock, J.A. and Oades, J.M. (1990) : Structural amelioration of a South Australian red earth using calcium and organic amendments. In Soil Structure Research in Eastern Canada. Proc. Eastern Canada Soil Structure Workshop, Guelph. pp. 131–141.

Baldock, J.A. and Kay, B.D. (1987) : Influence of cropping history and chemical pretreatment on the water stable aggregation of a silt loam soil, Can. J. Soil Sci, **67** : 501–511.

Caron, J. and Kay, B.D. (1992a) : Short term decrease in soil structural stability following bromegrass establishment on a clay loam soil, Plant Soil., **145** : 121–130.

Caron, J. and Kay, B.D. (1992b) : Rate of response of structural stability to a change in water content : Influence of cropping history, Soil Tillage Res., **25** : 167-185.

Cassman, K.G. and Rains, D.W. (1986) : Cropping systems approach to salinity management in California, Amer. J. Alt. Agric., **1** : 115–121.

Collis-George, N. and Greene, R.S.B. (1979) : The effect of aggregate size on the infiltration behavior of a slaking soil and its relevance to ponded irrigation, Aust. J. Soil Res., **17** : 65–73.

Disparate, A.A. (1987) : Effects of root mass density on infiltration among four Mediterranean dryland forages and two irrigated forage legumes. MS Thesis. University of California Press, Riverside, USA.

Dormaar, J.F. and Foster, R.C. (1991) : Nascent aggregates in the rhizosphere of perennial ryegrass, Can. J. Soil Sci., **71** : 465–474.

Evans, L.J. and Cameron, B.H. (1983) : The Brookston series in Southwestern Ontario : Characteristics, classification, and problems in defining a soil series, Can. J. Soil Sci., **63** : 339–352.

Isensee, A.R. and Sadeghi, A.M. (1993) : Impact of tillage practices on runoff and pesticide transport, J. Soil Water Conserv., **48** : 523–527.

Miller, W.P. and Baharuddin, M.K. (1986) : Relationship of soil dispersibility to infiltration and erosion of Southeastern soils, Soil Sci., **142** : 235–240.

Micthell, J.P., Shennan, C. Singer, M.J. Peters, D.W. Miller, R.O. Prichard, T. Grattan, S.R. Rhoades, J.D. May, D.M. and Munk, D.S. (2000) : Impacts of gypsum and winter crops on soil physical properties and crop productivity when irrigated with saline water, Agric. Water Mangt., **45** : 55–71.

Nadler, A. and Letey, J. (1989) : Adsorption isotherm of polymers on soils using tritium labeled compounds, Soil Sci. Soc. Am. J., **53** : 1375–1378.

Ontario Ministry of Agriculture and Food. (1988a) : Field crop recommendations. Publication No. 296. OMAF, Toronto.

Ontario Ministry of Agriculture and Food. (1988b) : Guide to weed control. Publication No. 756. OMAF, Toronto.

Page, A.L. (ed). (1986) : Methods of Soil Analysis-Part 2. ASA and SSSA, Madison, WI, USA.

Pojasok, T. and Kay, B.D. (1990) : Assessment of a combination of wet sieving and turbidimetry to characterize the structural stability of moist aggregates, Can. J. Soil Sci., **70** : 33–42.

Rasiah, V. and Kay, B.D. (1995a) : Characterizing rate of wetting : Impact on structural destabilization, Soil Sci., **160** : 176–182.

Rasiah, V. and Kay, B.D. (1995b) : Runoff and soil loss as influenced by stability parameters, cropping, and tillage practices, Geoderma., **68** : 321–329.

Rasiah, V. (1994) : Equations to predict measures of structural stability at minimum strength, Soil Sci., **158** : 170–173.

Rasiah, V. and Kay, B.D. (1994) : Quantifying the changes in clay stabilization after the introduction of forages, Soil Sci., **157** : 318–326.

Rasiah, V., Kay, B.D. and Martin, T. (1992) : Variation of structural stability with water content : Influence of selected soil properties, Soil Sci. Soc. Am. J., **56** : 1604–1609.

Shanmuganathan, R.J. and Oades, J.M. (1982) : Effect of dispersible clay on the physical properties of B horizon of a red-brown earth, Aust. J. Soil Res., **20** : 315–324.

Shennan, C. (1992) : Cover crops, nitrogen cycling and soil properties in semi-arid irrigated vegetable production systems, Hort Sci., **27** : 749–754.

Stivers, L.J., Shennan, C. Jackson, L.E. van Bruggen, A.H.C. Miller, P.R. and Griffin, C.J. (1990) : Winter cover cropping in vegetable production systems. *In* : Abstracts of the International symposium on Agroecology and conservation issues in temperate and tropical regions. 26 Sept. 1990. University of Padova, Italy.

Sumner, M. E. (1993) : Sodic soils : New perspectives, Aust. J. Soil Res., **31** : 683–750.

Swift, R. S. (1991) : Effects of humic substances and polysaccharides on soil aggregation. In Advances in soil organic matter research : The impact on agriculture and environment. W.S. Wilson (ed). The Royal Soc. Chem., Cambridge, UK. pp. 153–162.

Wyland, L.J., Chaney, L.E. Klonsky, W.E. Koike, S. T. and Kimple, K. (1996) : Winter cover crops in a vegetable cropping system : Impacts on nitrate leaching, soil water, crop yield, and management cost, Agric. Ecosystems Environ., **59** : 1–17.

異なる土性を持つ土壌の作付条件下における分散性及び安定性粘土の可能最大量

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要　旨

粘土分散の変化に作用する物理的・機械的なストレスは特に規模が大きく集約的な農業生産系において大きな持続的及び環境的問題である。しかしながら粘土の分散はストレスが減少し最小になるか除去されたとき安定する可能性が高い。本研究の目的は，(i) ストレス負荷の有無のそれぞれにおいて，異なる土性の土壌における分散性粘土（DC_{max}）と安定性粘土（SC_{max}）の可能最大量を定量すること，(ii) DC_{max} および SC_{max} に影響する固有土壌変数（S）を求めることである。粘土分散の測定は種々の作物条件下において 6 種類の土性の土壌を用いて 3 年間の間毎月行われた。研究に用いられた作物圃場は慣行的に耕作され，連作下のコーン（CTCC）と牧草であり，1989 年に設定された。そこは実験以前 10 年以上 CTCC 条件下にあった。CTCC は負荷を加えた時のシステム，牧草は負荷を減らした時のシステムをあらわす。全粘土量（TC）が 6.4〜33.8 %に比べて，負荷を加えたとき土壌の DC_{max} は 3.2〜16.6 %の範囲であった。DC_{max} は TC の増加，土壌の有機物（SOM）の減少に伴って大きくなった。負荷を減らしたとき土壌の SC_{max} は 1.2〜4.5 %の範囲であり TC，SOM，pH の増加に伴って大きくなった。DC_{max} の 11〜37 %は牧草の導入でストレスが減少したとき 3 年間安定していた。CTCC から牧草へ切り替える時期， すなわちストレスが減少させられる時期に存在する SOM の量は同程度の TC をもつ土壌中の分散粘土の安定化に大きな役割を演じた。この結果はストレス減少後の分散粘土の安定性が分散粘土含量と SOM に左右されることを示している。

キーワード : 分散性粘土，安定性粘土，土性，土壌有機物，物理的機械的ストレス

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