Note
Theory of Electroosmosis in Soil

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This paper aims to review the electroosmosis in soils. Electroosmosis is movement of a fluid with respect to a solid wall as a result of an applied electric potential gradient. The Helmholtz-Smoluchowski model is widely to describe electroosmosis processes. The rate of elecro-osmotic flow is controlled by the coefficient of electro-osmotic permeability of the soil which is zeta potential dependent. Numbers of researchers have studied the variation of the coefficient of electro-osmotic permeability of soils. These values range from 4.91×10^{-06} to 1.57×10^{-05} $cm^2 s^{-1} V^{-1}$.

1. INTRODUCTION

Electroosmosis involves water transport through a continuous soil particle network, where the movement is primarily generated in the diffuse double layer or moisture film where the cations dominate. When the direct electrical gradient is applied to a clay-water system, the surface or particle is fixed, but the mobile diffused layer moves and the solution with it is carried. According to Hausmann (1990), greater soil particle surface results in higher moisture film transfers[1]. Electrical potential applied and viscosity can also affect this phenomenon [1]. The main mechanism in electroosmosis is the migration of ions, meaning the cations migrate to the cathode and the anions move towards the anode [2]. (Figure 1).

Reuss (1809) discovered that water flow could be persuaded through a capillary by an external electrical gradient [3]. There are several theories for description of electroosmosis including Helmholtz-Smoluchowski theory, Schmid theory, Spiegler friction model, Buckhingham π theory, and ion hydration theory [4-5].

The electro-osmotic flow that results from the fluid surrounding the soil particles is induced by ionic fluxes [7]. In addition, the water molecules in flow in bulk phase can be carried out along with flow from the fluid surrounding the soil particles in the same flow direction. Interaction between flow in the fluid surrounding the soil particles as a first region and flow in the bulk phase as a second region enables the movement of water in the bulk phase, meaning a drag action is the main cause of the electro-osmotic flow. Therefore, the total observed electro-osmotic flow is attributed to the movement of these two water layers. It is noteworthy that positive surface charge has a contrary effect, meaning the electro-osmosis to occur from cathode to anode [8].
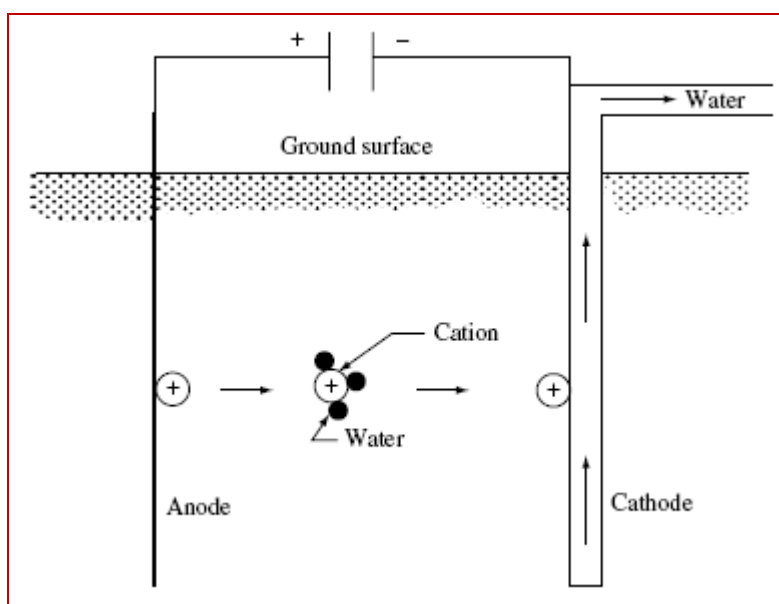

Figure 1. Principles of Electroosmosis (Adopted from [3])

2. HELMHOLTZ-SMOLUCHOWSKI THEORY

The Helmholtz-Smoluchowski theory is one of the widely used models to describe electroosmotic processes [9-10]. The Helmholtz-Smoluchowski theory assumes the pore radii are relatively large in comparison by the thickness of the diffuse double layer and the mobile ions are concentrated near the soil-water interface (Figure 2). Based on the Hemholtz-Smoluchowski, the zeta potential (ζ) and the charge distribution in the fluid adjacent to soil surface play important roles in determining the electro-osmotic flow. The ζ is the electric potential developed at solid-liquid interface in response to movement of colloidal particles; i.e., ζ is the electrical potential at junction between the fixed and mobile parts of the electrical double layer. The ζ is less than the surface potential of particle and shows the value at the slip plane, which is located at a small unknown distance from the colloidal surface [11-12].

The magnitude and sign of the ζ is dependent on the interfacial chemistry of both liquid and solid phase [8]. This potential is also influenced by ion exchange capacity, size of ion radius, and the thickness of the double layer [14-15].
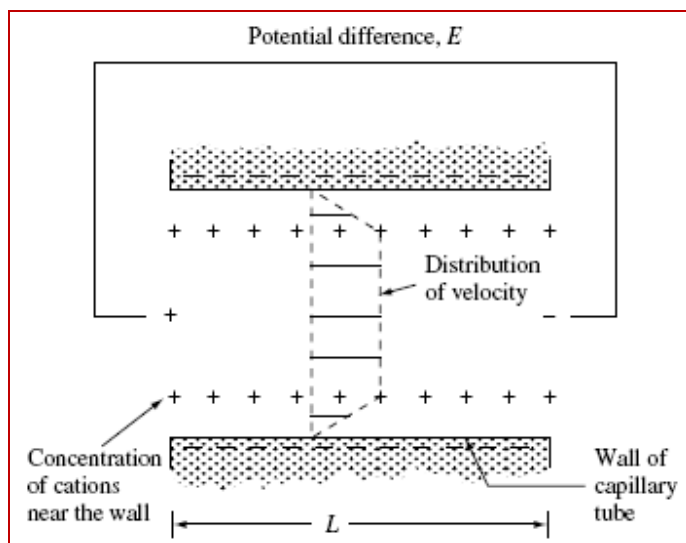

Figure 2. Helmholtz-Smoluchowski Theory for Electroosmosis (Adopted from [3])

The rate of elecro-osmotic flow is controlled by the coefficient of electro-osmotic permeability of the soil, k_e, which is a measure of the fluid flux per unit area of the soil per unit electric gradient. The value of k_e is a function of the ζ, the viscosity of the pore fluid, the soil porosity, and the soil electrical permittivity. The coefficient of electro-osmotic permeability is given by Equation (1):

$$q = \frac{\varepsilon\zeta}{V_t} n \frac{E}{L} A \tag{1}$$

Where:
ζ = Zeta potential
V_t = Viscosity of the pore fluid
n = Soil porosity
ε = Soil electrical permittivity
A = Gross cross-sectional area perpendicular to water flow
L = Length
q = Flow rate

Hydraulic conductivity, k_h, is significantly affected by the pore size and distribution in the medium, but k_e based on the Helmholtz-Smoluchowski theory is dependent mainly on ζ and n. ζ is one of the important electrokinetic properties of soil colloids (Figure 3).

Several researchers have studied the ζ potential of clay minerals in different solutions [13,17-20]. The results showed that concentration of electrolyte, type of electrolyte, valance of ions, and pH are important factors and can affect ζ values.

The value of k_e is assumed to be constant during the electrokinetic process as long as there is no change in the concentration of ions or pH of the pore fluid [4,5]. Based on the Hemholtz-Smoluchowski, the ζ and the charge distribution in the fluid adjacent to soil surface play important roles in determining the electro-osmotic flow.
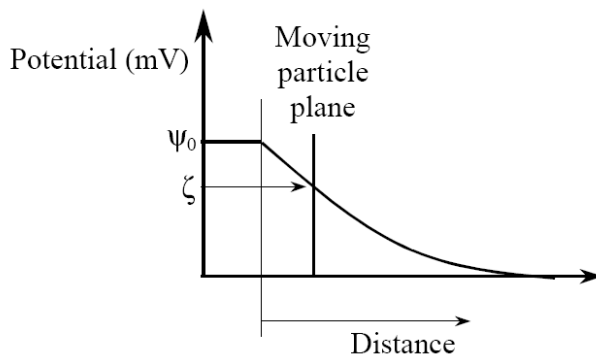

Figure 3. Potential Distribution Showing the Slipping Plane (Zeta) Potential (Adopted from [16])

The ζ can be measured by zeta meter (Figure 4), the measurement is very direct. The sample is placed in a chamber which is called an electrophoresis cell. Electric field is then activated. Then the colloids move with a velocity that is proportional to their zeta potential. The direction of the movement can show whether their charge is positive or negative.

1. Keypad 2. DC Power Supply
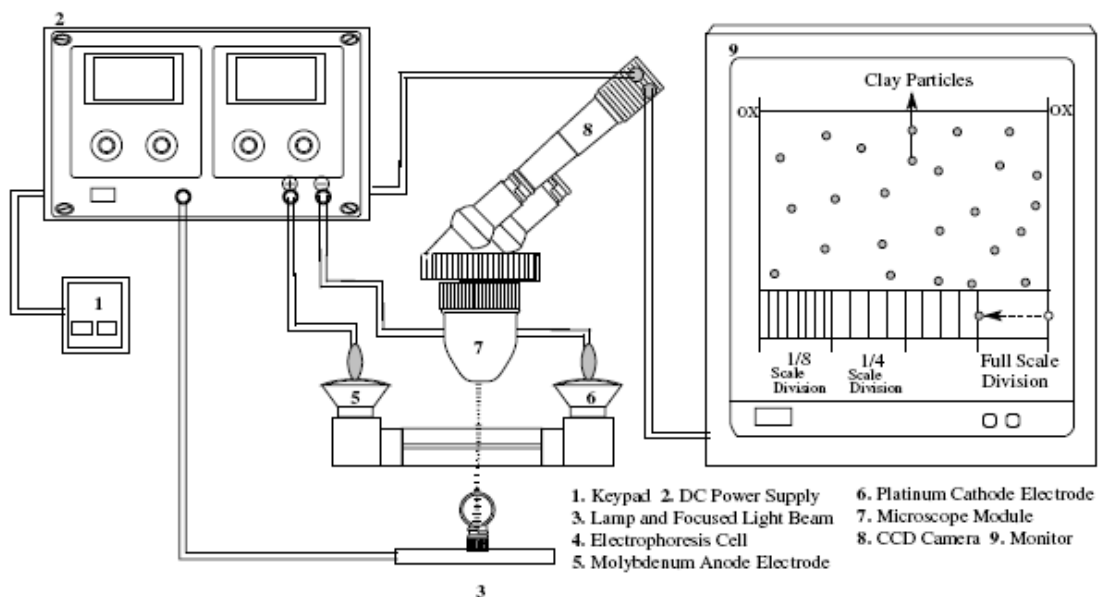3. Lamp and Focused Light Beam
4. Electrophoresis Cell
5. Molybdenum Anode Electrode
6. Platinum Cathode Electrode
7. Microscope Module
8. CCD Camera 9. Monitor

Figure 4. Arrangement of Zeta-Meter 3.0$^+$ Unit (Adopted from [6])

The Smoluchowski's equation, the most elementary expression for ζ gives a direct relation between zeta potential and electrophoretic mobility, which is (Equation (2)):

$$\zeta = 4\pi V_t \frac{EM}{D_t} \qquad (2)$$

Where:

ζ = Zeta potential

EM = Electrophoretic mobility at actual temperature

V_t = Viscosity of the suspending liquid

D_t = dielectric constant

It is preferable to calculate the ζ in millivolts instead of in electrostatic units. The formula then becomes (Equation (3)):

$$\zeta = 11300 V_t \frac{EM}{D_t} \qquad (3)$$

The ζ of a clay is usually negative, but the magnitude and sign of the ζ is dependent on the interfacial chemistry of both liquid and solid phase [8-13]. The ζ is a good indicator for the thickness of the double layer. As the ζ increases, the thickness of the double layer increases [11-12].

Negative ζ causes electroosmosis to occur from the anode to the cathode, while positive surface charge causes electroosmosis to occur from cathode to anode [8]. Some researchers have studied the variation of ζ in clays (for example, amorphous iron, gibbsite, and kaolinite) as a function of pH while there is no report of variation of ζ in organic soils. There is general agreement that ζ reduces in magnitude as acidity increases. The electro-osmotic flow can almost be eliminated at ζ of zero [21-27]

The Helmholtz-Smoluchowski theory assumes the pore radii are relatively large compared to the thickness of the diffuse double layer and all of mobile ions are concentrated near the soil-water interface. These assumptions are valid as long as soils with large pores are saturated with water. For small capillaries or unsaturated soils, the Helmholtz-Smoluchowski equation is less applicable.

Das [3] reported that Schmid in 1951 proposed a theory in contrast to the Helmholtz-Smoluchowski theory. It was assumed that the capillary tubes formed by the pores between clay particles are small in diameter and results in the excess cations would be uniformly distributed across the pore cross-sectional area (Figure 5). Based on this theory (Equation 4):

$$q = n \frac{r^2 A_o F}{8 V_t} \frac{E}{L} A \qquad (4)$$

Where:

r = Pore radius

A_o = Volume charge density

F = Faraday constant
n = Porosity
A = Gross cross-sectional area perpendicular to water flow
L = Length
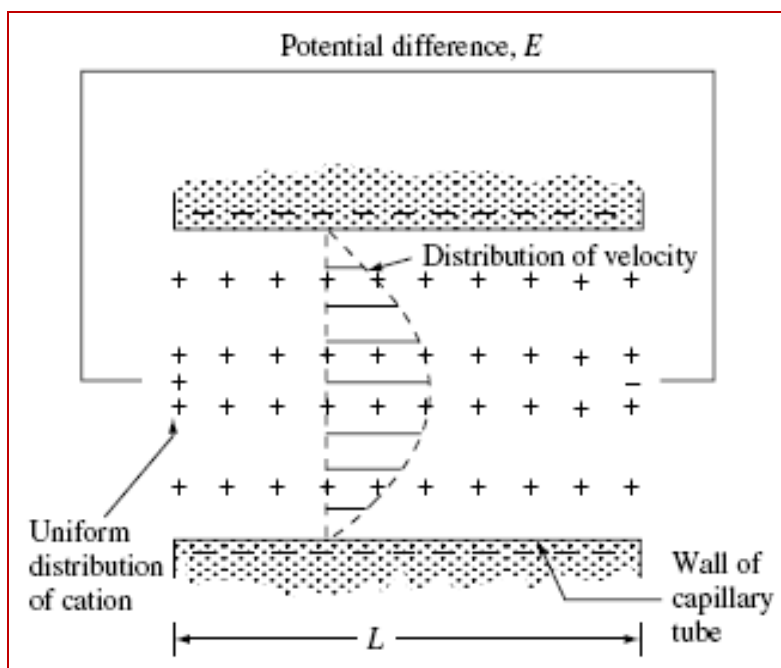V_t = Viscosity
q = Flow rate

Figure 5. Schmid Theory for Electro-osmosis (Adopted from [3])

However, the most widely used electro-osmotic flow equation for the soil system is proposed by Casagrande [32] (Equation (5)):

$$q = k_e i_e A \qquad (5)$$

Where:
A = Gross cross-sectional area perpendicular to water flow
i_e = Applied electrical gradient
k_e = Coefficient of electro-osmotic permeability
q = Flow rate

Table 1 shows some typical values of k_e for several soils [3-26-27-16].

Table 1. k_e of various soils

Soil type	k_e, cm²/s.V
London clay	5.8×10^{-5}
Boston blue clay	5.1×10^{-5}
Kaolin	5.7×10^{-5}
Clay silt	5.0×10^{-5}
Na-montmorillonite	2.0×10^{-5} to 12×10^{-5}
Peat	4.91×10^{-06} to 1.57×10^{-05}

(Adapted from [3-16-28-29])

Application of direct current through electrodes causes electrolysis reactions at the electrodes [22-25,30]. Oxidation of water at the anode generates an acid front and reduction at the cathode generate a base front. Electrolysis reactions are described by the Equations (6) and (7).

$$2H_2O - 4e^- \rightarrow O_2 \uparrow + 4H^+ \qquad \text{(anode)} \qquad (6)$$

$$4H_2O - 4e^- \rightarrow 2H_2 \uparrow + 4OH^- \qquad \text{(cathode)} \qquad (7)$$

Within the first few days of electrokinetic processing, electrolysis reactions decrease the pH at the vicinity of the anode and increase the pH at the vicinity of the cathode. These changes are dependent to the total current applied [22-25].

The acid generated at the anode advances through the soil towards the cathode. This is due to ionic migration and electroosmosis. The base generated at the cathode initially advances towards the anode. The base advance is because of diffusion and ionic migration. However, the counter flow because of the electroosmosis makes slower the back-diffusion and migration of the base front. The advance of base front is slower than the advance of the acid front because of (i) the counteracting electo-osmotic flow and (ii) the ionic mobility of H^+ is higher than OH^- [22-27,31].Geotechnical reactions in the soil pores significantly impact electrokinetic phenomena and can enhance or make slower the electrokinetic process. Geomechical reactions including precipitation, dissolution, sorption, and complexation reactions are highly dependent on the pH conditions [22-27,31, 34-36].

3. ELECTROOSMOSIS CELL

There is no standard setup. Figure 6 shows a schematic electro-osmotic cell (type I) which most of the researchers used for their experiments. Some limitations and advantages of this cell are as follows:

1-   It is hard to transfer the undisturbed soil samples into this cell.

2-   Potential gradient is relatively uniform along the cell.

3-   Natural soil samples are usually prepared vertically, while, electro-osmotic flow is horizontally.
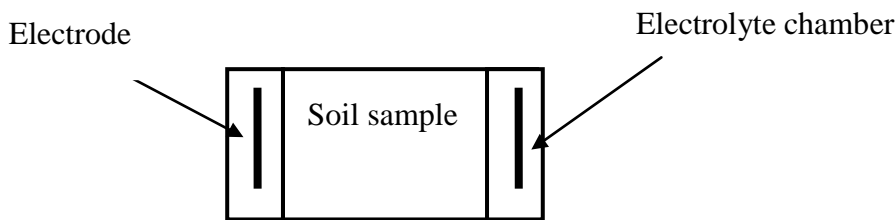

Figure 6. Schematic Diagram of Electro-osmotic Cell (Type I)

Figure 7 shows a schematic for another setup with the following limitations and advantages:

1-   It is similar to field electro-osmotic flow.

2-   Potential gradient is less uniform relative to type I

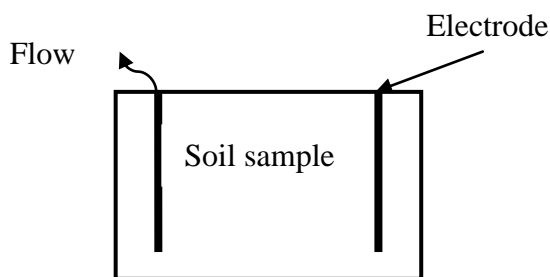3-   The analytical and experimental results may be less accurate in comparison with the previous cell.

Figure 7. Schematic Diagram of Electro-osmotic Cell (Type II)

4. CONCLUSIONS

Electro-osmosis is one of the electrokinetic phenomena and consists of the motion of liquid through a microporous medium under the influence of an applied electrical field. Reuss was the first to discover that a water flow could be induced through a capillary by an external electric field. In other words, if the soil is placed between two electrodes in a fluid, the fluid will move from one side to the other when an electromotive force is applied. In the presence of excess positive charges on the soil surface, a net electric driving force transports the water layer from the anode to the cathode. Based on the Helmholtz-Smoluchowski, the zeta potential plays the key role in electro-osmotic phenomena. Numbers of researchers have studied the variation of the coefficient of electro-osmotic permeability of soils. These values range from 4.91×10^{-06} to 1.57×10^{-05} $cm^2 s^{-1} V^{-1}$.

References

1. M.R., Hausmann, Engineering Principles of Ground Modifications, New York: McGraw Hill Publishing Company (1990).
2. S.A., Tajudin, I., Jefferson, C.D.F., Rogers, and D.I., Boardman, An International Conference on Recent Advances in Engineering Geology, Kuala Lumpur, Malaysia, (2008)143-150.
3. M.B., Das, Advanced Soil Mechanics. Taylor and Francis, New York, (2008) 594p.
4. D.H., Gray, *Geotechnique,* 20(1970) 81-93.
5. D.H., Gray, and H.K., Mitchell, *Journal of the Soil Mechanics and Foundations*, ASCE 93 (1967) 209-236.
6. Zeta-Meter System 3.0 Operating Instructions. Zeta-Meter, Inc., Staunton, VA.
7. J., Lyklema, and M., Minor, *Physicochemical Engineering Aspacts*, 140 (1998) 33-41.
8. G.R., Eykholt, and D.E., Daniel, D.E., *Journal of Geotechnical Engineering*, ASCE, 120(5) (1994) 797-815.
9. H., Helmholtz, *Annalen der Physik*, 7(1879) 337-382.
10. V.M.,Smoluchowski, Handbuch der Elektrizitat un der Magnetismus II, 2 (1921) 366-428.
11. J.R., Hunter, Zeta potential in colloid science. Academic Press, London, (1981)386 p.
12. J.R., Hunter, Introduction to Modern Colloid Science, Oxford Science Publications, Oxford University Press, New York (1993).
13. Y., Yukselen, and Y., Erzin, *Environmental Geology*, 54 (2008)1059-1066.
14. H.Y., Fang, and J.L., Daniels, Introductory Geotechnical Engineering. An environmental perspective. Taylor and Francis, Landon and New York, (2006) 545 p.
15. H.Y., Fang, Introduction to Environmental Geotechnology, CRC Press, Boca Raton, FL, (1997) 652p.
16. J.K., Mitchell, and K., Soga, Fundamentals of Soil Behavior. John Wiley and Sons, New Jersey, (2005) 577p.
17. J., Hamed, Y.B., Acar, and R.J., Gale, Journal of Geotechnical Engineering, ASCE, 117(2) (1991) 241-271.
18. J.T., Hamed, and A., Bhadra, *Journal of Hazardous Materials*. 55 (1997) 279-294.
19. L.J., West, D.I., Stewart, A.M., Binley, and B., Shaw, *Engineering Geology*, 53 (1999) 205-215.
20. L.J., West, and D.I., Stewart, D.I., Geotechnical Special Publication No. 46, ASCE, New York, N.Y., 2 (1995) 1535-1549.
21. P.B., Lorenz, *Clays and Clay Minerals*, 17 (1969) 223-231.
22. Y.B., Acar, R.J., Gale, G.A., Putnam, J., Hamed, and R.L.,Wong, *Journal of Environmental Science and Health, Part A* (6) (1990) 687-714.
23. Y.B., Acar, M.F., Rabbi, E.E., Ozsu, E.E., *Journal of Geotechnical and Geoenvironmental Engineering*, (1997) 239-249.
24. Y.B., Acar, R.J., Gale, J., Hamed, and G., Putnam, *Transportation Research Record, Geotechnical Engineering* 1288 (1990) 23-34.
25. Y.B., Acar, and A.N., Alshawabkeh, *Environmental Science and Technology*. 27(13) (1993) 2638-2647.
26. A.N., Alshawabkeh, and Y.B., Acar, Y.B., *Journal of Environmental Science and Health*, A27 (7) (1992) 1835-1861.
27. A.N., Alshawabkeh, T.C., Sheahan, X., Wu, *Mechanics of Materials*, 36 (2004) 453-465.
28. A., Asadi, B.B.K., Huat, M.M., Hanafi, T.A., Mohamed, and N., Shariatmadari, *Geosciences Journal*, 13(2) (2009) 175-181.
29. A., Asadi, B.B.K., Huat, M.M., Hanafi, T.A., Mohamed, N., Shariatmadari, *Geosciences Journal* 14(1) (2010) 65-75.
30. N., Cherepy, and D., Wildenschild, *Environmental Science & Technology*, 37 (2003) 3024-3030.
31. R.F., Probstein, and R.E., Hicks, *Science*, 260 (1993) 498-504.

32. L., Casagrande, *Geotechnique*, 1(3) (1949) 159–177.
33. L. *Casagrande, Journal Boston Society of Civil Engineers*. 69(2) (1983) 255-302.
34. Mohamedelhassan, E. and Shang, J.Q., 2003, *Canadian Geotechnical Journal*, 40 (6), 1185-1199.
35. A. Asadi, H. Moayedi, Huat B. B. K., F. Zamani B. A. Parsaie, S. Sojoudi, *Int. J. Electrochem. Sci*., 6 (2011) 1146-1158.
36. British Standard Institution, Methods of test for soils for civil engineering purposes. BSI 1377, Part 1-9, HMSO, London, UK, (1990) 427p.
37. Zeta-Meter System 3.0 Operating Instructions. Zeta-Meter, Inc., Staunton, VA. R. Mikutta, M. Kleber, K. Kaiser, and R. Jahn, *Soil Science Society of America Journal*, 69 (2005) 120-135.