

PRINCIPLES OF WATER AND NUTRIENT MOVEMENT IN SOILS

J. M. Davidson¹

The soil-water content in the root zone of an actively growing crop is constantly changing. The rate at which these changes occur depends upon the physical and chemical properties of the soil, plant activity and other environmental conditions. An understanding of the basic principles influencing the distribution and movement of soil water and plant nutrients is essential for minimum cost/benefit ratios in regions where agriculture uses irrigation water and/or fertilization for optimum production. This manuscript discusses the basic principles of soil-water and plant-nutrient movement in soils and the application of these concepts to field problems.

ENERGY STATUS OF SOIL WATER

Soil water, like other bodies in nature, has kinetic and potential energy. The velocity of water movement in soils is very small, as compared to that in a pipe or a stream, hence the kinetic potential component is small and can be neglected without introducing a serious error. The potential energy of a unit mass of soil water depends upon its position and internal condition in the soil profile. The potential concept of soil water is of primary importance in understanding the direction and amount of soil water movement. Soil water obeys the universal pursuit of equilibrium (uniform potential through the system) by moving constantly in the direction of decreasing potential energy.

The potential energy of a unit mass of water is defined as the amount of work required to transfer a small quantity of water from a reference pool at the soil surface to a given location in the profile. Thus, the total potential is the sum of the gravitational potential term, the location below the reference position, and soil-water potential term. Gravitational potential is defined to be zero at the soil surface and decreases with increasing depth. Soil-water

potential is zero in the reference pool, positive in a saturated soil (below the water table) and negative in unsaturated soil (above the water table).

Soil-water potential can be measured as a pressure or head. When expressed as a pressure it is called suction or tension to indicate its negative value in unsaturated soils. Common units of pressure are the bar (metric unit) or the atmosphere (U. S. unit). Any pressure can also be expressed as a hydraulic head, which is the height of a water column equivalent to that tension. Therefore, only small pores contain water at large tensions, while all pores are filled with water at zero tension (saturation). Pore size distribution of a soil thus determines the amount of water in a soil at a given tension. This concept is illustrated in Fig. 1. A large proportion of the pores are relatively large in a sandy soil and are emptied rapidly with small increases in tension. This explains why the soil-water content of sandy soils are generally low in a well-drained sand profile. Clay soils, on the other hand, possess a broad range of pores, resulting in a gradual change in water content with increasing tension (Fig. 1). Loam is intermediate between sand and clay.

SOIL-WATER FLOW

The direction and amount of soil-water flow between 2 locations in the soil profile can be determined from the total soil-water potentials at these locations. Soil water always moves in the direction of decreasing potential.² The amount of flow is proportional to the total potential (TP) gradient between the 2 locations. The gradient is defined as the difference in total potential ($TP_1 - TP_2$) divided by the distance between the 2 locations ($z_1 - z_2$).

²Soil water does not necessarily move from a region of high water content to a region of low water content, as indicated by the movement of water from an unsaturated zone into a water table (saturated).

¹Professor of Soil Physics, Soil Science Department, University of Florida, Gainesville.

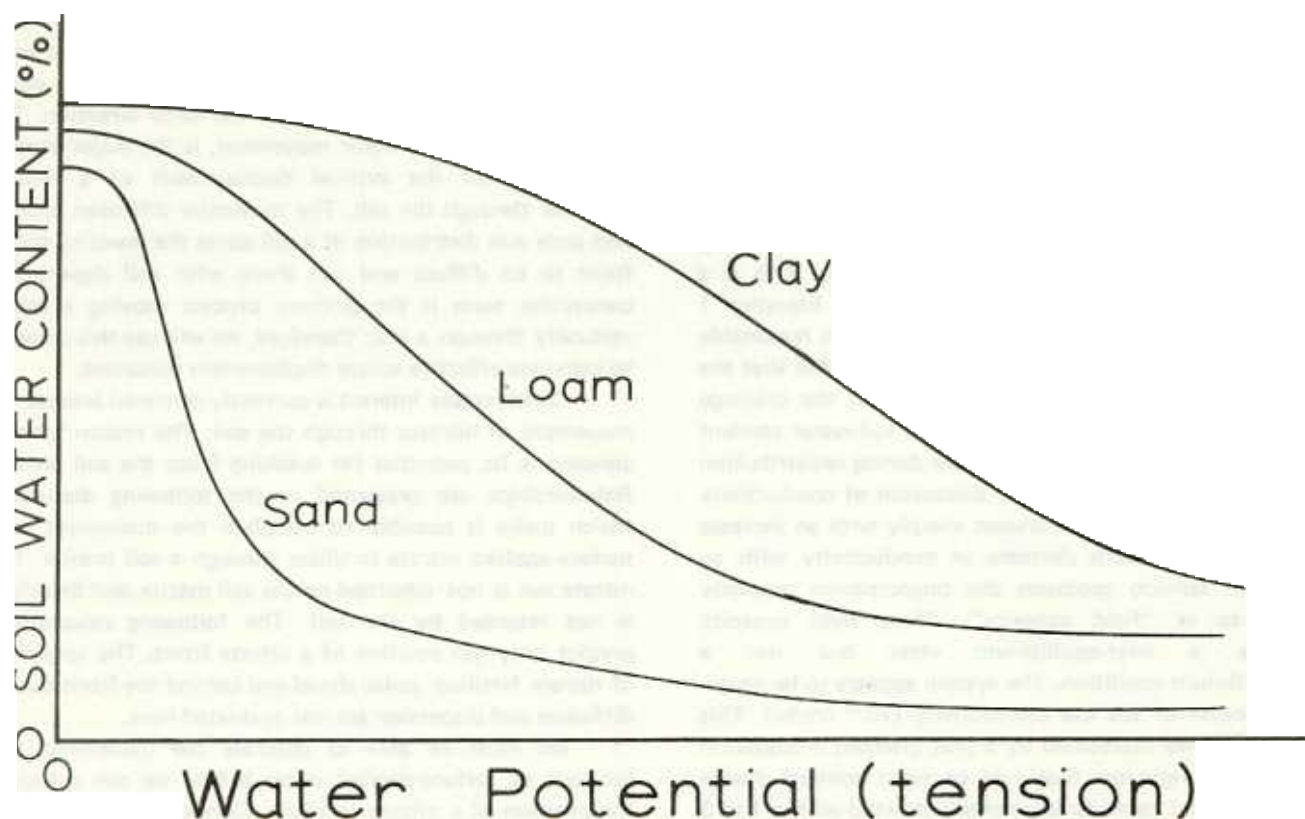


Fig. 1. Relationship between soil-water content and potential (tension) for clay, loam and sand.

The amount of soil water flow (q) is expressed by Equation 1:

$$q = (K) (\text{gradient}), \quad (1)$$

where K is the proportionally factor called hydraulic conductivity.

Equation 1 is called Darcy's law, and is analogous to Ohm's law for electricity.

The hydraulic conductivity, K , in Equation 1 varies with pore size distribution (e.g. soil texture and structure) and soil-water content. The conductivity of a water-saturated sand is generally much greater than that for a water-saturated loam or clay soil. This is because conductivity is proportional to the square of the soil pore size conducting water. Therefore, soils with large pores (sands and well-aggregated loams) have greater water-saturated conductivities. The larger pores fill with air when the soil becomes unsaturated, leaving the water to flow through the smaller pores. The conductivity of an unsaturated soil decreases sharply for this reason from its saturated value. For example, the conductivity decreases 100-fold at low water contents of high tensions when the water conducting pore size decreases 1/10 of the original size. The conductivity may be so low that very large differences in total potential are required to produce appreciable soil-water movement.

Infiltration is the term applied to the process of water entry into the soil, generally through the soil surface and vertically downward. This process is of practical importance and its rate can be calculated with Equation 1. An understanding of the infiltration process and how it is influenced by soil properties and initial soil-water content is necessary for efficient soil-water management as well as irrigation system design.

The infiltration rate (cm/hr) depends upon initial soil-water content (soil-water potential), texture and soil profile uniformity. We will assume for this discussion that the profile is uniform in texture and structure with depth and does not change during infiltration. Also, the initial soil-water tension or water content is the same throughout the profile and a lower soil-water tension (e.g. zero tension) is maintained at the soil surface during infiltration. We see from Equation 1 that the above condition produces a difference in total potential, high at $z = 0$ and low in the profile. The distance between the potential measurements from the soil surface to the position of the wetting front increases with time as infiltration proceeds. This results in a decrease in the gradient or difference in total potential divided by distance. Conductivity can be assumed to be constant and equal to the saturated conductivity, if free

water is maintained on the soil surface (tension = 0). The gradient decreases as water penetrates deeper into the soil profile and approaches unity which is the natural gravitational gradient. Thus, the infiltration rate decreases with time and approaches a constant value. This fact is important to irrigation system design for selecting the maximum water application rate.

The soil-water content decreases with time owing to drainage after the cessation of infiltration. This is a common observation in all well-drained soils. Equation 1 can also be used to describe this process. It is reasonable to assume for a uniform well-drained soil profile that the gradient in Equation 1 is unity throughout the drainage period. This means that the tension and soil-water content are the same at all depths at any time during redistribution or drainage. We know from our discussion of conductivity that this soil parameter decreases sharply with an increase in tension. This sharp decrease in conductivity with an increase in tension produces the phenomenon generally referred to as "field capacity". Thus, field capacity represents a near-equilibrium state but not a true-equilibrium condition. The system appears to be equilibrium because of the low conductivity (10^{-3} cm/hr). This low conductivity multiplied by a unit gradient in Equation 1 produces a very low flow rate or water content change with time. Field capacity is generally attained within 1 to 3 days depending upon drainage rate and the conductivity versus tension relationship. The field capacity water content can be taken as constant for many water management practices. The tension range in which field capacity generally occurs is 0.07 to 0.15 bars, and is not necessarily related to soil texture. The field capacity soil-water content is low for sands and high for fine textured soils.

It is obvious from the above discussion that the soil-water system is well-ordered, although complex, and follows specific physical laws. Also, soil-water contents in a soil profile are constantly changing, but these differences may not be readily discernible owing to low flow rates. It is possible to make some general statements about plant-nutrient movement, keeping these facts in mind.

PLANT-NUTRIENT MOVEMENT

Soil water is a solution and contains various soluble substances such as plant nutrients that move within and along with the soil-water phase. Some of the nutrients may be absorbed to the soil matrix, precipitated out of solution, taken up by the plant or leached from the root zone. An understanding of the relationship between soil water and plant nutrient movement is essential, therefore, for economic fertilizer usage and ground-water contamination prevention.

Substances dissolved in the soil solution can move by

molecular diffusion, due to concentration gradients within the solution, or by convection (Equation 1), due to mass transfer of the soil solution. These 2 processes occur simultaneously but not always in the same direction. The convective term, soil-water movement, is the major process responsible for the vertical displacement of a soluble fertilizer through the soil. The molecular diffusion process and pore size distribution of a soil cause the invading solute front to be diffuse and not sharp with soil depth. The convective term is the primary process moving a solute vertically through a soil; therefore, we will use this concept to calculate effective solute displacement distances.

Considerable interest is currently centered around the movement of nitrates through the soil. The reason for this concern is its potential for leaching from the soil profile. Relationships are presented in the following discussion which make it possible to calculate the movement of a surface-applied nitrate fertilizer through a soil profile. The nitrate ion is not adsorbed on the soil matrix and therefore is not retarded by the soil. The following calculations predict only the position of a nitrate front. The spreading of nitrate fertilizer pulse ahead and behind the front due to diffusion and dispersion are not evaluated here.

We must be able to describe the movement and location of surface-applied water before we can calculate the position of a nitrate fertilizer. Consider the infiltration of X cm of water into a soil profile at a uniform soil-water content θ . Soil-water content, θ , is expressed on a fractional basis, cm^3 of water/ cm^3 of total soil volume. The depth, d_{wff} , to which a wetting front will advance into a uniformly wet or dry soil can be calculated from Equation 2:

$$d_{wff} = \frac{X}{\theta_f - \theta_i}, \text{ where } \theta_f > \theta_i \quad (2)$$

and d_{wff} is distance (cm) from the soil surface to wetting front, X is depth of water (cm) that has entered the soil at $z = 0$, and θ_f and θ_i are the final and initial soil-water contents.

D_{wff} is 14.3 and 28.6 cm for X equal 5 and 10 cm of water when θ_i is 0 and θ_f is $0.35 \text{ cm}^3/\text{cm}^3$ (Fig. 2). The wetting front positions for the above water applications are 20 and 40 cm, respectively, if θ_i is $0.1 \text{ cm}^3/\text{cm}^3$ and θ_f is $0.35 \text{ cm}^3/\text{cm}^3$ (Fig. 3).

It can be concluded from Figs. 2 and 3 and Equation 2 that for a given water application, X , the distance from the soil surface to the wetting front will increase as the initial soil-water content, θ_i , increases. However, the water at the wetting front when θ_i is greater than zero is not the same water that was added, but that which was displaced ahead of the infiltrating water. This point is important when considering the distance a nitrate fertilizer will move into a soil. The water applied to the initially wet soil (Fig. 3) occupies approximately the same position and distri-

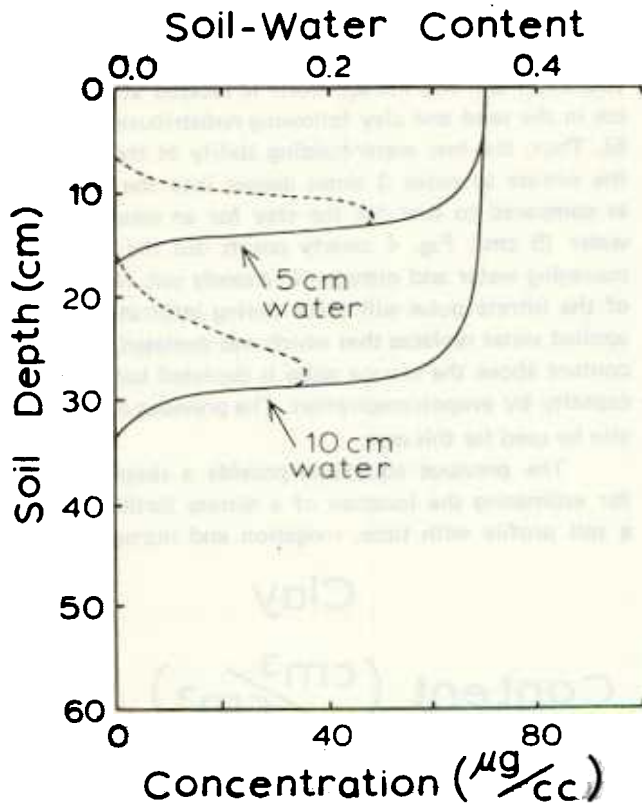


Fig. 2. Distribution of water (solid line) and nitrate (dashed line) after 5 to 10 cm of water had entered an initially dry soil. Nitrate was applied to the soil prior to the infiltration event.

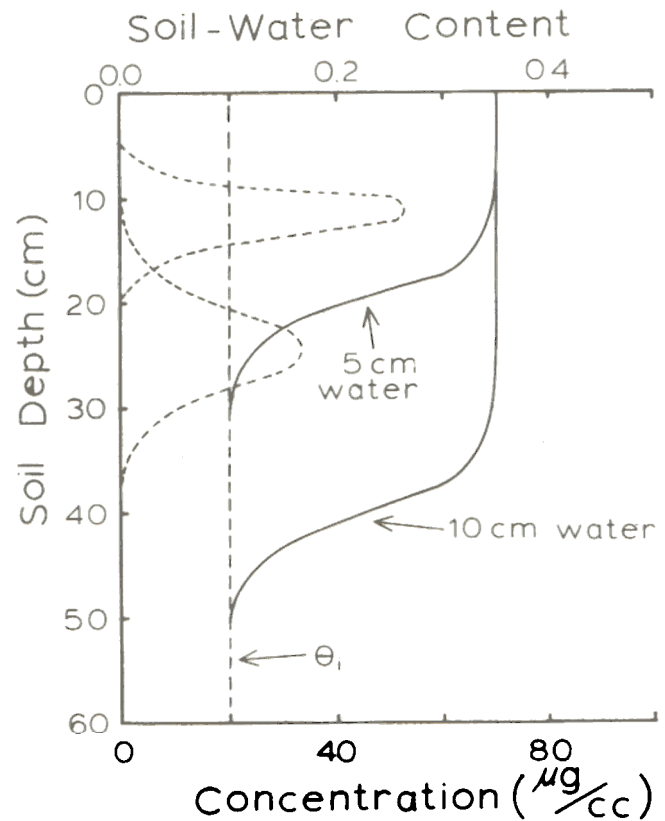


Fig. 3. Distribution of water (solid line) and nitrate (dashed line) after 5 to 10 cm of water had entered a soil with an initial soil-water content (θ_i) of $0.1 \text{ cm}^3/\text{cm}^3$ (vertical dashed line). Nitrate was applied to the soil prior to the infiltration event.

tribution as that for the dry soil (Fig. 2).

Nitrate front positions, d_{nf} , can be calculated from Equation 3:

$$d_{nf} = \frac{X}{\theta_f}, \text{ where } \theta_f \neq 0 \quad (3)$$

and d_{nf} is distance (cm) from the soil surface to the nitrate front.

Note that the nitrate front position depends upon the amount of water and the average soil-water content behind the wetting front, θ_f , but not the initial soil-water content (Figs. 2 and 3). This means that water does not move only through the empty (larger) pores, but rather interacts with all the pores that contain water.

The nitrate and water fronts are the same for X equal 5 and 10 cm and θ_i equal zero (Fig. 2). The nitrate front is not at the wetting front, however, when the initial soil-water content, θ_i , is $0.1 \text{ cm}^3/\text{cm}^3$ and X is 5 and 10 cm but is at the same position as it was for the dry soil case (Fig. 3 and Equation 3). It is obvious from Figs. 2 and 3 that nitrate and water fronts are not always analogous. Equation 3 can be used to calculate the depth any soluble non-adsorbed solute will move through a soil

profile following the application of X cm of water.

The soil-water content behind the wetting front decreases due to drainage or redistribution after the cessation of infiltration. This process results in a deeper penetration of the water and nitrate front. The additional movement of the nitrate front, d'_{nf} , due to redistribution can be determined by the amount of "drainable" water ($\theta_f - \theta_{FC}$) above d_{nf} . θ_{FC} is the field capacity soil-water content by volume. The nitrate front position after redistribution can be calculated with Equation 4:

$$d'_{nf} = d_{nf} + \frac{(\theta_f - \theta_{FC}) (d_{nf})}{\theta_{FC}}, \text{ where } \theta_{FC} > 0. \quad (4)$$

and d'_{nf} is the depth (cm) at which the nitrate front is located following redistribution and ($\theta_f - \theta_{FC}$)

(d_{nf}) is the amount of drainable water above d_{nf} .

Equation 4 can be rearranged and Equation 3 solved for X and substituted into Equation 4 to give Equation 5:

$$d'_{nf} = \frac{X}{\theta_{FC}}, \text{ where } \theta_{FC} > 0. \quad (5)$$

Equation 5 applies only for the case where the nitrate is at the soil surface when X cm of water was applied and

allowed to redistribute to field capacity. Equation 4 with X substituted for $(\theta_f - \theta_{FC}) (d_{nf})$ could be used to describe the additional movement or new location, d_{nf} , of the nitrate front if the nitrate pulse was located at a given depth, d_{nf} , because of a previous rainfall or irrigation event. Equation 5 is an important relationship and can be used to improve fertilizer management programs.

Fig. 4 and Equation 5 illustrate the importance of field capacity to the movement of nitrate or other non-absorbed solutes in sand and clay soils. The initial soil-water content, θ_i , in the sand and clay (Fig. 4) is $0.1 \text{ cm}^3/\text{cm}^3$. The soil-water content at $z = 0$ is 0.35 and $0.40 \text{ cm}^3/\text{cm}^3$ for the sand and clay, respectively. The field capacity soil-water contents, θ_{FC} , for the sand and clay are 0.1 and $0.3 \text{ cm}^3/\text{cm}^3$, respectively. The nitrate fronts are located at 14.3 and 12.5 cm in the sand and clay,

respectively, after 5 cm of water has infiltrated each soil (Equation 3). The nitrate front is located at 50 and 16.7 cm in the sand and clay following redistribution (Equation 5). Thus, the low water-holding ability of the sand causes the nitrate to move 3 times deeper into the sand profile as compared to that for the clay for an equal amount of water (5 cm). Fig. 4 clearly points out the difficulty in managing water and nitrogen in a sandy soil. No movement of the nitrate pulse will occur during infiltration until the applied water replaces that which was depleted, if the water content above the nitrate pulse is depleted below the field capacity by evapotranspiration. The previous equations can also be used for this case.

The previous equations provide a simple technique for estimating the location of a nitrate fertilizer front in a soil profile with time. Irrigation and nitrogen fertilizer

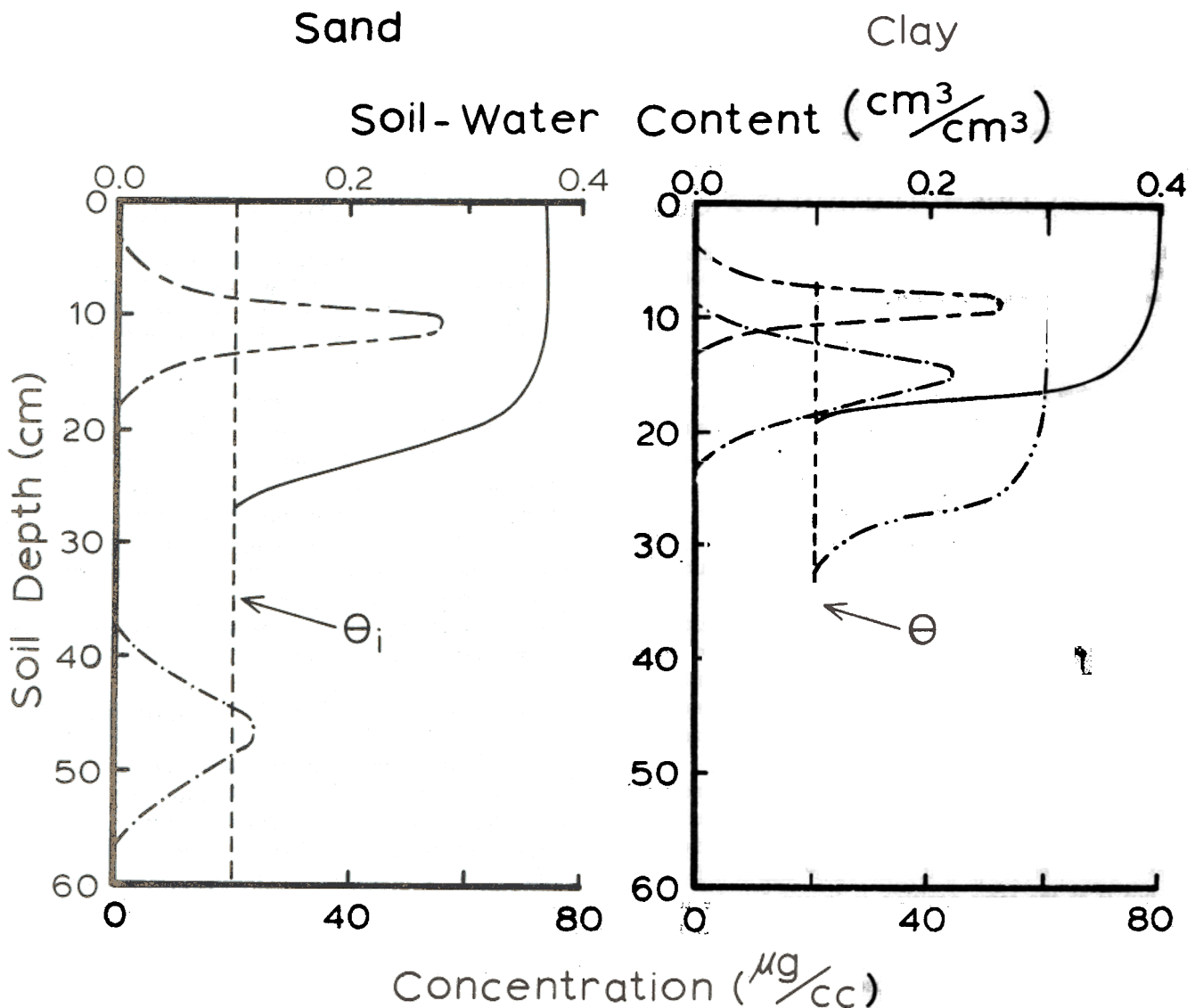


Fig. 4. Distribution of water following 5 cm of infiltration (solid line) and redistribution (dash plus 2 dots for clay, θ_i line for sand) in a sand and a clay soil. Initial soil-water content θ_i (vertical dashed line) was $0.1 \text{ cm}^3/\text{cm}^3$ for both soils. Nitrate distribution following infiltration (long plus short dash) and redistribution (dash plus dot) to field capacity soil-water content.

management programs for maximum recovery of the applied materials can be defined with this procedure. The only major soil parameter required for these calculations is a measurement of field capacity. This value can be obtained by removing a known volume of soil from a soil profile 2 or 3 days after a thorough irrigation or rainfall. The wet soil is weighed, oven dried (105°C for 24 hours) and weighed again to determine the amount of water lost by drying. The amount of water lost during drying is then divided by the volume of the soil sample to give soil-water fraction by volume (cm^3 or grams of water/ cm^3 of soil volume).

QUESTIONS

Q: Contrast the 2 situations where you have a dry soil: 1) you apply nitrogen fertilizer followed by 3 inches (75 mm) of water and 2) you apply 1 inch (25 mm) of water, followed by the fertilizer and another 2 inches (50 mm) of water. Isn't the second method the preferred one, due to the movement of the nitrogen?

Davidson: That's right. In fact, if you take the 2 inches (50 mm) and divide it by whatever the water content was, that will tell you the position of the nitrogen; whereas if you added 3 inches (75 mm) to a Lakeland (Astatula) sand, it will move 30 inches (76 cm) within 24 hours.

The initial water content does not influence the position of the nitrate. It only influences the position of the wetting front, so regardless of when the water arrives, when it is applied, by rain or by man, the depth to which the fertilizer will move depends on the amount of water that came in and the field capacity or the water content in that profile 24 hours later, regardless of the initial water content. Now what it does say in terms of management is that if we're to supply nitrogen for the whole growing season in 1 or 2 applications, we're going to be in much greater difficulty than if we put small amounts on at different times, because those pulses will follow one another sequentially through the profiles. If we put it all on at the beginning of the season, followed by irrigation to put it in, and then followed by rainfall, in many instances the fertilizer will leach through the soil. However, if you put a small amount on and come back in another 2 or 3 weeks and put another amount on, you will have these different pulses following one another, none of which will be a very high concentration in terms of ground water, pollution or total loss.

Q: What about the differences in movement of $\text{NO}_3\text{-N}$ vs $\text{NH}_4\text{-N}$ with respect to leaching through the soil profile?

Davidson: Let me give you an example of some things we have on Lakeland (Astatula) sands. We've put fertilizer on as an ammonium nitrate, put 3 inches (75 mm) of water on and went back the next morning to sample it. The nitrate for that ammonium nitrate, just the nitrate, will be at roughly 30 to 36 inches (76 to 96 cm), with little

spread behind it. Lakeland sand holds 10% water at field capacity—really closer to 8 or 9%. If I divide the 3 inches (75 mm) by the 0.1 that I know field capacity is going to be, that is exactly where that front will be—I will see all the nitrate that I applied at that position. Now that's not true for the ammonium because it was adsorbed and stayed back up in the profile. Maybe we ought to be looking at different sources of nitrogen in terms of reducing the rate of loss because of adsorption.

Q: Are you familiar with the charges of pollution of the groundwater supply by fertilizers used in agriculture? How does this relate to what you've said regarding nitrogen movement in the soil?

Davidson: Yes, I'm familiar with that, and I'd like to talk to Mr. Parker about that later. With all the drawdown we're getting, I fail to see where we're having a lot of contamination. If the wells are continuing to be drawn down without being recharged from agriculture, except in a few areas, I fail to see where nitrogen pollution as such is a serious problem.

Q: There's also concern about fertilizer pollution of lakes and streams due to runoff from agricultural areas. Will you comment on that?

Davidson: You mean it runs off in the surface water? Nitrogen as nitrate is extremely soluble and in most instances, it would move deep enough into the profile to protect it considerably from runoff, unless the water table is so high that infiltration is negligible. Even so, we found that very little nitrate would leave the surface because it is so soluble. Now if you put on something that is not soluble and you get some erosion, yes it will go off. However, nitrate should be soluble enough that it should move into the profile.

Q: What about the slower movement of ammonium through the soil? Why does ammonium move slower than nitrate?

Davidson: Ammonium would move about 1/2 to 1/3 the distance that nitrate would because of adsorption. The ammonium ion is positively charged, whereas the colloidal soil material is negatively charged, so ammonium goes on and comes off several times in cation exchange reactions. However, the nitrate ion is negatively charged and is repelled from clay surfaces, without being adsorbed, so it moves through the soil more rapidly.

Q: Why is it difficult in many cases to wet a dry soil in Florida? Is this considered a serious problem?

Davidson: I'll be honest with you—we don't know why some soils are unable to take water when they are dry. We know it exists and we know it is a problem, but we don't know the specifics nor the magnitude of it. The Soil Science Department is working on that now. In other areas, this condition exists in areas which have been burned over in a fire, but that is not the case here. There may, however, be similarities due to high temperature and lack of organic matter.