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EFFECTS OF THERMAL GRADIENTS UPON MASS TRANSPORT IN SOIL

by

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ABSTRACT

A field study of the movement of NO_3^- and Cl^- from surface applied $Ca(NO_3)_2$ and $CaCl_2$ was undertaken on Red River clay and Almasippi loamy sand. The downward movement of NO_3^- and Cl^-, the latter serving as a tracer for water movement, was quite small from application of the salt in July until April of the following year when the ground thawed. At that time NO_3^- and Cl^- moved to the water table.

The moisture contents of the soil profiles in the fields were found to be related to the soil temperature. The seasonal variation in the soil temperature at a fixed depth was found to be a typical cosine function. The amplitude of the cosine curve decreased with soil depth.

Laboratory investigations involved the study of water, NO_3^- and Cl^- movement in soil columns of different moisture contents incubated with and without a temperature gradient. Other factors studied included the effect of freezing one end of the column, reversal of temperature gradients, closed versus open columns and continuous columns as compared to those with an air gap.

In a closed continuous soil column with a temperature gradient but without freezing process, the movement of soil moisture was a circulation of soil water as a result of vapor condensation at the cold end and the return flow of liquid to the warm end. As the consequence of this circular movement the moisture accumulated at the cold end and salt concentrated at the warm end. The results obtained with discontinuous columns, in which the return flow of liquid was partially blocked, showed a similar concentration of salt near the warm end as was observed with continuous columns. It seemed, however, that the process of concentration of salt near the warm end of the soil column was due not only to the liquid water movement but also to the

Soret effect.

Both vapor and liquid forms of soil moisture moved to the frozen zone of soil columns. The rate of vapor movement was, however, greater than that of liquid water movement. The relative changes in Cl^- concentration based on soil solution and soil material in the frozen zone as compared to the initial values before subjecting to a temperature gradient were used in order to deduce the relative speed of vapor and liquid movement.

The distribution patterns of soil moisture, Cl^- and NO_3^- after thermal treatment in open soil columns were different from those observed in the closed columns. The position of maximum moisture content in the open column after subjecting to a temperature gradient was not located at the coldest end of the columns as was found in the closed column.

Reversing the direction of the thermal gradient during the period of thermal treatment, in order to simulate the freeze-up of the surface in fall and thawing from the surface in spring, resulted in an increase in salt transport to both ends of the soil column as compared to the column without such reversal treatment. The stability of the soil moisture in a system as governed by the direction of thermal gradients might be the cause of the increased salt transport.

A mathematical formulation for the simultaneous transport of vapor and liquid with condensation and vaporization under a thermal gradient in soil was carried out. Simultaneous partial differential equations for vapor and liquid transport in unsaturated soil columns were presented. Analytical or numerical solution of the differential equations could not be carried out.

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1 INTRODUCTION

Joffe (1949) defined soil as a natural body of mineral and organic constituents differentiated into horizons. Soil differs from the material below it in morphology, physical make up, chemical properties and composition, and biological characteristics. The definition fully embraces the non-equilibrium characteristics of soil. The temperature distribution within natural soil systems also follows the non-equilibrium characteristics of chemical composition and soil moisture. Moisture content, the presence of soluble substances and soil temperature are very important in governing plant growth and leaching or accumulation of soluble substances in the soil. These factors vary with plant growth and seasonal or diurnal fluctuations in atmospheric temperature and rainfall.

The soil moisture distribution in natural systems is never in equilibrium. The movement of soil moisture takes place within a soil profile. Movement induced by rainfall or evaporation from the soil surface is well known. The moisture moving downward after rainfall carries with it dissolved substances. The moisture moving upward accumulates the substances on the surface due to evaporation from the soil surface. Thus the direction and magnitude of soil moisture movement directly affects the movement of dissolved substances many of which are valuable plant nutrients. The movement of dissolved substances can also take place under uniformal soil moisture conditions. This process is generally called diffusion.

A temperature gradient within a soil profile either directly or indirectly induces mass transport. The mechanism by which mass is transported under a thermal gradient in soil is not fully understood. However, the mechanism seems different from convective or diffusive transport. Soil water may be present in vapor, liquid and solid phases while the transported substance of interest exists primarily in the liquid phase. The thermal gradient influences the movements of vapor, liquid and dissolved substances in different ways. In addition to influencing movement, the thermal gradient may also result in phase changes in soil moisture depending on local conditions. Because of varying solubilities of a substance in these phases, accumulation, depletion or exclusion of the substance may occur depending upon the magnitude of the phase change. Thus under a thermal gradient the movement of dissolved substances becomes very complicated.

In Manitoba, surface soil temperatures can range from about +30 to -35 C during a period of one year. The surface is the warmest part of the soil profile during the crop growing season. For more than half of the non-growing season, the surface soil is colder than lower horizons and frost may occur as deep as 1.5 meters. The transport phenomena that occur during the frozen period are not fully understood. The differences in NO_3^--N content of soil profiles sampled in fall and spring indicates that movement of water and dissolved substances does take place in the soil during this period.

In order to investigate the mass transport that occurs during the fall to spring period, field and laboratory experiments were conducted. The field experiment was designed to determine the magnitude of transport of surface-applied $Ca(NO_3)_2$ and $CaCl_2$ both of which contain water soluble anions. The laboratory investigation was initiated in order to determine the relative speed and direction of liquid and vapor flow and the movement of dissolved salt under a temperature gradient in a soil column. A mathematical modelling approach was also attempted.

2 LITERATURE REVIEW

2.1 Field Observation

Water is one of the most important materials for crop growth. The amount of water used to produce 1.25×10^3 Kg/ha of wheat is 3.05×10^6 Kg/ha but 99% of this water is lost by evaporation and transpiration (Shaykewich 1974). Water not only supports plant turgidity but also acts as a medium for the transport of essential plant nutrients. The ability of a soil to supply water and nutrients to crops is an important factor in agricultural production.

The direction and magnitude of water and solute movement under natural field conditions is very complicated. This is partly due to the heterogeneous nature of soil, microclimatic change and differences resulting from the presence or absence of a growing crop. Many field investigations have involved the measurement and prediction of water and solute movement under very dry or very wet conditions. Generally Darcy's law or a modified form of Darcy's law was successfully applied to describe the soil moisture transfer process. Diffusion and convective transport equations were used to describe solute transfer in soil. In applying these equations, an isothermal assumption was generally made in order to describe the water and solute transport in soil. Field observations and the theory of mass transport under isothermal conditions have been reviewed by several workers. Infiltration of moisture into soil, the general application of flow theory in the field and the factors affecting the flow were reviewed by Parr and Bertrand (1960), Swartzendruber (1966), Nielsen et al. (1972) and Klute (1973). Solute transport associated with water movement was discussed by Nielsen and Biggar (1973). The presence or absence of a water table upon moisture transport was reviewed by Raats and Gardner (1972).

Soil under natural conditions is not in a steady state with respect to temperature distribution. Seasonal and diurnal variations in atmospheric temperature affect the surface soil temperature. If the variation in the seasonal atmospheric temperature is expressed as a cosine wave then the soil temperature can be expressed by

$$T = T_o + T_1 e^{-kx} \cos(\omega t - kx) \qquad (1)$$

where T is the soil temperature, T_o is the average yearly temperature of the soil surface, T_1 is the amplitude of the surface temperature wave, ω is the frequency, $k = (\omega/2\Lambda)^{\frac{1}{2}}$, Λ is the thermal diffusivity, t is time and x is the depth (Carslaw and Jaeger 1959). The equation expresses the fact that the surface temperature wave is transmitted downward with damping. The diurnal temperature change is also expressible by a cosine wave, so that an equation similar to the above can be applied to the diurnal change in soil temperature (Cary 1965). In the latter case, however, the change in soil temperature throughout the horizon due to seasonal variation was taken into account by adding a linear term. Field observations made by Smith (1932) indicated that diurnal fluctuations of soil temperature occurred to a depth of approximately 30 cm and seasonal fluctuations occurred below this depth. The maximum soil temperature gradient due to diurnal temperature variation was found to be 10 C cm^{-1} (Rose 1968a). These temperature variations were known to induce mass transport in soil. Lebedeff (1927) and Edlefsen and Bodman (1941) attributed the upward movement of moisture during the winter season to vapor transfer caused by the temperature gradient associated with the annual wave. Rose (1968 a,b) observed water movement in the field corresponded to the diurnal temperature change. He found that the direction of liquid movement was upward through the profile even at suctions as low as 200 cm of water during both day and night. Water movement fluctuated in response to the diurnal temperature gradient with vapor moving downward at night time and upward during day time. At suctions greater than 5000 cm of water the predominant flow was in the vapor phase. He postulated a theory of mass transport due to a thermal gradient. However, the theory was found to be inadequate. He attributed this inadequacy to the assistance to vapor flux that can be provided by a discontinuous liquid phase. Jackson et al. (1973), during 16 days of measurement, observed a downward flux of soil moisture below 1 to 3 cm during several hours between sunrise and early afternoon. They concluded that there was soil water flux in the surface zone of a field subjected to diurnal variation. Soluble salts such as Cl^- also followed a diurnal pattern but out of phase with soil water during the first few days after irrigation in the 0 to 0.5 and 0 to 1 - cm depth increments. The diurnal amplitude of Cl^-, however, decreased with time as the soil progressively dried (Nakayama et al. 1973).

There are few field investigations concerning soil moisture transport during the winter period. Willis et al. (1961) detected no upward movement of soil water during the winter in North Dakota. However, in another study Willis et al. (1964) found that water table drop was associated with depth of frost. The drop was accompanied by an increase in soil moisture in the frost zone above the water table. Ferguson et al. (1964) found that an appreciable amount of water moved to the frozen zone in plots in which the unfrozen subsoil water was held at tensions less than about 2 atm.. They also noticed that water held at tensions of less than 5 atm. moved toward the frozen zone whereas soil water held by greater than 5 atm.

tension was not mobile toward the frozen zone. Sartz (1969), on the other hand, speculated that the frost was formed mainly by percolating water from the surface rather than by moisture transported from subsoil. He showed that water could readily infiltrate more than 60 cm of hard-frozen ground. However, he found that the frozen ground impeded percolation during spring melt.

2.2. Laboratory Investigation

Most laboratory studies were initiated to investigate the effects of hydraulic conductivity, soil-water characteristics, soil-salt reaction, salt-water interaction, temperature, temperature gradient and potential gradient upon water and salt movement. Movement under uniform temperature conditions is called isothermal mass transport and movement under the influence of a thermal gradient is known as nonisothermal mass transport.

2.2.1 Isothermal Mass Transport

Under constant temperature conditions, the description of mass transport is relatively simple and many studies have been conducted.

Darcy (1856) was the first scientist to derive an empirical mathematical formula to describe saturated water flow through a porous medium. This simple mathematical formulation is known as Darcy's law and is :

$$J = -K\nabla h \qquad (2)$$

where J is the total flux, K is the proportionality constant called the hydraulic conductivity and h is the hydraulic head.

Darcy's law was derived from observation of water flow through a sand. Olsen (1966) showed that this law was obeyed at low water gradients in saturated kaolinite over a wide range of porosities. Other studies (Fireman 1944; Low 1960; Olsen 1962,1965) also showed support for the application of Darcy's law to water flow in saturated clays. Lutz and Kemper (1959) showed that while Darcy's law was followed reasonably well for certain hydrogen - and calcium - saturated clays a positive deviation from Darcy's law was observed for other similar clays. It was also found that water flow in kaolinite and 50 per cent montmorillorite closely obeyed Darcy's law but this was not the case for 9, 30, and 40 per cent montmorillorite samples (Miller et al. 1969). Miller and Low (1963) reported the presence of a threshold gradient for water flow in clays. The threshold gradient decreased with decreasing clay content and increasing temperature. Even above the threshold gradient, they found the flow-hydraulic head relationship was curvilinear for samples of a high clay content at low gradients and for samples of a low clay content at any gradient. Swartzendruber (1962) found measured values for water flow exceeded that predicted by Darcy's law when sandy materials contained more than 5 per cent clay. Swartzendruber (1968) recalculated values for hydraulic conductivity, K, cited in the literature and found 2 to 4 fold variations in K to be fairly common with variability as high as 5 to 15 fold.

Factors which may account for differences between measured water flow and that predicted by Darcy's law has been discussed by several authors (Olsen 1966; Swartzendruber 1966,1968). Probable reasons for the deviations are : (1) the presence of a threshold gradient to initiate water flow and (2) increases in the hydraulic conductivity with increasing gradient. The tentative explanations of non-Darcian behavior are (1) quasi-crystalline water or modified water properties (Miller and Low 1963; Low 1961), (2) particle rearrangement (Micheals and Lin 1954; Martin 1962; Mitchell and Younger 1967), (3) electrokinetic effects or streaming potential effects (Micheals and Lin 1954; Kemper 1960), (4) range in pore sizes (Miller and Low 1963; Olsen 1966), and (5) experimental errors (Olsen 1965,1966).

Most of the processes involving soil-water movement in the field, and in the rooting zone, occur while the soil is in an unsaturated condition. Unsaturated water movement is more complicated and difficult to describe quantitatively than saturated flow. The processes of unsaturated flow change with changing water content, suction, and conductivity, which may be affected by hysteresis. Most studies have been conducted to investigate if Darcy's law would describe unsaturated water flow. Many authors (Richards 1931; Kemper 1960; Miller and Low 1963; Swartzendruber 1963; Olsen 1965; Thames and Evans 1968; Miller et al. 1969) reported unsaturated water movement deviated from Darcy's law. Deviations of 8-fold between measured values and that predicted by Darcy's law have been observed by Abdel-Aziz and Taylor (1965), Rawlins and Gardner (1963) and Swartzendruber (1968). Many factors causing non-Darcian behavior of unsaturated water flow in soil have been suggested, but the extent of the contribution by each factor is not fully understood. Richards (1931) found that K in equation (2) is a function of temperature and moisture tension. Kemper (1960) suggested the resistance to flow caused by a streaming potential affected the value of hydraulic conductivity. Swartzendruber (1963) and Thames and Evans (1968) accounted for some of the discrepancies between theoretical and experimental data by empirically adjusting the theory to account for non-Darcian flow.

Darcy's law was modified by Richards (1931) in an attempt to describe unsaturated water flow. The modification included the provision that the conductivity be a function of the matric suction head. Darcy's