Principles of Water and Heat Movement on the Canadian Prairie.

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Summary

The soil is able to support crop growth because its intricate arrangement leaves room for the movement of water within it. Water moves by saturated flow when all soil pores are occupied by water. It also moves by unsaturated flow when air and water share soil pores. The movement of water has environmental implications through leaching and runoff of agrochemicals and nutrients. It is also important for preventing the accumulation of chemicals near the soil surface. Heat energy transfer occurs at the soil surface by radiation and moves within the soil by conduction. These processes are influenced by the amount of water in the soil, the soil physical structure and the surface condition of the soil.

According to Einstein "nothing happens in the universe until something moves". Indeed movement is a common feature in the universe whether at the level of galaxies, planetary systems or the atomic level with electrons moving around a nucleus or the spin of the nuclei particles themselves on their own axes. Water in the soil is no exception to this universal tendency. Water moves in the soil in response to gravitational force that pulls everything toward the center of the earth or in response to the adsorptive forces of the soil particles.

Influence of Soil Properties

Before we look at principles of soil water movement in more detail, it is important to look at the composition of the soil within which water moves. Soil is made up of solid particles of varying sizes ranging from large sand particles that can be seen with the naked eyes to microscopic and colloidal clay particles. These particles are in intricate arrangement with spaces or voids which also vary in size and shape; the predominant size of the pores is determined by the predominant size of the solid particles that make up the soil. Soils that contain a high proportion of large particles e.g. sandy soil tend to form pores that are large in size. Conversely, soils that are made up tiny particles e.g. clay soils form pores that are very small in size. The pore size that predominates in soil affects how fast water can move through the soil as larger pores allow water to move faster than the small pores. Several properties of the soil including the drainage status of the soil, the ability of the soil to retain water for plants, its ability to readily accept water and not allow it to runoff, depend on how fast water moves into the soil.

While soil pore size range is important, another soil property that influences water movement is the total volume of these pores. They indicate how much room the soil has to store both water and air. Soils with a high proportion of small pores often have more water and air than soils with larger pores. Therefore, sandy soils allow water to move rapidly through the soil, but they do not retain large amounts of water for plants to use. Clay soils, on the other hand, do not transmit water very quickly because of the high proportion of small sized pores. However the large number of these small pores holds sizable amounts of water available for crop growth. A loam soil is intermediate in texture between a sandy and a clay soil. It is not surprising that irrigation is required more often on sandy soils as these soils do not hold much water to sustain plant growth for a long period of time. Clay and loam soils, on other hand, are more appropriate for dryland farming because they can hold sufficient water to sustain crop growth through extended dry periods.

Water Movement under Saturated Conditions

When soil pores contain water and air, as most soils on the prairies do, the soil is said to be unsaturated. Conversely, when all soil pores are completely filled with water, the soil is said to be saturated. On the prairies, most of our soils are usually saturated only for a short period of time following heavy rainfall, irrigation or during snowmelt. Unlike the more humid regions of Canada, the Canadian prairies do not receive sufficient rainfall to keep the soil saturated for long periods of time. The principles that govern the movement of water in the soil under saturated conditions are different than for unsaturated conditions.

In a saturated soil, water movement is maximized. Two forces are responsible for water movement under saturated flow, the force of gravity that pulls water downward and the weight (or hydraulic head) of water above the soil. The more water 'ponds' above the soil surface, the faster water will move into the soil. Because of the large influence of gravity, the overall direction of flow for a saturated soil is downwards. Water flow in a saturated soil is faster than in an unsaturated soil, therefore the risk that water will move beyond the root zone is greater with saturated flow.

Soil water contains nutrients like applied inorganic fertilizers and pesticides. Nutrients and applied pesticides may leach below the root zone. Once these chemicals leave the root zone (about 1.2 m or 4 feet) there is little opportunity for them to be intercepted by plant roots, and they may continue their downward movement and eventually contaminate ground water. Most people in rural prairie communities depend upon ground water as a source of drinking water. The quality of this water can be impaired when contaminated by nutrients like nitrate or pesticides. In addition, contaminated groundwater can re-enter surface water where groundwater seeps into surface water channels.

The risk of groundwater contamination is especially high for nutrients that dissolve readily in water, for example nitrate-nitrogen. Nitrate contamination of ground water is a concern in humid regions of the prairies and in sandy soils that allow water to quickly leach downwards. There are human and livestock health hazards associated with high levels of nitrate-nitrogen in drinking water. One way to control nitrate leaching is to ensure that inorganic fertilizers or manure are applied at rates that will meet crop demand with little or no residual levels left in the soil following crop maturity. The most vulnerable times of the year for nitrate leaching are when soils are saturated and there is little or no demand for water and nutrients by a growing crop. On the prairies this will occur during the fall period if lots of rain is received and but more so early in the spring season during snowmelt.

The second major concern under saturated soil water flow conditions is runoff of water on the soil surface. This occurs when saturated soils can no longer accept incoming rainfall or the rate of water supply to the soil surface is greater than the rate of entry of this water into the soil. These conditions may occur during and after intense rainfall events or when irrigation is supplied at a rate greater than infiltration. Similar to leaching conditions, the water that moves on the soil surface can carry with it nutrients and chemicals dissolved in the water.

Surface water flow can also carry soil particles causing soil erosion. The extent of soil water erosion will depend upon factors such as the intensity and amount of rainfall or irrigation, the slope of the land and the soil type. Sandy soils with large pores allow water to run through them very quickly reducing the risk of runoff and erosion. Clay soils, on the other hand, are prone to runoff and erosion as they do not allow rapid entry and movement of water into the soil. Because most prairie landscapes are flat and rainfall is not as intense as in the more humid regions of Canada, the risk of erosion is restricted primarily to areas with sloping landscapes. While nitrate contamination is the environmental risk associated with leaching, phosphorus contamination of surface water is the environmental risk with runoff. The amount of phosphorus that is lost may not be large from an agronomic perspective, however, it only takes a small amount of phosphorus to trigger algae growth and cause rapid water quality deterioration in rivers and lakes.

Water Movement under Unsaturated Conditions

The second mode of water movement in soil is unsaturated flow which is slower than saturated flow. This occurs when only a fraction of available soil pore spaces are involved in moving water. With unsaturated flow, the predominant force moving water is the attractive forces between water and soil particles and between water and soil pores. The more water we have in the soil, the less are these attractive forces. Conversely, the less water we have in the soil, the greater are these attractive forces. The net effect of this is that water moves from where it is plentiful to where it is scarce within the soil. The uniqueness of these forces is that they can move water in any direction, even upward against the force of gravity. The relatively small amounts of rain that we receive on the prairies combined with the fact that our predominantly unsaturated flow is slower than saturated flow means that nutrient leaching is not very widespread on the Prairies relative to other wetter regions in Canada. However, studies have shown that nutrients, such as nitrate, can be lost below the root zone in certain prairie soils and under certain environments and management regimes. For example, leaching is most likely to occur where the soil is sandy and where fallow (a practice of leaving the land un-cropped for one year to store water for the next season's crop) is included in the rotation. The lack of crop during the fallow period causes the soil to be wetter than usual and if this coincides with a wet year, considerable amounts of water can move within the soil carrying along with it dissolved nutrients that can be lost below the root zone. Fortunately, the practice of summer fallow has declined significantly on the Canadian prairies and has reduced the associated risk of nitrate leaching.

Although some of the consequences of water movement in soil may be negative, this process is also vital to our ability to grow crops. On average, the roots of annual crops occupy only about 5% of total soil volume. If water did not move within the soil, plant roots would have access to only about 5% of water and nutrients in the soil. Fortunately, as the root takes up water within its vicinity, the soil around the root becomes dryer causing water to move from wetter parts of the soil to the root surface. This in turn allows crops to access more water and nutrients from the soil. Also, with evaporation, water moves to the surface of the soil where it is lost in gaseous form. However, salts and nutrients contained in the water can be left at the soil surface. The ability of water to move down in the soil helps to leach these salts from the soil surface and prevent them from accumulating to levels that would affect crop growth.

Soil Temperature

Temperature is a measure of the heat content of a body. As a body, such as the soil gains heat, its temperature will rise and as the body loses heat, its temperature will fall. Heat can flow to and away from the soil in three ways: by radiation, by convection and by conduction.

Heat Flow by Radiation

Radiation is the flow of energy in the form of electromagnetic waves. All bodies, soils included, that are warmer than 0^oK (minus 273^oC) emit radiation. The only source of energy that is large enough to influence the temperature of the soil over large area is the sun. Solar energy comes in the form of radiation which is given off by the sun because its surface is warmer than 0^oK (actual temperature is about 6000 ^oC). When the soil receives radiation from the sun during the day, the soil surface becomes warmer because the incoming solar radiation is greater than the radiation energy emitted by the soil. The end result is an accumulation of heat which is transmitted down into the soil profile. During the night, the soil still continues to emit radiation energy to the atmosphere causing soil temperature to decrease. Since radiation from the sun undergoes a "diurnal cycle", it is reasonable to expect that soil temperature will undergo a "diurnal cycle" as well. Soil temperature increases during the day, reaches a maximum just a few hours after the solar noon and then declines. The temperature of the soil continues to decline during the night, reaching its minimum at sunrise.

Heat Flow by Convection

Heat flow by convection is the second way of warming soil. Convection occurs when heat moves as a result of something else moving. This can be a parcel of air, as in warm and cold weather fronts. As warm air travels it carries heat energy with it and this can be passed to a body it makes contact with such as the soil. Also, water that enters the soil can alter soil temperature in both directions depending on the relative temperature of water and soil.

Heat Flow by Conduction

The third way by which heat can move in the soil is through one molecule passing its energy of motion to another molecule, a process known as conduction. This process moves heat from regions of high temperature to regions of low temperature within the soil. For this to occur, particles in the soil must be in contact with each other. Two soil properties that are important to heat movement by conduction are the heat capacity of the soil and soil thermal conductivity. The heat capacity of the soil is the amount of heat the soil receives before its temperature can rise by one degree. This is important, as a soil with low heat capacity will warm up faster given the same amount of heat versus a soil with high heat capacity. Thermal conductivity on the other hand, is how fast heat can travel from one part of the soil to the other. The amount of water in the soil affects these two properties and this is important in the context of the

Canadian prairies, where soil temperature is generally below optimum for crop growth. The ability of the soil to transmit heat increases as the amount of water in the soil increases. This happens for two reasons. Firstly, water is a better conductor of heat than air. Secondly, as water content increases, separated soil particles become connected by this water, and since contact is needed for conduction, increased contact increases the flow of heat in the soil. In a similar fashion, it takes a lot of heat to raise the temperature of water. Therefore, as the water content of the soil increases, the heat capacity of the soil also increases and it takes longer for the soil to warm up. This is why clay soils, which may hold a lot of water, are often colder in the spring than a neighbouring sandy or loamy soil. Clay soil requires more heat to raise its temperature. One way to make these soils warm up faster is to drain them or dry them. Decreasing soil water will reduce the heat capacity of the soil and allow for more rapid increases in soil temperature. This is why farmers in areas with wet, heavy clay soils often till their soils in fall, to accelerate their drying and warming the following spring.

Impact of Soil and Crop Management on Heat Flow

Another factor affecting heat flow is the surface condition of the soil. Heat flow and soil temperature are affected by the amount of plant cover, crop residue cover and depth of snow on soil surface. For these reasons, farmers can either increase soil temperature or reduce the extremes of soil temperature. For example, in the more humid part of the prairies such as Manitoba, crop residue yield is high. The presence of these large amounts of surface residues will cause soils to be cold in the spring in part because they reflect incoming radiation thereby reducing total radiation energy at the soil surface. A cold soil will slow down seed germination and seedling emergence. Some farmers reduce this cover by burning or bailing off the straw in the fall. A soil surface with a growing crop will have a smaller daily average temperature than one that is bare or in fallow. This is because the crop canopy reduces day-time temperature by intercepting some of the incoming solar radiation. At night, the crop canopy has an opposite effect. It acts like a blanket intercepting the radiation from the soil and preventing it from escaping into the atmosphere.

In the case of winter crops, the survival of the crop through winter depends on maintaining the temperature of the crown (the growing point of a young plant within the soil) above a critical soil temperature. If soil temperature goes below this critical temperature, winter kill can be expected. The depth of snow cover on the land has a profound influence on whether or not this critical temperature is reached during the winter months. Practices such as leaving standing stubble in the field to trap snow will create a blanket effect which slows down the rate of heat loss from the soil thereby providing protection against low temperatures.

The Canadian prairies are an agriculturally important region of Canada. Many of the soils in this region are inherently fertile. However, for a soil to be a suitable medium for plants, chemical fertility is not sufficient. The soil must contain water and air in adequate and available forms. The soil pores must allow the entry, movement, and retention of air and water with a thermal regime that is optimal for crop growth. Thus, in addition to chemical fertility, physical fertility of soil is essential for soil productivity. Just like chemical fertility, the physical environment of soils that influences the movement of water and heat into and through soils can be modified by prairies farmers to ensure that these soils continue to produce food, fibre and possibly fuel.

Suggested Reading

Fundamentals of Soil Science Henry D. Forth 6th edition. John Wiley and Sons Inc 1978 Pages 63-83.
Introduction to Environmental Soil Physics - Daniel Hillel -Academic Press
Introduction to Soil Physics - Daniel Hillel - Academic Press.
The Pedosphere And Its Dynamics: A system approach to soil science Volume 1 1999. M Juma. Salman Production Pages 203-228.
Soil Physics - Agricultural and Environmental Application - H. Don Scott - Iowa State University Press.