Water, soil and organic matter: a complex relationship

by David Patriquin

SINCE THE MID 1990s, PRECIPITATION IN MANY PARTS OF CANADA HAS BECOME MUCH MORE VARIABLE AND WATER LIMITATIONS IN DRY YEARS MORE SEVERE THAN IN THE RECENT PAST. More use of irrigation is one response. Where that is not feasible, and even where it is, there may be room for improvements in efficiency of the capture, storage and use of water.

The amount of water that can be stored in a soil has a big impact on the efficiency of water capture and use. When the storage capacity is low, much of the rain that falls during extended periods of precipitation is lost. In contrast, a high water storage capacity, combined with the effective capture of rain and snowmelt over the fall, winter and spring can support a crop through an extended dry period.

In this article, the factors affecting water-holding capacity of soils are described. Interestingly, until the mid-1990s, the role of soil organic matter (SOM) in water storage had not been properly quantified, and most soil scientists believed that it had little effect.[2] That view has since changed and scientists now agree with organic agriculturalists on the important role of organic matter in soil water storage.[11]

Water is stored in micropores

Soil is a porous structure. Ideally about 50% of the volume is pore space, with half of it consisting of "macropores" of visible to invisible size (0.05 mm to several millimetres in diameter) and half being smaller "micro-" or "capillary" pores. During an extended, heavy rainfall, all pores may become filled with water. The water then drains from the larger pores by downward gravitational flow, leaving them air-filled; this is important for supplying oxygen to roots and soil life. The larger the pores, the more rapidly they drain, providing that such drainage is not impeded (e.g. by a hardpan). After those larger pores have drained—about 1 day after the rain stops in lighter soils, and 3 days in heavier soils—all of the micropores remain filled with water and the soil is said to be at *field capacity*. The micropores do not drain by gravitational flow; rather they hold water by a type of electrostatic attraction between the water and the soil surfaces. The smaller the pores or the closer you get to the surface of the particles, the more tightly the water is held.

Water loss by evaporation

Water evaporates from soil micropores at their exposed surfaces. That puts a tension on the water and draws more water towards the evaporating surface. Large evaporative losses can occur even when the soil is moist at the surface. However, as soon as the top few centimetres of soil dry out, these losses drop sharply. The dry, air-filled layer at the surface of the soil eliminates turbulent flow (wind movement) next to evaporating surfaces of soil particles. For air to move from deeper in the soil to the atmosphere, water must move through the air in the dry layer by diffusion, a very slow process. This is the basis of water conservation by fallowing in alternate years in regions where the annual water capture is not sufficient to support a crop of wheat. Weeds must be controlled because they transpire water. The practice has been discouraged because it has some ill effects, notably the loss of soil organic matter, and because fallowing is not very efficient. Only about 25% of the precipitation falling in the 21 month between crops is conserved. Improved water capture and water use through diversification of cropping systems, use of shelterbelts and conservation tillage are better alternatives.[4]

Sometimes we deliberately compact soil in order to draw capillary water to the surface, for example, by rolling after planting small seeds. This effect can also be seen in fresh wheel or shoe prints that remain moist well after the surface of adjacent soil has dried. Under most circumstances, however, compacting soil is not a good thing to do because it reduces soil aeration and water infiltration.

Water loss by transpiration

Once the surface layer has dried, the main route of movement of water to the atmosphere is via plants. This is driven by "transpiration," the evaporation that occurs from leaf surfaces during photosynthesis. Leaves have many tiny windows (stomata) which open when the sun comes up to allow carbon dioxide to flow in. The inside of the leaf is saturated with water vapour and when the stomata open, water vapour gushes out. It is an inevitable consequence of taking in carbon

dioxide for photosynthesis. Plants designed to sharply restrict water loss, such as cacti, are also very slow growing, no matter how much you water them. If a plant wants to grow fast, (or if a person wants to run fast), the plant (or person) must be prepared to lose water.

Transpiration accounts for over 98% of the water use by plants. (The rest is the water held in plant tissues). The total amount of water required for transpiration is closely related to crop yield, and to the weather conditions that affect water loss. More water is lost under hot dry conditions, than under cool moist conditions. For most crops, the water used in transpiration is the equivalent of 2–5 cm of rain under humid conditions, and 3–8 cm under semi-arid conditions for each tonne of dry matter produced per hectare.[1] Thus a wheat crop in the mid-west producing 5000 kg dry matter per hectare, of which 2500 kg is grain, requires the equivalent of about 25 cm water stored in the soil. The total annual precipitation involved in feeding the soil reservoir could be 2–3 times larger depending on patterns of precipitation and efficiency of water capture and storage.

Table 1: Typical water holding capacities and infiltration rates for soils of different textures[1]

Textural class	Water held at Field Capacity		Water held at Permanent Wilting Point		Available Water Capacity
	(cm/100cm soil)	–	(cm/100cm soil)	=	(cm/100cm soil)
sand	10		3		7
sandy loam	20		6		14
loam	29		9		20
silt loam	35		13		22
clay loam	38		18		20
clay	38		21		17

Water uptake by roots

Movement of water vapour out of the leaf creates a suction on the open ends of the vessels (xylem) which deliver water to the leaf. The suction extends right to the intake ends at the thousands of root tips where most of the water intake occurs, and out into the surrounding soil. The roots literally suck water out of the soil. Roots are constantly growing at their tips, and branching to produce more growing tips; as water is pulled out of one region of the soil, roots grow into other regions.

Visible signs of water limitation

As plants extract water from soil without replenishment by rain, the water is removed from progressively smaller pores which hold the water ever more tightly, and the rate of flow declines. If it becomes too slow to balance losses at the leaf, the leaf tissue begins to dry out. Then stomata close and photosynthesis stops. The stomata remain closed until the leaf has regained its water. The stomata may then reopen, and photosynthesis resumes until later in the day.

Plants need to maintain high internal water pressure or "turgor" to expand the cellulose fibres that enclose cells. When the water supply drops, one of the first consequences is that leaves and shoots stop growing. However, photosynthesis continues, storing energy.[6] Root growth also continues, searching for more water.[10] If the interval without rain is not so long as to cause severe stress, the plant will bounce back and grow very quickly once it rains, and largely make up for the lost time. If you have said, "I swear the corn grew 2 inches in a day," you were probably right. The point is that when the plant visibly stops growing, it is not inactive, in fact, some degree of water stress may benefit the plant in the long term by encouraging deep root growth.

When the leaf water deficit starts to get severe, leaves may undergo partial wilting; typically that occurs towards mid-day on hot, sunny days when transpiration losses are especially high. Stomata close, and by 2 or 3 p.m., leaves regain water and their normal stature returns. (Such midday wilting is sometimes observed in vegetable gardens in the more lush and dense vegetation, even when there is ample soil water—that is more a sign of overdoing it on the plant and fertilizer end, than it is of water scarcity.)

With further extraction of water from soil, the daily wilting becomes more severe, and finally becomes permanent. At that point, even with the stomata closed all of the time, the plant cannot regain its turgor, and it dies. The water level in the soil is then said to have dropped to the *permanent wilting point*. The remaining water, held in very small pores and films (less than 1/1000 of a millimetre diameter), is simply held too tightly to be taken up by crops even at a very slow rate.

Available Water Capacity (AWC) = Water at Field Capacity – Water at Permanent Wilting Point

Available water capacity (AWC)

Water that is held in macropores drains too quickly to be of much use to plants; water held in micropores below the permanent wilting point cannot be used at all. Thus the water available to plants is that held between the field capacity and the permanent wilting point. This quantity of water is called the *available water capacity* (AWC) of the soil. Of this amount, one half is usually readily available, meaning that until AWC has dropped to one half, there are no serious water limitations.

Table 1 gives typical AWC values for soils of different textures. In general, loams hold the most available water, and also have the best balance of macro- and micropores. Consequently, loams have both good water storage as well as good drainage and aeration. Sandy soils, with a predominance of larger pores, are well drained, but they do not hold much water and they dry out quickly. At the other end of the textural scale, clay with many very small pores holds a lot of water but much of it is not available (note the high value for water content at the permanent wilting point for clay in Table 1). Clay also lacks larger pores so drainage and aeration are poor.

How long will the water last?

The relationship of AWC to rainfall and crop growth is illustrated by this example. A potato crop is growing in 60 cm of sandy loam. Roots extend to 40 cm depth. From Table 1, AWC is estimated as 5.6 cm. (AWC= 40/100 x 14cm = 5.6 cm.) As a rule of thumb, vigorously growing crops require about 1/2 cm of water per day. Hence, starting at field capacity, soil water would be half gone, and growth would start to fall due to water limitations after 5.6 days, that is when the AWC is half depleted (this would be the time to irrigate). It would take much longer than 5.6 more days to deplete the rest of the AWC and for plants to die because as growth slows down, so does water consumption; the plant will protect itself as long as it can.

Rooting depth determines the effective soil depth

Roots can pull water from a distance of only 1–2 cm. So, the depth of soil from which crops can extract water is, in general, the depth to which roots are growing. This means that shallow rooting crops are, in general, more prone to water limitations than are deep rooting crops.

On the other hand, deep rooting crops can take advantage of water deeper in the soil only if their growth downwards is unrestricted. Removing barriers (such as plowpans) facilitates both water movement and root growth into deeper horizons. Double-digging, with deep incorporation of compost, is a good way to do it in gardens. Planting deep rooting cover crops with large tap roots, such as oilradish, or using rotations with alfalfa or sweet clover are effective biological ways to open up the subsoil.

The direction of root growth is always towards the more moist regions. For that reason, frequent watering discourages deep growth of roots. Watering deep and less frequently encourages deep growth.

Increasing available water capacity

The total water holding capacity of a soil can be improved by:

- adding more soil,
- opening up the subsoil as discussed above,
- changing the texture, or
- increasing the organic matter content. Texture should be a consideration when soil is being imported to make a garden. Manufactured topsoil used in new developments is often much too sandy for optimal water retention in a garden.[5]

In most cases where soil needs to be improved, building soil organic matter is a more practical option than changing the texture. Organic matter is about 5 fold lighter than mineral soil, and a small amount of organic matter by weight has a big impact on pore space. "Within all textural groups, as organic matter increased from 1 to 3%, the available water capacity approximately doubled. When organic matter content increased to 4%, it

Table 2: Rooting depths of common crops[4]

Crop	Rooting depth metres	Rooting depth feet
lettuce	0.3-0.5	1.0-1.6
cabbage	0.4-0.5	1.3-1.6
onions	0.3-0.5	1.0-1.6
potatoes	0.4-0.6	1.3-2.0
beans	0.5-0.7	1.6-2.3
carrots	0.5-1.0	1.6-3.3
grass	0.5-1.0	1.6-3.3
clover	0.6-0.9	2.0-3.0
soybeans	0.6-1.3	2.0-4.3
peas	0.6-2.0	2.0-6.6
cucumbers	0.7-1.2	2.3-5.0
tomatoes	0.7-1.5	2.3-5.0
sunflowers	0.8-1.5	2.6-5.0
spring grain	0.9-1.5	3.0-5.0
melons	1.0-1.5	3.3-5.0
corn	1.0-1.7	3.0-5.6
winter grain	1.5-2.0	5.0-6.6
sorghum	1.0-2.0	3.3-6.6
alfalfa	1.0-2.0	3.3-6.6

then accounted for more than 60% of total AWC".[8]

Organic matter increases the bulk of the soil so you actually have more soil depth as well as greater AWC per unit depth. It also improves infiltration, drainage and aeration, not to mention the benefits of improved soil nutrition and soil life. The message: it pays to conserve organic matter in soils of initially high organic matter, and to build it up in low organic matter soils. To do this, return residues to soil, cover crop and minimize tillage (tillage accelerates breakdown). That can be a slow process, but even in the short term, benefits can be realized from feeding the soil, because of immediate stimulatory effects on soil biota which improve soil structure.

The fastest way to increase levels of soil organic matter is to add mature compost, which has qualities similar to the humus that develops naturally in soil. For example, adding 5 cm of compost of 60% organic matter to the top 25 cm of a sandy soil would increase the organic matter content by about 2.5%. If it is well matured compost, only a small amount of organic matter will be lost by decomposition in the first few years, so it would be a net boost of about 2%; if it is immature, half or more of the added organic matter could be lost within a year. Compost is a rich material and is very water repellent once it has dried out.[9] Thus it is important to mix the compost into the soil, or when applying it as a top-dressing, make sure it is well moistened and mix it with some soil before applying it.

Capturing precipitation

We want to capture as much of the precipitation as possible. The maximum rate at which water can be absorbed is referred to as the *infiltration rate*. When rainfall intensity exceeds the infiltration rate, water runs off, or forms ponds or puddles on the soil surface.

The infiltration rate can vary from a few millimetres to more than ten centimetres per hour. The rate increases with the soil macro-porosity, which is naturally high in pure sands. In finer soils, the infiltration rate is very dependent on the formation of soil crumbs through binding of particles by humus, microbial gums and fungal hyphae, and on the channels formed by soil fauna and roots. Hence, it can be increased by adding compost and by regularly feeding the soil biota with plant residues and manures. Worm holes are especially important as they carry water quickly into deeper layers. On the other hand, pulverizing soil through intensive cultivation or compacting soil with heavy machinery can quickly and drastically reduce macroporosity and infiltration.

Equally important: protect the soil from direct impact of rain. Intense rain falling directly on soil smashes apart soil crumbs and plugs up larger pores with fine sediment. Anything that protects the soil from direct impact—a plant canopy or mulch—helps to maintain high infiltration rates.

Another approach to increasing water capture is to deliberately compact a region of bare soil, or cover it with plastic, in order to encourage runoff towards plants. This is a form of water harvesting, using part of the land base to collect water. At the same time, it is important to ensure good infiltration and high water-holding capacity in the downstream areas of plant growth.

Matching demand with supply

There is a rough equality between the water required for vegetative growth and that required for the development of mature fruits and seeds in crops such as tomatoes, beans, small grains and corn. When there are no serious water limitations, planting high yielding varieties, planting densely and ensuring adequate nutrient supply for a high yield makes efficient use of water. However, in a dry year, without irrigation, a high yield strategy can be a recipe for crop failure. The heavy growth, drawing on an ample supply of water at the beginning of the season, can lower soil water reserves well below that needed for reproductive growth. If soil water reserves are low and a dry season is anticipated, use the following techniques to provide a better match of crop demands and soil water supply:

- use shorter season, lower yielding varieties,
- fertilize modestly (if at all),
- plant at wider row intervals (or double planting rows with wider spaces between rows), and

The Gardener's Squeeze Test

(From the Center for Agroecology and Sustainable Food Systems)

"The squeeze test can help you determine whether the soil needs water: dig down a few inches and grab a handful of soil. You need to water when:

- sandy soil won't retain its shape when squeezed into a ball;
- loamy soil looks dry and won't form a loose ball under pressure;
- clay soil won't form a ball unless squeezed."

Adapting to more erratic and droughty weather

To increase water capture and storage in soil:

- build up soil organic matter and feed soil regularly
- break up hardpans, open up subsoil
- deep dig gardens and incorporate compost
- mulch or cover crop over winter
- mulch between rows
- on slopes, plant along contours
- practice water harvesting (e.g. by making water basins around plants, hilling between rows)
- apply water below the canopy and close to plants
- apply more water at fewer times rather than a little water frequently,
- allow more drying down as deep rooting crops grow deeper
- plant shelterbelts in windy landscapes

To vary patterns of water use and reduce water demands in crops:

- grow both summer annual and winter annual crops
- grow both shallow- and deep-rooting crops
- on deeper soils, grow deep-rooting crops or intercrop shallow- and deep-rooted crops
- choose shorter season varieties
- stagger plantings
- choose indeterminate varieties of beans and other pulses

In a mixed irrigated/rainfed landbase:

- on irrigated land, plant high yield species and cultivars, plant densely and fertilize well
- on rainfed areas, choose lower yielding species and cultivars, plant less densely with mulching between rows and fertilize modestly (if at all)
- mulch bare soil.

Flowering and plant pollination occur during phases of high water demand, and are especially sensitive to water stress. Crops with determinate habits, which flower over a short period of time—notably all cereals, and determinate varieties of pulses (grain legumes such as soybeans, dry beans, fabas)—yield well when there is ample moisture, but are risky when water supply is erratic. Staggering plantings of short season varieties reduces the risk of water shortages at critical stages. Indeterminate varieties, available for most pulses, are better choices for dry years. They flower over extended periods so that if conditions in early flowering are poor, it can be made up for later if conditions improve. They are also deeper rooting.

Managing water efficiently requires that you get to know well both the plant growth habits on your land and the soil profiles. Dig holes to observe rooting, take cores and feel the soil before and after rains, and look for runoff during rains to identify areas in need of management. Experiment with water and soil conservation techniques, keeping some areas under the old management for comparison. In larger scale operations, it's worth investing in water monitoring and irrigation control technology, but even with those, there are benefits to be realized by making your own observations and innovations.

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