Conservation of natural resources for sustainable **Agriculture**

what you should know about…

Soil moisture management

Soil moisture management

A significant cause of low crop production and crop failure in rainfed agriculture in the tropics is low and erratic rainfall. However, in many areas crop and land management do not optimise water flow along the rooting zone of the crop. Thus, poor yields are related to an insufficiency of soil moisture rather than to an insufficiency of rainfall.

Tropical and subtropical rainfed agriculture depends on an adequate supply of water in the rooting zone of the soil. It has been estimated that soil water limits crop production in approximately three-quarters of the world's arable soils and is the main factor responsible for low yields in the seasonally dry and semiarid tropics and subtropics.

Little can be done to increase rainfall or the number of rainfall events. In rainfed agricultural lands efforts should therefore be concentrated on increasing the proportion of water that enters the soil (infiltration), minimizing the moisture loss through runoff and evaporation and improving soil water availability and water use efficiency through improved soil management.

Especially in the subtropical and tropical agro-ecological zones with restricted, irregular or markedly seasonal rainfall with annual precipitation from 400 to 1000 mm. But also in areas, where seasonal shortages of rainfall can limit crop productivity, it is necessary to give more attention on the efficient capture of precipitation *in situ* and improve the soil moisture content of the rooting zone.

An understanding of the hydrological cycle is essential for the effective management of rainwater and soil water.

Water occurs not only as a liquid, but also as a solid (e.g. hail, snow) and as a gas - water vapour. The total amount of water in the world is constant, but water is continuously changing from one form to another and is continuously moving at different speeds.

PLATE 1
Precious rainwater is lost for agriculture as runoff, taking soil particles and organic matter with it.
T.F. Shaxon

Once rainfall reaches the land surface it can infiltrate into the soil, run off over the surface as overland flow, or accumulate on plant leaves or in puddles from where it evaporates back to the atmosphere. A combination of these processes is commonly the case.

The rainfall that infiltrates into the soil forms part of the soil water, of which some may be used by plants for transpiration, some may return to the atmosphere through evaporation from the soil surface, and some – if sufficient infiltration occurs – may move beyond the rooting zone to the groundwater.

Rainwater that runs off the land moves rapidly downhill towards river courses, contributing to peak flows, and is of great concern. Runoff is not only a waste of rainfall that could have contributed to crop production and groundwater supplies, but it frequently causes floods or damage to roads and farmland, and erodes soil that is redeposited in river courses and reservoirs downstream.

Management of the soil can significantly affect

- runoff;
- direct evaporation from the soil surface;
- the amount of soil moisture available to plants within range of their roots; and
- the depth to which roots can penetrate.

How much water reaches each of these destinations over a given period is not only determined by the amount of rainfall but also by soil chemical properties and the soil architecture or physical structure, including pores.

Soils differ in their architecture and capacity to hold plant-available water, depending on:

- soil texture
- soil depth
- organic matter content
- biological activity

Increased soil moisture will result in:

- higher yields, through maximised rainfall utilization
- recharge of groundwater and thus securing the water level in wells and the continuity of river and stream flows
- reduced risk of yield losses due to drought

Understanding soil water movement

A good understanding of the below-ground environment and of how this ecosystem (Organic matter module) functions is necessary so that it can be managed more appropriately.

The amount of rainfall that enters the soil (infiltrates) will be governed by the intensity of the rainstorm in relation to the soil's infiltration rate. Excessive tillage and loss of soil organic matter often result in reduced infiltration rate due to loss of surface porosity.

When storm intensity is greater than soil infiltration rate, runoff will occur, resulting in a waste of water that should have been used for crop production and for recharging the groundwater. The rate at which rainfall infiltrates into soil is influenced by the abundance, stability and size of the pores at the soil surface, their water content and by the continuity of the transmission pores into the rooting zone.

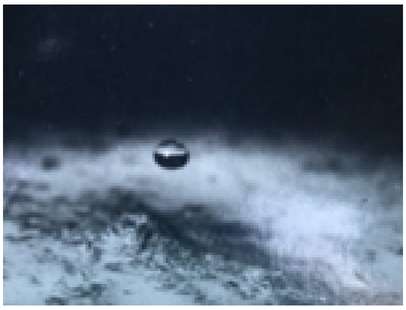
Infiltration rates are affected by

- the quantity of water present in the soil at the time of the rainstorm, which will depend on when the last rainstorm occurred and the permeability of the soil, and
- the soil's capacity to retain water, which will vary with soil depth, stoniness, and texture.

The most important factors responsible for low rainfall infiltration rates are:

- Exposure of soils to raindrop impact
- Soil compaction resulting in the deterioration of soil pores
- Low soil permeability

Exposure of soils to raindrop impact:
When raindrops fall directly onto the soil surface without first being intercepted by vegetation or other materials on the soil surface, the energy of the raindrops may disintegrate soil aggregates into small particles that are splashed into the air. These particles can clog surface pores and form thin rather impermeable layers of sediments at the surface, referred to as crusts, which make it difficult for rainfall to infiltrate.



Plates 2 and 3
The impact of raindrops on the soil without being intercepted by a soil cover result in the disintegration of soil particles.

USDA Soil Conservation Service

The greater the exposure of soils to raindrops, i.e. the less the soil is covered by vegetation, crop residues, mulches, etc., the greater will be the in-filling of surface pores and crust formation, and the slower will be the rainfall infiltration.

Soil compaction resulting in the deterioration of soil pores:
Soil compaction from machinery and implements and from the traffic of animals and humans can destroy or greatly reduce the sizes of soil pores, and so reduce rainfall infiltration rates. The extent to which soil pores are affected will depend on the pressure

applied and the soil's water content. The greater the pressure and the wetter the soil, the more readily the pores will be compressed and destroyed.

Low soil permeability:
Soil permeability refers to the rate at which rainwater moves *through* the soil, as distinct from infiltration which refers to the rate at which rainfall moves *into* the soil. If soil permeability is slow compared to rainfall intensity, pore spaces within the surface soil will quickly become saturated with water resulting in the loss of rainfall as runoff. This is likely to develop more rapidly in shallow soils with a limited volume of pore spaces, in soils that are already largely saturated with water, and in soils with a high water table.

When a heavy rainstorm falls on a well-structured soil, rainwater percolates down through the dry soil as a wetting front, temporarily saturating the soil and displacing air. This is accompanied by the rapid drainage of water from the larger pores (greater than 0.05 mm) through gravity and the pressure of the mass of rainwater above. These larger pores exert only small forces of attraction on soil water. After about two days of drainage field capacity will have been attained and air will have re-entered the larger pores.

PLATE 4

Soil compaction as a result of conventional practices leads to poor drainage of rainwater after a heavy storm, while conservation agriculture practices on the left have improved internal soil structure leading to rapid infiltration and percolation of rainwater.
D. McGarry

In poorly structured soils, rainwater will drain much more slowly. Drainage often continues for several weeks depending on the depth to the slowest horizon and the continuity of the larger pores with depth. In fine textured soils with cracks drainage water will flow down through the cracks in heavy rainstorms before the soil is saturated and while parts of the soil profile may still be dry. If the drainage water subsequently enters a smaller pore while passing through the soil, it will be retained, otherwise it will continue until it reaches the water table and contributes to the recharge of groundwater.

Once the drainage water has been lost from the rooting zone, further water movement within the root zone is slow and is referred to as capillary movement. This movement is caused by forces of attraction, known as surface tension forces, which are exerted by soil particles on water. This movement can occur in any direction and includes the upward movement of water from water tables. Surface tension forces pull water into pores within the soil and the smaller the pores the more strongly the water is attracted and held.

Water is also able to move through soils as water vapour. The most important example of this is the loss of water vapour by evaporation from soil surfaces. This occurs when the concentration of water vapour in the soil close to the surface is higher than that in the atmosphere immediately above. Water vapour will then move from the soil into the atmosphere. The drier and hotter the atmosphere compared with the surface soil, the greater will be the rate of evaporation from the soil, provided sufficient water can be supplied to the surface by capillary movement from below. Fine textured soils have an abundance of small pores and so more capillary movement of water to the surface will generally occur in fine textured than in coarse textured soils.

Runoff occurs when rainfall intensity is greater than the rate at which rainfall infiltrates into the soil. To a large extent it is the quality of the soil surface that determines how much rainfall infiltrates and how much is lost as runoff. Soil and crop management have a marked influence on how much of, and for how long, the soil surface is directly exposed to raindrops with the risks of destroying surface porosity. Management practices therefore have a profound influence on how much rainfall infiltrates a soil for the benefit of crops and groundwater.

Runoff will only occur when the land is sloping, and where there are few cross-slope obstacles to flow. Even slight differences in elevation and very slight gradients of less than 2% can cause substantial runoff. In situations where no runoff is lost from a field, there may still be substantial runoff within the field leading to pronounced differences in the amounts of rainfall received by crops in different parts of the field

Water is held in the soil by two means:

Water can accumulate in soil because of the presence of an impermeable subsurface layer, which impedes normal drainage. Such an accumulation results in saturation of the soil, a condition often referred to as waterlogging. Waterlogging is a permanent feature of some soils, but in others it may be temporary, occurring only during a period of slow-drainage following the input of excess water into the soil. Waterlogging of croplands is rarely a good feature, and the water stored in such cases is simply there because it cannot get out by the normal way.

The second mechanism of water retention by soils is capillarity. This phenomenon is caused by two forces:

- Adhesion: the attraction of soil particle surfaces for water molecules, and
- Cohesion: the attraction of water molecules for each other

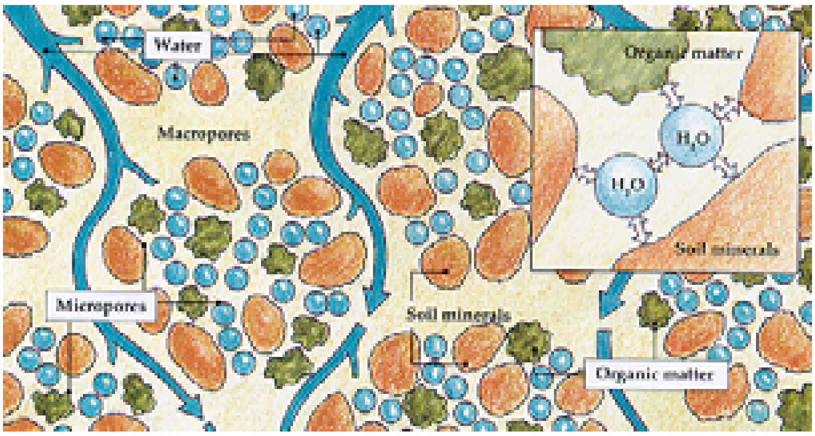


FIGURE 1
The components of soil structure. Soil minerals with organic matter form soil structure units, called "peds". Micropores inside the peds and macropores between the peds carry air, water and facilitate root penetration.

(USER manual, 1992)

If a small amount of water is present, it is held very tightly, and a strong force must be applied to pull it from the soil. In dry soils, most of the water present is held in very small pores, very tightly. Plants cannot use water from such pores, and therefore are unable to grow well under such conditions.

The water-holding capacity of a soil in a particular place depends on the depth of the soil, the volume of pore-spaces, and the proportion of the voids that retain water against the pull of gravity. In a sandy soil there is usually a relatively large total volume of pore-space among the large mineral particles, but the majority of the pores are so large that rainwater drains through most of them, and relatively little is retained within the profile. In clayey soils the opposite can be expected: there may be a large proportion of the pore-spaces so small that, while percolating rainwater may enter, partly under capillary action, the water cannot drain out and can only be removed by plant roots and/or by slow evaporation into any air-filled spaces within the soil. In very compact clay soils, both entry and exit of rainwater may be very slow.

The total volume of rainwater retained per unit volume of soil will vary according not only to the particle-sizes of the sand/silt/clay fractions making up the soil, but also with the range of pore-sizes between the particles. In addition, it is affected by the relative proportions of each size as affecting the rates of water-entry and of removal and the residual storage that is not drained by gravity. It is clear that methods of soil management affect total porosity and the size-distribution of pores in the root-zone.

In most areas where water shortages occur, maximizing the infiltration of rainfall into soil is crucial to achieving food and water security. Land management should encourage infiltration as opposed to slow down runoff. The key to infiltration is to keep the soil porous with a cover of crop residues which prevents damaging raindrop impact and provides a substrate for soil organisms.

Exceptions are where rainwater harvesting is necessary for crop production and where high infiltration can lead to risks of landslides or other forms of mass movement.

Factors influencing soil moisture content

Climate

At any given place, rainfall varies in its seasonality, frequency within a season, average amount over a given sub-seasonal period, annual reliability of occurrence in a given period, average and actual amount in each such period, and the amount and intensity/energy within every rainfall event.

The lower the reliability of rainfall for a given period, the greater the risk that there will be no, or insufficient rain for agricultural production.

Evaporation is what happens when a bowl of water is left in the sun; the water disappears as it becomes converted into water vapour, and the higher the temperature, the drier the air, and the greater the wind speed, the greater will be the rate of evaporation. Evaporation occurs whenever water is exposed to the atmosphere, i.e. from lakes, rivers and puddles, and from the raindrops that accumulate on a leaf after a rainstorm.

Evaporation from soil surfaces occurs when the concentration of water vapour in the soil close to the surface is higher than that in the atmosphere immediately above. Water vapour will then move from the soil into the atmosphere in an attempt to equalise concentrations. The drier and hotter the atmosphere compared to the surface soil, the greater will be the rate of evaporation from the soil, provided sufficient water can be supplied to the surface by capillary movement from below. Fine textured soils have an abundance of small pores, and so more capillary movement of water to the surface will generally occur in fine textured than coarse textured soils. Evaporation is usually higher on bare soil than on covered soil.

Winds across the land surface cause macro- and micro-turbulences around plants, which result in continual changing of the water vapour in the vicinity of plants. Besides the loss of soil moisture, wind will blow away those soil and organic matter particles that are not stuck together resulting in a loss of soil fertility.

Drought periods within a particular year may show up as a delay in the onset of a rainy season; as dry spells of a week or more at critical periods of crop growth within the season; or as an earlier-than-expected end of the rainy season.

Soil properties

The amount of soil moisture varies (besides the climate) with the type of soil, the soil depth and the amount of organic matter in that soil.

For optimum capture, percolation, storage and use of soil moisture, three physical capacities of the soil are important:

- the capacity to allow water to enter, referred to as infiltration
- the capacity to allow water to move readily through the profile, referred to as permeability
- the capacity to store the acquired moisture in the rooting zone and release it to plant roots, referred to as water holding capacity

The number, size and connectivity of pore spaces have a crucial role in determining the amount of water that a soil can absorb, hold and supply.

Many interconnected pores of a wide range of sizes, particularly at the soil surface, will maximize infiltration and reduce runoff, increasing available soil water.

Soils under natural vegetation generally exhibit high porosity because of high biological activity and lack of interference by man. Consequently they have superior physical qualities compared with most soils used for crops or grazing.

The network of soil pores varies according to the type of soil and how it has been managed. Appropriate land management has a great impact on restoring, improving and protecting soil porosity.

Pore spaces in soils vary in size, and both the size and continuity of pores have an important influence on the types of activities that occur in soil pores. Table 1 shows the functions of pores of different size ranges, and their names, together with the size of crop roots.

Table 1 Functions and sizes of soil pores (Hamblin, 1985)

Pores size (mm diameter)	Description of pores	Functions of pores
< 0.0002	Residual	Retain water that plants cannot use
0.0002–0.05	Storage	Retain water that plants can use
> 0.05	Transmission	Allow water to drain out and air to enter
> 0.1 to 0.3	Rooting	Allow crop roots to penetrate freely.
0.5–3.5	Worm holes	Allow water to drain out and air to enter
2–50	Ant nests and channels	Allow water to drain out and air to enter

Pore sizes from 0.0002 to 0.05 mm diameter retain water that can be absorbed by crops and are referred to as storage pores, whereas smaller pores (the residual pores) hold water too tightly for plants to be able to extract it. Pores larger than about 0.05 mm diameter, referred to as transmission pores, allow water to drain through the soil and enable air to enter the pores as the water drains out. This is why clayey soils can hold more water than for instance sandy soils.

The movement of water and air is affected by the soil structure: the geometric shape of the soil and the soil texture: the material that makes up the soil.

Table 2 Effect of soil structure on water and air movement

Type of structure	Water penetration	Drainage	Aeration
Columns	Good	Good	Good
Blocky	Good	Moderate	Moderate
Granular	Good	Best	Best
Plate-like	Moderate	Moderate	Moderate

In many soils the number of surface pores is rapidly reduced by the impact of raindrops, which break surface soil aggregates into small particles that clog surface pores and form surface seals or crusts with very few pores. This results in runoff over the surface when the rate of rainfall arrival exceeds the rate of infiltration. This sealing occurs because the original pore-spaces in the top 1 mm of the surface have collapsed to very much smaller voids. These become almost immediately saturated with water, through which the incident rainwater can move only much more slowly than before, if it can move at all. The destructive raindrop action is avoided where there is a protective cover of crop foliage, residues, mulches or even weeds at or over the soil surface.

Other factors that can reduce the number, proportion and continuity of transmission pores are traffic by machinery, humans and animals, which destroys large pores by compaction, and tillage which disrupts the continuity of transmission pores through the smearing and compression of pores during plough pan formation in the subsoil.

Pore spaces are also needed for roots to freely penetrate soils in order to take up nutrients and water. The sizes of roots vary with the type of crop, but the smallest roots, apart from root hairs, have diameters of 0.1 to 0.3 mm and so soils must have pore spaces of at least this size if the smaller roots are to penetrate freely. In most soils roots grow partly through existing pores, the transmission pores, and partly by moving aside soil particles. Roots can only force their way into smaller pores if the soils are sufficiently compressible; the compressibility of soils increases with increasing water content, since water provides a form of lubrication between soil particles.

The bigger the volume of exploration by roots, the higher the moisture reserves to which the plants have access and the bigger the "buffer" to allow plants to survive rainless periods. If soils are very shallow or physically degraded, plants' ability to withstand rainless periods will be reduced.

Organic matter can build a stronger internal and superficial structure in the soil profile to a condition allowing easy entry of water (water infiltration) and its storage (water retention) in plant available form. Also it can be a protection against surface sealing by raindrops. Organic matter acts as the "glue" to hold the framework of soil particles and pores together. A stable system of soil pores allows easy exchange of air and water.

Another consequence of increased organic matter content (and microbial activity) is an increase of the earthworm population. Soil moisture is one of the most important factors that define the presence of earthworms in the soil. One of the consequences of an increased earthworm population is the formation of channels and pores.

PLATE 5
The burrowing activity of earthworms provides channels for air and water, which has an important effect on the oxygen diffusion in the root zone, and the drainage of water from it.
FAO

Furthermore nutrients and amendments can be distributed easily and the root system can develop, especially in acid subsoil in the existing casts. The shallow-dwelling earthworms create numerous channels throughout the topsoil, which increases overall porosity. The large vertical channels created by the deep-burrowing earthworms and the channels left in the soil by decayed plant roots increase water infiltration under very intense rainfall conditions.

Soils with chemical limitations to plant growth often limit the percolation and water holding capacity of the soil. As little biological activity (plant roots and soil life) is present, macropores that normally guide the water through the soil are scarce.

Topography

Underlying geological formations, together with weathering and uplift processes, affect the form of landscapes. They influence the steepness or shallowness of slopes.

Water caught by a catchment will flow towards the lowest point at the outlet, where it may join water emerging from other catchments. The outer boundaries of a catchment are defined by ridgelines along the crests of the surrounding uplands. From the sides of a valley surface runoff tends to flow perpendicularly to the slope from crest to streamline.

PLATE 6
Rainwater lost as runoff will move to the lowest point in the catchment area.
T.F. Shaxon

The soil surface partitions rainfall between infiltration and runoff. The greater the proportion of a rainfall event that is lost as runoff, the less the proportion of that rainfall which can become soil moisture and groundwater.

For the purposes of enabling rainwater to soak into the soil and controlling the rate of flow of any excess runoff, we can subdivide a given catchment into a more detailed hierarchy of catchments. The smallest subdivisions may be measured in square centimetres, the larger in hectares, within catchments of square kilometres. The key challenge is how best to manage it so that avoidable surface runoff – representing lost potential soil moisture and groundwater - does not occur.

Soil cover

A vegetative or dead soil cover absorbs most of the energy of the raindrops that fall on it and by the time this rainwater reaches the soil below, its ability to disintegrate soil aggregates and detach fine particles is greatly reduced. Consequently, there is little or no clogging of surface soil pores by detached particles, and little deposition of soil particles that would form a crust on the surface.

The physical contacts between a cover and the soil surface obstruct the movement of the runoff, slowing it down, giving more time for infiltration and so reducing the volume of runoff. Thus two aspects of surface cover can be distinguished:

- *all surface cover* absorbs the energy of raindrops and so prevents the loss of pore spaces into which rainwater can infiltrate;
- *contact cover* slows down any runoff, giving more time for infiltration.

The degree of contact cover is important especially on steep slopes, on soils with naturally low infiltration rates, and on degraded soils with surface crusts or seals of low porosity. The conservation effects of forests are due not so much to the presence of the trees themselves but to the litter of fallen leaves, twigs and branches, plus any low-growing vegetation. If the soil surface has not been damaged by trampling, less rainwater will run off and more will infiltrate into the soil.

Furthermore, it is the contact cover that is immediately accessible to soil macro-organisms and can stimulate their activity. Thus greater numbers of biopores are likely to be formed, leading to more rapid infiltration and percolation.

This is why the removal of vegetative cover from the soil and major disturbances such as tillage or incorporation of residues, mulches or other organic matter drastically reduces these positive effects, leaving the bare soil vulnerable to the impact of raindrops, and the consequent runoff and erosion.

More information on soil cover can be found "Increasing water infiltration" and "Managing soil evaporation and transpiration"

PLATE 7
A soil cover of pebbles or stones can prevend erosion as good as a vegetative cover.
B. Steward

Practices that reduce soil moisture content

Conventional agriculture is mainly characterised by burning of residues and intensive tillage for seedbed preparation and weed control. It has contributed to land degradation through loss of organic matter, soil erosion, compaction and contamination of surface waters with sediments, fertilizers and pesticides. Most important, the forementioned practices of residue burning and soil tillage result in the loss of valuable soil moisture, whereas compaction of soil layers prohibit the entrance and percolation of (rain)water.

(Crop) residue burning

Burning of maize, rice, other crop residues and natural vegetation in the field is a common practice. Residues are usually burned to help control insects or diseases or to make next seasons' fieldwork easier. Burning destroys the litter layer and thus diminishes the amount of organic matter returned to the soil. The heat generated by the fire facilitates the loss of soil moisture.

The organisms that inhabit the surface soil and litter layer are also wiped out. For future decomposition to take place, energy has to be put first in rebuilding the microbial community before plant nutrients can be released.

PLATE 8
Soil moisture, organisms and soil organic matter to-be are destroyed when crop residues or natural vegetation is burned prior to cultivation.
FAO

Burning is often practised to improve the quality of grazing land. The philosophy behind the practice is that destroying the dry and non-palatable parts will induce the sprouting of fresh grass.

Soil tillage and mechanical weeding

It was thought that on soils with low infiltration rates due to surface crusting, shallow soil tillage and mechanical weeding with disc or tined implements will break up the crust and encourage rainfall infiltration. This practice has to be repeated after every rainstorm on crusting-susceptible soils and has many disadvantages as loss of organic matter or compaction. Therefore increasing the infiltration rate through tillage leads often to soil degradation.

However, the regular use of shallow tillage with disc or tined implements to break-up surface crusts to increase surface porosity and enhance rainfall infiltration is not recommended. The increase in surface porosity is only temporary and on crusting-susceptible soils tillage will need to be repeated after every rainstorm. Tillage leads to the disruption of pore spaces in the soil, and the use of discs, in particular, often causes

compaction, which may impede root growth and rainwater percolation. Tillage also accelerates the loss of soil organic matter leading to a progressive deterioration of soil architecture and a reduction in the number and stability of pores that allow growth of roots and movement of rainwater.
Regular tillage therefore is not recommended as a solution to restricted infiltration caused by low porosity of the soil surface.

Excessive tillage leads to pulverisation of soil and small particles can easily be washed away by runoff during rainshowers. These, usually very fine clay or organic particles can easily block micropores at the soil surface, and by doing so form a very thin film-like layer, also referred to as surface sealing. This continuous impermeable layer on the surface prevends rainwater to infiltrate and facilitates run-off.

PLATE 9
Surface crusts can obstruct the germination of crops and hinder aeration and water infiltration.

R. Barber

The less the soil is covered with vegetation, mulches, crop residues, etc. the more the soil is exposed to the impact of raindrops. When a raindrop hits bare soil, the kinetic energy of the impact of the terminal velocity detaches individual soil particles from soil clods. These particles can clog surface pores and form many thin, rather impermeable layers of sediment at the surface, referred to as surface crusts. They can range from a few millimetres to a centimetre or more and are usually made up of sandy or silty particles. These surface crusts impede rainwater infiltration. The breaking down of soil aggregates into smaller particles depends on the stability of the aggregates, which largely depends on the organic matter content.

The use of machinery and implements and even the trampling of animals can destroy, or greatly reduce the sizes of soil pores. Compacted soil (Soil compaction module) does not provide adequate space for the storage or movement of soil air and water. Soil animals and root growth are also restricted. Most importantly, large, continuous soil pores are lost or are reduced in size, leading to poor water infiltration, slow drainage and reduced aeration for healthy root growth and nutrient uptake for maximum crop yield.

More important, soil compaction often is not visible at the soil surface and therefore often disregarded as a problem. In case soil compaction is not a serious problem, crops with taproots (sunflower, pigeon pea or radish) might be taken up in the rotation to break the hard layer.

Drainage

Drainage of water beyond the crop's rooting zone may reach the groundwater and help to maintain the level of water in wells, streams and rivers. However, the water 'lost' by drainage could have been used for crop production. Deep drainage occurs when rainfall exceeds the amount of water that is needed to bring the rooting zone to field capacity. Sometimes, deep cracks in clay soils at the surface during the dry season can cause deep drainage. In soils that contain montmorillonitic clay, cracks often develop to depths of 30 to 60 cm or even deeper. If precipitation occurs while these cracks are open, some of the water will move quickly to the bottom of the cracks. However, unless the crack is open to the surface, water will not move into the crack regardless to how much precipitation is received. For example, if a soil that is cracked to 30 cm is tilled to a depth of 10 cm, then precipitation that occurs will be largely retained in the upper 10 cm unless the amount of rainfall is very large; and even then it will move downward only by gravitational and capillary forces. On the other hand, if the land is not prepared, some of the water will move quickly to the bottom of the cracks where it will be much less available for evaporation.

In addition, drainage beyond the rooting zone can be favoured by biopores - continuous pores of 0.5 mm and wider formed by earthworms, ants and termites that extend from the soil surface to the subsoil. The amount of water lost through deep drainage is higher in coarse textured soils, compared to fine textured soils.

Deforestation, overgrazing and the cultivation of one single crop every year (mono-cropping) are all management practices that lead to a reduction of the moisture content in the soil. These practices result in reduced soil porosity which in turn reduces the infiltration of rainwater and the capacity of the soil to retain moisture.

Increasing water infiltration

Approaches to increase water infiltration can be grouped into four categories:

- Protection of the soil surface porosity from the direct impact of rainfall
- Improvement of soil structure through biological processes
- Detention of run-off by means of physical or structural barriers
- Increasing porosity through tillage and land preparation

Porosity of the soil surface is best maintained by first protecting it from the disruptive action of raindrops through a protective cover, usually of residues from the previous crop, a cover crop or mulch, and by ensuring the soil is not disturbed by tillage.

The benefits of a soil cover are many. However, the most direct effect of a soil cover is the interception of rainfall and thus reducing the impact of raindrops on the soil. This will reduce soil particle detachment and consequently, there will be little or no clogging of surface pores by particles detached from soil aggregates, and little deposition of soil particles to form a crust on the surface. Rainwater can enter the soil through the open surface pores.

The benefits of a residue cover are most apparent on soils initially in reasonable physical condition, but even under these conditions runoff can sometimes occur despite a good soil cover. Runoff can still occur when rainfall intensity is higher than the soil's infiltration rate, or when the soil's pore spaces are already filled with water because the soil is shallow, the water holding capacity is low, or its subsoil is only slowly permeable. The physical contact between a protective cover and the soil surface will slow down runoff and give more time for infiltration.

When a residue cover is applied to a soil with a very degraded surface of low porosity, the beneficial effect of the cover on infiltration may be initially limited. In such situations, it is advisable to accelerate the recuperation of surface porosity before applying residue covers by tilling the soil once to break-up the crust and any subsurface pans, followed by a fallow period under a cover crop to enhance the formation and stabilization of soil porosity.

The choice of a cover material depends on what is locally available. Soil covers can be distinguished according to their management:

- Mulches: vegetative and non-vegetative
- Crop residues
- Cover crops
- Natural vegetation

Mulches can either be vegetative or non-vegetative materials.

The vegetative material is usually harvested in one area and applied to another area that is to be used for crop production.

Examples of mulches are grasses and sedges, banana leaves and pseudostems, shrubs such as Lantana and wild sunflower (*Tithonia*), forest litter, weeds, soybean, black gram and rice husks, sawdust, etc. The main disadvantage of applying mulch is the cost of labour of collecting, transporting and applying mulch. Another disadvantage is that the soils where the mulching materials are produced progressively lose nutrients with each harvest unless manures or fertiliser are applied. Mulches are seldom applied to steep slopes because of the labour and because the mulching material are easily washed downhill.

PLATE 10
Dead and living mulch in annual and perrennial crops. The annual crop is directly seeded into the mulch of residues and grass vegetation.
T. Friedrich

It is estimated that 80 percent cover appears to be appropriate to reduce runoff to 5 percent of the seasonal rainfall, which for straw would be equivalent to about 4t/ha.

If the soil surface is degraded (e.g. compacted, sealed) it is advisable to improve the structure by tillage or a cover crop. Mulches are generally applied to high value horticultural crops and home gardens on easily accessible fields with gentle slopes. It is not economically viable to transport large quantities of mulch for large-scale cropping.

In dryland areas, two other forms of mulching are popular, using non-vegetative mulches. The main reasons for the application of non-vegetative mulches are rainfall infiltration and reduction of evaporation. As they lack the other advantages of vegetative mulches, these practices will be discussed in "Managing soil evaporation".

Crop residues left on the soil surface lead to higher soil aggregation, higher porosity and higher number of macropores, and thus facilitate rainwater infiltration. Their decomposition depends on the activity of microorganisms but also on soil meso and macro fauna. The macro fauna as earthworms, beetles, termites and ants promote the integration of residues into the soil.

Residue cover reduces or eliminates splash erosion. Therefore surface crusting, sealing and rainfall-induced compaction are reduced. The soil cover forms small diversion dams that cause pounding of runoff of slow the runoff and thus allows more time for infiltration. Sediment is deposed behind these diversions and remains in the field.

PLATE 11
Livestock grazing crop residues on steep slopes in El Salvador. Enough residues will be left to protect the soil.
R.G. Barber

Residue cover is one of the most effective and least expensive methods for soil protection. Additionally, the residues can be used for grazing, when excessive amount of residues is available. To prevent soil compaction, grazing periods should be minimised and limited when the soil is dry. Especially in many parts of the subhumid and humid tropics planting a crop in the residues of the previous crop is becoming a successful cropping practice. Numerous experiences from small, medium and large farmers from USA and South America are well known. Recently, small-scale farmers in Central Asia have changed their rice-wheat production system drastically, which generates yield increases of 15-20 percent.

Compared to mulches crop residues have similar advantages; additional advantages of crop residues are reduced labour, machinery and fuel costs, as there is no need to collect, transport and apply the residues.

Moreover yields are higher when directly sown into residues of the previous crop, because the old root channels from the previous crop facilitate deeper rooting and enhance the infiltration and percolation of rainwater. Direct sowing into crop residues is much more applicable to steep slopes, inaccessible fields and low value crops compared to mulching.

Higher benefits may be obtained when sown into the residues of a legume crop because of the increased nitrogen availability in the soil, on the other hand high nitrogen contents make them easily decomposed and leave a sparse surface cover.

Generally the main constraints are the inability to produce and leave sufficient quantities of crop residues on the soil surface and the likelihood with certain crop sequences that weed, pest or disease problems will become intensified.

In some areas it is economically much more interesting to use the natural vegetation as soil cover in cropping areas. It is not a new practice, as this is usually done in shifting cultivation systems, when the use of fire is abandoned. One example is the Quesungual system in Honduras.

In other places, one dominant weed species can form such dense vegetation and generate substantial amount of biomass, that the introduction of cover crops is probably not feasible. The best option is to look for ways to best manage the weed specie and use it as soil cover instead. This has been done with "Chinese Lantern" (*Lantana sp.)* in Karatu area, Northern Tanzania.

When soils are so badly degraded that they must be taken out of production, soil porosity can be restored through the action of biological processes. This can be achieved by fallowing for 1 or several years under natural vegetation, natural vegetation enriched with fast-growing leguminous trees, or planted fallows. Whereas a natural vegetation fallow may require 3-5 years, a cover crop may recuperate soil porosity in 1 year.

The accumulation of biomass on the soil surface promotes the recuperation of soil porosity and thus water infiltration. If the natural vegetation is not very rich in species, one can opt for "improved" fallow vegetation, in which certain species are sown by the farmer, like horseradish, black oats, castorbean, sunflower or common vetch.

A well-adapted, deep-rooting leguminous cover crop often speeds up the recuperation of soil porosity compared with a natural vegetation fallow because larger amounts of biomass are rapidly produced by the cover crop.

Cover crops are sown to produce a dense cover, which is usually eliminated and left on the surface to protect the soil. Cover crops may be grown in association with perennial crops, or with annual crops as an intercrop, or as a relay, sequential or rotation crop. Annual cover crops are usually eliminated at peak flowering to maximise their nutrient content. Elimination can be done by hand scything, cutting and flattening with knife-roller, applying desiccating herbicides or mechanically with mower or chopper.

To reduce runoff and enhance the amounts of nutrients supplied by cover crops to the following crop, it is often desirable to use cover crops with a spreading habit, and a low harvest index of less than 10% as in certain varieties of cowpeas and pigeon peas. Legume cover crops are particularly useful when planted in association with perennial crops such as bananas and coffee, as well as with cassava and sweet potatoes. Cover crops are particularly useful for providing a cover during fallow periods and for the regeneration of degraded lands, as well as providing farmers with immediate tangible benefits, such as food for humans, food for animals and firewood.

Main constraint of using cover crops for small-scale farmers in subhumid and humid regions is the availability of seeds. Small-scale farmers generally adopt cover crops only when it is not feasible to sow another crop, when the cover crop requires no cash inputs and no additional labour or when the cover crop has additional benefits to the farmer.

PLATE 12
Hairy vetch is used as a cover crop in southern Brazil to generate biomass in between two commercial crops.
S. Vaneph

Cover crops are suited to areas where land is normally left fallow during a certain period of the year and runoff, soil erosion and weed proliferation should be prevented. The selected cover crop must be suited to the local soil and climate, fit into the existing cropping and farming system, and be economically acceptable to the farmer. Some of the more important criteria are: biomass production, length of growing period, fixation of nitrogen, ease and speed of establishment, edible or non edible, ease of elimination, resistance to drought, resistance to low temperatures, tolerance to low fertility, ability to compete with weeds, resistance to pest and disease, speed of decomposition of residues, deep rooting, ability to act as a biological subsoiler, etc. Some tropical species can be found in table.

Biological processes to improve soil structure are mainly those aiming at an increase of organic matter in the soil. Organic material added to the soil will increase biological activity. Microorganisms use the soil organic matter as food. The waste products produced by microorganisms become soil organic matter.

"Loss of structure" (Soil compaction module) is a characteristic, which is often used to describe soil profiles that have been tilled for a long time. Partly this is caused by a reduction in organic matter and humus content of the soil. Organic matter plays an important role in the formation and stabilization of soil aggregates, resulting in a higher resistance to disintegration. Organic matter loosens the soil, which increases the amount of pore space. This has several important effects. The density of the soil goes down (it becomes less compacted) and the soil structure improves. This means that the sand, silt and clay particles in the soil stick together, forming aggregates or crumbs.

The quality of the crop residue will determine the effect on soil structure and aggregation. Especially the chemical composition of residue serves different roles. Soil aggregation process can take place in two ways:

- waste products of bacteria - polysaccharides
- fungal and bacterial hyphae

Besides promoting biological activity and thus creating more pores, organic matter plays an important role in the formation and stabilization of soil aggregates through connecting the organic structures to inorganic soil particles, resulting in a higher resistance to disintegration.

PLATE 13
Sticky substances on the skin of earthworms help bind particles together.

Polysaccharides are known to promote better soil structure through their ability to bind inorganic soil particles into stable aggregates. Recent research indicates that the heavier polysaccharide molecules may be more important in promoting aggregate stability and water infiltration than the lighter molecules. Microorganisms synthesize most of the soil polysaccharides, as they decompose fresh residues. Soil aggregation is caused primarily by polysaccharide production in situations where residues contain low nitrogen levels.

Although their activity is temporary and will be substituted annually, the hyphae of actinomycetes and fungi play an important role in connecting soil particles. Research showed that a reduction in soil macroaggregates was strongly correlated to a decline in fungal hyphae after 6 years of continuous cultivation (Gupta and Germida, 1988).

Detention of runoff

Alternative, but less favourable solutions to restricted infiltration are the use of physical structures, which may be necessary under certain situations:

- When it is not immediately feasible to implement conservation agriculture or simple soil cover because, for example, crop residues are used as fodder.
- As backup measures to support conservation agriculture where the problem of restricted infiltration is owing to rainfall intensities that are higher than soil infiltration rates even in the presence of a residue cover.

In these situations, the volume of water soaking into the soil may be increased by giving more time for infiltration by slowing down runoff, by means of physical or vegetative structures constructed across the slope and parallel to the contour.

Closely spaced structures on the contour (e.g. ridge and furrow series of planting lines and irregularities formed by contour tillage and crop management operations) may be formed over the whole field so that rainfall is detained where it falls. Widely spaced structures at intervals down the slope (e.g. fanya juu terraces, stone walls, earth bunds, live barriers and trash lines) used on their own without contour field operations between them will result in rainwater running downslope until it is detained or slowed down at the next barrier.

PLATE 14
Slow forming terraces with permanent soil cover will result in high rainwater infiltration. The surplus rain will be carried away as clear run-off.
FAO

Details of the layout, design, construction and maintenance of these structures appear in many Soil and Water Conservation (SWC) handbooks, such as FAO Soil Bulletin 70 (FAO, 1996), and other documents produced by governmental and other agencies for specific countries or particular environmental conditions.

Managing soil evaporation and transpiration

- Modifying soil cover
- Modifying micro-climate

The most effective solution to high evaporation losses of soil water is a cover of plant residues on the soil surface. Agronomic practices that increase shading of the soil surface, and physical structures that concentrate rainwater, encouraging percolation to deeper layers, also reduce evaporation losses. Wasteful transpiration losses may be the result of weeds or excessive crop transpiration in hot windy conditions, and can be reduced by appropriate weed control practices and windbreaks, respectively.

Soil cover reduces soil water losses through evaporation by acting as an insulating layer. This diminishes the temperature of the surface soil and eliminates the effect of wind. Heat from the sun is only slowly transmitted from the surface of the residues through the air trapped within the layer of residues to the soil surface. Consequently the soil surface remains cooler and the rate of evaporation of soil water is slowed down. The thicker the layer of trapped air, the greater will be the insulating effect. However, the quantity of residues required to reduce evaporation losses is considerably greater than the quantity needed to ensure that most rainfall infiltrates where it falls.

The reduction of topsoil temperatures will also benefit the germination of most seeds. Soil temperature not only influences the absorption of water and nutrients by plants, seed germination and root development, but also microbial activity and crusting and hardening of the soil. Roots absorb more water when soil temperature increases, up to a maximum of 35ºC. Higher temperatures restrict water absorption. The ideal rooting-zone temperature for germination and seedling growth ranges from 25-35ºC. Temperatures exceeding 35ºC reduce drastically the development of maize seedlings and there is hardly no germination of soya seed when temperatures exceed 40ºC.

However, the main disadvantage of using residue covers for reducing direct evaporation is the large quantities of residues required to significantly reduce evaporation. Often, the regions with high evaporation losses also suffer from a shortage of rainfall, which restricts the production of vegetative matter. Frequently there are also other demands on residues, which take priority such as fodder, thatching and construction.

PLATE 15
Even in drylands, in this case Ethiopia, it is possible to conserve enough crop residues both for animal fodder as well for protection of the soil surface.
J. Ashburner

As was discussed earlier, soil cover can be applied in different froms: vegetative and non-vegetative. Examples of non-vegetative covers or mulches are the use of stones very common in China and dust-mulching.

One of the most important ways to reduce water evaporation from the soil surface is to get the water as deep into the profile as feasible. Understanding cracks and how water moves into cracks is important for managing soils that have substantial cracking.

Modification of the micro-climate is usually done by reducing the wind speed across the surface and providing shade to crops and soil surface.

Natural windbreaks are strips of forest left after deforestation. Since a much drier and windier microclimate develops in these strips of forest compared with that in the undisturbed forest, many trees in natural windbreaks often die, sometimes leaving holes through which the wind passes at increased velocity. The important guideline for natural windbreaks, as for planted windbreaks, is that the porosity of the vegetation should be about 40 percent.

Artificial windbreaks may consist of single, double or triple rows of trees and shrubs, but also sugarcane and tall erect grasses that protect areas from wind. Well-designed windbreaks will significantly reduce evapotranspiration rates of crops in windy conditions resulting in the conservation of soil water and less subsequent moisture stress when water is limiting. A 50 percent reduction in wind velocity (from 32 to 16 km/h) will reduce evapotranspiration rates by 33 percent (McCall and Gitlin, 1973).

Windbreaks may provide additional benefits to crops by reducing mechanical damage and the loss of flowers, and by creating better conditions for insect pollination. They are also beneficial in reducing wind erosion, especially in fine-sandy and silty soils, and in diminishing air pollution problems. Depending on the tree species selected, windbreaks may also provide fruit, nuts, fodder and timber, but the harvesting of these products must not result in pronounced gaps being formed within the windbreak.

The main disadvantage for farmers with small plots is the loss of cropping area due to the windbreak and the risks of competition between the windbreak and the crop for water, nutrients and light leading to lower crop yields. This zone of competition may extend over a distance equal to 1.5 times the height of the windbreak.

In areas where there are severe shortages of fodder, fuelwood and timber, windbreaks may need to be fenced to prevent indiscriminate grazing and harvesting. To ensure that wind cannot pass around the ends of individual windbreaks, the establishment of windbreaks should be planned on a community basis.

Windbreaks will be favoured in areas subject to strong dry winds during the growing season, and where windbreaks cause a net gain in soil water (i.e. where the gain in soil water due to reduced crop transpiration exceeds the loss of water due to windbreak transpiration). Windbreaks are also likely to be favoured where they consist of species that provide additional benefits, such as fodder, fruit, nuts, fuelwood and timber that can be harvested without damaging the windbreak.

Shade can be provided by all manner of materials, whether artificial such as nets, cloths, plastic sheets and others, or plant-derived, such as cut branches, cut grass supported on nets, or living trees which provide high-level and wide-spreading shade. Shade is necessary in plant nurseries in hot regions to protect seedlings and other plants with shallow roots from rapid desiccation. While shade may ameliorate the severity of hot dry conditions and limit undesirable losses of soil moisture, it can also be so dense as to limit solar energy reaching leaf surfaces and limit photosynthesis and growth rates.

Where shade may be desirable, its density should be adjusted to provide an appropriate balance between losing water too fast, limiting sunlight intensity and avoiding scorching of leaves due to temporary dehydration and cell-damaging high temperatures. Using living shrubs and trees to provide long-term shade for tea and coffee can cause difficulties in maintaining the desired degree of shade above the crop over the long term. In tropical areas, shade is often used to protect seedlings during the first few weeks of their development.

Increasing sub-soil storage capacity

- Increase in organic matter content
- Increase in effective soil depth
- Fallow

Usually addition of organic matter to the soil will increase the water holding capacity of the soil. This is based on the fact that addition of organic matter increases the number of micro- and macropores in the soil, either by "glueing" soil particles together or by creating favourable living conditions for soil organisms. Soil water is held by adhesive and cohesive forces within the soil (pores) and an increase in porespace will lead to an increase in water holding capacity of the soil. The increase in in-soil storage of water as a consequence of increased organic matter is shown in figure 15 of Soil Fertility module. Especially in the topsoil where the organic matter content is higher, more water can be stored.
[Check numbers of figures…]
Figure 16 of the same module clearly indicates the effect of burning the vegetation on the amount of water stored in the soil. The in-soil storage of water does not only depend on the type of cover or previous vegetation on the soil but also on the type of land preparation.

A study to evaluate the resilience of agroecosystems, which was conducted in 1999 in Honduras, Guatamala and Nicaragua showed that 3-15 percent more water was stored in the soil under more ecologically sound practices (table) (World Neighbors, 2000).

Table 1 Average soil depth (cm) at which moisture starts (World Neighbors, 2000).

Country	Agro ecologically sound practices	Conventional practices	Difference (%)
Honduras	9.98	10.28	2.9
Guatemala	2.44	2.99	15.0
Nicaragua	15.81	17.80	11.2

All practices aiming at the increase of effective soil depth will result in an increase of in-soil water storage. The effective soil depth may be limited by compacted layers (Soil compaction module), hard pans or plough pans. By removing these layers, plant roots and soil biota can explore a bigger quantity of soil and by doing so, create favourable conditions for water storage. Another example is the use of planting pits.

A common practice in semi-arid and arid areas is to increase in-soil water through the practice of a clean weeded fallow during the first year. The water stored in the soil during the fallow period does add some stability to crop yields the following year. It can be used for seed germination and initial crop growth. However, little or no additional soil moisture is stored in sandy soils compared to continuous cropping. Clean weeded fallows are mostly in use in areas where extensive land areas are available and where weeds can be controlled mechanically. Disadvantage of clean weeded fallow is the exposure of bare soil to climate conditions, resulting in loss of soil structure, loss of organic matter and increase in soil erosion.

Additional water from other sources

- Rainwater harvesting
- Irrigation

Rainwater harvesting is appropriate to semiarid and arid areas where droughts are common and irrigation is not feasible. General information about water harvesting can be obtained from the FAO document on Water harvesting.

Runoff should be concentrated either in pits, ditches or basins or behind barriers made of earth or stone. In dry seasons yields can increase by as much as 300% compared to yields without runoff harvesting. In the wet season yields may be reduced because only a part of the land is cropped or because of waterlogging.

Rainwater harvesting includes different practices:

Sheet-flow runoff harvesting: runoff is collected from gently sloping surfaces. Mostly sheet-flow runoff is collected from a larger catchment/collection area and is concentrated in a smaller cropping area. The ration of catchment to cropping area generally varies from 1:1 to 1:3. It is recommended that the slope of the catchment area does not exceed 5 percent. Bare catchment areas yield most runoff, but work is needed to maintain the land in this condition. They can be also left under natural vegetation and may sometimes be sown to short-season crops, but the efficiency (water collection) will be less than under bare soils. Diversion ditches may be necessary upslope of the area used for runoff harvesting to prevent excessive damage by runoff.

Concentrated runoff harvesting: concentrated runoff is collected from narrow channels such as footpaths, cattle tracks, temporary streams or residential areas and roads.

Floodwater harvesting and water spreading is the diversion of flood water from watercourses either for spreading water over land that is to be cultivated or for storage in deep farm ponds.

Rooftop harvesting is the direct harvesting of rainwater from roofs.

Supplementary irrigation is not within the aim of this module. Information on irrigation can be obtained at http://www.fao.org/ag/agl/aglw/cropwater/default.stm.

Successful water management in drylands

Several approaches may be used to diminish the impact of low and erratic rainfall:
- match land use to soil characteristics;
- use drought-resisting and drought-escaping crops;
- increase the efficiency with which crops utilize rainwater;
- concentrate rainfall by water harvesting;
- divert river water;
- intercept floodwater; and
- apply supplementary irrigation.

Matching land use to the most suitable soil types within a farm may increase the efficiency with which the available soil water in the different soil types is utilized for crop production. Crop water requirements vary, as do the capacities of soils to retain and supply water to crops.

Successful water management in a dryland farming system is based on:
- retaining precipitation on the land;
- reducing evaporation;
- utilizing crops that have drought tolerance and fit rainfall patterns (Stewart, 1985).
-
- This raises three questions:
- Can water get into the soil fast enough to avoid runoff?
- Is the soil in a condition to allow water uptake through plants without their suffering damaging water stress in their tissues and to allow downwards transmission of excess to the groundwater?
- How is it possible to raise people's skills in soil and crop management to close the yield gaps between research-station experience and in-field practice?

In order to prevent poor utilization of rainfall by crops, it is necessary to understand the processes that lead to deterioration in soil architecture. Two different areas in the soil need to be considered:

1. <u>At the soil surface</u>

The impact of raindrops on the bare surface can cause decreased porosity as a result of the formation of surface seals and crusts.

2. <u>Beneath the soil surface</u>

- Tillage and traffic by machinery, humans and animals can destroy pore spaces and consequently result in soil compaction, especially in wet soils. This leads to increased runoff and to restricted root development (therefore reduced soil depth).
- Tillage, in particular soil inversion by ploughing, also causes a decline in soil nutrient fertility through losses in organic matter and decreases in soil biological activity.
- The collapse or compaction of pores of all sizes is the prime reason why water may not enter the soil and runoff can occur.
- A key factor for soil sustainability is the maintenance of biological capacity for self-recuperation and how to encourage this biological activity in the field.

In low rainfall areas, it is frequently difficult to know when the rains have truly started, as initial rains are often followed by a dry period. Many farmers wait until the topsoil has been moistened to a depth of about 15-20 cm before planting, so that even if there is a subsequent short dry period there is sufficient water within the soil. However, this results in a delay in planting and for every day's delay yields will decrease (by about 5-6 percent for maize in eastern Kenya, Dowker, 1964), largely due to the loss of rainwater by drainage and evaporation, together with the loss of some released nutrients.

To overcome this problem and to allow crops to develop deeper rooting systems earlier on so that more of the rainfall can be utilized during the initial stages of the season, some farmers "dry plant" when soils are dry prior to the onset of the rains. To avoid premature germination before sufficient rain has fallen, the seeds are usually placed deeper than normal. Dry planting also has the advantage of spreading labour over a longer period.

Crops may also benefit from this practice by being able to utilize the nitrogen released at the start of the rains from the decomposition of soil organic matter, which reduces leaching and pollution of groundwater. However, there are a number of problems associated with dry planting, notably that some soils, and in particular hardsetting soils, are difficult if not impossible to till when dry. If seeds are not planted sufficiently deeply, they may germinate at the first rains and then die during a subsequent dry period.

Applying fertilizer to speed up crop canopy development and increase the shading of the soil surface will decrease the soil water lost by evaporation so that more is available to the crop. Planting crops equidistantly (i.e. with between-row spacing similar to within-row spacing) so that the soil surface becomes shaded more quickly would also be expected to reduce the proportion of soil water lost by evaporation. However, the effects of these agronomic practices on reducing evaporation losses will be much less than applying surface residues.

On permeable sandy soils that retain small quantities of available water for crop use, it is preferable to introduce deep-rooting crops that can utilize soil water at depth that would not be available to shallow-rooting crops. Examples of deep-rooting crops are almond, barley, cassava, citrus, cotton, grape, groundnut, olive, pearl millet, pigeon pea, safflower, sisal, sorghum, sunflower, sweet potato and wheat.

PLATE 16
Even under dryland conditions conservation agriculture lead to increased plant-available soil moisture. This durum wheat crop remains fotosynthetic for a longer time, which results in a higher quality of the grains. Compared to the wheat on the right, which was grown under conventional farming.
A.J. Bot

How much plant-available soil moisture remains at a given time depends on the texture and porosity of the soil, the previous volume of soil moisture, the volume removed by direct evaporation, evapotranspiration and deep drainage.

Irrigation (if available) is normally required when about two thirds of the available water - between field capacity (FC) and permanent wilting point (PWP)- has been depleted. If irrigation is not an option, it makes sense to manage the soil to develop and retain a maximum amount of soil pores of a wide range of sizes. This will maximize the capacity for water retention and enable plants to withstand drought for longer periods. Loam textures generally have the largest available water capacity, while sand on the one extreme has a small available water capacity, as does clay at the other.

Effects of CA on plant-available soil moisture

Residues on the soil surface reduce the splash-effect of the raindrops, and once the energy of the raindrops has disappeared the drops proceed to the soil without any harmful effect. This results in higher infiltration and reduced runoff, leading to less erosion. The residues also form a physical barrier that reduces the speed of water and wind over the surface, of which the latter reduces evaporation.

Maintenance of crop residues on the soil surface increases the conservation of moisture in the soil profile, especially in dry areas. Crop residues on the surface:

- increase water infiltration through prevention of crust formation and improve the soil structure
- capture more moisture than bare soils, because of rough surface
- give shade to the soil and thus reduce the evaporation
- increase water retention capacity of the soil, through improving the structure

PLATE 17
Preservation of moisture beneath a soil cover of crop residues.
A.J. Bot

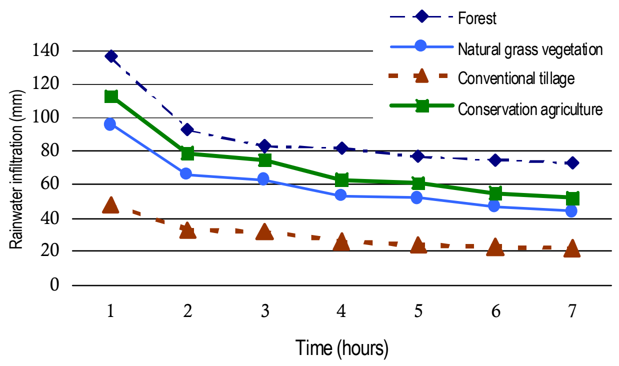
The preservation of aggregate stability is important in order to reduce surface sealing and increase water infiltration rates. With increased stability the surface runoff is reduced (Roth, 1985). Higher aggregate stability under conservation agriculture is the result of the following aspects (Kochhann, 1996):

- presence of a mulch layer, which protects the soil surface against the impact of raindrops;
- no soil disturbance;
- presence of decomposing organic matter on the surface, which induces aggregation in the upper 0-3 cm;
- increase in soil density, which makes aggregates more resistant to changes;
- higher concentration of calcium and magnesium in the superficial layer, which affects the structure positively.

The burrows dug by earthworms and the channels left in the soil by decayed plant roots are a result of the preservation of residues on the soil surface. It increases soil porosity and improves biological activity and soil particle aggregation. Porosity improves the infiltration and percolation of water and reduces runoff.

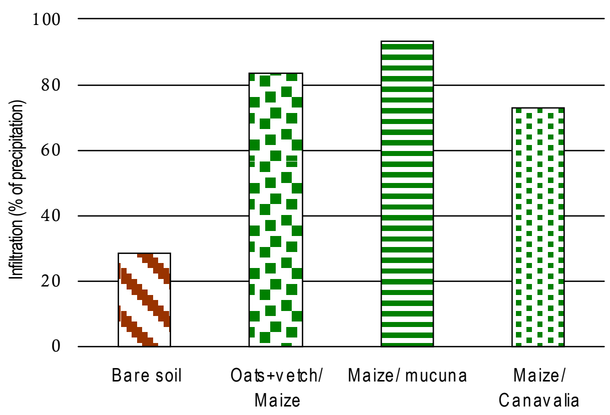
Areas in which conservation agriculture has been practised for a long time have developed a good soil structure and macroporosity. Water infiltrates easily, almost similar to forest soils, as is shown in figure 1.

FIGURE 1
Water infiltration under different types of management (Machado, 1976).



Infiltration of rainwater is increased because of the higher number of large pores (Roth, 1985). In southern Brazil rainwater infiltration increased from 20mm h^{-1} under conventional tillage to 45mm h^{-1} under no-tillage (Calegari *et al.*, 1998). In an experiment under natural rainfall conditions, Debarba and Amado (1997) found an increase in rainwater infiltration in maize-cover crop systems under no-tillage, with prominent results in oats+vetch/maize and maize/mucuna (figure 2).

FIGURE 2
Infiltration of rainwater under different maize production systems (Debarba and Amado, 1997).

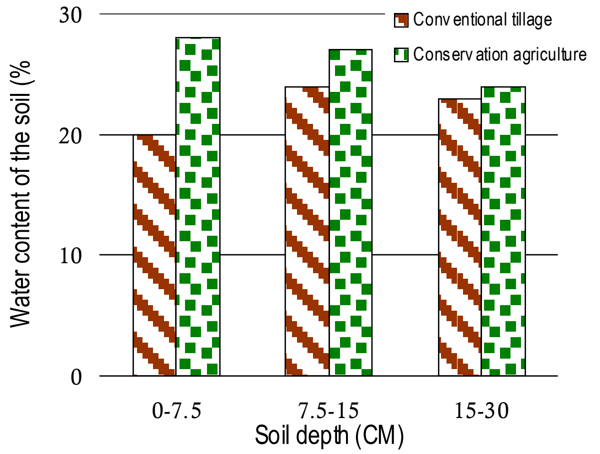


The consequence of increased water infiltration combined with a higher organic matter content is increased in-soil storage of water as is shown in figure 3. Especially in the topsoil where the organic matter content is higher, more water can be stored.

The in-soil storage of water does not only depend on the type of land preparation, but also on the type of cover or previous vegetation on the soil. As was discussed in "Practices that decrease soil moisture" (crop) residue burning is one of the practices that affects the soil moisture content negatively; this is clearly illustrated in figure 4.

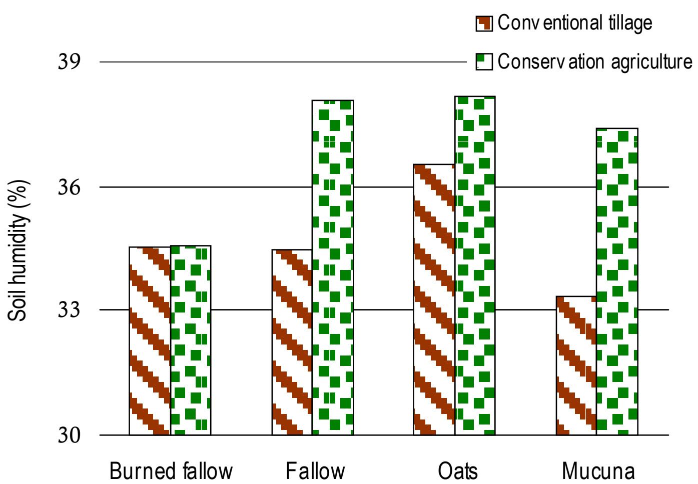
Conserving the fallow vegetation as a cover on the soil surface, and thus reducing the evaporation, results in 4 percent more water in the soil. This represents 80 thousand liters of water in the upper 20 cm of the soil (or an extra rainfall of 8 mm). It is clear that this amount of "extra" water can make a difference between wilting and survival of a crop during temporary dry periods.

FIGURE 3
Quantity of water stored in the soil under conventional tillage and conservation agriculture (Gassen and Gassen, 1996)



The soil cover not only protects the soil against the impact of raindrops, but also protects the soil from the impact of the sun. The cover reduces the soil temperature and thus reduces the loss of water from the soil through evaporation.

Figure 4
Effect of different soil covers on in-soil storage of water (Siqueira, *et al*., 1993)



The increased organic matter content together with soil cover leads to increased water holding capacity of the soil.

As a consequence less irrigation water is needed to irrigate the same crop as is shown in the table for the Brazilian Cerrados. Especially in areas with lack or scarcity of (irrigation) water, conservation agriculture can result in a larger area irrigated with the same amount of water.

Table 1 Economy of irrigation water through soil cover (Perreira, 2001).

Percentage of soil cover	Water requirement (m^3 ha^{-1})	Reduction in water requirement (%)	Number of times irrigated during season	Number of days in between irrigation
0	2660	0	14	6
50	2470	7	13	6
75	2090	21	11	8
100	1900	29	10	9

More water infiltrates into the soil with conservation agriculture rather than running off the soil surface. Streams are then fed more by subsurface flow than by surface runoff. Thus, surface water is cleaner and more closely resembles groundwater in conservation agriculture than in areas where intensive tillage and accompanying erosion and runoff predominate. Greater infiltration should reduce flooding, by causing more water storage in soil and slow release to streams. Infiltration also recharges groundwater, and thus increasing well supplies.

A study to evaluate the resilience of agroecosystems, which was conducted in 1999 in Honduras, Guatemala and Nicaragua showed that 3-15 percent more water was stored in the soil under more ecologically sound practices (table) (World Neighbors, 2000).

Table 2 Average soil depth (cm) at which moisture starts (World Neighbors, 2000).

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Honduras	9.98	10.28	2.9
Guatemala	2.44	2.99	15.0
Nicaragua	15.81	17.80	11.2

From this different viewpoint, important changes in emphasis on soil management include:

- focus on saving pore spaces, more than saving solid particles.
- emphasize increasing infiltration more than reducing runoff.
- to minimize erosion, maintaining a cover of plant residues on the soil is a better first action than building cross-slope banks at intervals downslope.
- on seeing a muddy river in flood, it is more sensible to ask “why so much water?” than to exclaim at the sediment being transported.
- consider water and soil conservation (wsc) rather than soil and water conservation (swc).
- reduce risks of failure due to drought, rather than bemoaning increased severity of drought.
- build soil from the surface downwards, particularly by favouring biotic activity, rather than merely waiting for it to deepen from the bottom upwards.

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