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SOIL MOISTURE REGIME OF LOESSIAL SOILS IN WESTERN GERMANY AS AFFECTED BY ZERO-TILLAGE METHODS*

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Abstract. Continued application of zero-tillage on structurally instable leossial soils in W. Germany resulted in reduced total porosity of the top-soil, in an increased structural homogeneity down the soil profile, and—due to enhanced earthworm activity—in a system of continuous large pores connecting the atmosphere with deeper soil layers. Conventionally tilled soils, though generally less densely packed than untilled soils, were more or less compacted at a depth of 25–30 cm, due to puddling and smearing actions during ploughing.

In consequence of the structural changes the water holding capacity of untilled soil was increased, yet the soil water tension was decreased as compared to tilled soils.

Whereas in tilled soils, after heavy rainstorms, water infiltration was impeded by the plough pan, in untilled soil rainworm channels effected a rapid downward movement of rain water against the existing gradient of hydraulic potential. Thus run-off was decreased and water storage increased as compared to conventionally tilled soils.

Also, near water saturation, the water conductivity of untilled soils was calculated to be greater than in tilled soils. Estimated losses by evaporation during rainless period were equal on both soils.

Grey brown podsolic soils (sols lessive) derived from loess are widely distributed in central Europe and, if used for arable farming, of high productivity. Yet, under the prevailing conditions of a humid climate these soils are subject to erosion, since their top layers have lost the original content of calcium carbonate and clay by downward percolation. The clay has been accumulated in deeper soil layers. This negatively affects the drainage properties of the soil. Due to the increased silt content of the topsoil and the segregation of silt from clay particles, the soil surface is prone to severe slaking. Hence, water infiltration is hampered and run-off promoted.

On similar soils in Ohio, U.S.A., application of zero-tillage methods increased the grain yield of maize by about 10% as compared to conventional seed-bed preparation (spring ploughing, discing and harrowing; cultivation after planting).[9] Therefore, zero-tillage of row crops is increasingly used in the U.S.A. and has been becoming an important subject to research in this country and elsewhere.[1,3]

Prerequisite for the success of zero-tillage is the possibility to control all weeds entirely by chemical means and to incorporate seeds into the soil at the proper depth and with sufficient soil cover, though with minimum disturbance of the soil. With suitable drilling machines and non-selective, non-persistent herbicides at hand, zero-tillage methods became feasible and have been tried on all field crops of the temperate climate region in long-lasting experiments. First experiences have been summarized by Baeumer *et al.*[2] From this review, the conclusion can be drawn that extremely reduced tillage does not result necessarily in yield reductions, if annual and persistent weeds can be effectively controlled by chemical means. Except on heavy clay soils, similar yields can be obtained by conventional and zero-tillage methods.

After continuous application of zero-tillage, distinct changes in chemical and physical soil properties can be observed. Since these changes are of consequence for the moisture regime of arable soils and, hence, to crop growth even under humid climate conditions, our observations—though only locally significant—might be of general interest.

Changes in Soil Structure. In contrast to clean-tilled fields, a no-tilled site is covered always by some plant residue and, of course, by a more or less closed plant canopy. This soil cover enhances the activity of earthworms and other soil inhabiting animals. Earthworms deposit their casts on top of the soil and collect plant debris which they pull into their burrows. Thus, organic matter is incorporated into the soil and slowly accumulates in the top layer (Fig. 1).

In combination with the protective action of the residue cover, this accumulation of organic matter near the soil surface will improve the stability of soil aggregates. Therefore, on untilled silt-loam slaking and sealing of the soil surface by raindrop impact energy is prevented or at least retarded.

Another dominant feature of zero-tillage is that soils are loosened only locally and superficially, yet that they have to bear the normal load of traffic in the field. Hence, natural consolidation and mechanical compaction will cause a denser packing of zero-tilled topsoils as compared to the ploughed layer of conventionally tilled soils.

Figure 2 shows the result of a time series of porosity measurements in the top 2-6 cm layer of arable silt-loam soil derived from loess. It can be seen that zero-tillage results in a smaller total porosity, but also in reduced variability of sampling means; consequently, homogeneity with time increases in naturally compacted soils. Fig. 2 shows further that

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increases and decreases in total porosity are accompanied by concommitant changes of other pore-size fractions. This is most pronounced with large pores on conventionally tilled soil, less to not at all with medium to very small pores.

Figure 3 shows the vertical pore-size distribution of a silt-loam soil. Though in this case the total porosity and the fraction of large pores do not differ much between zero-tilled and conventionally tilled soils, the pattern of porosity reveals an important difference:

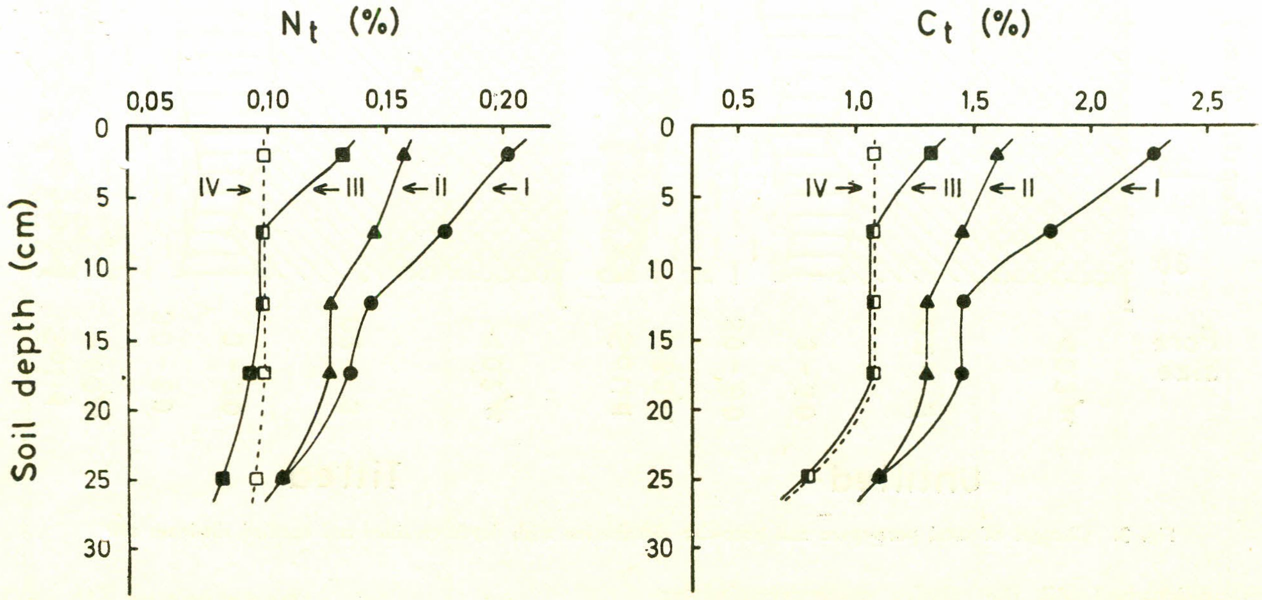

Fig. 1. Average distribution of total nitrogen content and total carbon content in tilled and untilled silt-loam soil after five years of experimenting: (i) permanent grassland; (ii) former grassland, zero-tilled; (iii) arable land, zero-tilled; (iv) arable land, conventionally tilled.

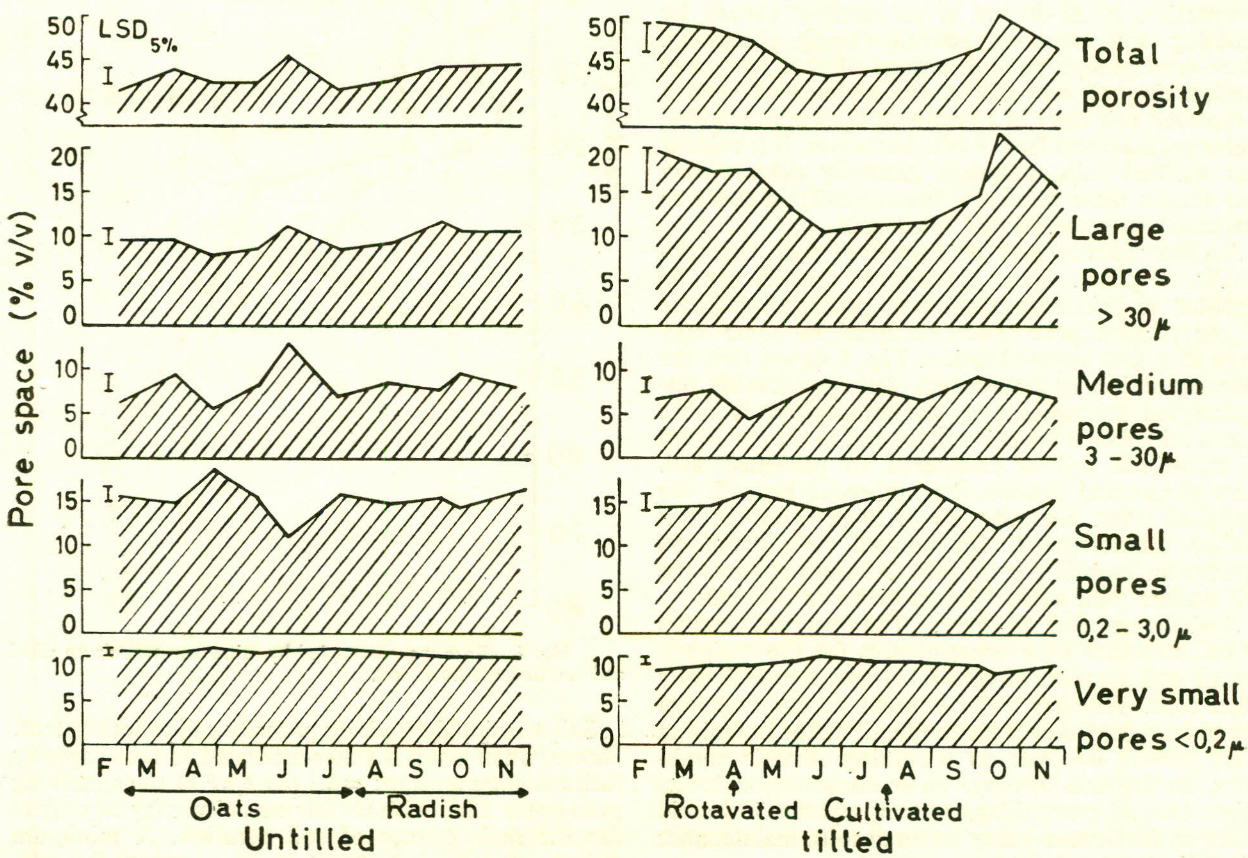

Fig. 2. Changes of total pore-space and pore-size distribution with time at depth of 2–6 cm on tilled and untilled silt-loam soil.

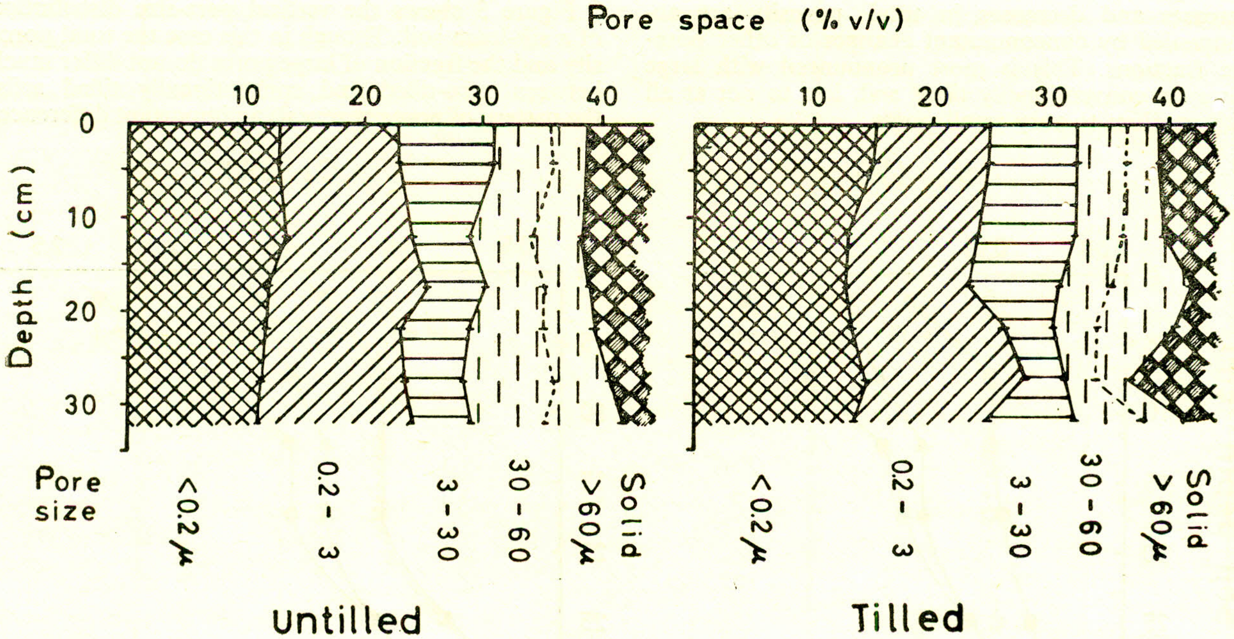

Fig. 3. Changes of total pore-space and pore-size distribution with depth on tilled and untilled silt-loam soil

on undisturbed soil, the relative space occupied by each pore-size fraction varies less than on the ploughed soil, where the layers at 0–15 and 25–30 cm are compacted as compared to the layer at 15–20 cm. The compaction at 25–30 cm is presumably caused by puddling and smearing actions during ploughing. Since such plough pans disappear after a few years continuation of zero-tillage, the absence of such a compacted soil layer is a pertinent feature of untilled arable soils derived from loess. Moreover, it is evident that untilled soils, although generally denser, may also exhibit more structural homogeneity in space as compared to conventional tilled soils.

Another feature may be connected with the continuity of pores. Since earthworm tunnels can be regarded as primarily continuous pores, an estimate of the relative pore space occupied by them may serve as a first approximation. Fig. 4 shows that the space occupied by large pores with presumably uninterrupted connections to the atmosphere is more than doubled near the soil surface and in the top 20 cm of zero-tilled soil as compared to ploughed soil. Here earthworm tunnels are numerous beneath the ploughed layer, but only few of them reach the soil surface uninterrupted. On untilled soil, about 50 earthworm tunnels per m^2 (dia >5 mm) connect the soil surface with subsoil layers down to 200 cm.

Aeration and Soil Moisture. The observed changes in soil structure have consequences for the moisture regime and aeration of zero-tilled and conventionally tilled soils. Whether water content or gas exchange has to be regarded as a predominant factor in limiting plant growth depends on prevailing climatic conditions. In dryland-farming, water conservation is the prime task of every tillage system, whereas in humid zones on medium to heavy textured soils, maintenance of good aeration has to be ensured.

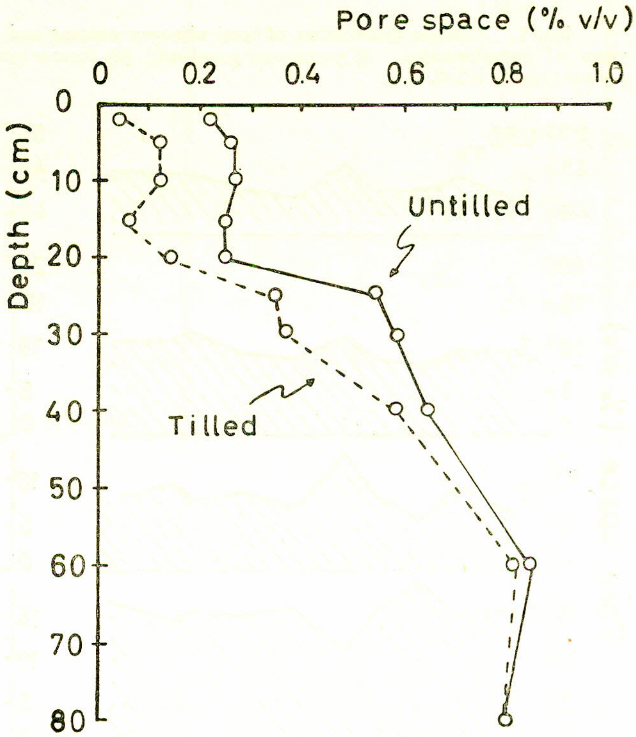

Fig. 4. Pore-space occupied by rainworm tunnels on tilled and untilled silt-loam soil.

Soil aeration depends on porosity and water content. Hence, when a soil is water-saturated to field capacity (soil moisture tension: ≈ 0.1 bar $\triangleq pF\,2$), the remaining pore space filled with air (air capacity) may be critical for the maintenance of soil aeration. A minimum volume of 10% is thought to be necessary for adequate exchange between the soil air and the free atmosphere.

Figure 5 shows that, due to the reduction of large pores, the naturally compacted soil can have a smaller air-filled pore space in the top layer than a ploughed soil (ranges 9–30% versus 13–32%). The same holds for the air capacity (10 vs 13%). But it has to be considered that the air-filled pore space of untilled soil, though smaller, partly consists of a system of uninterrupted large pores. Thus aeration may not be decreased by application of zero-tillage.

Since water-holding capacity of a soil generally increases with increasing space of pores with equivalent diameter < 30 μ, the observed relative increase in the amount of medium to small pores on untilled soil is related to a relatively larger part of waterfilled pore space (% v/v). Yet this is of no consequence for the amount of water per unit weight of soil (% w/w), as has been shown by Van Ouwerkerk *et al.*[10] and Ehlers.[4]

In addition to the water-holding capacity, information about the energy associated with soil water is essential if its movement in soil or its availability for plant growth is to be understood.

Figure 6 shows the matric and hydraulic potentials together with the gravimetric water-content down the profile of a silt loam during beginning and advanced stages of water depletion. Most remarkable is the observation that soil water tension ($\triangleq$ — matric potential) was affected by the tillage system down to a soil depth of 220 cm. This demonstrates the consequences of changing the structure of the top soil layer for the moisture regime of a whole profile.

Differences in gravimetric soil water-content between tilled and untilled soil were relatively small and inconsistent as compared to differences in soil water tension and hydraulic potential. With a similar water-content, the zero-tilled soil generally had lower soil water tensions. This indicates that different pore-size fractions were filled with water as compared to the ploughed soil. Since lower water tensions implicate a smaller resistance to water uptake by plant roots, availability of soil water to plants should be increased by zero-tillage on loessial soils.

Water Infiltration. The continuous record of changes in matric potential during a phase of rapidly rewetting a dry soil reveals differences in water infiltration of tilled and untilled soil. Fig. 7 shows the effect of a heavy rainstorm in June on a fairly dry silt-loam cropped with wheat. During the first 10 hr most of the observed changes in soil water tension to the untilled soil occured at a depth of 30–150 cm. This indicates a quick transport of precipitation water into the deeper soil layers. Contrary to this, in the tilled soil most changes occurred at a depth of 0–20

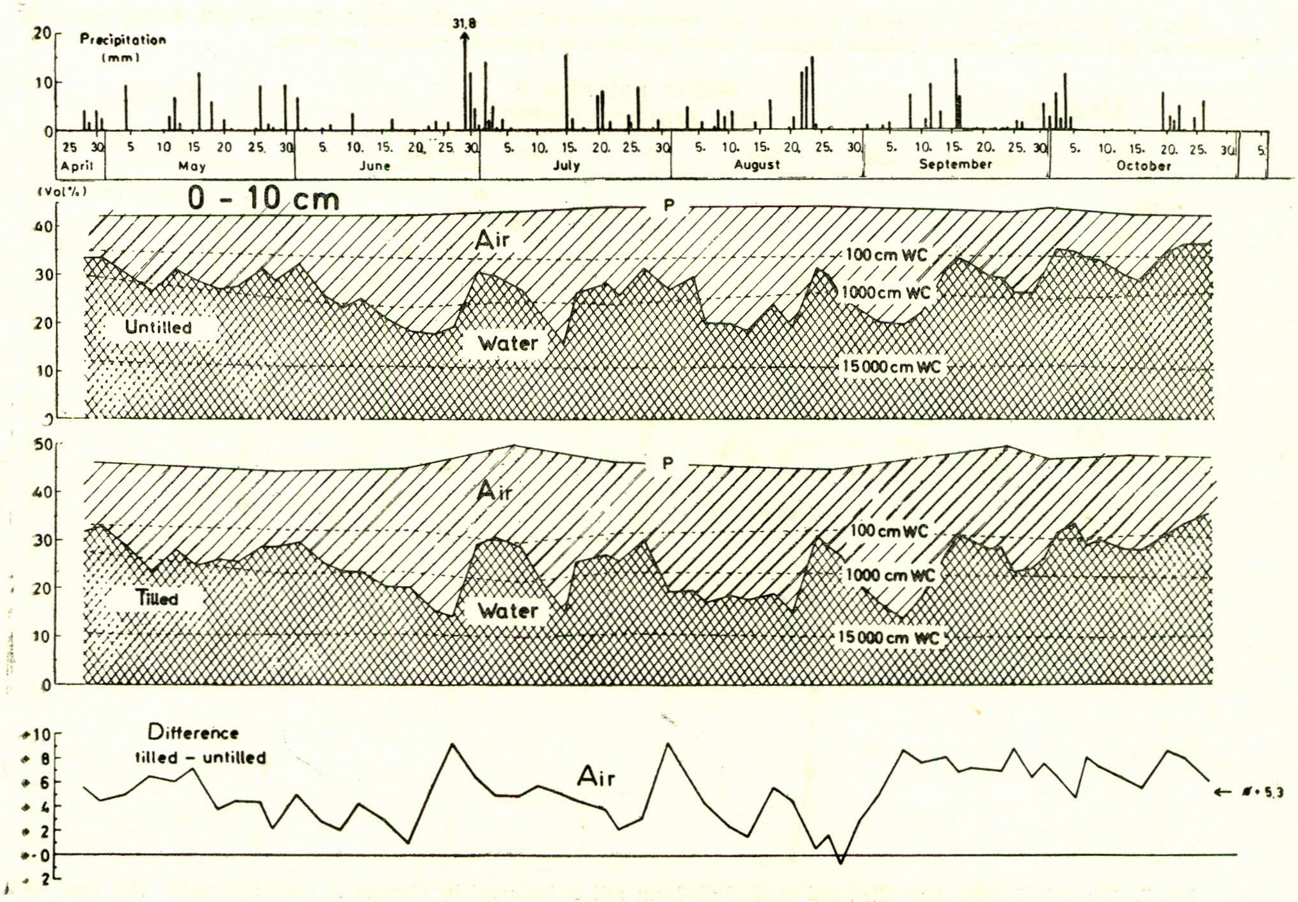

Fig. 5. Changes of air-filled pore-space and water-filled pore-space with time on tilled and untilled silt-loam soil (WC: water column).

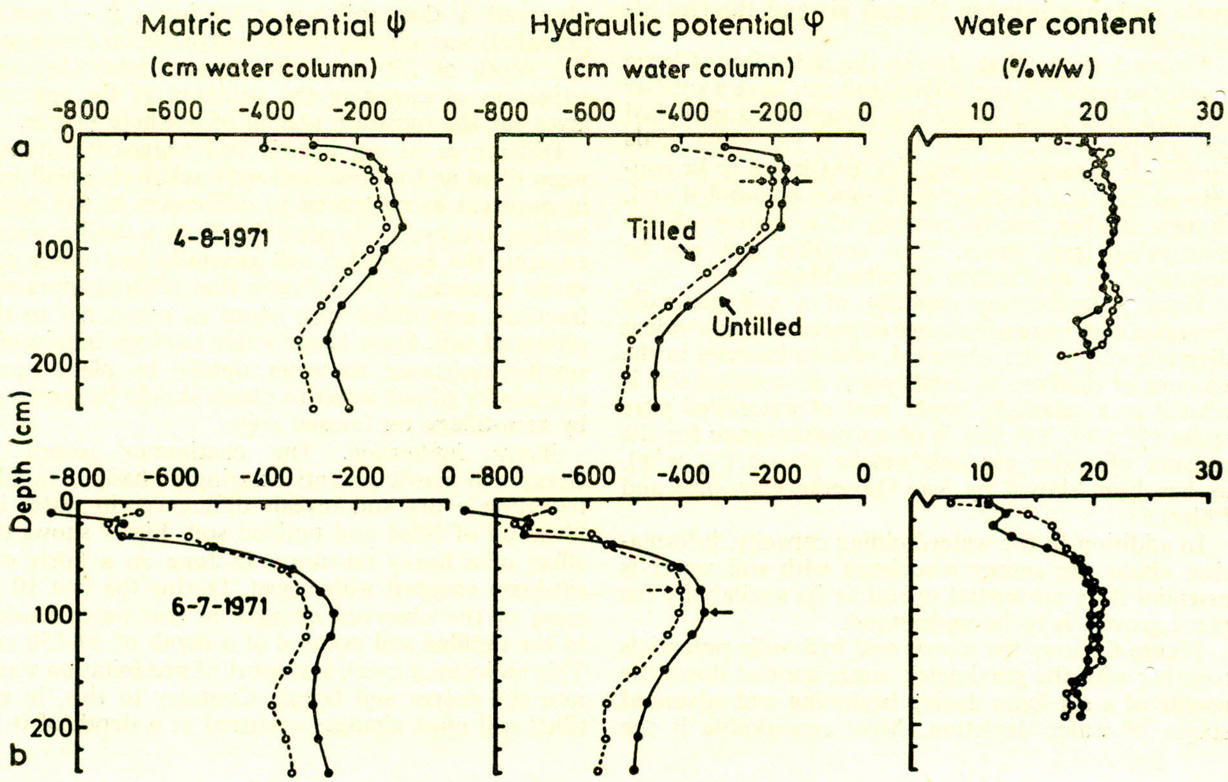

Fig. 6. Matric potential, hydraulic potential, and water-content of tilled and untilled silt-loam soil during phases of depletion of soil moisture. Arrows indicate situations where gradients of hydraulic potential are zero.

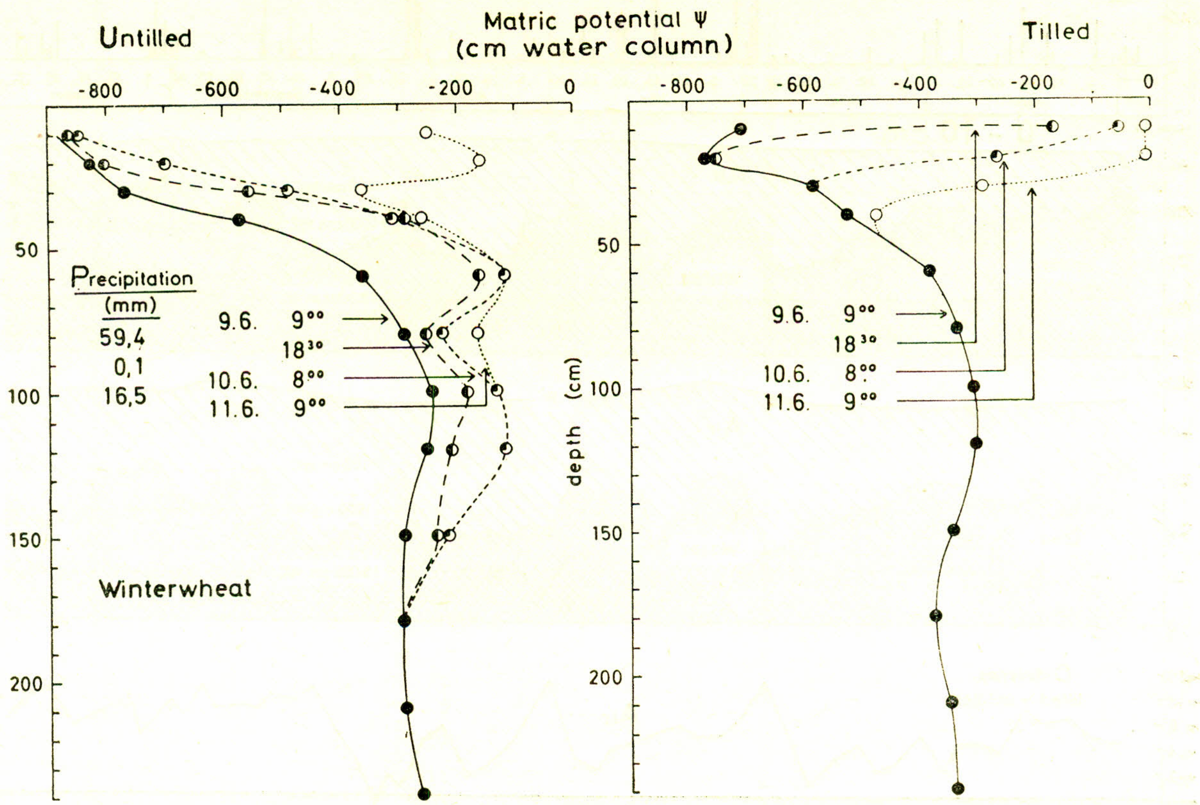

Fig. 7. Water infiltration into tilled and untilled silt-loam soil as indicated by changes of matric potential with time in a cropping situation (winter wheat).

cm. The wetting front moved down very slowly during the observation period of two days.

Obviously water infiltration is impeded by the plough pan which is characterized by the reduction of large pores and a lowered water conductivity at a water saturized state (Figs. 7 and 8).

Changes in soil moisture tension really do not allow conclusions on the direction of water transport in a soil profile. This is possible only by the gradient of the hydraulic potential, since soil water generally moves from points of higher to those of lower hydraulic potentials (hydraulic potential: sum of matric potential and gravitational potential with soil surface as the reference point). Before rewetting of the soil started, the lowest hydraulic potential existed in the upper 10 cm layer of both tilled and untilled soil. Therefore, soil water movement was in upward direction.

During the first two days of infiltration, the zone of the lowest hydraulic potential moved down to 40 cm depth on both soils. Therefore, beneath this zone the soil water can be expected to move still in upward direction, whereas the infiltration water should move downward. This is clearly the case with the tilled soil. Yet, on the untilled soil, as indicated by changes of the matric potential and the gravimetric water-content, some of the infiltration water must have passed the zone of the lowest hydraulic potential. From this it can be concluded that water has been transported downward against the existing hydraulic potential, and that very rapidly too.

Such water transport in soil can be expected only, if water moves down with zero tension. Prerequisite for water movement, in a tensionless state are large infiltration channels connecting the soil surface with deeper soil layers, for instance earthworm tubes as observed on untilled soils. As shown by the result of an infiltration test with tainted water, these earthworm tubes are the main cause for the increased water infiltration on untilled soils as compared to conventionally tilled silty soils. This holds for all cases where rainfall intensity is very high. With low intensities the differences in rates of water infiltration are less pronounced between tilled and untilled soils.

The same holds, if the soil moisture-content is higher, i.e. near field capacity, as can be derived from Fig. 9. The data compiled in these graphs refer to the same situation, but for two sites which had been left uncropped and chemically black-fallowed.

The continuous record of changes with hydraulic potential and volumetric water-content do allow to conclude on the magnitude of water movement in tilled and untilled soils. Hence the water conductivity K can be calculated between different observation points down the soil profile.

Figure 9 shows the relationship between water conductivity K and soil moisture tension in the soil layer from 20 to 30 cm of tilled and untilled silty loam soils. As generally known, the values of K increase with decreasing soil moisture tension and increasing moisture content. In all soil layers investigated this increase was greater on untilled soil than on conventionally tilled soil. The difference between both soils appeared to be most pronounced at the layer from 20 to 30 cm. This demonstrates the positive effect of a continuous pore system on the untilled soil

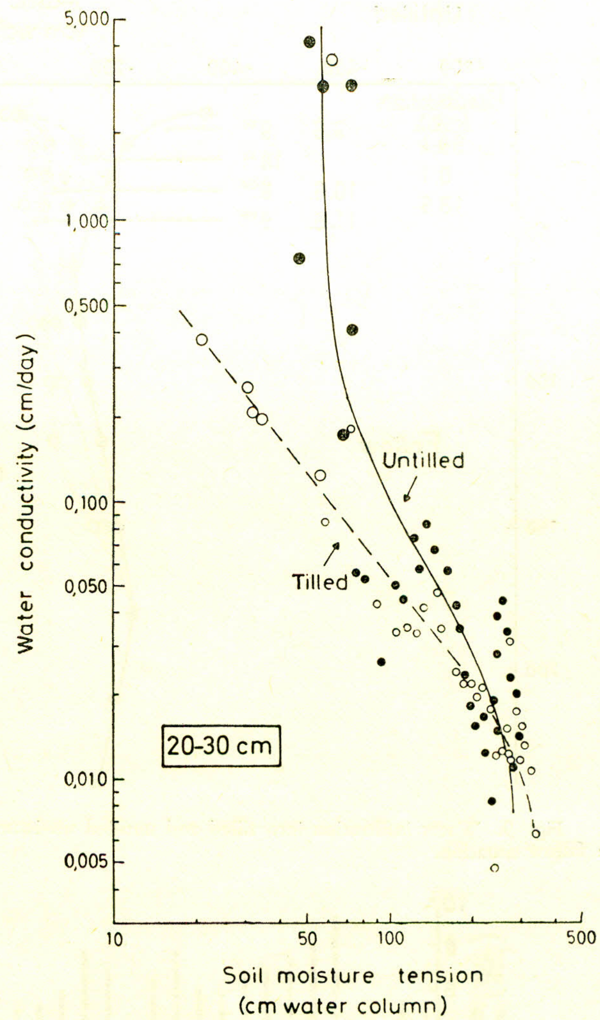

Fig. 8. Water conductivity at depth of 20-30 cm on tilled and untilled silt-loam soil.

as well as the negative effect of a plough pan on water movement in the conventionally tilled soil.

In combination with the system of large, fast draining pores, this increase of water conductivity is of great importance to the capacity of untilled soil for higher water infiltration. Consequently, zero-tillage should increase the total water intake of silt-loam soil and reduce run-off. On such soils with 8–10% slope planted with row crops, the reduction ranged between 1/2 to 1/16 of the amount observed on clean tilled land.[6–8] The greatest absolute reduction of run-off reported, was 88 mm during the growing season in Virginia, U.S.A. (two year average, Jones *et al.*[7]).

As indicated by our own observations during a rainy period of 4 days with a precipitation of 48 mm, at this occasion the untilled soil took up 45 mm, the tilled soil only 25 mm. The difference of 20 mm can be ascribed largely to reduced run-off.

Evaporation. If differences in downward movement of water exist, differences may be expected as well in upward movement. The denser packing of the top layers of untilled soil as well as the greater continuity of pores should promote upward movement of

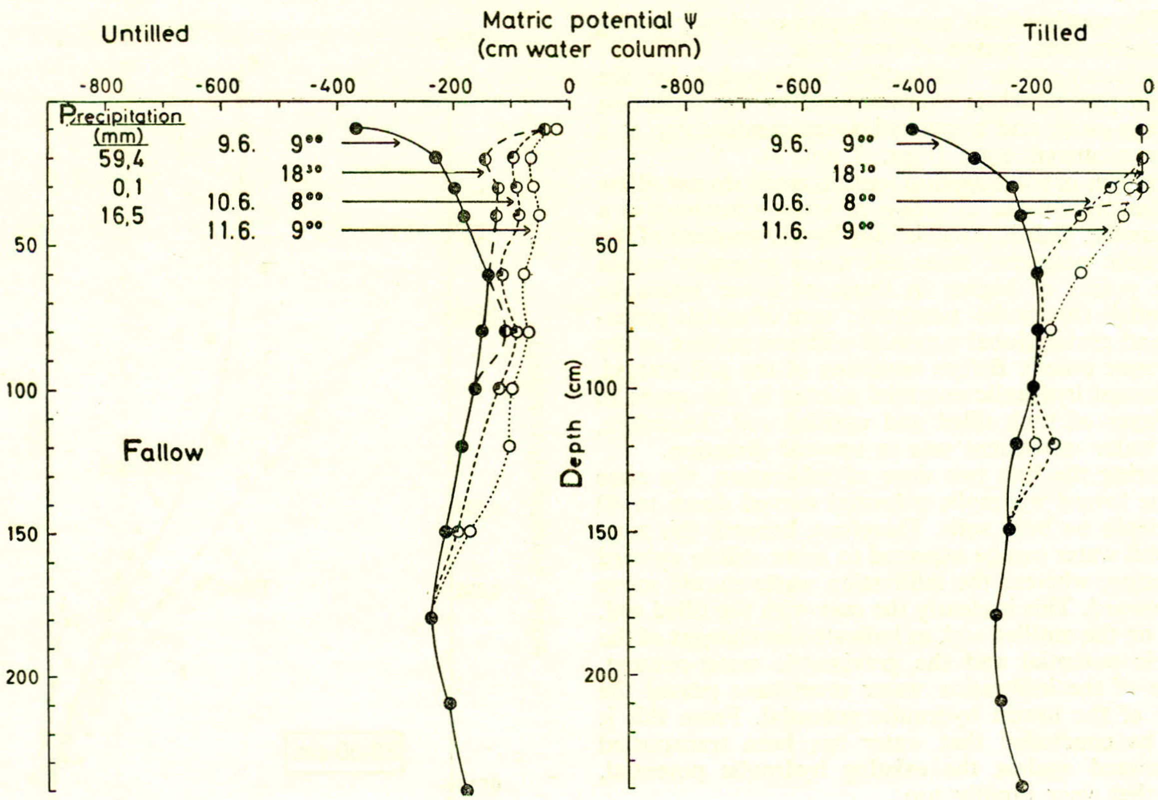

Fig. 9. Water infiltration into tilled and untilled silt-loam soil as indicated by changes of matric potential with time in a fallow situation.

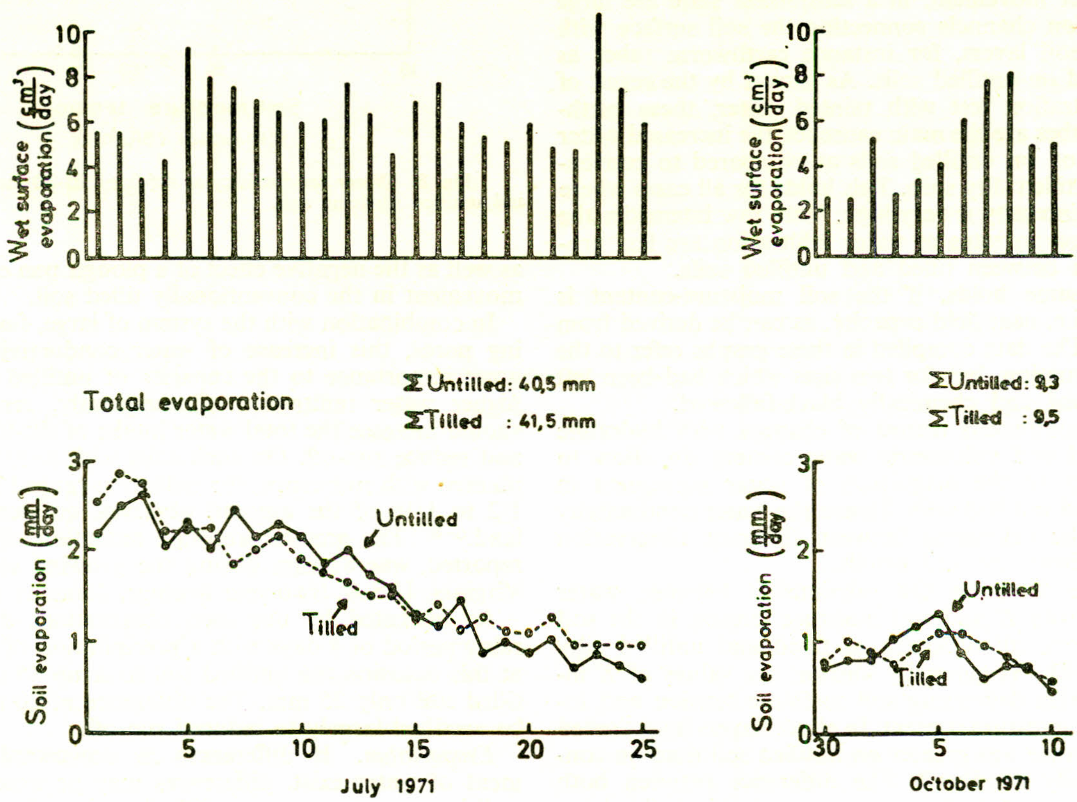

Fig. 10. Changes of wet surface evaporation and total soil evaporation with time on tilled and untilled silt-loam soil during periods of drought.

water during spells of drought. Therefore, prolonged periods with high rates of evaporation could be expected on untilled silt-loam.

This hypothesis is supported by the repeated observation that during dry spells untilled soil has a higher water-content in the top layers than conventionally tilled soil. Yet, the final proof of this hypothesis can be reached only by measuring evaporation rates on bare, fallowed soil.

Since direct measurements of water evaporation from tilled and untilled soil have not been made, calculations of evaporation rates from the chemically fallowed plots may serve as a first approximation. These calculations are making use of the changes with gravimetric water-content down the soil profile, taking the position of a zero gradient of hydraulic potential as the border of the soil layer from which water is evaporating.

Figure 10 shows that there are no great differences in calculated evaporation rates between both soils, indicating that upward movement of soil water is at least not increased on untilled soil as compared to the conventionally tilled soil. Therefore, the hypothesis of increased evaporation from untilled soils cannot be accepted. Considering the reduced rates of run-off on untilled soils as well as their similar total evaporation, another hypothesis may be forwarded: a system of uninterrupted large pores combined with peds of normal porosity, as given in untilled silt-loam soils, may act as a trap for percolating water. Rapid and increased water intake is combined with normal rates of upward water movement, thus resulting in increased water storage in soil. This hypothesis has still to be tested in further investigations.

Conclusions

The changes in soil structure and soil moisture regime as induced by zero-tillage application are of consequences for plant production. In a humid climate where water uptake does not limit frequently plant growth, increased infiltration and, hence, greater water storage of untilled soils should not affect the soil productivity to a relevant extent.

Indeed, the yield of small grains, maize and sugar-beet produced by conventional and zero-tillage methods on average do not differ much. There are as many cases in favour for the one tillage system as for the other. The inconsistency of results for both systems depends more on interaction between weather and soil properties like temperature and availability of plant nutrients, than on soil moisture regime, though in some cases water may become the most important factor.

More important for farming in a humid climate may be two other features of zero-tillage. As has been stated above, untilled soil becomes compacted at the top layer but, owing to the system of continuous pores, very permeable to surface water. Thus trafficability of the soil is greatly improved, as has been observed especially during prolonged spells of rainy weather, when root crops had to be harvested with heavy implements.

Still of greater importance is the fact that zero-tillage is most effective in controlling soil erosion. Harrold,[5] for instance, found that zero-tillage of maize on a silt-loam with a 9% slope reduced soil losses to 0.2 per ha between 1964–1970, as compared to 20.5 per ha with conventional tillage. Thus, the application of zero-tillage should be taken into consideration as an alternative to conventional tillage, where the need for soil conservation is the prerequisite to arable farming.

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