DEVELOPMENT OF CRITERIA AND METHODS FOR IMPROVING THE EFFICIENCY OF SOIL MANAGEMENT AND TILLAGE OPERATIONS, WITH SPECIAL REFERENCE TO ARID AND SEMIARID REGIONS

APPENDIX 3. TO FINAL REPORT

FIELD EXPERIMENTS ON INFILTRATION, RUNOFF, TILLAGE AND MILLET EMERGENCE IN MALI

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1981
DEVELOPMENT OF CRITERIA AND METHODS FOR IMPROVING THE EFFICIENCY OF SOIL MANAGEMENT AND TILLAGE OPERATIONS WITH SPECIAL REFERENCE TO ARID AND SEMI-ARID REGIONS.

Appendix 3.

Rainfall infiltration and runoff, tillage, sowing and emergence of millets on a sandy soil near Niono, Mali.

W.B. Hoogmoed.

1981.

A joint project between the Tillage Laboratory, Agricultural University, Wageningen, the Netherlands, and the Department of Soils & Water, Faculty of Agriculture, Hebrew University, Rehovot, Israel.

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1. INTRODUCTION.

The workings visits to Mali, in March 1978 and in the period May – September 1979, formed part of the research activities of the "tillage for arid regions" project executed by the Tillage Laboratory (Agricultural University, Wageningen) and the Dept. of Soils and Water, Hebrew University, Israel. In Mali, research was carried out in cooperation with members of the PPS project: Primary Production in the Sahel (Penning de Vries and Djiteye, 1981).

Some of the important problems encountered by the investigations in Mali in the field of soil and water were:
- the extremely variable rainfall pattern
- the high rainfall intensities
- the high runoff rates during rainfall as a result of low infiltration capacities
- the hard, sandy soils

In particular the tendency of the (even sandy) soils to form a crust on the surface, in combination with the high intensity rainfall, may create large losses of rainwater by runoff along the surface. As a result, even in years where rainfall should be sufficient for crop production, poor yields due to water shortage may be encountered, because of runoff losses. To find the mechanism of the crust formation and ways to minimize or eliminate the problem, it was decided to use a rainfall simulator, where rainfall with a known and adjustable intensity can be applied. In the course of this (artificial) rainstorm infiltration and runoff can be measured. During the visit of 1978, preliminary experiments were carried out with a simple rainsimulator, in 1979 an improved version was used and a more extensive research program was carried out. Before and during the rainy season, research was carried out on:
a. Infiltration and runoff under rainfall on sandy soil and the effect of soil tillage and surface configuration on these phenomena (1978 and 1979).
b. Seed germination and emergence in relation to tillage and sowing depth (1979).

This report contains the basic data from the measurements mentioned under a and b. Climate data, rainfall analysis and application of the processed data will be given in appendix 4. A report on the observations of a local farmer (c) is given in appendix 5.
2. SOILS.

For a general description of the soils at the ranch, reference is made to Stroosnijder (1977). An important part of the area (which is also in use for agriculture) has sandy soils. In the 1978 and 1979 experiments, emphasis is given to work on the sandy soils of the ranch, in particular the S1 soils. Some of the characteristics of this soil type, as analysed by the PPS team, are given below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH water</td>
<td>6.1</td>
</tr>
<tr>
<td>pH KCl</td>
<td>5.3</td>
</tr>
<tr>
<td>EC (1:5) mmho/cm at 25°</td>
<td>0.03</td>
</tr>
<tr>
<td>CEC (pH 7) me/100 g soil</td>
<td>2.25</td>
</tr>
<tr>
<td>Ca (% of complex)</td>
<td>66</td>
</tr>
<tr>
<td>Mg (&quot;&quot;&quot;)</td>
<td>26</td>
</tr>
<tr>
<td>K (&quot;&quot;&quot;)</td>
<td>8</td>
</tr>
<tr>
<td>C/N ratio</td>
<td>1.33</td>
</tr>
<tr>
<td>P (Bray) ppm</td>
<td>7</td>
</tr>
<tr>
<td>K ppm</td>
<td>78</td>
</tr>
<tr>
<td>Fe₂O₃ * %</td>
<td>0.87</td>
</tr>
</tbody>
</table>

* measured in Holland.

A detailed particle analysis was made for two types of sandy soils, the S1N soil (experimental site) and "mil" a farmer's field in the immediate area of the ranch, where agronomic observations were taken. Results are given in fig. 2.1.

For S1N, the major particle size classes were:
- clay <2 μm: 6.7 fine sand
- silt 2 - 50 μm: 12.6 sand
- >105 μm: 25.7

In view of the experimental work on water movement in the soil, measurements were carried out (in the laboratory) to obtain relations between moisture content and suction and moisture content and hydraulic conductivity.

Retention curves (ψ - θ relation) were obtained both from undisturbed samples and artificial samples with different densities. The K - θ relation was measured by using the "hot air method" (as described by Arya et al, 1975), both on undisturbed samples in Mali and "artificial" samples in the laboratory.

Results are given in fig. 2.2. (S1N) and 2.3. ("mil").
3. RAIN SIMULATOR EXPERIMENTS

3.1. INTRODUCTION.

Water obviously plays an important role in the production of agricultural produce in the semi-arid "Savanna and Sahel" area of West Africa. Looking purely at the meteorological records, the total amount of rainfall during a given rainy season should be sufficient for a reasonable yield of the crops in many years. In practice however, there is often still a serious lack of water for optimal production during these years. It was found from observations by scientists of the PPS project, that on the experimental sites near Niono (Mali), some soil types showed the formation of surface crusts (Stroosnijder, 1977). This phenomenon, also cited by French workers in Senegal (Charreau et Nicou, 1971a, b, c and d), occurs especially on sandy or loamy soils.

Detailed research has been undertaken by the PPS team on these crusts. It was found, that the crust was not only physical, but it had also hydrophobic characteristics, due to the presence and growth of algae. During preliminary experiments, this hydrophobism seemed to retard water infiltration seriously (e.g. an apolar liquid like gasoline was absorbed by the soil much more quickly than water). This water "repellency" was closely investigated in the laboratory in Wageningen, and it was found, that the hydrophobic nature of the crust disappeared within 5 minutes after wetting (Rietveld, 1978). On the other hand, the physical crust is a very important factor in the water balance of a field. Detailed measurements on moisture content and flow of (sloping) fields were made during the rainy season. It was found, that a high percentage of rainwater did not enter the soil on the spot where it fell, but was transported as runoff water along the surface. As a result, there usually is a lush vegetation in depressions of sandy, crust forming soils, while on the slopes and on higher levels often there is clearly a water shortage and less vegetation.

On cultivated fields, local farmers have to deal with the problems of crusts as well; the soil is many times cultivated in the early cropping stage, to improve infiltration and so to avoid losses of water by runoff.
3.2. CRUSTS AND CRUST FORMATION.
Research on the mechanism of the formation of crusts is extensively undertaken by Morin and co-workers (Seginer and Morin (1970), Morin and Benyamini (1977), Morin, Benyamini and Michaeli (1977), Chen et al (1980)). General aspects of crust formation are reviewed by Cary and Evans (1974), with a more detailed description of the chemical processes involved. Rhebergen (1979) made a review of literature on research with respect to crust formation and their importance on emergence in semi-arid regions. Rietveld (1978) made a computer model approach on water movement through both hydrophobic and physical crusts.

The physical mechanism of the formation of a crust – as explained by the work of Morin – is roughly as follows: by the impact of falling raindrops, small particles, like the clay and silt, attached to larger grains (sand) will be separated at the soil surface. The small particles will form a colloidal suspension in the rainwater and because of the suction from the underlying drier layers, this suspended material will be forced downwards in the water through the voids between the grains. These voids now will become choked with the particles and so a very thin layer has been formed. This layer (often far less than 1 mm thick) has a very low hydraulic conductivity. This phenomenon will occur even on sandy soils with only a small percentage of clay particles.

3.3. INFILTRATION INTO CRUSTED SOILS.
A crust at the surface of an otherwise permeable soil (sandy soils) may seriously decrease the infiltration capacity of the soil. To measure the conductivity of the crust sec however, is almost impossible, the more so on the sandy soils where crust thickness may be less than 1 mm. Research on the effects of crusts on infiltration is undertaken by various authors (Hillel, 1960,1964, Hillel and Gardner, 1969, 1970, a,b). For use on field scale, it is important to know also the characteristics of the infiltration (conductivity) during the formation of the crust, so during the rainstorm and the following drying stage. Infiltration measurements, like the standard double ring infiltrometer, utilizing a constant hydraulic head on the soil surface, are not suited for measurements on crusting soils. Here, apart from the presence of a layer of approx. 50 mm of water on the surface, the impact of the raindrops, destroying the aggregates on the surface and so forming the crust,
is not taken into account. The best way to investigate this process for obtaining e.g. its effect on the water balance of a field, is probably by using a rainfall simulator.

3.4. RAINFALL SIMULATORS.

Rainfall simulators have been used in many different types of experiments, often in erosion research (Hudson, 1971; Wischmeyer and Smith, 1958; Wischmeyer, Smith and Uhland, 1958). The major concern in the construction of a rainfall simulator is the creation of water drops which are similar to the drops in a natural rainstorm. Various types of simulators have been developed with this purpose (Hudson 1971).

The following characteristics should reach those of a natural rainstorm:

a. drop size and -distribution
b. velocity of the drop when reaching the soil surface (terminal velocity)
c. intensity of the storm

Two distinctly different types may be distinguished; the drip type and the sprayer (nozzle) type. The drip type operates very small apertures (hypodermic needles, capillary tubes) from which (usually under a low pressure) drops of water will be formed. With this type, the formation of drops of the proper dimensions and the required intensity is generally not a problem, but to achieve an acceptable velocity (kinetic energy!) will cause problems. To reach a terminal velocity (the constant speed of a falling raindrop of a given size), the drops have to fall from a height of preferably 5 or more meters. For laboratory work this may be possible (rain towers), but for field application this is not practical. The experiments in Mali in 1978 however, were carried out with a simple, drip type simulator. Here the drops formed did fall only over a distance of 1 m, but the larger-than-natural size of the drops would compensate for the lower velocity (see chapter 3.5.1.).

The nozzle type simulator is used more extensively in field work. Here drops are being formed by pumping water under pressure through a nozzle which breaks up the water stream into drops. The major problem here is the disproportionality between the size of the drops and the intensity of the simulated rain. To achieve the proper size of drops with an acceptable velocity, one has to use a nozzle with a large opening. This large nozzle will work properly only if the volume of water passing through is very high, thus giving an intensity which is far higher than any natural rain intensity.
Various ways of decreasing this intensity have been used; mounting the nozzle(s) on a rotating or oscillating boom, or by a disc with a radial slot, rotating under the nozzle opening. This later type is developed by Dr. Morin, Israel (Morin, Goldberg and Seginer, 1967) and is in use by the Erosion Research Station in Israel.

3.5. THE 1978 EXPERIMENTS.

3.5.1. Description of the simulator.
The rainsimulator was developed by the Department of Land and Water Use, Agricultural University, Wageningen (Spaan, 1976). The simulator operates a perspex plate of 500 x 1000 x 20 mm, in which holes of ø 1.6 mm have been drilled. To decrease the outflow aperture, a piece of stainless steel bar of ø 1.5 mm is inserted in each hole. This results in an effective opening of $0.25 \text{ mm}^2$, which is large enough to allow raindrops of ø 5.6 mm to be formed at the bottom of the plate. On top of this perforated plate (holes are placed one per square of 30 x 30 mm), a second plate is placed, leaving a room of approx. 10 mm high between the two. This room is sealed watertight by rubber gaskets and a positive waterpressure may be maintained by means of a "Mariotti bottle". By altering the height of the waterlevel in the Mariotti bottle, the intensity of the rain can be influenced. The Mariotti bottle is filled by a larger container placed on a frame (at a higher level) near the simulator.
The simulator itself is placed on a frame 1 m above the soil surface. The drops produced, falling over this distance, should result in a rainstorm with a kinetic energy equal to a natural rainstorm with an intensity of approx. 100 mm/h. To avoid drops falling repeatedly on the same spots at the soil surface, a wire mesh screen (3 mm openings) is placed 250 mm below the bottom plate. In the soil, a rectangle of 500 x 1000 mm should be constructed, by inserting sheets of metal or plywood approx. 200 mm into the soil, leaving a height of 50 mm above the surface to avoid water loss by splash. The longer sides of the rectangle should be parallel to the axis of the slope of the field. At the bottom end, a collecting device (sheet metal funnel) will be installed, allowing the runoff water to be collected in a beaker. Shields of plywood or plastic sheets have to be used to avoid drift of the raindrops due to wind.

3.5.2. Operation and measurements.
Operation of the simulator is as follows: after installation of the simulator/container/soil plot, the plot is covered by a plastic sheet and water is allowed in the system. By means of two screws, entrapped air may escape through the top plate. Once the system is completely filled
with water and the desired level in the Mariotti bottle is set, the
experiment starts by removing the plastic sheet.
The following measurements should then be taken at regular time intervals:
- the outflow of water from the container (by reading waterlevel e.g.
every 2 minutes)
- the runoff (by measuring volume of water collected, also every 2 minutes)
Time at which runoff starts should also be recorded.
The measurements preferably have to be continued till it may be expected
that a uniform (final) infiltration rate of the soil is reached.

3.5.3. Observations on the rainsimulator.
Some comments should be given about the use of the simulator:
a. The Mariotti system requires a completely airtight system, even small
leaks will result in a failure of this system.
b. The simulator, as it is working with a large number of very small
apertures for the formation of raindrops, is very susceptible to con-
taminated water. Due to blocking of part of the openings, there are two
effects:
- the intensity of the rain applied will decrease
- the uniformity of the rain produced over the plot will decrease.
During the experiments in Niono, this phenomenon was observed and it was
decided to test the performance of the simulator on uniformity. In this
test, the uniformity of the rain was measured by catching the rainwater
in 126 soil sampling rings (the bottoms of which were sealed with plastic
caps). The rings (Ø 50 mm) were placed in a triangular pattern on the
floor below the simulator:

Uniformity was calculated according to the method also used by Spaan:

\[
C = 100 \cdot (1 - \frac{X}{m \cdot n})
\]

where \(X\) - difference between actual value and
average value (m) in ml
\(m\) = average value in ml
\(n\) = number of measurements

The C value of the simulator, as measured after 2 days of experiments was
37 (measured without a screen) and 42 (measured with screen). So a
screen might improve uniformity by approx. 10%.
Because of the low uniformity, it was decided to open the simulator and
to clean it using some soap (detergent) for removal of any grease. It was observed that especially the openings near the intake (Mariotti bottle) were blocked, indicating that suspended particles in the water were the major cause of the problem. After cleaning, some of the openings had to be sealed, because outflow was much too high compared to the others. Another uniformity test was run and resulted in a C value of 68 (without screen). Additionally, the intensity of the rainfall was much higher now (at the same waterpressure level).

During later experiments, water was filtered as a precautionary measure. However, the rainfall intensity of the simulator, as a function of the waterlevel in the Mariotti bottle, dropped very quickly again and was at the original level after approx. 20 minutes! Uniformity remained reasonable for a couple of days (some 8 experiments) and then also seemed to deteriorate. A cleaning (without opening the simulator) improved the situation and a uniformity of C = 62 (with screen) was obtained.

To summarize the uniformity experiments:

<table>
<thead>
<tr>
<th>Screen</th>
<th>No Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>C value</td>
<td>by Spaan 82^x</td>
</tr>
<tr>
<td>in lab. Wageningen</td>
<td>72</td>
</tr>
<tr>
<td>Niono, before cleaning</td>
<td>42</td>
</tr>
<tr>
<td>Niono, after cleaning</td>
<td>68</td>
</tr>
<tr>
<td>Niono, after 2nd. cleaning</td>
<td>62</td>
</tr>
</tbody>
</table>

^x It should be noted that Spaan used tins with a larger diameter (approx. 75 mm), which will yield a higher uniformity anyway (by collecting outflow of more openings per tin).

c. An important point, which appeared after calculation of the results is the accuracy of measuring the rainfall intensity by the rate of outflow from the container. This should be done very carefully especially in cases where the intensity tends to drop gradually in the course of an experiment. A resolution of 1 mm in the waterlevel of the container has the same accuracy as 71 ml of runoff water collected! So while waiting for the soil system to reach its final infiltration rate, this may be misleading when the runoff seems to be uniform but the intensity drops slightly.

3.5.4. Experiments and results.
The experiments at the ranch in Niono were carried out at three sites with the soiltypes S1, S2 and "degraded" (W). The degraded field was of
particular interest, since runoff is severe here and experiments are being
carried out to reclaim these soils. S1 and S2 are sandy soils which are
important since they are often used for arable farming in a system
where millet (1 year) is alternated by grazed fallow ("jachère", several
years).

In the following table the experiments are shown:

Summary of experiments at Niono, March 1978.

<table>
<thead>
<tr>
<th>exp.</th>
<th>soil</th>
<th>treatment</th>
<th>slope</th>
<th>I mm/h</th>
<th>time min.</th>
<th>I mm/h</th>
<th>time min.</th>
<th>days after 1st exp.</th>
<th>I mm/h</th>
<th>time min.</th>
<th>days after 2nd exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>degr.</td>
<td>undist.</td>
<td>2.1</td>
<td>51</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>1</td>
<td>42</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>degr.</td>
<td>tilled</td>
<td>1.9</td>
<td>40</td>
<td>60</td>
<td>45</td>
<td>32</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>degr.</td>
<td>dune</td>
<td>2.8</td>
<td>52</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>S1</td>
<td>tilled</td>
<td>3.0</td>
<td>70</td>
<td>60</td>
<td>70</td>
<td>54</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>S1</td>
<td>undist.</td>
<td>1.2</td>
<td>76</td>
<td>60</td>
<td>59</td>
<td>42</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>S2</td>
<td>undist.</td>
<td>1.5</td>
<td>65</td>
<td>44</td>
<td>62</td>
<td>45</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>S2</td>
<td>undist.</td>
<td>0.6</td>
<td>108</td>
<td>36</td>
<td>70</td>
<td>60</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experiments 1, 2 and 3 were conducted on the degraded soils. Exp. 1
was on an undisturbed plot with the surface crust present. Three experiments
were carried out (1, 1a and 1b) on this plot. 1 on a dry soil, 1a one
day later and 1b five days later. The infiltration rate of the soil was
calculated by deducting the volume of the runoff from the volume of rain
per time increment of 2 minutes.

The infiltration rate I (mm/h) of the soil dropped during the course of
an experiment. This is a normal situation: I decreases in time and will
eventually reach a final (uniform) infiltration rate. Many formulae have
been developed, trying to describe this process (see Stroosnijder, 1976).
For short duration infiltration processes, the equation may be expressed
as \( I_{\text{inst}} = a \cdot \frac{1}{\sqrt{T}} + b \), so infiltration rate \( I_{\text{inst}} \) is proportional to
the inverse of the square root of time. This should be valid for processes,
where no major changes in the surface layer will occur. Morin and Benyamini
(1976) however, found in experiments using a rainfall simulator on
crusting soils, that:

1. The decrease in infiltration rate was (between
certain extremes) independent of the intensity of the rain, but was related
to the volume of the rain applied: \( P \cdot t \), where \( P \) = precipitation rate (mm/h) and \( t \) = time (h).

b. This relationship could be expressed by the equation

\[
I_{\text{inst}} = I_f + (I_i - I_f) e^{-\frac{P \cdot t}{\gamma}}
\]

where \( I_{\text{inst}} \) = instantaneous inf. rate (mm/h), \( I_i \) = initial inf. rate (mm/h), \( I_f \) = final inf. rate (mm/h), \( \gamma \) = dimensionless parameter

In relevant cases, a curve was drawn through the data points as a best fit by eye. Using this curve as a base, curves following either \( 1/\sqrt{t} \) or \( e^{-\frac{P \cdot t}{\gamma}} \) were tried to be fit, to see which type of equation would give the best results. This should give an indication whether there was crust formation or not.

For experiments 1, 1a and 1b, the curves are shown in fig.3.1., 3.2., 3.3. and 3.4. All curves have approx. the same shape, starting with an \( I_i \) of around 60 mm/h and reaching an \( I_f \) of 17, 15.6 and 11.2 mm/h respectively. Curves following \( 1/\sqrt{t} \) and \( e^{-\frac{P \cdot t}{\gamma}} \) were tried: the parameters are given in the figures.

In exp. 1, the \( 1/\sqrt{t} \) curve shows a good fit, in 1b, the \( e \) curve fits better. It can further be seen, that after the soil has been wetted once, the infiltration starts again at the same level (surface was dry again), but reaches its \( I_f \) value sooner, which means that during following rainstorms less water will infiltrate.

The results of exp. 2 are shown in fig.3.5. On this plot the soil surface was "tilled" by breaking the crust and digging into the soil 3 - 4 cm deep with a knife. The effect is striking; under a rainstorm of 40 mm/h (lasting one hour), all rainwater infiltrated. However, because of the rainfall intensity chosen, it was not possible to calculate the maximum infiltration rate of the soil in this condition. A repetition of the experiment (2a) after 3 days was not able to supply more information on the degree of slaking (formation of a new crust) since unfortunately the plot was partly damaged by the activities of a jackal. From the observations on the undamaged part of the plot, it may be expected that infiltration rate will drop earlier than after 13 mm of rain as was found now.

Since during the rainy season differences in runoff were observed between
the degraded soils and the (micro) sand dunes on top of this soil, exp. 3 was carried out. Here the infiltration rate was measured for a dune, formed by a layer of only 2 cm of sand on top of the degraded soil surface. The result is shown in fig.3.6. A very high $I_i$ occurs, while the $I_f$ will probably be around 25 mm/h. Due to a misjudgement resulting from a slight decrease in rainfall rate (as mentioned in 3.5.3.), the experiment was terminated before a final infiltration rate was completely reached. Curves of $1/\sqrt{t}$ and $e$ showed approx. the same fit. Time did not permit a repetition of this experiment.

On soil S1, experiments 4 and 5 were carried out. The experimental sites here were in the same condition as compared with a "jachère", so it was interesting to investigate on the effect of tillage on infiltration. In exp. 4, the soil was tilled superficially with a knife, as in exp. 2. Hay from a sparse stand of grass was also left on the surface (though hardly any positive action of a mulch might be expected). The infiltration rate of this plot appeared to be higher than the rainfall applied (70 mm/h) and runoff was again negligible. Even during a second run 2 days later (4a) with the same rainfall intensity no runoff started, so 140 mm of rain infiltrated without any runoff.

The picture was different in the experiment with the undisturbed S1 soil (exp. 5 and 5a). Results are shown in fig.3.7. During the first shower, $I$ drops from 89 mm/h (= rainfall intensity $P$ at start experiment) down to a near constant rate of 30 mm/h after 76 mm of rain. The second run (5a), 2 days later shows that the $I_f$ is slightly lower (although it may be so that I at prolongation of experiment 5 eventually had reached the same level). However, $I_f$ is reached much sooner, so far less water will infiltrate during the second (and probably following) rainstorm. It looks as if the $e$ curves fit better than the $1/\sqrt{t}$ curves, which might indicate a change of surface condition.

Finally, experiments 6 and 7 were carried out on soiltype S2. It was intended to investigate here if differences in rainfall intensities indeed had no effect on the function $I(P,t)$. However, while running the experiments, it appeared that runoff and infiltration here were depending very much on the condition of the surface; soil which was covered by an (algae)crust showed (visually) almost immediate runoff, but it was also clearly observed, that this runoff water could be absorbed easily on a spot where the crust (because of whatever reason) was damaged or removed.
In case of experiment 6, runoff was negligible since all runoff water from the crust-topped part of the experimental plot infiltrated in a (relatively small) area of soil without crust downhill:

In experiment 7 (see fig. 3.8), the situation was different, here approx. 60% of the plot area was covered by crusts, but the other 40% was now situated uphill:

To have some indication as what might be a figure for a completely crust-covered plot, the runoff values of 7 and 7a were assumed to represent 60% of the surface and an extrapolation to 100% was made. The resulting infiltration rate is shown as the broken line in fig. 3.8. The curves still show a rather high \( I_f \) of approx. 85 mm/h in the first case and 68 mm/h in the second case, which does not confirm the observations during the wet season.

To compare the results found with those found from other systems, some results are given in fig. 3.9, for experiments on the degraded soil, both with the double-ring infiltrometer (open system) and the closed system, in which case no positive waterpressure has to be applied.

There are considerable differences:

- on the degraded soil, \( I_f \) for double ring
  - closed system 32 mm/h
  - rainsimulator 15 mm/h

- on the dunes (on top of the degraded soils)
  - \( I_f \) for double ring 47 mm/h
    - closed system 29 and 24 mm/h
    - rainsimulator 25 mm/h

It should be noted that in fig. 3.9, I is shown against time, as compared with P.t in the previous figures.
3.5.5. Conclusions.
The following conclusions may be drawn from the experimental results:

a. Regarding the performance of the rainsimulator.
- The simulator is susceptible to contaminated water; care should be taken to filter water thoroughly. A low uniformity will be the result of blocking of openings.
- Intensity of the rain tends to drop gradually, so measurements on the waterlevel in the container should be taken regularly and precisely.

b. Regarding the infiltration experiments.
- On the degraded soils: a severe runoff may be expected on the bare surface, right from the onset of the rains. Breaking of the crust (even superficially) results in a very high infiltration rate. Even a thin layer of sand, as in the case of the microdunes, gave a much higher infiltration rate. This higher rate cannot only be a result of a storage of water in the sand layer, so the effect could be due to a "softening" of the crust.
- On the S1 soils: a higher infiltration rate (as compared to the degraded soils) is observed on spots with a very sparse vegetation (dry grass) under fellow (jachère). During a second shower after a few days, the final infiltration rate will be reached sooner. Superficial tillage increased infiltration capacity considerably. Even a second shower did not result in surface sealing and subsequent runoff.
- On the S2 soils: the system here is rather complicated, a surface with a crust will give runoff, but on the other hand, on a patch where the crust is absent (destroyed by animal treading, vegetation), infiltration rates may be very high and may well be able to take the runoff from other spots as well. It is hard to forecast what the overall result on a larger area will be. Besides, it was observed in this stage, that even with a crust \( I_f \) remained rather high (approx. 55 mm/h).

It was clearly observed that crust-topped parts of soil showed almost immediate microrunoff but this runoff water could infiltrate via small cracks, open termite holes and uncrusted spots. Thus present measurements on S1 and S2 show infiltration rates which are probably not valid after the start of the rainy season when a new and active crust has been established and has covered all "dry season irregularities".
3.6. THE 1979 EXPERIMENTS.

In the summer period of 1979 a simulator built by the T.F.D.L. in Wageningen after the design of Dr. Morin, but with some modifications of the frame (after Rawitz et al., 1972) was used.

The simulator operates a nozzle, which is mounted at an angle of 20° with the axis on the slowly rotating water supply tube. Directly under the nozzle a disc rotates, intercepting all water from the nozzle but for a small part, created by a radial segment cut out of the disc. By using discs with different openings, the intensity of the rain may be changed. All excess water, intercepted by the disc is collected in a circular pan, surrounding the disc, and from there returned to a storage tank.

Water is pumped by a small electric pump to the nozzle, while the disc and nozzle are driven by a small electric motor. This unit is driven in the field by a gasoline powered generator.

3.6.1. Procedure and measurements.

The rain from the simulator covers a circular area with a diameter of approx. 3 meters. Within this area, an infiltration/runoff plot of 1.5 x 1.5 m is situated. Since rain will also fall outside the plot area, it was assumed that there was no horizontal flow of water in the soil of the plots. So it was sufficient to border the plot with (steel) strips pressed or hammered into the soil for only 5 cm.

For the measurements, the soil surface should be sloping: at the lowest part of the plot a trough is placed to collect the runoff water. The runoff water (being the balance of rainfall and infiltration), is collected in a small collecting bin, and from there pumped to a calibrated container by means of a suction system. The level in the calibrated container is recorded manually at fixed time intervals and thus the runoff rate can be calculated. Since the intensity of the rainfall is known and constant in time, the infiltration rate can be calculated as the difference between rainfall rate and runoff-rate. The intensity of the rain applied was kept at constant rate of 49 mm/hour.
The intensity was checked regularly by covering the plot area with plastic sheets, thus arriving at a runoff rate of 100% of the rainfall rate. Uniformity of the rainfall reaching the plot was also measured; this was done by placing 24 cans (diameter approx. 70 mm) evenly distributed over the plot area. Uniformity R, as calculated according to Christiansen (1942)

\[ R = 1 - \frac{\sum |\bar{x} - x|}{n.x} \], where 
- \( \bar{x} \) = volume of rain collected per can 
- \( x \) = average volume 
- \( n \) = number of observations

R ranged between .80 and .85.

On a few occasions, it was observed that there was some dripping at fixed points on the plots. This however did not give any effect on the results. All runs have been carried out with one rainfall intensity of 49 mm/hr. The reason for using only one intensity was:

a. limited amount of time available.
b. the findings of the work by Morin, who found that the cumulative volume of rain applied was governing the infiltration, quite independent of intensity.

As a result however, in most cases the runoff will start only after a certain time. The complete curve therefore can only be made by extrapolation. This explains the sometimes extremely high initial infiltration rates found after curve fitting. For practical use (in further calculations) however, this is no problem, because this means that the soil surface will take rainfall of almost any intensity right at the beginning. Experiments have been carried out on the "S1" soils of the experimental area. This soil type is widely found in the area and is described in detail in section "soils" (2) of this report.

3.6.2. Experiments. Basically, the experiments with the rainsimulator on the S1N soil could be distinguished as follows:

a. natural soils (not disturbed, none or very slight vegetation at end of dry season)
b. natural soils, surface treated with NONIDET, a detergent to diminish the hydrophobic effect of the crust
c. soil plowed by moldboard plow
d. soil plowed, ridges made by hoe
e. natural soil, crust removed superficially.

For each situation, it was tried to obtain information on the "extreme" characteristics to determine what may be expected in the course of a rainy season. In general, experiments were made: a. on a dry soil, either undisturbed after the dry season, or freshly plowed, but in both cases with a dry soil profile; b. in a situation a short time afterwards, where the profile is wetted, and the soil surface still wet (but crust already formed by 1st rain); c. in a situation some days (5-10) later, where the surface is dry and crusted.

In each experiment, rainfall application was continued until an equilibrium was obtained between rainfall intensity and infiltration- and runoff-rate.

A summary of the experiments of summer 1979 with the rainsimulator is given in table 3.1 and 3.2.

Runs were made on 11 different plots on "SIN" soil, in the direct vicinity of each other. These plots are:

plot 1 : undisturbed
2 : undisturbed
NON 1 : undisturbed, sprayed with NONIDET
NON 2 : undisturbed, sprayed with NONIDET
O1 : crust superficially removed
P1 : plowed
P2 : plowed
P3 : plowed + ridges
P4 : plowed + ridges
P5 : plowed + ridges
P6 : plowed + ridges

3.6.3. Results.
The direct results of the experiments are shown in figures 3.10 - 3.19. Here the infiltration rate is shown as a function of cumulative rainfall.

In this case, the curve will have the same shape as presented as a function of time, since the intensity of the applied rainfall is constant.

3.6.3.1. Undisturbed plots.
Observation of the graphs shows first of all, that there may be a
considerable difference between replicates: Fig. 3.10, and 3.11. show the results of rainfall application on two undisturbed plots, located close to each other, with virtually no vegetation, as they appear at the end of the dry season. With regard to the first experiment (rain on dry soil) we can observe that the curve (infiltration rate v.s. cum. rain) is approx. the same for the two replicates.

Figs.3.12. and 3.13. show the results of rainfall again on undisturbed plots, but here the surface is treated; sprayed one day before rain application with a solution of Shell NONIDET, a detergent, which was tested for the possibilities to eliminate the hydrophobic properties of the crust. A striking result is shown in Fig.3.12, where the infiltration rate during the first run virtually decreases to zero!

It is unlikely that this is a (negative) effect of the treatment with NONIDET; the results of exp. 14 show a different curve.

Fig. 3.14. shows the results of an experiment, where the crust was removed (approx. 5 mm of the top soil), whilst care was taken not to create any surface storage. The result of the absence of a top layer of 5 mm is clear. A second rainfall application after 2 days shows that a crust had been formed again under the first rain; infiltration rate now drops soon to a final infiltration rate (which is however not much lower).

3.6.3.2. Tilled plots.

A number of plots was plowed at the beginning of the rainy season (end of May), after a few showers had fallen. Plowing was done with a small mold-board plow, as commonly used in the area. Plowing depth was 10 – 15 cm. Moisture content (θ) approx. 6%. Since the plots were not used for experiments immediately, they were protected in case of rainfall by plastic sheets, and exposed to the sun otherwise.

Out of 6 plowed plots, 2 plots were left plowed (P1 and P2), and 4 were made into ridges. Fig.3.15 shows the results of the experiments on plot P1: with the applied intensity, it takes approx. 80 mm of rainfall, before any runoff starts, and approx. 125 mm before the infiltration rate has reached a constant value.

The effect after the surface crust has formed, (plus the fact that the soil profile is wet) is shown in the curve of the run one day later; the run 11 days later shows the same pattern.

The effect of superficially breaking the crust (by hoe) has again a very
important effect on infiltration rate.
Fig. 3.16 (plot P2) shows the same pattern as fig. 3.15 although here during the first rain, even more rainwater is infiltrated, before the infiltration rate reaches a final value.
On plots P3, P4, P5 and P6 ridges were made by hand (hoe), ridges in the direction of slope, with a distance of 50 cm.
The same type of experiments was carried out on these plots. Fig. 3.17 and 3.18 show the results of the rains on plot P3 and P4: the same pattern as for the plowed plots is obtained.
On plots P5 and P6, basically the same type of experiment was carried out. From other research on crust formation, it was shown that drying and wetting cycles had a positive effect on crust formation (Hillel, 1960)
To investigate the hypothesis on these soils, 2 replicates of the experiments on plot P3 and P4 were carried out, with the difference that here during the first run rainfall was terminated after 24.5 mm of rain, regardless whether there was runoff or not. The surface was then allowed to dry and the experiment continued after 1 or 2 days.
The results are shown in fig. 3.19: there is a small tendency for the runoff to start sooner, a comparison with fig.3.17 and 3.18 shows that this 40 - 60 mm of rain.

3.6.4. Curve-fitting.
In soil physics and irrigation sciences, various relations between infiltration rate and time (or cumulative volume of rain) have been proposed. For processing the results of the rainfall simulator experiments (e.g. to calculate the water balance of a field, or to use in models calculating runoff using rainfall data), it is necessary to find a mathematical relation between infiltration rate and time or cumulative rainfall.
With the resulting infiltration/cum. rain (or time) curves, it was tried to fit two types of equations: a. the "sorptivity" curve (Stroosnijder, 1976) following the criterium that infiltration rate decreases in time with the inverse root of time: 
\[ I_t = a + b \frac{1}{\sqrt{t}} \]
b. The relation proposed by Morin and Benjamini (1977), where the infiltration rate is a function of cum. volume of rain by power e:
\[ I_t = I_f + (I_i - I_f) e^{-\gamma Pt} \]
\[ I_f = \text{final inf. rate}, \ I_i = \text{initial inf. rate}, \ \gamma = \text{soil coefficient.} \]
P.t. = cum. rain (rain intensity P x time t).
The Morin equation should be more appropriate for conditions where the
infiltration is affected by the build-up of a crust at the surface.
From the work with the rainsimulator, a curve representing the infiltra-
tion rate versus cumulative rainfall will have the following general
shape:

Two "processes" may be distinguished:

a. where runoff starts almost immediately after the start of the rain
b. where runoff does not commence until a certain volume of rain has
reached the surface.
Case a. is typical for a situation where there is no or a very low sur-
face storage capacity and an infiltration capacity lower than the rain-
fall intensity.
Case b. represents the situation with a soil having a high (initial)
infiltration rate and/or a high surface storage capacity. For curve
fitting, the original data set should not be extrapolated left from
points A and B, since these areas are not relevant for the runoff process.
Equations resulting from the curve fitting may have very high initial
infiltration rates (higher than feasible in practice), but it should
be noted in these cases, that rain falling in the first period will not
cause any runoff in practice.

3.6.4.1. Undisturbed plots.
The results of the curve fittings for the undisturbed spots (plots 1, 2,
NONIDET 1, NONIDET 2, (01)), are shown in figs. 3.20-3.29 and table 3.1.
In most cases, we may observe the following:
the exponential curves do follow the original curve best near the end,
but tend to have a value for Pt=0, which is lower than what was found
during the experimental run. This is due to the fact, that first the surface storage had to be filled up by the rainfall. Apart from that, since in runoff-calculations utilizing natural rainfall data results will be given for different values of surface storage and detention, this is not causing errors, the more so since the original curves show approximately the surface storage of the plot analysed. On the other hand, the sorptivity curve shows, because of its relation vs. $\frac{1}{\sqrt{t}}$, that $I_f$ is not reaching a final value but continues to decrease in time. The exponential fit appears to be the best in most cases and especially in cases where a crust has been or is being formed. In all cases however, the final value $I_f$ will not be reached by the "sorptivity" fit.

3.6.4.2. Tilled plots.

Results for the curve fitting for the tilled plots (plots P1, P2, P3, P4, P5 and P6) are given in figs. 3.30 - 3.45 and in table 3.4. As for the undisturbed plots, the situation is here again that the "sorptivity" fit may have a reasonable fit during the decreasing phase of the curve, but the final values will be lower.

For both the undisturbed and the tilled plots, the curves of infiltration rate vs. $P\cdot t$ under crusted conditions are better approximated by an exponential curve, whereas the fitting of the curves from uncrusted plots does not give much difference between "sorptivity" and exponential relations.

3.6.5. Final infiltration rates.

A summary of the results, in terms of final infiltration rates is shown in table 3.5.

For the undisturbed plots there is a clear pattern, where the final infiltration rate in the curve one day after the first run, is the lowest, (compared with the first run and the run later on). The reason for this will probably be the water present in the soil profile. (plots 1,2 on NON 1,2). The $I_f$ at plot 01 is lowest after the last run; here weathering probably has made the (new) crust even more impermeable. Plowing and ridge forming has a dramatic effect on the infiltration rate: this is not only shown by the value of $I_f$, but also by the amount of rainwater required to reach this final rate.
3.6.6. Moisture content of wetted soil.

For a number of runs, moisture content determinations have been made (in calculations: \( \rho_d = 1.48 \) for undisturbed soil).

For run 15 (NON 2):

Samples have been taken before and after the run.

<table>
<thead>
<tr>
<th></th>
<th>Before 0-10 cm: 8.03% (by weight)</th>
<th>0-10 cm</th>
<th>10-20 cm: 13.64%</th>
<th>20.2 mm</th>
<th>32.1 mm water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After 0-10 cm: 11.35%</td>
<td>16.8 mm</td>
<td>10-20 cm: 14.70%</td>
<td>21.8 mm</td>
<td>38.6 mm water</td>
</tr>
</tbody>
</table>

Gain of moisture in profile 6.5 mm

With a graphical calculation of the curve (fig. 3.13) a cumulative infiltration of 8 mm is obtained.

For run 16 (NON 1):

<table>
<thead>
<tr>
<th></th>
<th>Before 0-10</th>
<th>0-10 cm: 6.79% (by weight)</th>
<th>20.0 cm</th>
<th>15.0 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10-20</td>
<td>11.71%</td>
<td>27.3</td>
<td>18.7 mm</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>0-10 cm: 11.77%</td>
<td>38.6</td>
<td>28.0 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10-20 cm: 14.32%</td>
<td>21.2</td>
<td></td>
</tr>
</tbody>
</table>

Gain of moisture 11.3 mm

A graphical calculation of the cumulative infiltration (according to the curve), resulted in 7.5 mm. It is likely, that the moisture of the layer 10-20 cm is not as calculated, and the moisture front may not have reached down to 20 cm depth, but e.g. 15 cm (see 2nd column; 9.3 mm gain).

For run 18 (P2, surface loosened):

Infiltration was also monitored before and after exp. 18 (P2, surface loosened with hoe). Samples were taken down to a depth of 40 cm.

Calculation of the moisture uptake in the layer 0-40 cm showed an increase of 71 - 76 mm:


<table>
<thead>
<tr>
<th>Layer</th>
<th>Before</th>
<th>After (Spot A)</th>
<th>After (Spot B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>11.08</td>
<td>29.98</td>
<td>34.08</td>
</tr>
<tr>
<td>10-20</td>
<td>12.80</td>
<td>30.77</td>
<td>31.43</td>
</tr>
<tr>
<td>20-30</td>
<td>13.45</td>
<td>31.70</td>
<td>30.83</td>
</tr>
<tr>
<td>30-40</td>
<td>13.00</td>
<td>29.23</td>
<td>30.58</td>
</tr>
<tr>
<td>Total</td>
<td>50.3</td>
<td>121.7</td>
<td>126.9 (mm)</td>
</tr>
</tbody>
</table>

According to the graphical calculation however, increase of moisture in the profile should be approx. 96 mm. Observing the moisture contents of the 30 - 40 cm layer, it can be concluded that the water has infiltrated deeper than 40 cm, probably down to approx. 55 cm.

Exp. 21: ridges (P4)

Moisture content was determined before and after exp. 21: rain application on initially dry ridges.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>7.1%</td>
<td>3.5</td>
</tr>
<tr>
<td>10-20</td>
<td>7.4</td>
<td>30.2</td>
</tr>
<tr>
<td>20-30</td>
<td>10.2</td>
<td>30.6</td>
</tr>
<tr>
<td>30-40</td>
<td>12.3</td>
<td>31.3</td>
</tr>
<tr>
<td>40-50</td>
<td>11.9</td>
<td>28.2</td>
</tr>
<tr>
<td>Total</td>
<td>57.4</td>
<td>162.6</td>
</tr>
</tbody>
</table>

(assuming average layer ridges 5 cm.)

Moisture content was also determined before run 4 (plot 2), so one day after an infiltration of 26.5 mm in dry soil (run 3). In the top 15 cm of the soil, Θ was approx. 16%, which means a suction of approx. 150 cm (= field capacity).

Measurements before run 6 (plot P1), one day after infiltration of 127 mm of water in dry, plowed soil (run 5), showed that soil water in the top 20 cm was also approx. at field capacity.
3.7. DISCUSSION AND CONCLUSIONS.

- Some general remarks on the accuracy of the experiments: because of the nature of the measurements, all results are based on the assumption, that rainfall is applied exactly with a known intensity. Runoff water is collected and its volume measured: the infiltration rate thus is the difference between rainfall and runoff rate. As a consequence, under conditions with a high runoff percentage, care must be taken to avoid errors. E.g. with a rain intensity of 50 mm/hr, and a runoff rate of 40 mm/hr, the resulting infiltration rate will be 10 mm/hr. An error of 2% (1 mm/hr) in rain intensity will magnify to an error of 10% in the infiltration rate!

- The curve fitting showed, that the runs with a crust present, the Morin type equation gave a somewhat better fit, whereas the sorptivity-type curve is almost equal in other cases, where either the soil was drier or no crust was present. In general the restriction of the sorptivity curve was where a final infiltration rate is achieved. There was however, no clear difference to observe between fits on "crusted" or "uncrusted" runs.

- The effect of plowing, ridging or hoeing the soil is in terms of infiltration improvement dramatic; this effect is due to
  a. destruction of the surface crust
  b. loosening the top layer of the soil
  c. creation of a surface storage for water

The crust will reappear soon, as is shown on the experiments on plot 01: the second run shows a very clear crust, and the 3rd run after again 2 weeks (with some rainfall) shows that the crust has become even more limiting.

The higher final infiltration rates in the plowed and ridge plots are probably more a result of better surface storage than a loosening effect; even on a crusted soil, a hydraulic head of a few cm will cause a higher infiltration compared with infiltration under rainfall, after the soil profile has been wetted to a certain depth.
4. RUNOFF PLOTS (NATURAL RAINFALL)

In addition to a. the experiments with the rainfall-simulator, and b. the runoff observations by Stroosnijder and Koné, some runoff plots were constructed for observations on runoff from cultivated plots, sown with millet.

4.1. PROCEDURE AND MEASUREMENTS.
For the experiment plots were selected on the same experimental field (SI Nord) as where the rainfall-simulator experiments were made. The plots had the same area as the simulator plots (square of 1.5 x 1.5 m).
Runoff from these plots was collected by a trough at the downslope side of the plot into a barrel (oildrum cut in half), covered by a plywood board.
Lay-out: 8 plots were constructed.

H 1 - flat, during crop season only (careful) removal of weeds
H 2 - flat, frequent hoeing (if possible after each shower)
H 3 - as H 1
H 4 - as H 2
R 1 - ridges (directed downslope, 3 ridges per plot, removal of weeds only)
R 2 - ridges (as R 1), frequent hoeing (if possible after each shower).
R 3 - as R 1
R 4 - as R 2
Slopes of plots: H 1 - 0.9% R 1 - 1.5%
H 2 - 1.1% R 2 - 2.2%
H 3 - 1.4% R 3 - 2.1%
H 4 - 1.3% R 4 - 0.9%

Runoff water was measured by reading the level in the runoff-tank, if possible after each shower. The tank was emptied after each reading. Since the collecting trough was not covered, a correction had to be carried out for the amount of water directly intercepted by this trough.

* will appear in a PPS report
4.2. RESULTS.

Following is a table with the results of the measurements during the (early) rainy season of 1979.

<table>
<thead>
<tr>
<th>date</th>
<th>23/7</th>
<th>25/7</th>
<th>30/7</th>
<th>31/7</th>
<th>17/8</th>
<th>20/9</th>
</tr>
</thead>
<tbody>
<tr>
<td>runoff</td>
<td>mm %</td>
<td>mm %</td>
<td>mm %</td>
<td>mm %</td>
<td>mm %</td>
<td>mm %</td>
</tr>
<tr>
<td>R 1</td>
<td>3.9</td>
<td>11.6</td>
<td>2.7</td>
<td>9.5</td>
<td>6.7</td>
<td>47.9</td>
</tr>
<tr>
<td>R 2</td>
<td>3.4</td>
<td>10.1</td>
<td>0.5</td>
<td>1.8</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>R 3</td>
<td>6.8</td>
<td>20.4</td>
<td>3.5</td>
<td>12.3</td>
<td>12.1</td>
<td>86.4</td>
</tr>
<tr>
<td>R 4</td>
<td>1.1</td>
<td>15.3</td>
<td><em>14.5</em></td>
<td>43.3</td>
<td><em>3.4</em></td>
<td>11.9</td>
</tr>
<tr>
<td>aver. 1 &amp; 3</td>
<td>16.0</td>
<td>10.9</td>
<td>67.2</td>
<td>2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot; 2 &amp; 4</td>
<td>10.1</td>
<td>6.9</td>
<td>18.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| H 1    | 3.2  | 44.4 | 0.3  | 3.8  | 5.6  | 16.7 |
| H 2    | 6.0  | 83.3 | 0.5  | 6.3  | 2.7  | 8.1  |
| H 3    | 3.4  | 47.2 | 0.4  | 5.0  | 19.8 | 59.1 |
| H 4    | 2.8  | 38.9 | 0.1  | 1.3  | 9.2  | 27.5 |
| aver. 1 & 3 | 45.8 | 4.4  | 37.9 | 46.0 | 47.5 |
| aver. 2 & 4 | 61.6 | 3.8  | 17.8 | 11.9 | 8.9  |

| rain (mm) | 7.2  | 8.0  | 33.5 |

*, o and + : no correct measurements, results not used in average values.

Rainfall of 86 mm (4/8) gave runoff values >40% (collecting barrels overflowed).

The consistent lower values of runoff for plots 2 and 4 show the effect of breaking the crust and opening of the surface on moisture conservation.
5. EFFECT OF TILLAGE SYSTEMS ON EARLY GROWTH AND DEVELOPMENT OF MILLET.

5.1. INTRODUCTION.

The early stage of development of a crop (germination and emergence) is in most cases very important and usually directly influencing final crop yields. Plant density will be a result of the small seedlings that survive the stage of germination and emergence.

The effect is even more important in cases, where it is almost impossible to carry out any improvements with respect to growing conditions (e.g. by extra fertilization, irrigation etc.).

In the semi-arid tropics the moisture supply to the germinating and emerging seed will play a crucial role.

By proper tillage operations before or during sowing and planting, the moisture supply (seed-soil contact) can be affected and improved strongly.

With this objective, experiments have been carried out during the rainy season of 1979 on the S1 Nord field of the PPS project.

It was tried to observe the effect of soil tillage on emergence and early growth of a locally grown grain crop (millet).

5.2. METHODS AND MATERIALS.

Five different systems of tilling the soil were applied:

1. deep tillage with hoe (approx. 10 cm)
2. superficial tillage with hoe (approx. 3 - 5 cm)
3. ridges, made with hoe; sowing on top of ridges
4. ridges, made with hoe; sowing in between ridges
5. no tillage; just opening up the soil for planting of seeds.

Plots used were 4 x 4 m, with a small separating levee, 0.5 m wide.

It was tried to have two different conditions during tillage; dry and moist, to observe whether there would be any difference in emergence effect. There were two replicates of each treatment, randomly chosen over the experimental area (see fig. 5.1).

Sowing of millet was carried out immediately after tillage, by scraping a small furrow and placing seeds by hand at a depth of approx. 2-3 cm.

There were 6 rows per plot (distance between rows 60 cm). Ridges also
were 60 cm wide, height of ridge after construction approx. 20 cm. Seeds used were "petit mil" (Pennisetum typh.), type "tardif", which should require a long growing period. This type of seed is commonly used by the farmers in the area. Seeds were sown after tillage; approx. 13 grams per plot. With a 1000 grain weight of 9.5 g, 1350 seeds per plot were sown, approx. 56 seeds per meter row.

5.3. RESULTS.
5.3.1. 1st experiment.
The "dry tilled" treatment is tilled and sown on 2/6. Rainfall after sowing: 2/6: 8.3 mm - 3/6: 0.8 mm - 5/6: 11.4 mm - 8/6: 3.3 mm - 9/6: 14.4 mm.
Emergence was counted on 12/6; the number of seedlings per central 2 m of all rows. Averaged over 6 rows the emergence per treatment is shown in table 5.1
Emergence of treatment 5 was very good and regular; it could be observed that water had collected on the bottom between ridges of treatment 4, thus affecting emergence.
A second count was carried out on 27/6; see table 5.2.
The differences are clear: stand density has decreased in all treatments. The effect is striking for the no-till treatment; a decrease from 49.7% to 20.4%.
From various visual observations in the time of development, it appeared that, although the no-till treatment had a quick start, the small plants did not show any growth. This is most probable due to a very poor root development.
Measurement of the length of plants, plus some visual observations of 27/6 are shown in table 5.3.
On 2/7, after a fairly long dry period, the following "markings" were given to the treatments: see table 5.3.
From the sequence of observations it can be seen, that a. the no-till plots (treatment 5) give a good emergence, but do not show any further growth or development; this may probably be due to poor root development (hard subsoil) but mainly (especially in the dry spell) because of an absolute moisture deficit. The crust on the plot had remained fairly undisturbed, and although there was hardly a slope, water did runoff to the border of the plot (where indeed a better growth of millet and weeds was observed).
b. Tillage. The deep-tilled plots (treatment 1) in general showed the best
growth, plant development was quick and plants were able to survive a
longer dry period. On the superficially tilled plots (treatment 2),
growth and development was clearly less; in this treatment there was
a considerable difference between the 2 replications.
Perhaps this is due to the fact that the two plots were tilled by two
different persons. On the ridges plots (treatments 3 and 4), development
and vigor of the plants on top of the ridges remained better than the
plants in the furrow between ridges. After the dry period (end of June),
it showed from the plants that there was more water still available in
the furrow.
More than 5 weeks later, the general picture had not changed very much.
Observations on 5/8: D 1 : surviving plants reasonable
D 2 : one replication reasonable, other one dead
D 3 : a few plants left
D 4 : reasonable
D 5 : nothing left; all plants dead

On 16/7, the "wet-tilled" plots were tilled and sown; this was done
in the same way as with the "dry-till" treatments. On 19/7 some plants
were already emerging.
At a count on 27/7, the N 4 and N1 treatments showed the best results;
N 5 and N3 were medium, N 2 was clearly the poorest in this experiment,
see table 5.4.
On 5/8, after a heavy shower of 86 mm on 3/8, stand of the plants was
observed:
N 1: small plants but even stand
N 2: poor stand (no plants); surface of field flat again
N 3: soil is washed off from roots (plants tumbled over)
N 4: very small plants, almost covered with soil eroded from ridges.
N 5: poor to very poor stand.

5.3.2. 2nd. experiment.

After the first crop, the soil has been tilled and sown again. This time
a shorter period variety of millet ("nâtif") has been used.
Sowing was now carried out in the local way; making a plant hole with the
hoe, placing a small handful of seeds (12 - 15) in this hole, covering
by foot with soil again.  
A visual observation of the stand of the crop after approx. 4 weeks (with sufficient rainfall) showed that deep tillage and sowing on top of the ridges again had the best results.  
Superficial tillage here was better than sowing in the furrow between ridges, possible because of the better general moisture situation.  
No-tillage again showed the poorest results.

5.4. DISCUSSION AND CONCLUSIONS.

Considering the limitations of this experiment in soils and seed used, still very clear differences were observed between tillage treatments;  
- No-tillage gives very poor results; this must be attributed mainly to moisture supply problems for the plants. Rainwater cannot infiltrate into the soil because of the crust; root development will be poor because of the dense soil.
- Deep tillage shows the best results; when the surface is sufficiently rough, rainwater may enter easily and over a fairly long period. Emergence in the cases observed was not negatively affected by the rough seed bed. Because of the flat topography of the plots, plants stayed upright even after a heavy rainstorm.
- Superficial tillage does not seem to be very advantageous. It is likely, that conditions are still not optimal for early seedling development. Although the crust is broken by the tillage, the surface will become flat and crusted soon after a few showers.
- Planting on top of ridges shows good results, although the disadvantages may be a quick drying out of the top of the ridge, which is dangerous in early stages of plant development. Washing away of roots after heavy showers is possible.
- Sowing in between ridges may give problems because of water logging (again particularly in the early stage). Because of the way of making ridges, either by plow or hoe, the soil at the bottom between ridges will usually be hard and not loosened.
- Planting of the millet in bunches will probably be better, compared with single plants evenly distributed in the row. A bunch will be more stable under heavy rainstorms and the chances for emergence and survival in the seedling stage will be higher.
6. EFFECT OF SOWING DEPTH ON GERMINATION AND EMERGENCE OF MILLET.

6.1. INTRODUCTION.

Germination and emergence is a very critical period during the growth of a crop. Often the conditions during this stage have the largest effect on final crop yields.

In semi-arid regions especially the moisture supply to the emerging seed may be problematic.

Depth of sowing will be of utmost importance. In the period at the beginning of the rainy season in semi-arid climates (and particularly in West Africa), rain showers and periods with a high evaporation (hot and sunny) will be alternating. As a result, the moisture content of the top layer of a soil will also change very quick: in a few hours, moisture content of the top 5 cm may dry out from field capacity to wilting point.

By adapting the depth of sowing, the risk of failure may be minimized. The major problem however is the unpredictability of the weather: in some cases it may be better to sow deep, in other cases it may be better to sow superficially. The following are advantages and disadvantages of deep and superficial sowing:

advantage deep: no extreme high temperatures, usually less problems with insects. When the moisture has reached sowing depth, there will be sufficient storage on the layer.

disadvantage deep: seedling needs more time and energy to emerge. Small showers cannot be utilized.

advantage superficial: may use small showers, (provided they come regularly), and so have a better start. Quick emergence (green parts to use sun energy).

disadvantage superficial: quick shortage of water, which may be disastrous is seed just starts germinating. Higher temperatures, insect problems (ants!).

Of course one is also kept to a maximum length of the plumule; the seedling has to reach the surface before the energy (stored in the seed) is exhausted. For a small seed as is millet, this will be approx. 7-8 cm.
6.2. METHODS AND MATERIALS.

On the S1 Nord site a number of experiments were carried out to investigate the effect of sowing depth on emergence. In the experiment, two millet varieties have been used: "tardif" (A) and "hātif" (B). Tardif is a variety requiring a long growing period, hātif requires a shorter period. (Is used mainly later in the season). The following treatment were chosen:

- 2 grains per planting hole: 1 - 3 - 5 and 7 cm depth
- 6 grains per planting hole: 1 - 3 and 7 cm depth
- 2 grains per planting hole: 3 cm: compacting soil on top of seeds
- 6 grains per planting hole: 3 cm: compacting soil on top of seeds

All treatments (for two varieties) have been carried out in three (I, II & III) replications. Plot size was 2 x 2 m, on which in 5 rows (distance between rows 30 cm), plant holes were made, 20 per row (distance in row 5 cm).

Planting was done by "punching" a hole with diameter of approx. 1 cm with a tool, enabling the operator to achieve accurately the required depth. The experimental layout is shown on fig. 6.1.

Because of the soil surface structure and the weather conditions it was unfortunately not possible to plant all plots on the same day:

- Sowing dates: IA, IB and IIB on 18/7, IIA on 21/7 and IIIA and IIIB on 23/7.

As a result, there is a difference between the replicates.

6.3. RESULTS.

Fig. 6.2 shows the average emergence of all replicates. There is a clear difference between emergence of IIB, IIIA, IIIB.

Effect of sowing depth.

As can be seen in fig. 6.3 and 6.4 the best emergence for this case is from 3 cm sowing depth. It could be observed, that in many cases seed from shallow planting (1 cm) was removed by ants.

Even young seedlings were eaten and destroyed. In particular seed on plot IIA-5 (6 grains at 1 cm) was almost completely removed by ants.

Effect of number of grains.

The differences in emergence as a function of the number of grains per planting hole is also clear from fig. 6.5: for all sowing depths, seeds planted with 6 per hole have a better emergence than 2 seeds per hole. It should be noted here, that counts were made from the number of holes from where there was emergence, irrespective of number of plants per hole.
This means, that emergence e.g. of one plant from a hole with originally 6 seeds could also be regarded as successful. To know exactly, how many grains had emerged at one time (30/7) all individual plants were counted. From plots I and II, where emergence was final at that time, the average number of plants from a hole with 2 grains was 1.6 (80%). From the plots with 6 grains, only 3.3 plants per hole had emerged (55%). Fig. 6.5 shows that there is also a small sowing depth effect. Plots III were also counted, but since the emergence was not final yet at that time, it is not possible to give exact numbers, the more so because the emergence from plant holes was not counted. It was typical here, that on plots III in some treatments the average number of plants per hole was larger than the number of grains sown! This is probably due to irregularities during sowing.

Effect of compaction.
Compaction of the soil above the seeds at a depth of 3 cm was also a treatment:
With seeds of the "tardif" variety there is a clear positive effect of compaction. With the "nātif" variety this is difficult, compaction has in 3 out of 6 cases even a negative effect. The positive effect appears to be greater with 2 grains per hole than 6 grains per hole.

6.4. DISCUSSION AND CONCLUSIONS.
- The experiment showed, that for the given conditions and seed type, there was a clear optimum sowing depth (3 cm)
- The weather conditions (affecting soil moisture and temperature) are important, seen the differences between 2 sowing dates, only 3 days apart.
- A larger number of grains per planthole gives a better assurance for plant emergence.
7. LITERATURE


ANNEX

LIST OF FIGURES AND TABLES

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simulator experiments. 1978.
" 3.20 - 3.29 Curve fitting (undisturbed plots)1979
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" 3.3 - 3.4 Parameters curve fitting.
Table 3.5 Values of $I_f$.
Tables 5.1 - 5.2 Plant counts tillage experiment.
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N.B. In figures 3.20 - 3.45
——— is the measured curve,
-------- is the exponential fit (I) and
-------- is the "sorptivity" fit (II).
PARTICLE SIZE ANALYSIS:  

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<th>% S1N</th>
<th>&quot;mil&quot; (%)</th>
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<td>600 - 850</td>
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<td>850 - 1200</td>
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<td>0.2</td>
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</table>

Fig. 2.1

% of total (cumulative)
Fig. 3.1

Experiment: 1 (1978)
Soil: degradé
Treatment: undisturbed

\[ I = 17 + (60 - 17) e^{-0.15 P.t} \]

\[ I = 66.5 \frac{1}{\sqrt{t}} + 6.5 \quad \text{(coincides with "eye" fit line)} \]

Fig. 3.2

Experiment: 1a (after 1 day) (1978)
Soil: degradé
Treatment: undisturbed

\[ I = 15.6 + (65.6 - 15.6) e^{-0.25 P.t} \]

\[ I = 53.8 \frac{1}{\sqrt{t}} + 6.4 \]
Fig. 3.3

Experiment: 1b (1978)
Soil: degraded
Treatment: undisturbed

- $I = 11.2 + (61.2 - 11.2) e^{-0.3 P.t}$
- $I = 28.3 \frac{1}{\sqrt{t}} + 10.3$

Fig. 3.4

Summary of experiments 1, 1a and 1b (1978)

best fit by eye

1
1a (after 1 day)
1b (after 5 days)
Fig. 3.5
Experiment: 2 and 2a (after 3 days) (1978)
Soil: dégradé
Treatment: tilled

Fig. 3.6
Experiment: 3 (1978)
Soil: dégradé + microdune
Treatment: undisturbed

---

$I = 27 + (86.3 - 27)e^{-0.08P.t}$

$I = 110 \frac{1}{\sqrt{t}} + 15.1$

---

$2$ (no runoff)

Best fit by eye
Fig. 3.7
Experiment: 5 and 5a (after 2 days) (1978)
Soil: S1
Treatment: undisturbed

\[ I = 30 + (126.8 - 30) e^{-0.04 P.t} \]
\[ I = 187.7 \frac{1}{\sqrt{t}} + 15 \]
\[ I = 26.7 + (115.2 - 26.7) e^{-0.16 P.t} \]
\[ I = 88.4 \frac{1}{\sqrt{t}} + 14 \]

Fig. 3.8
Experiment: 7 and 7a (after 2 days) (1978)
Soil: S2
Treatment: undisturbed

---extrapolated to 100% crust cover---
Fig. 3.9
Infiltration measurements: (1977 and 1978)
1: "degradé" double ring
2: "degradé" closed system
3: microdune double ring
4 and 5: microdune closed system
FIG. 3.11

PLOT 2,

EXP. 3, 4, 12, 35

- mm/hr

- Pt mm

- 50

- 45

- 40

- 35

- 30

- 25

- 20

- 15

- 10

- 5
FIG. 3.12

PLOT: NON1,

EXP: 13, 16, 23, 36
FIG. 3.14

PLOT 0 1,
EXP. 28, 29, 33
FIG. 3.15

PLOT P1,

EXP. 5, 6, 10, 17
FIG. 3.16

PLOT $P_2$

EXP. 7, 8, 9, 18
FIG. 3.17

PLOT P3,

EXP. 19, 20, 32
FIG. 3.18

PLOT P4,
EXP. 21, 22, 31
FIG. 3.19

PLTOTS, P5/P6,
EXP. 26,30
FIG. 3.42
PLOT P4, EXP. 22,31
(I)

FIG. 3.43
PLOT P4, EXP. 22,31
(II)
FIG. 3.44
PLOT P5/P6, EXP. 26,30
(I)

FIG. 3.45
PLOT P5/P6, EXP. 26,30
(II)
Fig. 5.1

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Experimental lay-out tillage experiment.

D: "dry" tillage
N: "moist" tillage

1 deep tillage
2 superficial tillage
3 ridges (sowing on top ridge)
4 ridges (sowing in between ridges)
5 no-tillage

Plot size: 4 x 4 m.
Fig. 6.1  

Lay-out sowing depth experiment.

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<th>6.3 *</th>
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</tbody>
</table>

I, II and III: replications.

A: millet "tardif"
B: millet "hâtif"

2.1  2 grains: 1 cm depth
2.3   "  3 cm   "
2.5   "  5 cm   "
2.7   "  7 cm   "

6.1  6 grains: 1 cm depth
6.3   "  3 cm   "
6.7   "  7 cm   "

2.3 * 2 grains: 3 cm depth, soil compacted
6.3 * 6  "  3 cm   "  "  "  "
FIG. 6.3

% emergence

seeds A

% emergence

seeds B

0 2 4 6 8 cm
sowing depth

K = 2 grains per hole

o = 6 grains per hole

FIG. 6.5

number of plants per hole

% of original nr. plants/hole

0 1 2 3 4 cm
sowing depth

K = 2 grains per hole

o = 6 grains per hole
Table 3.1  Summary of simulator runs; undisturbed plots.

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<th>Date</th>
<th>Exp.nr</th>
<th>Condition of plot: time after previous rain application</th>
<th>Mm rainfall on the (uncovered) plot during this period:</th>
<th>Duration (min)</th>
<th>Volume rain applied (mm)</th>
<th>Volume infiltrated (mm) during run</th>
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<td>75</td>
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<td>(Fig. 3.10)</td>
<td>220</td>
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<td>50</td>
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<td></td>
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<td>(Fig. 3.11)</td>
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Table 3.2 Summary of simulator runs; tilled plots.

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(Fig. 3.15, 3.16, 3.17, 3.18, 3.19)
### Table 3.3  Curve parameters; undisturbed plots

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<th>( I_f )</th>
<th>( \gamma )</th>
<th>corr. coeff.*</th>
<th>( I_t = I_f + (I_i - I_f)e^{-\gamma P\cdot t} )</th>
<th>&quot;Sorptivity&quot; fit</th>
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* Curve fitting covers only the descending part of the curve; this should be kept in mind when considering the correlation coefficients for the "sorptivity" fit, fitted curve will deviate from original curve after \( I_f \) has been reached.
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*Curve fitting covers only the descending part of the curve; this should be kept in mind when considering the correlation coefficients for the "sorptivity" fit; fitted curve will deviate from original curve after $I_f$ has been reached.*
Table 3.5  Final infiltration rates (mm/hr)

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<td>34.6</td>
<td>29.4</td>
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</tbody>
</table>
Table 5.1  Counts 12/6.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plants/2m</th>
<th>Average</th>
<th>%</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 1a</td>
<td>35.7</td>
<td>41.5</td>
<td>31.7</td>
<td>36.9</td>
</tr>
<tr>
<td>1b</td>
<td>47.2</td>
<td></td>
<td>42.0</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>37.0</td>
<td>43.8</td>
<td>32.9</td>
<td>38.9</td>
</tr>
<tr>
<td>2b</td>
<td>50.5</td>
<td></td>
<td>44.9</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>41.7</td>
<td>38.5</td>
<td>37.1</td>
<td>34.2</td>
</tr>
<tr>
<td>3b</td>
<td>35.3</td>
<td></td>
<td>31.4</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>55.8</td>
<td>51.5</td>
<td>49.6</td>
<td>45.8</td>
</tr>
<tr>
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<td>47.2</td>
<td></td>
<td>42.0</td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>49.2</td>
<td>55.9</td>
<td>44.2</td>
<td>49.7</td>
</tr>
<tr>
<td>5b</td>
<td>62.0</td>
<td></td>
<td>55.1</td>
<td></td>
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</table>

Table 5.2  Counts 27/6.

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<th>Plants/2m</th>
<th>Average</th>
<th>%</th>
<th>Average</th>
</tr>
</thead>
<tbody>
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<td>D 1a</td>
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<td>27.8</td>
<td>22.2</td>
<td>24.7</td>
</tr>
<tr>
<td>1b</td>
<td>30.5</td>
<td></td>
<td>27.1</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>18.2</td>
<td>28.5</td>
<td>16.2</td>
<td>25.3</td>
</tr>
<tr>
<td>2b</td>
<td>38.7</td>
<td></td>
<td>34.4</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>35.5</td>
<td>30.3</td>
<td>31.6</td>
<td>26.9</td>
</tr>
<tr>
<td>3b</td>
<td>25.0</td>
<td></td>
<td>22.2</td>
<td></td>
</tr>
<tr>
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<td>38.6</td>
<td>35.8</td>
<td>34.3</td>
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<tr>
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<td></td>
<td>32.8</td>
<td></td>
</tr>
<tr>
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<td>16.3</td>
<td>22.9</td>
<td>14.5</td>
<td>20.4</td>
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<tr>
<td>5b</td>
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<td></td>
<td>26.2</td>
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</table>
Table 5.3.
Visual observations.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Description</th>
<th>27/6 Average Length (cm)</th>
<th>Description</th>
<th>2/7 Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 1a</td>
<td>good</td>
<td>10 - 15</td>
<td>reasonable good</td>
<td>1 (best)</td>
</tr>
<tr>
<td>1b</td>
<td>good</td>
<td>10 - 15</td>
<td>reasonable</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>very poor, thin, dry</td>
<td>&lt;5</td>
<td>dead</td>
<td>4</td>
</tr>
<tr>
<td>2b</td>
<td>reasonable, equal stand</td>
<td>8 - 15</td>
<td>strong drought conditions</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>good, few dry plants</td>
<td>10 - 12</td>
<td>fairly poor</td>
<td>3</td>
</tr>
<tr>
<td>3b</td>
<td>reasonable/poor</td>
<td>&lt;10</td>
<td>fairly poor</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>reasonable/poor, uneven</td>
<td>6 - 12</td>
<td>very reasonable</td>
<td>2</td>
</tr>
<tr>
<td>4b</td>
<td>thin stand</td>
<td>6 - 10</td>
<td>very reasonable</td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>very poor, dried out</td>
<td>&lt;3</td>
<td>dead</td>
<td>5</td>
</tr>
<tr>
<td>5b</td>
<td>very poor, dried out</td>
<td>&lt;4</td>
<td>dead</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 Emergence count wet-tillage experiment.
Counts of 27/7.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plants/2m</th>
<th>Average</th>
<th>%</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 1a</td>
<td>32.0</td>
<td>31.1</td>
<td>28.4</td>
<td>27.6</td>
</tr>
<tr>
<td>1b</td>
<td>30.3</td>
<td></td>
<td>26.9</td>
<td></td>
</tr>
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<td>2a</td>
<td></td>
<td>5.7</td>
<td>9.5</td>
<td>5.1</td>
</tr>
<tr>
<td>2b</td>
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<td>13.3</td>
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<td>11.8</td>
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<tr>
<td>3a</td>
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<td>19.0</td>
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<td>16.9</td>
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<tr>
<td>3b</td>
<td></td>
<td>19.5</td>
<td></td>
<td>17.3</td>
</tr>
<tr>
<td>4a</td>
<td></td>
<td>33.2</td>
<td>33.9</td>
<td>29.5</td>
</tr>
<tr>
<td>4b</td>
<td></td>
<td>34.7</td>
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<td>30.8</td>
</tr>
<tr>
<td>5a</td>
<td></td>
<td>23.0</td>
<td>24.7</td>
<td>20.4</td>
</tr>
<tr>
<td>5b</td>
<td></td>
<td>26.5</td>
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<td>23.6</td>
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</tbody>
</table>