Mechanized farming in the humid tropics with special reference to soil tillage, workability and timeliness of farm operations

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Mechanized farming in the humid tropics with special reference to soil tillage, workability and timeliness of farm operations

A case study for the Zanderij area of Suriname

Proefschrift
Ter verkrijging van de graad van
doctor in de landbouwwetenschappen,
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Abstract

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Description of experimental work and discussion of results concerning: yields of maize, groundnuts, cowpea, soya bean and sorghum and soil properties as influenced by soil tillage methods including conventional and no tillage. Workability limits for tillage operations in terms of soil moisture. The course of moisture content of grains during the harvest period. Timeliness of harvesting operations. Expectations of workable time for farming operations are calculated with simulation models relating the course of soil moisture and grain moisture status with meteorological data. Prospects for mechanized farming are evaluated with a linear programming model.

Voor Liesbeth
Jacob, Marina en Matthijs

STELLINGEN

1. De opbrengst van gewassen en de kwaliteit van de werkuitvoering worden in het Zanderij gebied van Suriname in hoge mate bepaald door het weer. Kennis van het weer en de wijze waarop de boer daarop weet in te spelen zijn bepalend voor het succes van zijn bedrijf.

   Dit proefschrift.

2. De éénfase-methode voor de oogst van pinda's, die in Canada wordt beproefd, verdient met het oog op klimatologische factoren ook voor Suriname overwogen te worden.

3. Van boeren wordt verwacht dat zij zich flexibel opstellen in het toepassen van grondbewerkingssystemen. Daarom is het zaak om in proeven niet alleen behandelingen maar grondbewerkingsstrategieën te vergelijken.

4. Uitspraken over optimale mechanisatiesystemen zonder daarbij rekening te houden met werkbare tijd zijn niet verantwoord.

   Ademosun, O. C.,1986. Determination of optimum capacities of farm machines to adapt for medium scale crop-production. Agricultural systems, Vol 21, No. 1, 1986.

5. Veldproeven die betrekking hebben op de gewasbescherming dienen zich uit te strekken tot en met de oogst. Deze dient uitgevoerd te worden volgens een voor het gebied representatieve methode.

6. Het ontwikkelen van een betrouwbaar, automatisch functionerend weerstation kan een belangrijke bijdrage leveren aan de ontwikkeling van de landbouw in ontwikkelingslanden, mits men in staat is voor het onderhoud zorg te dragen.

7. Als de gemechaniseerde rijstteelt in het kustgebied van Suriname een rol wil blijven spelen in de economische ontwikkeling van het land is het zaak zo snel mogelijk te beginnen met de ontwikkeling van management informatie systemen zoals dat thans voor een aantal takken van landbouw in Nederland plaats vindt.

8. Om voor de inzet van menselijke energie in de landbouw uit te gaan van het totale energie verbruik per dag van een werkende mens in plaats van het deel dat wordt besteed aan produktieve arbeid, is een ongelukkige keus.

De Lange, J.M. Energie huishouding in de Nederlandse land en tuinbouw. Imag publicatie no. 12. 1974.

9. De mogelijkheid om mechanisatiesystemen aan te passen aan de bestaande sociale en culturele omstandigheden in een ontwikkelingsland moet niet worden overschat. Een volk zal om te overleven zich aan veranderende omstandigheden, inclusief technische ontwikkelingen, aanpassen.

10. De gedachte goedkoop uit te zijn door vakante leerstoelen gedurende enige tijd niet in te vullen komt een instelling voor universitair onderwijs duur te staan.

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Wageningen, 15 mei 1987.

AKNOWLEDGEMENT

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CONTENTS

CHAPTER 1

INTRODUCTION

1.1 AGRICULTURE IN SURINAME

There is no reason to believe that earliest agricultural practice in Suriname differed much from the way shifting cultivation is applied as yet in the interior. Commercial agriculture was commenced along the Suriname river around 1650 when settlers began growing tabacco and sugar cane. At about 1670 Dutch settlers started with plantations on the clay soils in the coastal area where fertility was higher than along the river banks. Cultivation was on beds and mostly in polders. Next to sugar cane, cacao and coffee became important crops. A high point in agricultural activity was reached around 1765 when there were some 590 plantations occupying 180,000 ha of land. In the nineteenth century a decline in agricultural activity set in and accelerated by the abolition of slavery in 1863. To offset labour shortages contract labour was hired from India and Java, these labourers often began farming for themselves on small holdings upon termination of their contracts. With few exceptions large scale agricultural production declined to insignificance, production on small holdings increased and rice became one of the most important crops.

In 1947 a beginning was made with a more systematic approach towards agricultural development and in this connection investigations were carried out into the possibilities of mechanized wet land rice farming on the heavy clay soils in the coastal area. These led to a system of fully mechanized rice production as is now practised on the 10,000 ha farm in the Wageningen polder in north west Suriname and also adopted by most farmers in the coastal area even by those with only a few hectares of land.

Attempts to grow other annual crops in rotation with rice were not successful. Poor physical soil structure on fields where rice is grown and inability to control weed competition with mechanical means are mentioned as significant agricultural reasons for the failure (Fortanier,1962).
In the nineteensixties the Centre for Agricultural Research in Suriname, CELOS, carried out further investigations into the possibility of growing

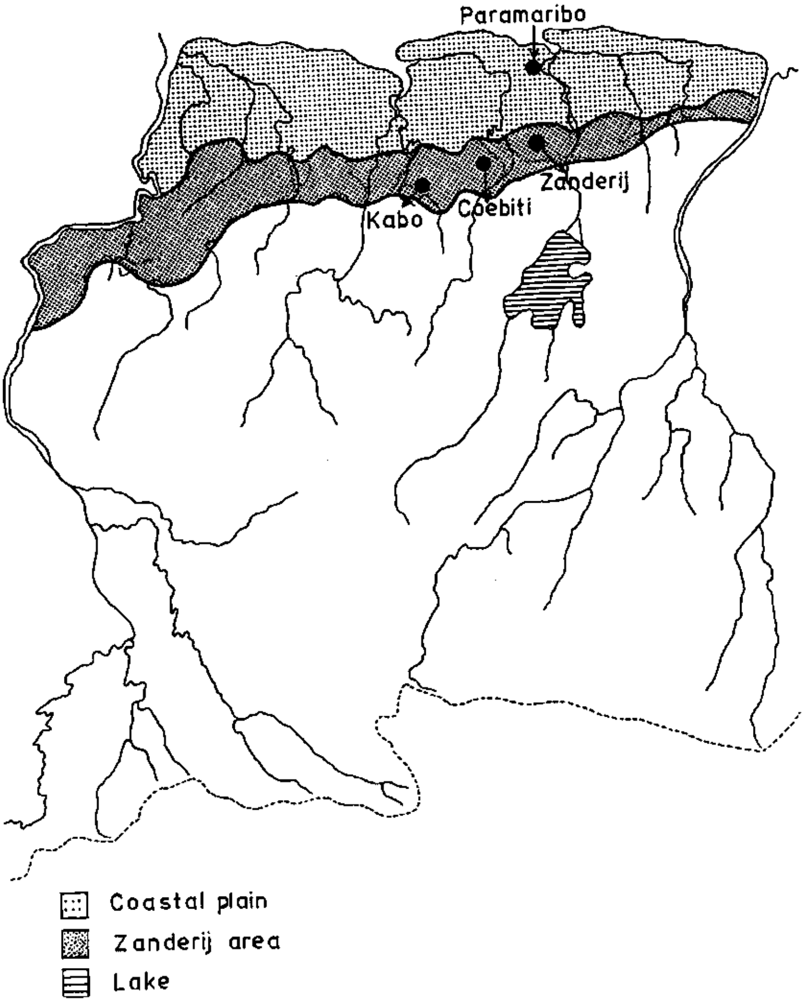


Figure 1. Map of Suriname

annual crops other than wet land rice and perennial crops on the clay soils in the coastal area.

For the experimental work a polder with cambered beds was built. An analysis of relevant CELOS reports learns that experiments often failed, the combination of heavy clay soil and large amounts of rain led too often to non workable conditions, especially for mechanized operations. Contrary to the establishment of mechanized wet land rice farming, mechanized farming for dry annual crops on the heavy clay soils was not successful.

Meanwhile attention was also given to agricultural development in accessible areas of the interior and oilpalm was established. In the early seventies when roads, primarily intended for wood hauling, opened up the Zanderij area a research project was set up regarding the permanent cultivation of rain fed annual crops on the loamy soils of Zanderij. The work described hereinafter forms part of this project. For experimental work, farms were established at Coebiti and Kabo in the Zanderij area.

Considering the success with mechanized rice farming, an overall population density of only 2.3 inhabitants km^{-2} and scarce and expensive labour, government favoured a mechanized farming system for rainfed annual crops. The well drained soils of the Zanderij area showed characteristics suitable for mechanized farming.

Agricultural activities are as yet mostly concentrated in the coastal plain where about 88 percent of the 350,000 inhabitants live. A summary of crop areas and production values for 1980 is presented in table 1. The area under rice has doubled since 1960, a significant surplus for export is produced, since 1965 banana production in the coastal plain has shown good development. Sugar cane, coconut, citrus, coffee and cacoa are mainly grown on old plantations. Vegetables are grown on sand ridges in the coastal plain. The production of maize, soya bean and groundnut is small and does not meet local requirements, around 1980 imports amounted to the equivalent of 5,000 ha for maize and soya bean each and 400 ha for groundnuts.

Table 1. Agricultural production Suriname 1980.

crop	area planted ha	gross production value Sfl x 1000
rice	64,956	63,634
oilpalm	2,557	4,091
sugarcane	2,392	4,058
citrus	1,933	5,316
banana and plantain	1,909	12,509
coconut	1,097	822
vegetables	719	6,546
cocoa	250	169
groundnut	208	687
pulses	189	271
maize	183	261
coffee	152	486
other crops	1,074	5,925
Total	77,619	104,775
pastures	14,973	

Ministery of Agriculture, Paramaribo. 1 Sfl = .55 US $

introduction

The interior uplands are apart from Amerindian and Bushnegro settlements virtually uninhabited. Recent agricultural developments in this area are oilpalm and livestock.

1.2 SOIL OF THE ZANDERIJ AREA

The Zanderij formation covers about 875,000 ha and is situated between the coastal plain with heavy clay soils in the north and the interior uplands with residual soils in the south. The soil is a sediment of weathered material over a partly eroded soil mantle, which was placed in a previous period over the crystalline basement rock. Erosion has lowered the surface, at times reaching the base. A complex distribution of soil materials resulted and thickness of the sediment varies considerably (Lucas et al., 1982).

The soils of the formation can be divided into bleached and unbleached soils. The bleached, white sandy soils are the most weathered of the formation. They have a coarse sandy texture and clay content is less than one percent, they are extremely infertile and have low water holding capacity. About fourty percent of the formation is covered with this soil type, there is a savanna type vegetation and this area is not considered suitable for agriculture. The coloured unbleached soils can be regarded as Yellow Kaolinitic Oxisols intergrading towards Ultisols with a sandy to a sandy clay loam texture

Table 2. Properties of a brown sandy loam under forest, Kabo (Boxman, unpublished data).

soil layer m	0-0.20	0.20-0.40	0.40-0.60
org. C g kg^{-1}	12	8	4
org. N ,,	0.8	0.5	0.3
pH-Kcl	3.7	3.9	4.1
pH-H_2O	4.2	4.5	4.7
exch. Ca 1/2 mmol kg^{-1}	1.5	0.5	0.3
exch. Mg 1/2 ,,	0.9	0.3	0.3
exch. K ,,	0.4	0.3	0.1
exch. Na ,,	0.1	0.1	0.1
exch. Al 1/3 ,,	10.2	9.9	7.3
ECEC ,,	13.1	11.1	8.1
100 x exch. Al/ECEC	78	89	90
CEC pH 7 mmol kg^{-1}	34	24	18
P-Bray I mg kg^{-1}	2	1	1
Pore volume %	50	46	46
available moisture	11	10	9
textural class	loamy sand	sandy loam	sandy clay loam

(Bennema, 1982). The silt fraction is less than five percent, in general the top soil has a lower clay content than the subsoil. The fertility of these soils is low, they contain low amounts of bases, micro nutrients and available phosphorus. The effective cation exchange capacity, ECEC, is low and exchangeable aluminium 3^+ is relatively high, pH ranges between 4.6 and 5.2. Chemical and physical properties of a Zanderij soil under forest are presented in table 2. These soils are covered with a heavy rain forest vegetation. Natural drainage is generally good but water holding capacity is low. The sandy clay loams of these coloured soils are suited for agriculture and accordingly aforementioned research was concentrated on locations with that soil type.

It is estimated that after allowing for swampy creek beds, slopes and outcrops of underlying residual rock, some 157,500 ha gently sloping , well drained loamy clay soils are suitable for agriculture. Variability in soil type is large and creeks are in a narrow grit, consequently suitable soils will be available in relatively small patches of 100 to 1,000 ha (Poels, unpublished).

1.3 CLIMATE

Climatological data based on a twenty five year record of observations at the "klima station" Zanderij over the years 1958-1982 are presented in table 3. The Zanderij station is located some 50 km landinwards from the coastline. The experimental farms at Coebiti and Kabo are situated 42 km east and 80 km east of this Zanderij station. For this investigation the meteorological observations of Zanderij station are considered representative for the central part of the Zanderij area. Detail on collection and treatment of meteorological data is given in appendix A. Variation in the average monthly temperature is small and climatic seasons are therefore determined by the distribution of rainfall during the year. The meteorological service of Suriname formulated four seasons on the basis of observations made in Paramaribo between 1901 and 1966 as follows:

- Long rainy season	(LRS)	april 20	-	august 14
- Long dry season	(LDS)	august 15	-	december 4
- Short rainy season	(SRS)	december 5	-	february 9
- Short dry season	(SDS)	february 10	-	april 19.

Wet and dry seasons are defined as uninterrupted series of decades with more, respectively less than average rainfall. The date of change between seasons corresponds with the average of the decades in which seasonal change occurred. The start of the seasons as well as the amount of rain for each season show considerable variation. This is particularly true for the short seasons. The probability of occurrence of a short rainy season is 83 percent and for the short dry season 82 percent (anon, 1968). The dryest month is

Table 3. Climatological data Zanderij station, Suriname 1958-1982.

		J	F	M	A	M	J	J	A	S	O	N	D
maximum temperature	°C	30.6	30.8	31.3	31.6	31.3	31.5	32.0	33.1	34.0	34.0	33.1	31.4
minimum temperature	,,	21.7	21.3	21.7	22.3	22.7	22.5	22.2	22.3	22.4	22.4	22.6	22.1
temperature 8.00 hr.	,,	23.5	23.3	24.0	24.8	25.1	24.8	24.6	25.1	25.5	25.7	25.3	24.3
temperature 14.00 hr.	,,	29.0	29.3	29.8	29.9	29.5	29.6	30.5	31.8	32.9	32.9	31.8	29.8
temperature 18.00 hr.	,,	26.0	26.4	26.8	26.6	26.3	25.9	26.3	27.1	28.0	27.9	27.1	26.0
relative humidity 8.00 hr.	%	93	93	91	90	90	91	90	88	86	86	88	92
relative humidity 14.00 hr.	,,	68	65	64	66	70	68	62	56	51	51	56	66
relative humidity 18.00 hr.	,,	81	77	76	81	85	87	84	79	74	75	80	84
wind speed 8.00 hr.	ms^{-1}	0.3	0.3	0.4	0.7	0.7	0.6	0.6	1.0	1.7	1.7	1.3	0.6
wind speed 14.00 hr.	,,	2.8	3.2	3.2	2.7	2.5	2.1	2.2	2.3	2.5	2.8	2.5	2.4
wind speed 18.00 hr.	,,	1.7	2.3	2.3	1.8	1.3	1.0	1.1	1.2	1.2	1.4	1.1	1.1
sunshine duration n/N		0.49	0.51	0.48	0.48	0.46	0.51	0.63	0.73	0.77	0.76	0.68	0.53
precipitation mm m^{-1}		200	136	146	223	286	309	251	181	103	95	117	187
evaporation mm d^{-1} *)		3.9	4.1	4.1	4.2	4.0	4.1	4.5	5.3	5.6	5.6	4.9	3.8

* Class-A open pan 1973-1980.
precipitation 2234 mm yr^{-1}

october with an average rainfall of 94.7 mm, the climate in Suriname can therefore be classified as an Af climate according to Köppen. The relative humidity is high, during nights values of 95 percent are observed and even in the long dry season average values at 14.00 hr are above 50 percent. The short dry season does not reflect in the average numbers for the mean sunshine duration, which are at the same level as in the short rainy season and the first half of the long rainy season. In the second half of the long rainy season there is already an increase in the mean sunshine duration, rainfall is in that period more concentrated in heavy showers.
Average windspeed is low and does not vary much through the year, strong winds are only observed during short periods preceding a shower and wind damage to agricultural crops seldom occurs. Suriname has as far as is known never been hit by a hurricane.

1.4 OBJECTIVES

The objective of this study was to collect information on aspects of mechanized farming in the humid tropics of Suriname and to formulate with this and further information from literature prospects for a mechanized farming system in this environment.
This objective must be seen in a wider context. Large parts of the tropics belong to tropical rainforest climate, in which shifting cultivation together with commercial cultivation of perennial crops is one of the important farming systems. The weakness of shifting cultivation is that it cannot absorb an increase in the population depending for subsistence on this system (Ruthenberg, 1980). In "Year 2000 Scenarios" the projected population growth rates require an agricultural output some 50-60 percent larger than in 1980. In developing countries demand will double and the additional production should come from expansion of arable land, increased cropping intensity and increased yields, (FAO, 1981). Research for sound and efficient permanent farming systems for production of food and feed should therefore have high priority.
The research project "Permanent cultivation of rainfed annual crops on the loamy soils of the Zanderij formation" set up in 1976 jointly by the Agricultural University of Wageningen (LH) and the University of Suriname (UvS), of which subject study forms a part, fitted well within aforementioned concerns and priorities.
Large areas of the humid tropics, including subject research area, are covered with acid infertile soils mostly Oxisols and Ultisols and for South America this area is estimated at 1,043 10^6 ha (Sanchez and Cochrane, 1980). The most important constraints of these soils are low availability of phosphorus, strong acidity and high aluminium toxicity, low reserve of primary minerals and low effective cation exchange capacity. In studies to replace shifting cultivation, the traditional way of farming, by a system of permanent cultivation much attention was therefore given to aspects of soil fertility. Results show that most of the fertility problems can be overcome

by balanced and substantial application of fertilizers, much site specific work is however required to establish same (Bandy and Sanchez, 1982).
Weed competition, pests and diseases are often mentioned as to be limiting to permanent farming in the humid tropics. A conclusion from above mentioned LH/UvS-02 project is that development of weeds, pests and diseases is not too much different from other areas in the world with permanent crop cultivation and that adequate control is possible with proper agronomic measures (anon, 1983). Much of present research on above mentioned aspects is directed to finding lower cost alternatives for the inputs needed in a sustained farming system because of the generally poor cost return ratio (Sanchez and Nicholaides, 1982).
The physical degradation of soils, apart from erosion, particularly when mechanized farming is introduced is a matter of concern. Mechanical land clearing is required to allow mechanized farming of annual crops. In case clearing operations are not carried out under favourable soil conditions and without appropriate discipline, physical soil conditions will deteriorate considerably and significantly lower farming returns in the earlier years of cultivation will result (Seubert et al., 1977).

The temperature regime in the humid tropics allows year round crop production and cropping seasons are determined by the pattern of rainfall. To obtain the yields corresponding with optimum planting periods, the necessary field operations must be carried out in time. The working conditions under which these field operations are performed are determined by the climatological circumstances and specially mechanized farming operations are very sensitive to working conditions with regard to their possible execution as well as their effect.

This investigation on mechanized farming in the Zanderij area concerns:
- Effects of primary tillage methods and pertaining agricultural practice on the yields of various crops and on soil physical and chemical properties.
- Conditions under which mechanized field operations can take place and workable time for field operations.
- Timeliness of planting and harvesting of certain crops.
- Formulation and evaluation of a mechanized cropping system with the use of information obtained in the investigations.

CHAPTER 2

SOIL TILLAGE

2.1 INTRODUCTION

Soil tillage is applied for different specific purposes, but it should ultimately serve to enable long term cultivations of crops at economic yields. The farmers choice to apply tillage or not, and which system and technique, depends upon many factors such as:

- The economic environment in which the farmer operates.
- The specific economic circumstances of the farmer at the moment in time.
- Soil characteristics and lay out of the fields.
- Climate and short term variations there in.
- Crop and cropping pattern.
- Availability of machines and labour.

In a farming system, with the objective of permanent crop production, soil tillage plays an important role, because soil tillage serves many purposes.

- Weeds and/or crop residues which remain after the preceding crop will hinder direct planting or deep tillage operations. POST HARVEST TILLAGE will facilitate such operations.
- A good soil structure is essential for optimal plant growth. This can be promoted by PRIMARY TILLAGE, the deepest tillage operation in the cropping cycle.
- Organic matter, fertilizers and manure can be INCORPORATED in the soil by various soil tillage operations.
- Hardpans that hinder root development and water infiltration can be broken by SUBSOILING.
- Low spots in a field will result in pools during wet periods, causing poor crop development and problems with trafficability. A tillage operation with a LEVELLING action is desirable in such cases and is of specific importance if surface irrigation is applied.
- A friable, permeable soil is required for good germination. Planting must be done at a constant depth. Both conditions can be established by SEED BED PREPARATION.

- Weed control can be carried out at several stages in the cropping cycle. POST HARVEST TILLAGE reduces perennial weeds and well performed inverting PRIMARY TILLAGE will hinder regrowth of perennial weeds and bury away weed seeds. During the SEED BED PREPARATION weeds already germinated are killed and the planted crop is given at least an equal start. Upon crop establishment weeds can be killed by CROP MANAGEMENT OPERATIONS.
- Carry over of certain diseases and pests on crop residues can be reduced by a PRIMARY TILLAGE operation carried out to adequate depth with a good inverting action.
- INCORPORATION of herbicides, nematocides and insecticides can be done with soil tillage equipment. In certain cases special injection equipment is developed. For some volatile pesticides a special treatment of the top layer of the soil is required.
- For efficient harvesting of root crops clod free soil, RIDGES and BEDS can be established.
- RIDGES to guide surface irrigation water and CONTOURS to prevent soil erosion can be made.

To perform these tillage operations a great number of implements is available, which vary in operating principle, size, combination and use of power source. For a number of the mentioned tillage operations alternatives are available.

- Elimination of weeds and crop residues can be done by means of post harvest tillage, but in some cases mowing is also acceptable to make primary tillage or direct planting possible.
- Seed bed preparation can be limited as in strip tillage where conditions for good germination are made by tillage in row only, in no tillage seed bed preparation is limited to opening the soil for seed placement.
- Soil structure can be adequate and stable and be kept in good condition by biological activity, obviating the need for a soil tillage operation to improve the structure.
- Herbicides are available to control weed growth, and pesticides can be used to control diseases.
- Tillage methods, that leave crop residues on the surface can prevent erosion.

The farmer as the decision maker has to choose between the various alternatives that are available to him. The decision process is influenced by the effect of the working method on production cost and yield, and the applicability specifically regarding weather conditions and soil type. For some soils there is a very narrow range of soil moisture content under which soil tillage operations can be performed. Cultivations followed by a dry period will be very successful in weed control. In case the operation should be followed by a wet period regrowth of weeds will occur. Wet conditions can even hinder access to the fields with cultivating implements.

In evaluating the various tillage techniques and their alternatives available for a specific purpose, the farmer is at times confronted with considerable uncertainty regarding the prevailing operating environment. The expected result and possible risk of each tillage operation should not be judged on its own, but always within the entirety of the farming system.

Primary tillage plays an important role in the whole farming system. It is a time and energy consuming operation and operating costs are relatively high, either in terms of human time and energy, animal usage, or in terms of fuel, depreciation and interest.
Within the research project "Permanent cultivation of rainfed annual crops on the loamy soils of the Zanderij formation" tillage research as reported here concentrated on primary tillage. The influence of different primary tillage methods with their relevant cultural practices on the yields of various crops was investigated and evaluated within the total farming system.
Physical and chemical properties of the soils under different tillage treatments were determined to gain insight in possible relationships and evaluated with respect to yield performance.

2.2 MATERIALS AND METHODS USED IN THE EXPERIMENTS

The soil tillage experiments were carried out on the fields of the experimental farm Coebiti and at the Kabo site. Field operations were mechanized, a standard agricultural tractor of 55 kW with rear axle drive was used as the power source, for chisel and disc ploughing at Kabo a 75 kW tractor was used. In the first step of a cropping cycle possible residues and weeds were reduced to managable size with a rotary mower. Disc ploughing to a depth of 0.25 m was done with a mounted disc plough with three, at Kabo four, discs of 0.66 m diameter. A chisel plough with eight tines mounted on three bars and working width of 2 m was used. With the available power source a working depth of 0.25 m could be obtained. For rotavating a 1.5 m wide rotavator was used, with L shaped blades and reverse revolution. The maximum working depth was 0.15 m. Disc harrowing was carried out with an offset disc harrow, 1.8 m wide. The intended working depth of 0.15 m could however only be achieved under fairly wet conditions.
In the cases with a primary tillage operation of disc or chisel ploughing a seed bed was prepared by means of a 3 m wide power driven rotary harrow with a working depth of 0.05-0.10 m. In case of rotovating the seed bed was made in one pass without a second tillage operation.
Crops were planted with a four row pneumatic precision planter, hoe type openers were used for no tillage instead of the standard runner type openers. In cases with much residue on the no tillage fields clogging of the planter occurred occasionally and additional labour was required to free the planter. Tillage and planting were carried out directly in sequence.

soil tillage

The first application of fertilizer was done in one operation with planting, 0.05 m beside the plant row. On tilled soils the placement was slightly deeper than the seed, such depths could not be reached on no tilled soils under dry conditions. The second application of fertilizer was given with a reciprocating spout broadcaster. For maize an attachment was mounted on the same broadcaster which allowed spreading the fertilizer along the plant rows. Fertilizer and calcium additions were in line with the recommendations formulated within the LH/UvS-02 project and are presented in table 4.

Table 4. Fertilizer recommendations for Zanderij soils kg ha^{-1}.

	1977			1980			1983		
crop	N	P	K	N	P	K	N	P	K
maize	120	40	60	150	50	100	200	40	80
sorghum	100	40	60	100	40	80	100	30	60
soya bean	20	40	60	20	40	80	20	30	60
groundnut	20	40	60	20	40	80	20	30	60
cowpea	20	30	40	20	30	60	20	30	60

Liming was done at a yearly rate of 1000 kg ha^{-1} EMkal. For economic reasons rock phosphate was used occasionally to meet part of the lime and phosphor requirements.

Harvesting was done with a small commercial combine, to enable maize harvesting a picking table was installed instead of the mowing platform. Groundnuts were loosened mechanically, hand harvested and threshed with a small thresher. Yields are reported as obtained by the harvesting method applied, standardized at 12 percent moisture wb. Crop residues were left on the fields.

Pesticides were applied with a tractor mounted sprayer with an 8.0 m and from 1982 onwards with a 12.0 m wide beam. Chemical weed control was done by means of pre-emergence herbicides. Allachloor, 2.4 kg a.i. ha^{-1}, in the case of legumes and atrazine, 3.0 kg a.i. ha^{-1}, for maize and sorghum. On the no tillage fields paraquat was applied about one week before planting and again in mixture with the pre-emergence herbicide shortly after planting.

The crops grown in the experiment were: Maize, *Zea mays L.*, open pollinating varieties, from 1979 onwards originating from the CYMMIT pool. Soya bean, *Glycine max (L.) Merr.*, cvs Laris and Jupiter. Cowpea, *Vigna unguiculata (L.) Wolp.*, cv African Red. Sorghum, *Sorghum bicolor (L.) Moench*, cv Martin. Groundnut, *Arachis hypogaea L.*, cv Matjan.

2.3 LONG TERM TILLAGE EXPERIMENT AT COEBITI

2.3.1 Experimental site

The site was cleared from rain forest in 1970 by means of a crawler tractor equipped with a tree pusher. Windrowing was done with a rake on the same tractor and a windrow was situated over the whole length of the field equidistant from both sides. After burning of the windrow the remainders were removed and tropical kudzu, Puerarice phaseoloides (Roxb.) Benth., was planted. Cropping started in 1973 with three cycles under conventional tillage i.e. disc ploughing and harrowing, which allowed for the removal of wood and levelling of the site. The result of a soil textural analysis made in 1980, is presented in table 5, the soil can be classified as a sandy loam over a sandy clay loam. The plots measuring 63 x 12 m for three different treatments were laid out in a random block design in three replications. The strip of land with the residue of the burnt windrow crossed the centre of each plot.

Table 5. Particle size distribution in percentage, of the soil under cultivation at Coebiti 1980.

separate	clay	silt	very fine sand	fine sand	medium sand	coarse sand	very coarse sand	
	equivalant diameter range mm							
depth cm	`0.002	0.002 -0.050	0.05 -0.10	0.10 -0.25	0.25 -0.50	0.5 -1.0	1.0 -2.0	textural class
0-10	15.0	2.4	3.6	12.2	37.0	18.1	11.5	sandy loam
10-20	16.4	2.4	4.2	13.0	37.6	16.2	10.1	sandy loam
20-30	19.5	1.7	3.6	11.6	34.8	16.3	12.4	sandy loam
30-40	21.9	2.4	3.8	13.0	30.0	15.9	12.7	sandy clayloam
40-50	23.3	1.6	3.8	12.4	29.8	15.6	11.6	sandy clayloam
50-60	25.5	2.0	3.3	12.4	28.9	16.7	11.2	sandy clayloam

2.3.2. Tillage treatments

After site preparation as discussed in paragraph 2.3.1. experiments were started in january 1974 to study the effect of depth of tillage on crop yields in 22 cropping cycles. The tillage treatments used were:

- -PL Disc ploughing to a depth of 0.25 m, followed by one pass with a power driven rotary harrow for seed bed preparation.
- -RO Rotavating to a depth of 0.15 m, providing a seedbed in one operation.
- -NT No-Tillage however up to the fourteenth cropping cycle one pass of rotavating to a depth of 0.05 m was applied to provide a seedbed.

The same tillage treatment was applied in each cropping cycle on each field except in the seventh cycle when the PL and NT treatments were mistakenly interchanged. In the beginning mechanical weed control was practised and at times under wet conditions also paraquat was applied between plant rows with a knapsack sprayer equiped with a plant protective cap. In the cropping cycles 7-11 fields were left for some ten days after the respective tillage treatments upon which one pass with a rotary harrow was applied to a depth of 0.05 m before sowing to eliminate weeds meanwhile germinating, no chemical weed control was applied during these cropping cycles. Weeds could however not be adequately controlled by these methods and complete chemical weed control as described in paragraph 2.2 was applied from cycle 14 onwards. In the earlier experiments fertilizer was applied by hand after sowing, later practice as described in paragraph 2.2. was followed. Maize was hand harvested till 1977 and combine harvested from then onwards.

2.3.3 Crop Yields

The experiments were carried out by Van der Sar from 1974-1977 and continued by the author till 1981 (Van der Sar, 1975; 1976; 1978). Product yields obtained in the eight year trial period for 22 cropping cycles are presented in table 6.

For maize all occupations show higher yields for the deeper tillage treatment. It would appear that the loss of yield with shallow and no tillage is smaller in the early years of the trials than in the later years. In cycle 16 high timeliness loss due to the non availability of a combine occurred. In cycle 19 the crop suffered from an application with a contaminated insecticide.
For sorghum all occupations show lower yields for the less deep tillage treatments. In cycles 8 and 14 yields were low because of dryness. Poor germination and weed competition caused low yields in cycle 12. Because of poor germination the no tillage fields were replanted in cycle 22.
For cowpea and soya bean yields were lower for the less deep tillage treatments. The effect was larger for cowpea than for soya bean.
For groundnuts the effect of tillage treatment on crop yield is less pronounced than for the other crops. In cycle 13 strong weed competition occurred.

Table 6. Crop yields at Coebiti in three different tillage treatments.

cycle	planting date	yields kg ha^{-1} PL 0.25 m	RO 0.15 m	NT	sign %	s.d. kg ha^{-1}	% relative yield PL=100 RO	NT
maize								
2	3- 4-74	2978	2728	2414	1	71	91.6	81.1
6	10- 9-75	2900	2537	2439	2.5	103	87.3	84.1
10	15- 3-77	2423	2211	2149	n.s.		91.3	88.7
16	25- 4-79	2801	1638	1760	2.5	250	58.5	62.8
19	3- 4-80	2237	1633	1199	2.5	238	72.6	53.5
21	22- 4-81	2371	1724	1646	n.s.		72.7	69.4
	average	2618	2077	1917			79.4	73.2
sorghum								
4	30-12-74	3032	2734	2513			90.2	82.4
8	28- 7-76	280	271	262				
12	15-12-77	1396	1304	1381			93.4	98.9
14	29- 8-78	445	414	334	5.0	38		
18	25-11-79	2648	2020	1571	1.0	100	76.3	59.3
22	2-12-81	2710	2200	2256			81.2	83.3
	average	2447	2065	1930			84.4	78.9
cowpea								
1	17- 1-74	836	736	596	10.0	92	88.0	71.3
9	17-12-76	871	735	554			84.4	63.6
17	7- 9-79	772	750	647	2.5	33	97.2	83.8
	average	826	740	599			89.6	72.5
soya bean								
5	14- 5-75	1517	1465	1155			96.5	76.1
11	10- 8-77	1433	1374	1420	5.0	6	95.9	99.0
15	20-12-78	1745	1436	1268	1.0	87	82.3	72.7
20	19-11-80	2084	1965	1892			94.3	90.1
	average	1695	1560	1433			92.0	84.6
groundnut								
3	24- 8-74	1947	1901	1675			97.6	86.0
7	29- 1-76	2245	2329	2110		110	103.7	94.0
13	2- 5-78	1519	1456	1364			95.9	89.8
	average	1903	1895	1716			99.6	90.2

Table 7. Plant characteristics.

	soya bean crop cycle 15			soya bean crop cycle 20		
tillage treatment	PL	RO	NT	PL	RO	NT
plants ha^{-1} 10^{-3}	88	86	85	129	111	178
yield kg ha^{-1}	1745	1436	1268	2084	1965	1892
	sorghum crop cycle 18			maize crop cycle 19		
plant height m	1.20	1.12	0.85	1.71	1.68	1.55
plants with ear %	92	83	75	67	61	58
yield g/ear	18.2	14.4	10.6	59.0	50.3	42.0
yield kg ha^{-1}	2648	2020	1571	2237	1633	1199

2.3.4 Plant characteristics

The number of plants and the yield per plant were determined for some crop cycles detailed in table 7.
Sorghum and maize showed better plant development and higher yields for the deeper tillage treatments. For the cropping cycles 20 and 18 conditions during planting and germination favoured the no tillage treatment resulting in higher plant numbers for this treatment. Notwithstanding this, overall yields were lower than for the PL and RO tillage treatment.

A qualitative inspection of the rooting profile of soya bean during the 15 th cropping cycle showed that in the no tillage fields roots were concentrated in a narrow band of about 0.15 m wide around the slot opened for planting up to a depth of 0.09 m. In the rotavating treatment roots were spread over the whole surface but only few beyond a depth of 0.23 m. In the ploughed fields roots were also spread over the whole soil surface down to a depth of 0.45 m. At the end of the maize crop of the 19 th cropping cycle root counts were made in profile pits over a width of 0.30 m down to a depth of 0.70 m. The

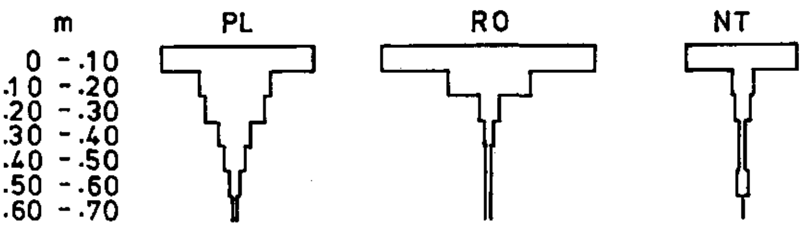


figure 2. Maize, relative root densities in 0.10 x 0.30 m cross sections for three tillage treatments. PL ploughing, RO rotavating, NT no tillage.

average of two observations per treatment which showed wide variation are presented in figure 2. The lowest root count is found in the no tillage fields and in the soil layers beyond 0.10 m the ploughed fields show the highest root density.

2.3.5 Soil properties

Penetration resistance

The penetration resistance of the soil in the experiments was measured with a recording penetrograph using a conus of 0.0001 m^2 with a top angle of 90^o. The data as presented in figure 3 are averages of 10 measurements per treatment in one replication.
The three series of measurements made halfway the crop growing cycle in the short and long rainy seasons show great similarity. For ploughing to a depth of 0.25 m resistance remains up to a depth of 0.30 m below 1 MPa. On the fields which were rotavated to a depth of 0.15 m and on the no tillage fields resistances increased rather steeply with depth to maximum values between 2.7 and 3.5 MPa at depths around 0.20 m. For all treatments the penetration resistance converges to a level of 2-2.5 MPa at depths around 0.40 m. On the rotavated and no tillage fields higher values are measured in the soil around 0.20 m depth. The resistance at the rotavating depth of 0.15 m was found to be higher than the resistance at the ploughing depth of 0.25 m. The data obtained point to rather severe compaction on the rotavated and no tillage fields and corroborate observations in literature that in this soil type, a Yellow Kaolonitic Oxysol, compact subsurface layers occur especially in mechanized farming systems (Bennema, 1982).

Pore volume and moisture content at pF 2

Soil pore volumes, calculated with a specific density of 2.60 Mg m^{-3}, and moisture contents at pF 2 as measured during the course of the experiment are reported in figure 4. Sampling was done before the start of tillage operations. The samples of january 1979, january 1980 and december 1980 were taken under crop.
The pore volumes on the rotavated and no tillage fields show a diminishing trend to a level of about 40 percent. Differences between these two treatments are relatively small. The moisture content at pF 2 appears to settle at values around 21 percent.
On the ploughed fields pore volumes, specifically of the larger pores, remained at a higher level, although the latest measurements do not confirm this. The soil moisture content at pF 2 is sligthly lower than for the other treatments.
The observed values indicate that compaction occurs during cultivation as applied in this experiment for all three treatments. Alleviation occurs by ploughing in so far as larger pores are restored.

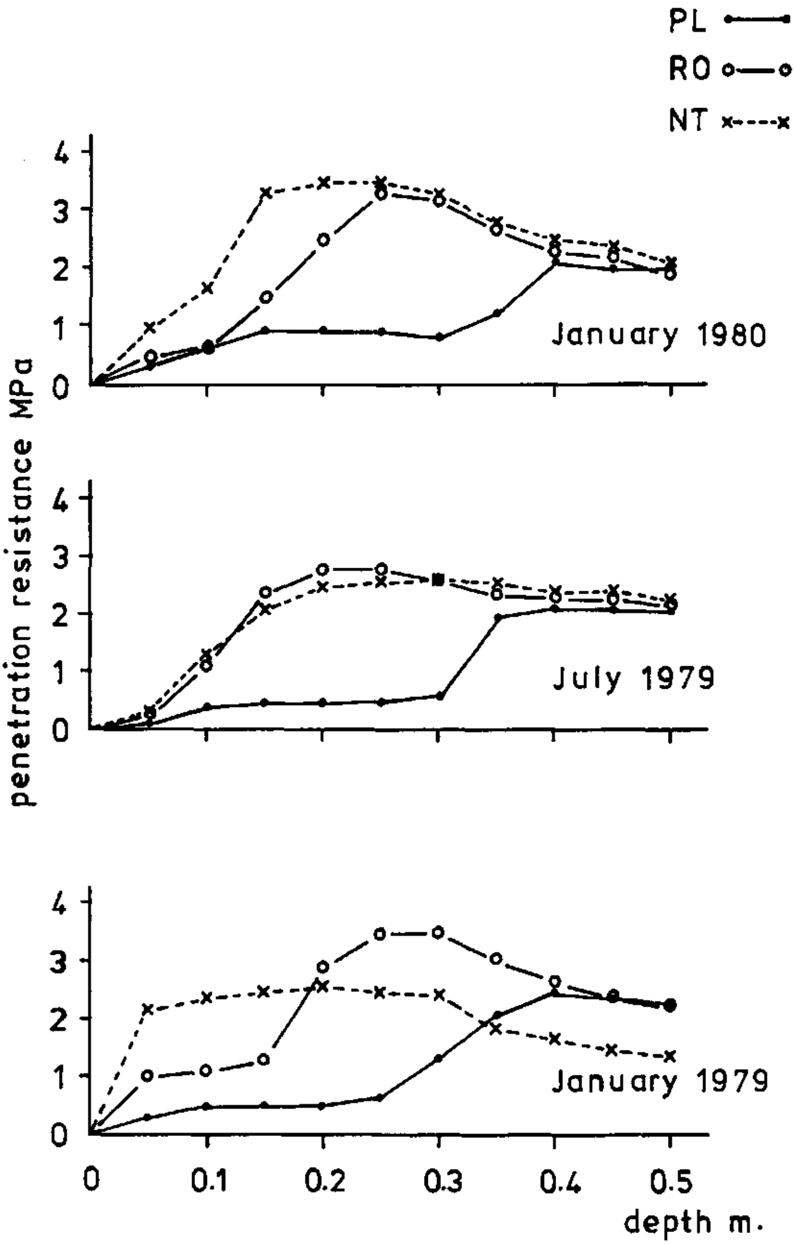


Figure 3. Penetration resistance, january 1979 under soya bean, july 1979 under maize, january 1980 under sorghum for three tillage treatments.

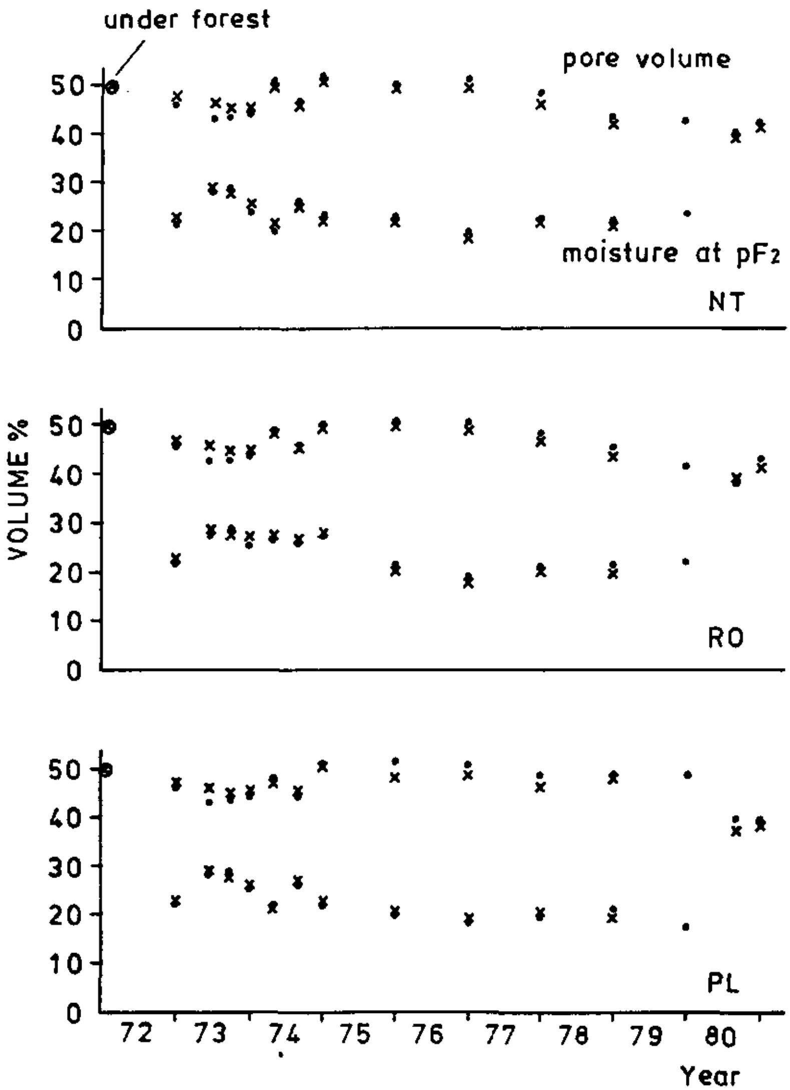


Figure 4. Soil pore volume and soil moisture content at pF2 for three tillage treatments. Data are averages of 30-45 observations per treatment except january and august 1980 when 5 observations were made in one replication and december 1980 when 12 observations per treatment were made. × 0.10-0.15 m • 0.20-0.25 m

Table 8. Soil chemical properties under three tillage treatments.

soil layer		0-0.20 m		0.20-0.40 m	
date	treatment	july '78	july '80	july '78	july '80
org. C, g kg^{-1}	PL	12.6	10.9	8.4	8.4
	RO	11.3	10.9	7.5	6.2
	NT	12.3	12.8	7.7	7.6
org. N, g kg^{-1}	PL	1.0	0.8	0.7	0.6
	RO	1.0	0.8	0.8	0.5
	NT	1.0	0.9	0.7	0.5
pH-KCl	PL	4.4	4.5	4.1	4.3
	RO	4.3	4.6	4.1	4.2
	NT	4.3	4.3	4.0	4.0
exch. Ca, 1/2 $mmol^{+}kg^{-1}$	PL	19.4	14.0	9.5	10.2
	RO	15.1	15.0	4.6	5.9
	NT	15.2	19.4	4.7	6.1
Mg, 1/2 ,,	PL	2.1	3.4	1.3	1.8
	RO	1.7	3.3	0.7	3.1
	NT	1.7	3.4	0.7	1.5
K, ,,	PL	0.7	0.7	0.6	0.6
	RO	0.6	0.9	0.4	0.7
	NT	0.8	0.6	1.1	0.8
Na, ,,	PL	0.5	0.5	0.2	0.3
	RO	0.2	0.7	0.2	0.4
	NT	0.7	0.4	0.4	0.4
Al, 1/3 ,,	PL	3.2	2.8	6.5	4.6
	RO	3.8	1.1	8.7	6.3
	NT	4.7	2.2	10.4	7.0
ECEC ,,	PL	25.9	18.4	18.1	18.1
	RO	21.4	20.2	14.6	14.7
	NT	23.1	23.6	13.4	12.7
100 x exch. Al/ECEC	PL	12	14	36	25
	RO	18	5	60	39
	NT	20	13	78	39
P-Bray I mg kg^{-1}	PL	27.1	20.3	8.5	13.8
	RO	24.2	32.6	4.2	7.5
	NT	24.1	32.7	4.7	4.1

Natural improvement is considered difficult since shrinkage and swelling of the soil are virtually absent, and no substantial activity of micro fauna is observed on these soils (Van der Werf, unpublished information).
The pore volumes measured in january 1979 and 1980 are consistent with the measured penetration resistances at that time.

Chemical properties

Table 8 shows soil chemical properties as measured in july 1978 and 1980. A comparison of these analyses with those of the soil under forest as reported in table 2 shows clearly the effects of fertilization, downward movement of fertilizer can be observed. In the individual soil samples, effects of land clearing were still apparent after ten years. In the former windrow area higher values are found for organic matter, pH and bases (Goense, unpublished).
The distributing effect of the tillage method applied is illustrated in figure 5, where exchangeable calcium and percentage aluminium saturation as measured in 1980 in one replication of the experimental field are presented for 0.1 m soil layers down to 0.6 m. Rather clean separations occur at depths of 0.10, 0.20 and 0.30 m in the no tillage, rotavated and ploughed fields respectively.

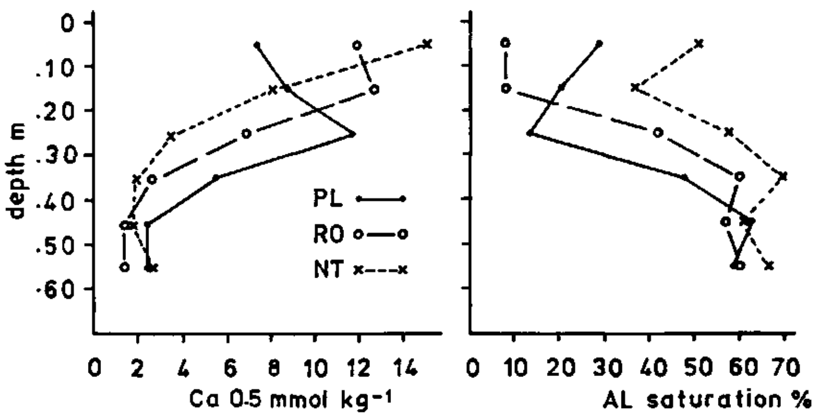


Figure 5. Exchangeable Ca and Al-saturation for three tillage treatments, august 1980.

Organic carbon content

The organic carbon content as presented in figure 6 refers to the averages of the 0.10-0.15 m and 0.20-0.25 m soil layers except for the data for 1972, 1978 and 1980 which refer to the 0-0.20 m soil layer. Differences between the two soil tillage treatments ploughing and no tillage are small and also the data obtained on the rotavated fields, not included in the graphs, move within the same band. From a value of 1.2 percent under forest the organic

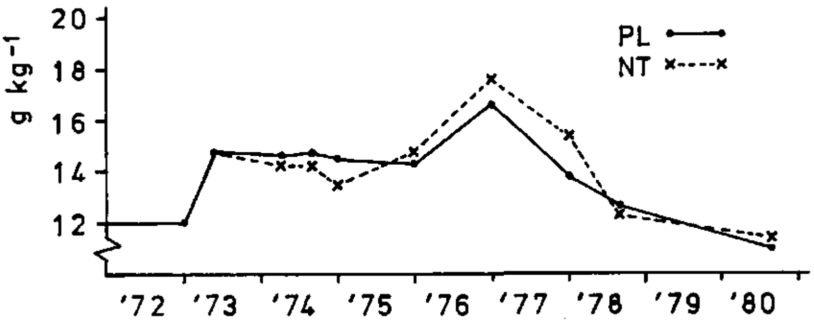


Figure 6. Organic carbon for two tillage treatments during eight years of cultivation.

carbon content initially increases under cultivation but decreases in the later years. In this respect it may well be significant that in the early years of cultivation heavy weed growth, in which <u>Elusine indica (L.) Gaert.</u> was dominant, occurred specially during the fallow periods. With the application of complete chemical weedcontrol in the later years this was very much reduced. Thus far cultivation and fertilization as applied in the experiment have as yet not resulted in large decreases of soil organic matter. Bandy and Sanchez (1982) reported from Yurimaguas, Peru, in a comparable experiment, a decrease of organic carbon from 1.2 percent to 1.0 percent in eight years cultivation after forest clearing. Over this period values between 0.9 and 1.4 percent are reported.

2.3.6. Discussion

The average crop yields obtained in a consecutive series of 22 cropping cycles under three different tillage treatments were highest for ploughing to a depth of 0.25 m followed by rotavating to a depth of 0.15 m, no tillage gave in near all cycles the lowest yield.

It should be noted that the data for no tillage include the observations made on the same fields when rotavation to a depth of 0.05 m was applied.

Differences in the relative yield effects occur between crops. Maize, sorghum and cowpea showed here to be more sensitive to tillage treatment than soya bean and groundnut. Variations from the average relative yield for each crop are large suggesting that specific climatological circumstances at each experiment played a significant role, also crop sequence may have been of influence.

It may be concluded from this long term experiment at Coebiti that a cropping system in which no tillage is practised continuously will result in considerably lower yields compared with a system with ploughing in each cycle. Shallow tillage like rotavating gives intermediate results. This conclusion is valid for mechanized farming on the fields found at Coebiti, a sandy loam over a sandy clay loam, and the pertaining climate.

Compaction in the upper 0.30 m soil layer in terms of pore volume and penetration resistance is more severe on the fields with no or shallow tillage than on the ploughed fields. Observed values of 40 percent pore volume and penetration resistances beyond 2.5 MPa are reported as being restrictive to root development (Nicou and Chopart, 1979; Maurya and Lal, 1979).
Values around 40 percent aluminium base saturation at about 0.20 m depth were measured in the no and shallow tillage fields. Lower values were found in the ploughed fields because added lime had been worked deeper into the soil. At the above mentioned levels of aluminium saturation effects of aluminium toxicity such as impeded root development occur (Kamprath, 1980; Gonsalez and Kamprath, 1979).
Qualitative inspections showed lesser root development and specifically in depth for the shallower tillage treatments.
Notwithstanding equal nutrient additions under the three tillage treatments yield differences occur as the lesser root development will result in lower plant nutrient uptake and possibly more important, less deep rooting in these soils with their low water holding capacity will make plants less able to withstand drought during short dry periods which even during the rainy seasons occur.

Weed competition is not considered to have been of significant influence on the yield differences obtained, certainly not since complete chemical weed control was applied which was very effective at Coebiti.
Since application of chemical weed control the vegetation during the fallow periods was very scarce on all three treatments. A protective cover of vegetation to protect soil and fauna against adverse conditions, often mentioned as an advantage of no tillage farming, was not present.

2.4. SOIL TILLAGE EXPERIMENT AT KABO

2.4.1. Experimental site

The site at Kabo was cleared from heavy rain forest with a crawler tractor in 1978. Clearing operations were carried out under marginal conditions with respect to soil moisture and in particular the windrowing operations caused severe soil compaction. Bulk densities up to 1.65 Mg m^{-3} at a depth of 0.35 m were measured (Poels, unpublished). The site for the experiment was 200 x 90 m on which length wise in the middle a windrow was situated. After growing a maize and a sorghum crop under conventional tillage the windrow was removed. Working conditions for this operation were excellent. After a third cropping cycle with maize under conventional tillage the site was sufficiently levelled and freed of wood to enable starting of the experiments. Plots measuring 75 x 12 m were laid out in a random block design for four different treatments with four replications. The field was situated on a sligth slope

Table 9. Properties of soil under forest, Kabo (Neeteson and Poels, unpublished).

soil layer m	0.00-0.09	0.09-0.33	0.33-0.59
org. C g kg^{-1}	12.9	8.4	4.5
org. N g kg^{-1}	1.0	0.7	0.4
pH KCL	3.8	3.9	4.1
pH H_2O	4.4	4.5	4.7
exch. Ca, 1/2 mmol kg^{-1}	5.1	0.5	0.5
exch. Mg, 1/2 ,,	3.3	0.0	0.3
exch. K, ,,	0.5	0.2	0.1
exch. Na, ,,	0.0	0.0	0.0
exch. Al, 1/3 ,,	5.8	12.7	10.7
ECEC ,,	14.7	13.4	11.6
100 x exch. Al/ECEC	39	95	92
CEC, pH7, mmol kg^{-1}	33.7	24.9	17.2
P-Bray I mg kg^{-1}	1.3	0.4	0.0
sand %	90.7	79.1	75.6
silt ,,	1.7	0.2	2.0
clay ,,	7.6	20.7	22.4
pore volume %	51.5	50.2	50.2
water pF 2.0	24.5	25.4	23.0
,, pF 4.2	5.8	9.1	11.2

and is described as a well drained profile with a brown loamy sand to sandy loam topsoil and a brown yellowish brown sandy clay loam subsoil. This description holds true for the first three replicates, in the fourth a sharp discontinuity was observed and the very coarse sandy soil structure on two plots made it necessary to exclude those from the experiments. Some physical and chemical properties of the soil at the experimental site, before clearing, are given in table 9.

2.4.2. Tillage treatments

In this experiment disc ploughing and no tillage were included as references and for possible comparison with the Coebiti experiment, additionally chisel ploughing and disc harrowing were investigated as follows:

- -PL Disc ploughing to a depth of 0.25 m, followed by one pass with a power driven rotary harrow.
- -CP Chisel ploughing to a depth of 0.25 m, followed by one pass with a power driven rotary harrow.

-DH Two passes with a disc harrow to a maximum working depth of 0.15 m.
-NT No-tillage.

For methods and materials paragraph 2.2 refers.

2.4.3. Crop yields

A series of four cropping cycles was carried out, the results are reported in table 10 with the following comments in elucidation.

Cycle 1. Maize
Very dry conditions after planting resulted in poor germination and replanting on all plots was required, the first applications of fertilizer and herbicides were not repeated. The crop stand was poor and not free of weed. In a later stage a heavy plague of Spodoptera Frugiperda J.E. Smith. and Mocis Lapides Guen did much damage to the crop. Weather conditions did not permit combine harvesting and plots of 10 x 12 m were hand harvested instead. Average yields were higher for the deeper tillage methods, variability however was high.

Cycle 2. Soya bean
Because of dryness germination showed great differences between the treatments. Germination was poor on the tilled plots, specially where planted in the wheel tracks, on the no tillage fields germination was good. The highest yield was obtained on the no tillage plots, differences between treatments were however small.

Table 10. Crop yields at Kabo for four different tillage treatments.

cycle	planting date	yields kg ha^{-1}				sign %	s.d. kg ha^{-1}	% relative yield PL=100		
		PL	CP	DH	NT			CP	DH	NT
Maize										
1	4-81	2400	2383	2031	2008	5.0	396	99.2	84.6	83.7
3	12-82	3887	3889	3105	2878			100.0	79.9	74.0
average		3144	3135	2568	2443			99.7	81.7	77.7
Soya bean										
2	11-81	2035	1989	1997	2319			97.8	98.1	113.9
Sorghum										
4	7-83	1526	1342	1041	894	1.0	154	87.9	68.2	58.6

Cycle 3. Maize

Because of external circumstances the experimental fields had been left fallow for some 8 months. On the no tillage fields residues of the heavy weed vegetation killed by repeated application of paraquat, caused clogging of the planter and possibly therefore a thinner stand on those plots. As february was very dry a short crop resulted, yields differed significantly in favour of the deeper tillage treatments.

Cycle 4. Sorghum

During flowering of the sorghum the rainy season ended abrubtly, this resulted in moisture stress in this critical period. Yields were low, with significant differences in favour of the deeper tillage methods.

2.4.4. Soil properties

Penetration resistance

The penetration resistances, measured in february 1983 during the third cropping cycle, are reported in figure 7. The data are averages of ten

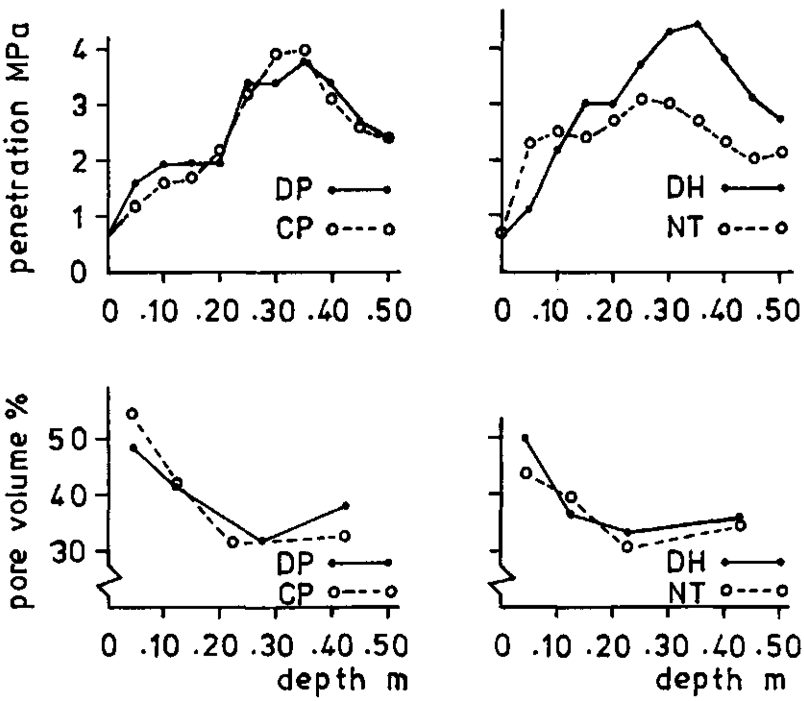


Figure 7. Penetration resistance and percentage pore volume for four tillage treatments at Kabo, february 1983, under maize.

measurements per treatment in one replication. The plots where no tillage or disc harrowing was applied showed the higher resistances down to a depth of about 0.25 m. Maximum values for all treatments were found at depths of 0.30-0.35 m and varied between 3.1 and 4.4 MPa with the lower values for no tillage treatments. At depths of 0.45-0.50 m the penetration resistances converge towards a value of 2.5 MPa.

Pore volume

Soil samples for the determination of pore volume were collected at the same time when the resistance measurements were made, results presented in figure 7 are the average of 2 measurements per depth per treatment in one replication.
Pore volume variations with depth show similar patterns as measured for soil resistance and from inspection of figure 7 it may be inferred that minimum pore volume and highest resistance occur at 0.30-0.35 m depth. In the upper 0.25 m soil layer pore volumes are higher for the deeper tillage treatments. This soil under forest had a pore volume of 50 percent to a depth of 0.6 m. Severe compaction as now observed some 4.5 years after land clearing is most likely to have occured during forest clearing operations which were carried out under too wet conditions. Also ploughing during wet conditions in the first three crop cycles on all fields may have contributed to this compaction.

Organic carbon content

Organic carbon was determined on samples taken february '83 and results are presented in table 11. About equal amounts are found for the four different tillage treatments. In the no tillage and harrowed fields organic carbon concentrations in the top soil layer are somewhat higher than for the ploughed fields. The organic carbon content of this soil 4.5 years after forest clearing with six cropping cycles is as yet about equal to that under forest.

Table 11. Soil organic carbon under four tillage treatments at Kabo.

tillage treatment	PL	CP	DH	NT
soil layer m		organic carbon g kg^{-1}		
0.00 - 0.10	10.6	11.3	14.0	11.8
0.10 - 0.20	10.5	9.8	11.4	10.3
0.20 - 0.30	9.9	7.0	9.2	8.3
0.30 - 0.40	5.9	5.1	6.3	4.4
0.40 - 0.50	3.7	3.9	4.8	3.2
0.50 - 0.60	2.9	3.2	3.2	3.2

Chemical properties

The chemical analyses represented in table 12 were made during the third cropping cycle of the experiment. The distributing effect of the tillage treatment on fertilizer additions is already showing in the analyses, specially considering that before beginning the experiments all fields were subject to three crop cycles under conventional tillage with the recommended fertilization.

Table 12. Soil chemical analyses under four tillage treatments at Kabo february 1983.

	tillage treatment	sampling depth m 0.0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.6
pH-KCl	DP	4.1	4.2	4.2	4.0	3.9
	CP	4.6	4.2	4.0	4.0	3.9
	DH	4.6	4.1	4.0	3.9	3.9
	NT	4.6	4.1	4.2	3.9	3.9
exch. Ca, 1/2 $mmol^{+}kg^{-1}$	DP	14.3	16.5	17.7	8.8	3.5
	CP	19.4	18.5	10.4	6.1	3.3
	DH	22.4	17.2	9.4	6.3	3.5
	NT	20.9	15.5	15.0	7.2	5.0
CEC pH 7 ,,	DP	36.0	35.4	34.0	24.8	15.8
	CP	33.8	34.0	25.6	20.4	17.5
	DH	40.8	37.8	31.2	25.2	18.6
	NT	36.2	33.4	29.4	20.0	16.6
P-Bray I, mg kg^{-1}	DP	13.8	11.0	10.4	7.3	1.9
	CP	15.7	10.4	3.4	1.4	1.0
	DH	26.0	14.5	4.5	1.7	2.4
	NT	20.1	7.6	5.5	1.9	1.3
100 x exch.Al/ECEC	DP	19	17	13	35	65
	CP	2	11	42	43	65
	DH	35	21	45	52	64
	NT	5	23	18	48	50

2.4.5. Discussion

The results of the Kabo experiment with Sorghum and Maize regarding the relation between crop yield and tillage method applied are in line with the experience in the long term trials at Coebiti. For the crop cycle with soya bean the highest yield was obtained on the no tillage fields, prevailing conditions during the growing period were such that the greater plant numbers in this case also resulted in relatively higher yields. Disc and chisel ploughing both to a depth of 0.25 m resulted in about the same yields. Disc ploughing provided a better distribution of fertilizer in the soil layer to working depth. Indications are that disc harrowing and rotavating to the same depth are not greatly different in respect of relative yield performance.

Nothwithstanding the short duration of the trial, soil physical and chemical properties reflect tillage treatments applied, and it appears that reasons for relative yield loss with less deep tillage as discussed in paragraph 2.3.6. do also apply here.
Response to the chemical weed control was less complete than at Coebiti because of other weed species. Weed residues at times hindered planting, this resulted on the no tillage fields in localized thinner plant stands and more weed competition.

Experience obtained elsewhere with reduced or no tillage in its many forms varies, apart from erosion control which did not apply in this investigation, with crop, soil properties and agroecological environment. Reported yield effects are mostly negative or neutral. (T.J. Vyn et al, 1982; L. ten Holte, 1982; H.P.F. Curfs,1976).
It is observed that soil characteristics should be suitable and that a high standard of management is required to apply continuous no tillage successfully (R.Q. Cannel, 1985).
P. Stengel et al. (1984) sought from experience in the U.K. and France to classify soils for no tillage on the bases of the following physical properties of the top soil:

- Slaking by water, the stability of soil structure to excess water.
- Compactability, the resistance to mechanical stress.
- Fragmentation by shrink/swell activity, the possible natural recovery from damage to the soil.

Soils with low clay contents and high proportions of sands or silts were identified as those likely to be problematic with no tillage.
R. Lal (1983) prepared a tentative soil suitability guide for different tillage systems in the tropics based on a numerical rating system considering; soil erosion, hydrothermal regime, soil compaction characteristics and nutritional and chemical properties. It is stated that soil properties favouring no tillage include; course texture in the surface horizon, resistance to compaction, high biological activity, good internal drainage and friable consistency over a wide range of soil water contents.
In both references, which cover extensive experience and research, the resistance to compaction and natural recovery from compaction are indicated as important soil properties to allow successful continued application of no tillage. In the experiments at Zanderij these properties were not observed.

soil tillage

2.5. FREQUENCY OF NO-TILLAGE.

2.5.1. Introduction

The experiments at Coebiti and Kabo as described before showed that for the soil types investigated a practice of permanent no tillage results in lower yields when compared with systems where tillage such as ploughing is applied. This yield difference varies with crop and other factors. No tillage has however also advantages:

- The field operating system is simpler.
- Labour, equipment and direct energy costs are lower.
- The workability range for planting is wider.
- Less time is required to establish a planted area.

Foregoing suggests, that specifically when workability is the limiting factor in planting, there may be place for incidental application of no tillage in a cropping system laid out primarily for deep tillage. The choice should then not be between permanent no tillage and tillage, but the approach should be more flexible. The choice should be made as late as possible in the crop cycle, considering crop, weather conditions and progress of field work.
The objective of the experiments described hereafter was to gain insight in the applicability and effect of alternating deep tillage and no tillage (incidental no tillage). Physical and chemical properties of the soil were determined for possible elucidation of crop performance in relation to applied tillage.

2.5.2. Experimental site

The experiment was carried out at Coebiti near the fields of the long term tillage experiment described in chapter 2.3., with a somewhat heavier soil. Before this tillage experiment commercial crops had been grown under conventional tillage. Four treatments were laid out in a random block design with four replications,the size of the plots was 50 x12 m.

2.5.3. Tillage treatments

Treatments were:

A - Permanent deep tillage, disc ploughing to a depth of 0.25 m and one pass with a power driven rotary harrow.
B - Deep tillage alternated with no tillage.
C - Two cycles of deep tillage alternated with one cycle no tillage.
D - Permanent no tillage.

The instructions for the third cropping cycle were mistakenly also used for cycle four, the intended scheme for treatment B and C could therefore not be followed.

2.5.4. Crop yields

Six cropping cycles were investigated and yield data are reported in figure 8 to which the following comments apply.

Cycle 1. Sorghum
Development of the crop was good on the ploughed as well as on the no tillage fields. The average yield on the latter was 82.4 percent of the yield obtained on the ploughed fields.

Cycle 2. Maize
Upon completion of planting on the no tillage plots, field work was interrupted because of heavy rains, therefore the tilled fields were planted five days later, when conditions were still marginal. Development in the early growth stage was better on the no tillage fields, rainfall during growth was abundant. In the second half of the growing season visual differences became less, but yield on the no tillage plots was higher than on the ploughed ones.

Cycle 3. Soya bean
At planting time no specific inoculum was available which caused a deficiency of nitrogen in the earlier growing period of which the effects were more visible on the no tillage fields than on the ploughed fields. Yields from the ploughed fields were higher than from the no tillage fields. Differences between series A and C and between B and D were small, no influence of previous tillage treatments was apparent in this cycle.

Cycle 4. Maize
Standing water was observed on some places of the ploughed fields in the early growth period during the long rainy season. The ploughed fields gave nevertheless the highest yields with minor differences between the treatments A and C. The yield on the permanent no tillage fields was 20 percent lower than on the no tillage fields in series B, suggesting influence of ploughing in the earlier cycle.

Cycle 5. Sorghum
Emergence was poor especially on the direct planted fields of the series C and D, which resulted in relatively large open spots at harvest time. The ploughed fields gave the highest yield with small difference between series A and B. The yield on the fields of series D, permanent no tillage, was 42 percent lower than on the no tillage fields of series C suggesting influence of ploughing in the previous cycle.

Cycle 6. Maize
Early development was less on the ploughed fields than on the direct planted fields, water stagnation on the ploughed fields may well have been the reason for this lesser initial development. Later in the growing season

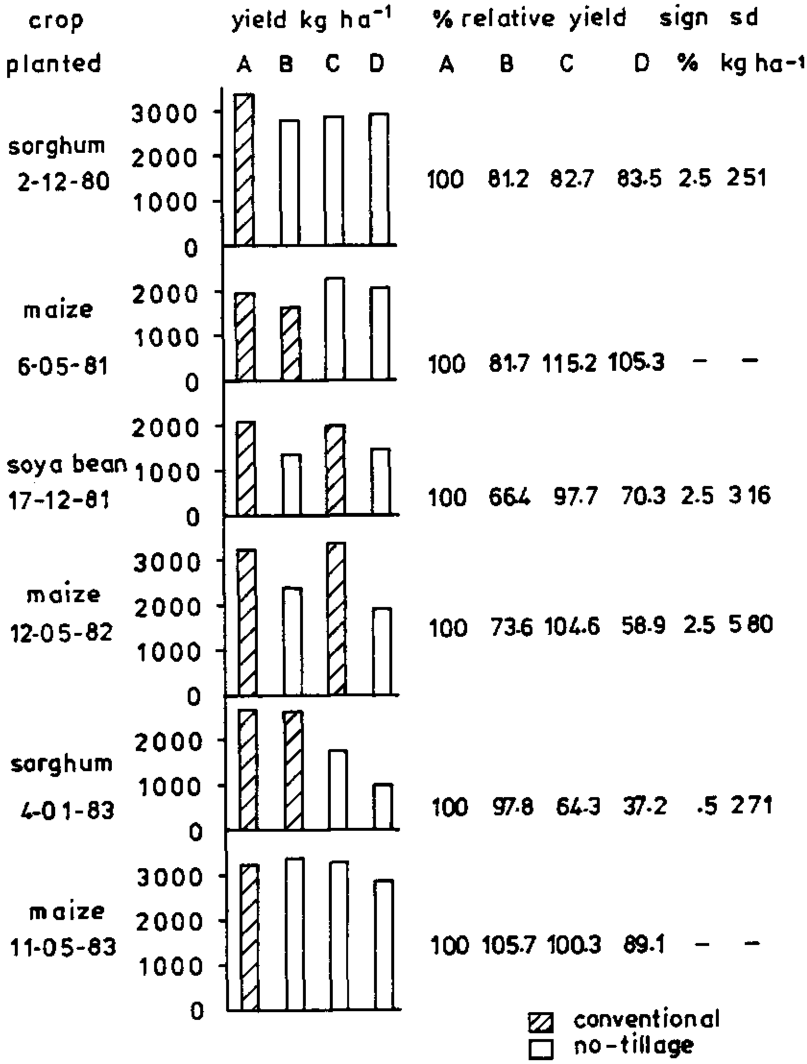


Figure 8. Yields for continuous no-tillage, continuous conventional tillage and alternated conventional and no tillage treatments.

visual differences diminished. The average yield obtained on the permanent no tillage plots of series D was 11 percent lower than on the permanent ploughed fields of series A. The average yields from the no tillage fields of the series B and C were 14 percent above that from the permanently no tilled fields of the series D.

2.5.5. Soil properties

Infiltration rate

Infiltration rates were measured with the double ring method during the second half of the 6th cropping cycle and are reported in table 13. Two measurements were made on each plot and because of the non normal distribution of the infiltration data the natural logarithm of same was used for averaging and variance calculations. The infiltration rates were lowest on the fields of series A where ploughing was applied in all six cycles and this is in line with the water stagnation on these plots during wet periods in the growing season.

Pore volume

The samples for the determination of pore volume were taken from the areas within the inner ring used for infiltration measurements two days before. Results are reported in table 13. The fields of series A where ploughing was applied in all 6 crop cycles showed lowest pore volume, series B the highest.

Table 13. Physical soil properties as measured in the second half of the 6th cropping cycle.

experimental series		A	B	C	D	
		tillage treatment				
		PL	NT	NT	NT	
		PL	PL	NT	NT	
		PL	NT	PL	NT	
		PL	NT	PL	NT	
		PL	PL	NT	NT	
		PL	NT	NT	NT	
						s.d.
pore volume %	0.05-0.10 m	39.6	43.4	39.4	40.8	2.8
	0.15-0.20 m	39.6	43.6	41.1	43.4	1.6
	0.25-0.30 m	40.3	43.8	41.3	43.0	2.8
	average	39.8	43.6	40.6	42.4	
ln infiltration rate		-3.72	-2.31	-2.80	-2.32	0.9
infiltration rate cm min^{-1}		0.024	0.100	0.065	0.098	
water at pF 2		28.1	27.6	23.4	23.0	
air at pF 2		11.8	16.0	15.2	19.3	
intrinsic air permeability (Ki)						
log Ki		2.81	3.62	2.82	3.00	
log Ki/free air at pF 2		0.24	0.23	0.19	0.15	

soil tillage

Tillage operations on a tilled soil under rather wet conditions resulted in relatively more compacting of the soil than on the untilled fields.

Air permeability

Air permeability was measured on soil samples taken for determination of pore volume and results are reported in table 13. The intrinsic air permeability Ki was calculated from the time necessary to pass a standardized volume of air under standardized pressure through the soil samples at pF 2, for which an air permeameter according to Kmoch (Kmoch, 1961) was used.
The average volume of free air at pF 2 was lowest, 11.8 percent, for series A, permanent deep tillage, the highest value with 19.4 percent was measured for permanent no tillage series D. Air permeability per volume of free air is highest for series A and lowest for permanent no tillage indicating that under tillage the larger pores that do not contain water at pF 2 are better interconnected.

Table 14. Chemical properties as measured on soil samples taken in the second half of the 6th cropping cycle.

experimental series	depth m	A	B	C	D
org C g kg^{-1}	0.05-0.10	11.6	11.2	10.8	11.8
	0.15-0.20	10.7	11.8	9.3	11.5
	0.25-0.30	8.6	10.0	6.5	9.4
pH-KCl	0.05-0.10	4.5	4.4	4.3	4.1
	0.15-0.20	4.6	4.3	4.5	4.3
	0.25-0.30	4.5	4.3	4.2	4.2
exch. Ca 1/2 mmol kg^{-1}	0.05-0.10	17	11	10	9
	0.15-0.20	16	13	15	10
	0.25-0.30	13	8	10	7
CEC pH 7 $mmol^{+}kg^{-1}$	0.05-0.10	40	40	38	44
	0.15-0.20	39	41	36	40
	0.25-0.30	37	39	32	38
100 x exch.Al/ECEC	0.05-0.10	19.3	37.1	34.3	41.1
	0.15-0.20	19.3	31.9	22.7	37.1
	0.25-0.30	26.9	41.0	33.6	52.9
P-Bray I mg kg^{-1}	0.05-0.10	27.3	45.7	43.7	43.4
	0.15-0.20	31.3	32.7	29.4	19.1
	0.25-0.30	14.2	22.3	7.1	6.3

Chemical properties

Chemical properties were measured on samples as for the measurement of physical properties and are reported in table 14. Variability between replications was high. The data for series D where no tillage was applied for all six crop cycles reflect the absence of mixing applied fertilizer with the deeper soil layers.

2.5.6. Discussion

A series of six cropping cycles during three years is a narrow base for conclusions and observations here after should be seen within this limitation.
Crop yields obtained in cycles 4, 5 and 6 indicate that the relative yield for incidental no tillage crop cycles are higher than those obtained when no tillage is applied for a longer period. Under unfavourable conditions for field operations as occurred in the cropping cycles 2 and 6, yields for incidental no tillage can be as good as for deep tillage. For the short rainy season when planting takes place during a rather dry period deep tillage results in better yields.

2.6 CONCLUSIONS

The physical and chemical characteristics of the soils under investigation on the Coebiti and Kabo farms, that are representative for about 155.000 ha of the Zanderij formation are not ideal for permanent mechanized annual rainfed crop cultivation.

- The water holding capacity of 10 - 12 percent is low and deep rooting is required to overcome periods of drought of a week which are not unusual in the rainy seasons.
- Apart from fertilization with N, P and K large amounts of lime are required on these acid soils. To incorporate this lime to the appropriate depth to allow for deep rooting periodic deep tillage as disc ploughing is required.
- The soils have a poor structural stability and under a system of mechanized farming compaction occurs leading to an unfavourable environment for root growth of many crops. Compaction can be alleviated by tillage operations and chisel ploughing appears to be adequate for this purpose on these soils.

Continuous application of no tillage or shallow tillage with a rotavator or a disc harrow not beyond 0.15 m depth results on average in lower yields than when disc or chisel ploughing is practised down to depths of 0.25 m. Maize, sorghum and cowpea yielded on average 25 and 15 percent less when repectively no tillage and shallow tillage were applied. For soya bean these yields were about 15 and 10 percent less and for groundnut 10 and 0 percent. Variation from these averages are rather wide.

With incidental no tillage in between deep tillage crop cycles the relative yield reduction can be considerably smaller, specially for plantings in the long rainy season when marginal conditions for mechanized field operations can occur.

Considering foregoing it is concluded that in a mechanized farming system on these soils the approach to the tillage operation should be flexible. Continuous disc ploughing would be superfluous and continuous no tillage would result in low productivity.

Disc and chisel ploughing as well as direct planting with or without shallow tillage can be applied appropriate to crop and prevailing circumstance of field, weather and work progress. However in the long term the tillage required to contain or alleviate the three basic shortcomings of these soils should be provided for.

CHAPTER 3

WORKABILITY FOR MECHANIZED FARM OPERATIONS

3.1 INTRODUCTION

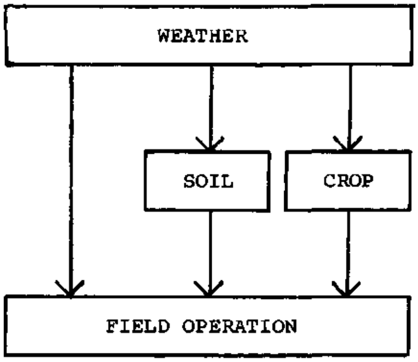
Not all available working hours within a certain time period are suitable for field operations in mechanized farming. Soil, product and climatic conditions can be such that

- work cannot be carried out at all,
- results will not meet quality standards,
- negative side and after effects occur.

Workability is defined as the possibility to apply a working method in respect of the condition of the material, the soil and the atmosphere.
Mechanical clearing of tropical rain forest under wet conditions damages the soil and farming results will be negatively effected for years to come. Harvesting groundnuts during wet or very dry conditions will result in non recoverable losses. Sometimes compensating measures can be applied. Decreasing combine speed when harvesting material with high moisture content can restrict otherwise increased combine losses. Harvesting with high moisture content is possible if sufficient product drying capacity is available.
Poor work quality leads to less revenue or higher cost in comparison with good quality work. Longer term effects however will not always be easy to quantify. An eventual alternative method will often include uncertain elements and evaluation in terms of additional costs or revenue will be accordingly.

Whether a certain time period is workable or not is mostly subjectively determined from experience by the farmer. The criteria used by the farmer must be translated into, or substituted by, objective, measurable criteria to be able to quantify workable time for planning and executing farm operations. These criteria are measurements of the conditions and can be divided into conditions of the weather, the soil and the material to be handled. A schematic view as given by Portiek (1978) is presented below.

workability of mechanized farm operations



This figure shows how workable time is directly and/or indirectly determined by the weather, it is the variability of the weather that causes variability of the available workable time.
Available workable time must be known for agricultural planning and can be estimated by two different methods.
One is based on direct observations. The results from direct observations obtain value if they are made over a long period. The results can however only be applied in the area of observations and for the working methods used by the farmers. Examples are the observations made by Hokke in the Netherlands (Hokke and Tanis, 1978) and by the Iowa crop and livestock reporting service (Williams, 1978).
The second method is indirect. It uses observations on workable time over a short period and a model that formulates the relation between workable time and the weather variables. This type of model is a descriptive model, because the relation between weather and workability is a direct one and is not based on the physical process relationships causing workable or non-workable conditions. The applicability of this type of descriptive model is restricted to areas with the same climatic conditions, soil type, crop and working method.
The observations over a rather short period can also be used to give the criteria used by farmers a physical meaning in terms of the conditions of weather, soil and material. The relation between the physical parameter and the weather variables can be formulated in a model. Such a model can be descriptive and has for that reason the same restrictions as given before, as far as soil type and climatic conditions are concerned. Because the dependent variable of the model is a physical parameter describing condition of weather, soil and material, classes with their specific criteria can be calculated.
An explanatory model which is based on a description of all physical processes should have a wide range of conditions for which it is valid. However often one or more of the many physical processes is not, or just partly understood. The formulation of such a process is then more or less of a descriptive nature, and applicability of the model is limited accordingly.
Suitable information on workability in the Zanderij area was not available

and direct observations would take too long. It was therefore decided to approach workable time with indirect methods as described hereinafter.

In most research on workability and/or planning of machine systems for northern latitudes, workability is treated as a "go" versus "no-go" decision for whole day periods (Link, 1962; Rosenberg, 1982; Tulu, 1974; Rutledge and McHardy, 1968). Rain and evaporation are the most important weather variables in regard to workability. If fluctuations in these variables during a time period of one day are not too extreme this approach can be justified. At lower latitudes fluctuation in both rain and evaporation within a day time period are more extreme. The effect of a shower early in the morning, followed by a period with high evaporative demand differs much from the same amount of rain in the late afternoon. To account for such effects, shorter time periods than a full day must be considered and it was therefore decided to make calculations on workable time for periods of one hour. With this more detailed approach also loss of information on simultaneousness of workability for various field operations that will occur when whole day periods are accounted for, can be avoided.

3.2 WORKABILITY OF SOIL TILLAGE OPERATIONS AND PLANTING

3.2.1. Criteria for soil tillage operations

To perform a tillage operation with a certain set of equipment the soil conditions should meet criteria regarding:

- Trafficability. Movement of machinery and transport equipment must be possible without causing unacceptable damage to the soil.
- Tractability. Soil conditions should be such that a tractor or other power source can move on the soil and deliver sufficient drawbar power to move the tillage implement without unacceptable damage to the soil.
- Tillage resistance. Conditions of the soil must be such that for the given set of equipment the available power is sufficient to perform the tillage operation at the desired depth.
- Workability of the soil. The condition of the soil must be such that the action of the tillage implement results in the desired structure of the soil and shape of its surface.

These conditions depend on soil type, moisture content and actual status.

Rutledge and McHardy (1968) estimated the required shear strength for plastic soils to provide traction for farm machinery. For conditions in Alberta, Canada, this shear strength was developed at moisture contents near field capacity. Selirio and Brown (1972) concluded from two year experiments in Ontario, Canada, on well drained loamy soils that spring cultivation was possible when moisture content of the 0.12 m top soil layer was at or below

90 percent of moisture content at field capacity. The authors do not distinguish between primary and secondary tillage. Perdok et al. (1982) paid attention to the workability of the soil for spring time secondary tillage operations in the Netherlands. Soil samples of the top 0.08 m soil layer were collected at the time farmers started with seed bed preparation. They found that the moisture content of such samples was close to the moisture content at which a prepared sample of the same soil compressed to 4 bar reaches an intrinsic air permeability of 1 u m^2. This criterion was applicable for a wider range of soils than the moisture content at pF 2.7 found in earlier investigations. The test procedure is however limited to silt and clay soils, because sandy soils will not produce the required granules in the compression test.

Investigations on workability for tillage operations are mostly limited to the northern latitudes and concern too wet conditions. A too high plough resistance under dry soil conditions is often a limiting factor for agriculture in arid regions in the tropics. Quantification of this aspect in terms of workable time is apparently as yet not available.

Soil moisture content is generally considered an adequate measure to define limiting conditions of soil suitability for tillage operations and machine trafic. For the investigations described hereinafter limiting conditions are also described in terms of soil moisture.

3.2.2. Field experiment december 1978 - february 1979

Field experiments were carried out with the objective of establishing a relationship between workability and soil moisture content for:

- Primary tillage, disc ploughing.
- Secondary tillage, rotary harrowing.
- Planting.

Post harvest tillage was not included as in the situation under reference this operation was replaced by mowing of the stubble and weeds.

The experiments were carried out at Coebiti on a soil described as a loamy sand on a sandy loam on a sandy clay loam (Zale-A), with a clay content in the range of 10 to 15 percent. Work organisation allowing, the operations ploughing, harrowing and planting were performed two times a day and in some instances three times a day. Operations were carried out on adjacent strips of land 50 m long and 3 m wide. The power source for ploughing and harrowing was a standard agricultural tractor with rear wheel drive and a rated power of 55 kW. Operations were carried out with a gear setting and engine speed that would result, without slip, in a speed of 2.7 km. hr^{-1}. This low speed was chosen to be able to keep working depth of the plough and rotary harrow over the short length of the field as constant as possible throughout the experiments. When ploughing the tractor was driven with two wheels in the furrow. A disc plough with three discs of 0.66 m diameter was used and intended ploughing depth was 0.30 m. During ploughing the percentage slip was estimated by counting the number of revolutions of the rear wheel of the tractor over a distance of 25 m.

Fields were harrowed two days after ploughing with a 3.0 m power driven rotary harrow.
Planting was done with a four row pneumatic precision planter, without fertilizer attachment, mounted on a standard agricultural tractor with rear wheel drive and a rated power of 35 kW, in total a rather light combination. Planting was done two days after harrowing.
Two times a day, preferably around 08.00 and 14.00 hr soil samples for the determination of water content were taken at depths of 0.0-.20, 0.20-.40 and 0.40-.60 m. In the fields to be ploughed 5 samples were taken, in the tilled ones three. The samples were weighed immediately after collecting and were weighed back after drying 48 hours at 105 ^{o}C. Water contents were expressed in percent weight wet base. Operations were discontinued during rain.

Ploughing.

In the case of ploughing most attention was given to the tractability performance of the soil. Percentage slip was used as a measure. When this measure is plotted against moisture content of the top 0.20 m soil layer, a broad range is obtained (figure 9). Percentage slip also depended on the time of the day. In most cases slip was higher in the morning hours than later in the day. Moisture content of the top 0.20 m soil layer also decreases during the day, but the decrease in the percentage of slip was relatively higher, probably because of dew on the stubble vegetation. Based on observed work

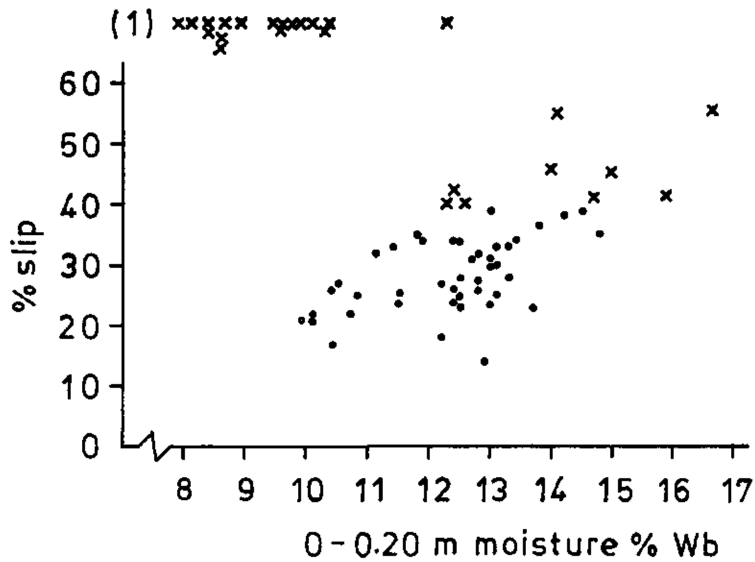


Figure 9. Ploughing, percentage slip as function of moisture in the 0.0-0.20 m soil layer. (1) Intended ploughing depth could not be maintained.

quality a percentage slip of 40 was used as cut off for tractability. This is relatively high but must be seen in respect to the rather large ploughing depth.
The measurements showed that the soil becomes too wet for ploughing as intended in this experiment when the water content of the 0.0-.20 m soil layer reaches levels around 14 percent. The transition from workable to non workable conditions because of dryness occurs between 9.9 and 10.4 percent.

Harrowing

As a criterion for the workability of harrowing attention was given to the tilth of the soil. When the soil loaded on the depth roll of the rotary harrow, conditions were qualified as being non workable. In the range of 12.4 - 13.3 percent moisture in the top 0.20 m soil layer both workable and non workable conditions were observed, for moisture contents above 13.3 percent conditions were unworkable (figure 10).
Too dry conditions for seed bed preparation were not observed.

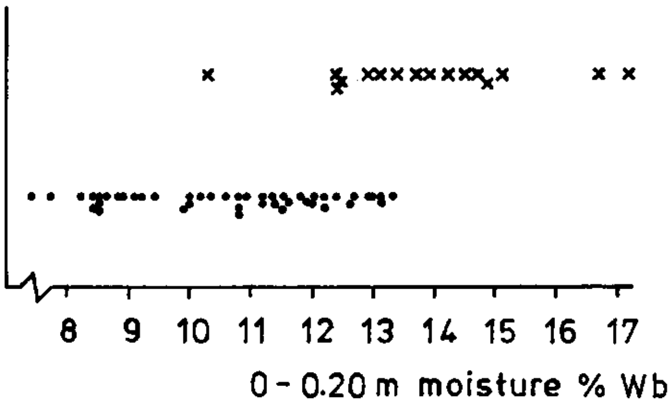


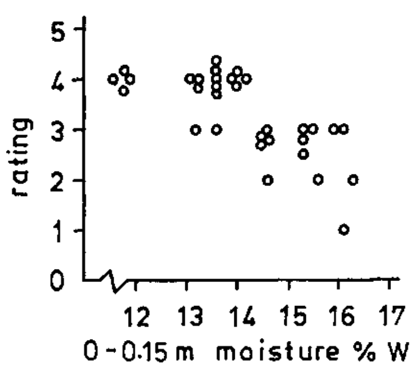
Figure 10. Harrowing, occurrence of workable (•) and non workable (x) conditions as function of moisture in the 0.0-0.20 m soil layer.

Planting

A relatively light tractor and planter were used in the experiment and unworkable conditions because of a too wet soil did not occur in respect of tractability, except during and immediately after rain. Conditions on the Zandery soils under research will never be too dry for planting on tilled soils as long as the activity is seen as a field operation. However, dry conditions will hinder seed emergence. From information on germination of the sorghum, planted during this field experiment, no criteria could be formulated on conditions of the soil and the weather at planting and during a period up to 9 days after planting, with regard to germination.

3.2.3 field experiment april-june 1980

This second experiment was carried out at Coebiti with the purpose of measuring effects on crop growth of conditions under which preceding mechanized field operations were carried out. For this purpose plots measuring 3 x 50 m were ploughed, harrowed and planted with maize. It was intended to harrow one to seven days after ploughing and to plant two, five, eight and eleven days after ploughing. It was intended to obtain a variety of conditions during the successive field operations but the planned schedule could not be maintained because heavy rains interfered, neither could the investigation into a possible relation between crop performance and the conditions during, and quality of field work be completed satisfactorily.
During the field operations observations were made on workability, and soil moisture content was measured in duplicate in the 0.0-0.15 m and 0.15-0.30 m soil layers of each plot before an operation was begun. The soil of the field is described as Zale-A and Zale-C, with a clay content ranging from 10 to 20 percent, less homogeneous than the field used in the experiment of december 1978 - february 1979.
Ploughing was done with a disc plough with three discs of 0.66 m diameter and the intended ploughing depth was 0.30 m. Harrowing was done with a power driven rotary harrow with working width of 3.0 m. The power source for both operations was a standard agricultural tractor with rear wheel drive and a rated power of 55 kW and operations were carried out at a speed of around 2.7 km hr^{-1}.
The field was covered with a heavy weed vegetation and was therefore disc harrowed on april 12, and experiments were started on april 22. A grassy weed vegetation covered the field gradually and this was cut down periodically.



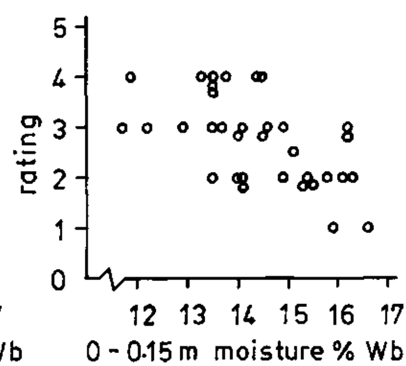


Figure 11. Ploughing. Figure 12. Harrowing
Work quality rating as function of moisture in the 0.0-0.15 m soil layer.

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Workability of the operations was qualitatively judged on a scale of 1 to 5. For ploughing tractability, inverting efficiency and maintenance of intended depth were considered, and for harrowing loading of the depth roll, seedbed quality, slip and wheel tracks. Good quality work rated 5, satisfactory quality 4, poor quality 3, bad and impossible rated 2 and 1. Workable conditions rated four or higher. In figures 11 and 12 the observations on workability and measured moisture content in the 0.0-0.15 m soil layer are presented. The transition zone between workable and non workable conditions for ploughing was in this experiment observed between moisture contents of 13.2 - 14.2 percent. The transition between workable and non workable conditions for harrowing occurred over wide range of moisture contents.

3.2.4 Conclusions

The soil moisture contents where the transition between workable and non workable conditions occurs were as follows for the two experiments.

experiment	I	II
season	short rainy season	long rainy season
depth of soil layer m	0.0-0.20	0.0-0.15
	---------- soil moisture % wt wb ---------	
disc ploughing too wet	14.0	13.2 - 14.2
too dry	9.9 - 10.4	
rotary harrowing too wet	12.4 - 13.3	11.7 - 14.5

In the two experiments the reference soil layers are not of equal thickness. For the second experiment the equivalent moisture content of the 0.0 -.20 m soil layer can be approximated by 0.83(m.c. 0.0-.15) + 0.17(m.c. 0.15-0.30). The average difference between the equivalent 0.0-0.20 m moisture content and the measured 0.0-0.15 m moisture content was -0.06 % wb for stubble fields and 0.10 % wb for ploughed fields with standard deviations of 0.21 and 0.25 respectively. A plot of these equivalent moisture contents against the quality ratings of the field operations indicated that the transition zone between workable and non workable conditions was numerically the same as shown in figures 11 and 12 and it is concluded that the data in the above table are comparable.

The transition from workable to unworkable conditions was not found at one definite soil moisture content but rather a transition zone is observed. This is not unexpected because of soil variability and also the quality ratings included subjective elements such as maintaining work quality.

Notwithstanding foregoing it is concluded that soil moisture content is a good criterion for workability of tillage and other related operations.

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Therefore the next step, finding a relation between weather and soil moisture content with the aid of a soil moisture model is justified.

3.3. SOIL MOISTURE MODEL

3.2.1 Description

The soil moisture model used to calculate changes in moisture content of various soil layers is based on physical process descriptions available in literature (Driessen, 1986). Water movement in the model described here is assumed to take place in a vertical direction only, and it is realised that therefore the conclusions based on the outcome of the model on workability may not be valid for sloping land with lateral moisture movement.

Input for the model are hourly precipitation and evaporation data. The methods used to calculate these from available meteorological data are presented in appendix A. To describe soil physical conditions the soil moisture- matric head relation and data on permeability are required and for an possible vegetation the leaf area index (LAI) and the specific evapotranspiration factor.

The model allows the division of the soil between the top and ground water level in 2 to 10 soil layers, provided the sum of all layers equals initial groundwater depth. When a living vegetation is present the number of soil layers in which roots are present must be given.

Infiltration.

Measurements of infiltration rates in the Zanderij area indicate that restrictions on infiltration rate are not necessary (chapter 2.5.5.). In the few cases that surface run-off was observed this was very local and precipitation drained rarely beyond the field borders. In the model it is assumed that soil layers will be filled up to 100 percent of pore volume by infiltration sequentially from the top downwards. Precipitation is divided over the whole hour in cases that the calculating period is reduced to periods shorter than one hour.

Evaporation.

Hourly free water evaporation E_o is calculated with the Penman formula (appendix A). Potential evaporation E_p under a vegetation is calculated from Eo and LAI following the formula presented by Ritchey (1972),

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$$E_p = E_o \times e^{(-0.4 \times LAI)} \quad mm\ hr^{-1} \qquad (3.1)$$

LAI = leaf area index $m^2\ m^{-2}$.

Actual evaporation from the top soil layer equals potential evaporation when moisture is equal or more than moisture content at pF 2. Evaporation ceases when wilting point (pF 4.2) is reached. In the case of evaporation from a bare soil after ploughing the moisture content at which evaporation ceases is set at half the value of volumetric moisture content at pF 4.2. Evaporation from the soil at moisture contents between mentioned limits is made proportional.

Transpiration.

Potential transpiration T_p of the vegetative cover is calculated from potential evapotranspiration from the vegetation at full canopy ET_p(f.c.) following Driessen (1986):

$$T_p = (ET_p(f.c.) - 0.1 \times E_o) \times (1.0-e^{(-0.7 \times LAI)})\ mm\ hr^{-1} \qquad (3.2)$$

The potential evapotranspiration of the vegetative cover at full canopy is obtained by multiplying E_o with a dimensionless crop factor.
Transpiration is assumed to extract moisture from all rooted layers and for each rooted soil layer a transpiration factor is calculated. Transpiration is not limited when moisture content of the soil layer is more than 60 percent of available moisture between pF2.0 and pF4.2, and in that case the transpiration factor is set at 1.0. Transpiration is assumed to cease when moisture content is below wilting point, pF4.2, and the transpiration factor for that soil layer is set at 0.0. For moisture contents between the mentioned values, the transpiration factor for the specific layer is proportional to the actual moisture content. A weighted average transpiration factor is calculated from those of the individual soil layers. Transpiration of the vegetation is calculated by multiplying potential transpiration with the average transpiration factor and is substracted from each rooted soil layer, proportional to the transpiration factor and thickness of the layer.

Drainage and capillary rise.

The groundwater level in the Zanderij area is at depths of 5 m and more, and because of the course texture of the soil it is assumed that there is no capillary rise from groundwater. Subsurface drainage from the forelast soil layer into the last soil layer is calculated as follows. Below the forelast soil layer an imaginary soil layer is assumed, with the same thickness as the forelast one. This layer has a constant matric head in correspondence with a pF value of 2.3. In cases that the forelast soil layer has a pF value equal or more than pF 2.3 there is no moisture transport through the lower boundary. In case of higher moisture content drainage is calculated following the described procedures for water movement between adjacent layers.

Velocity of moisture flow

The velocity of moisture flow between soil layers is calculated for each time period using the Darcy equation,

$$V = K_u(a) \times ((PSI_i - PSI_{i+1}) / D) + 1 \quad cm\ d^{-1} \qquad (3.3)$$

D = distance between the center of the two soil layers cm
$K_u(a)$ = average unsaturated conductivity cm d^{-1}
PSI_i = matric head soil layer i cm.

The average unsaturated hydraulic conductivity between two soil layers is calculated from the unsaturated hydraulic conductivity for each soil layer, by means of averaging, weighed for thickness of the soil layer.
K_u for each soil layer is calculated following Rijtema (1965),

$$K_u = K_o \times e^{(-alpha \times PSI)}\ cm\ d^{-1} \qquad (3.4)$$

or

$$K_u = beta \times (-1 \times PSI^{-1.4})\ cm\ d^{-1} \qquad (3.5)$$

K_o = saturated hydraulic conductivity cm d^{-1}
alpha = texture specific empirical constant cm^{-1}
beta = texture specific empirical constant $cm^{2.4}\ d^{-1}$.

The maximum value from both formulas is chosen as the unsaturated hydraulic conductivity.

Time step.

All calculations are made with a time step of maximum one hour. The time step of one hour will in some situations result in an unstable system. Therefore the restriction is made that moisture flow between two soil layers will not exceed 1/3 of the difference in moisture content. This restriction is limited to 0.01 hour, to limit computing time.

3.3.2. Calibration and evaluation.

Calculations are made for six soil layers with depth ranges of 0-0.1, 0.1-0.2, 0.2-0.4, 0.4-0.6, 0.6-1.0 and 1.0-5.0 m.
The pF curves used in the model to describe soil moisture - matric head relation of the Zanderij soil are presented in figure 13. In the case of a ploughed soil it is assumed that the volume of a 0.30 m soil layer is

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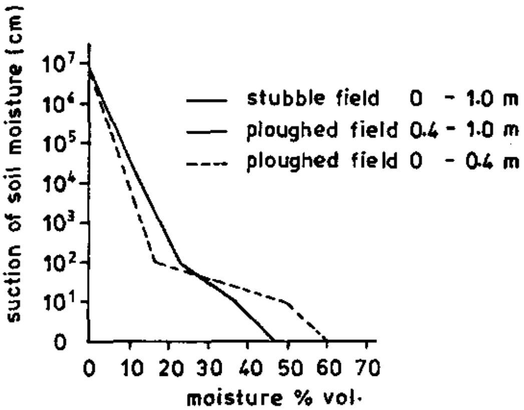

Figure 13. Soil moisture characteristic.

increased to 0.40 m and the pF values for the soil layers in the top 0.40 m are adapted accordingly.

On the fields to be ploughed a green weed vegetation, mainly grasses, was present with a root system active to 0.4 m depth and an LAI of 1. The crop specific evapotranspiration factor for this vegetation was set at 0.8, corresponding with the value found for Toko grass by Koopmans (1973).

Unsaturated hydraulic conductivity is unknown for the Zanderij soils under study, and the values of K_o, alpha and beta as used in the equations 3.4 and 3.5. were found by parameter fitting. The values for the top three soil layers and the lower three soil layers were kept as a unity. The moisture contents measured during january and february 1979 for the experiment described in paragraph 3.2.2. and pertaining meteorological data from the Coebiti station were used. For rainfall hourly data were available and hourly values for other data were reconstructed from the three observations per day, as described in appendix A.

Table 19. Values for K_o, alpha and beta, obtained by parameter fitting.

soil layer	depth m	stubble field K_o	stubble field alpha	stubble field beta	ploughed field K_o	ploughed field alpha	ploughed field beta
1	0.0-0.1						
2	0.1-0.2	8.2	0.020	7.2	12.5	0.029	56.6
3	0.2-0.4						
4	0.4-0.6						
5	0.6-1.0	7.9	0.033	13.9	7.9	0.033	13.9
6	1.0-5.0						

Table 20. Coefficients a and b in y = a + bx, correlation coefficient r and root mean square difference (rms) between y, the calculated soil moisture content wb and x, the measured value.

	soil layer m	n	range % wb	a	b	r	rms % wb
stubble	0.0 -.20	59	7.9-16.7	0.43	0.95	0.94	0.80
	0.20-.40	59	10.8-15.6	1.00	0.92	0.89	0.81
	0.40-.60	59	11.5-16.1	4.97	0.63	0.84	0.71
ploughed	0.00-.20	58	6.5-17.3	2.25	0.83	0.93	1.20
	0.20-.40	58	8.0-16.9	2.60	0.80	0.88	1.27
	0.40-.60	58	9.4-15.2	6.94	0.50	0.78	1.47

Results obtained in model development with measurements of the january - february 1979 experiments are presented in table 20.

The moisture contents measured during the april - june 1980 experiment were compared with values calculated with the model and meteorological data for Coebiti obtained as described above. The results are presented in figures 14 and 15. The rms difference between the measured and the calculated values is 0.66 percent wb for ploughing and 0.88 percent wb for harrowing.
As the difference in thickness of the layers in this evaluation is of minor importance (paragraph 3.2.4.) the representations obtained are considered adequate for simulating soil moisture contents of the top soil layer to serve for calculating workable time for tillage operations.

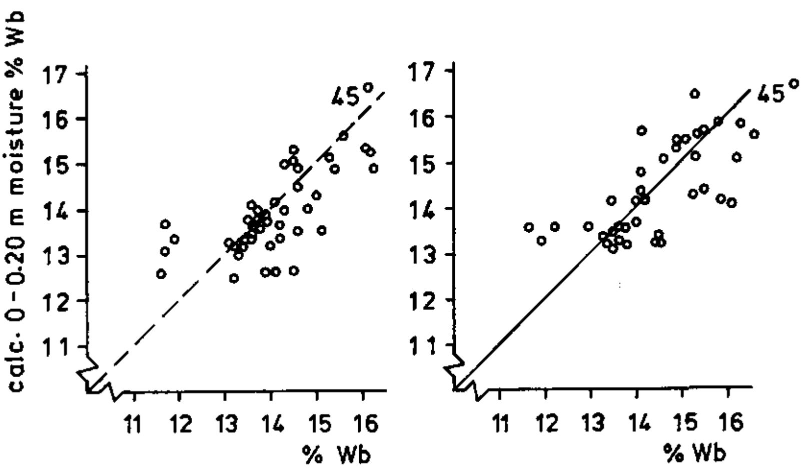

Figure 14. Figure 15.
Calculated moisture in the 0.0-0.20 m soil layer versus measured moisture in the 0.0-0.15 m soil layer.

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3.4 WORKABLE TIME FOR TILLAGE OPERATIONS

3.4.1 Basic data and criteria

The instrument for calculating workable time is the soil moisture model discussed in chapter 3.3. The soil moisture content was calculated with this model for each hour of the 25 year period between 1.1.1958 and 31.12.1982. The required meteorological information was obtained from Zanderij station as discussed in appendix A.
To obtain information on workable hours from the soil moisture contents additional input to the model was set as discussed hereinafter.

Available time

Sundays and the holidays on 1-1, 25-2, 1-5, 1-7, 25-11, 25-12 and 26-12 are excluded from available time. Normal working hours for monday till friday are the 8 hrs per day between 07.00 and 15.00 hr total 40 hrs wk^{-1}. Overtime hours are the hrs between 15.00 and 18.00 hr on a normal working day and the 8 hrs between 07.00 and 15.00 hr on saturday total 23 hrs wk^{-1}.

Direct influence of the weather.

It is assumed that field operations are interrupted during rain, because fieldworkers will take shelter, materials to be handled like fertilizer deteriorate and soil and product conditions can also become unworkable. An otherwise workable soil may become unworkable during rain because wet top-soil clogs implements and may cause undesirable compaction.
Hours with 0.5 mm or more rain are considered unworkable. Information on rainfall intensity covering a long period was not available. Observations made in a three month period showed that amounts of up to 0.5 mm fall on average at a rate of about 1 mm hr^{-1}. Rainfall is less than 0.5 mm hr^{-1} for 36 percent of all hours with rainfall during day time. The loss of workable time because of rain depends on the season. The average loss per week over the 25 year period ranges between 3.5 and 20.6 percent of available time including overtime.

Soil moisture limits for workability.

The soil moisture contents, percent wb, limiting field operations were based on the experimental results obtained (paragraph 3.2.2.-3.2.4.)and set as follows.
Ploughing is not possible when the moisture content of the 0.0-0.20 m soil layer of a stubble field is less than 10.3 percent or higher than 13.9 percent. Harrowing is not possible when the moisture content of the 0.0-0.20

m soil layer of a ploughed field is higher than 13.2 percent.
At the wet end of the range an hour is considered not to be workable if the moisture content at the beginning or at the end of the hour is beyond the limits.

3.4.2 Workable time for ploughing and harrowing

The average number of workable hrs wk^{-1} for disc ploughing and harrowing and the dependable level for 20 out of 25 years, the 20th percentile (p-20), are presented in figures 16 and 17.

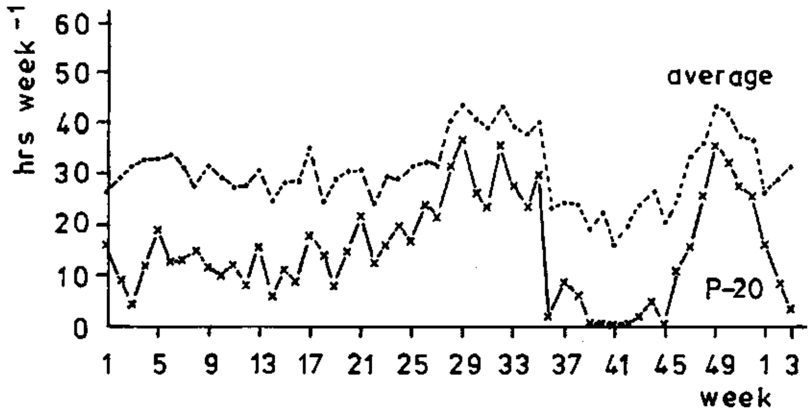

Figure 16. Average (•---•) and p-20 (x—x) workable hours per week for disc ploughing.

Figure 16. Average (•---•) and p-20 (x—x) workable hours per week for harrowing.

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Limitations in workable time for ploughing occur in the SDS because of too dry as well as too wet conditions, in the LDS too dry conditions are limiting.
As rainfall and thus workable hours are not normally distributed a more precise determination of dependable levels at a certain probability is rather involved. Such refinement is not considered to be required for this exercise. The sensitivity of workable time to the limiting criteria can be summarised as follows.

Table 21. Effect in the average workable hrs wk^{-1} because of a change of 0.1 % wb in the limiting values of the soil moisture content.

season	SRS	SDS	LRS	LDS
ploughing				
range 10.3-10.5 % wb	.6	.6	.3	.9
range 13.5-14.1 % wb	1.4	1.0	2.3	0.5
harrowing				
range 13.2-13.4 % wb	1.0	0.7	1.4	0.4
Effect in average workable hrs wk^{-1} because of changing the limiting value of rainfall from 0.5 mm hr^{-1} to 0.4 mm hr^{-1}.				
	0.4	0.5	0.5	0.2

3.4.3. Conclusions

The limiting values of the soil moisture content in respect to workability refer to operations with a standard 55 kW agricultural tractor and matching equipment. These values were obtained considering slip of the tractor, loading of the depth roll of the rotary harrow and work quality. Compaction of the soil at the various moisture contents was not considered specifically. The maximum soil moisture content for disc ploughing, 13.9 percent wb, corresponds with 97 percent of the moisture content at pF2. The maximum soil moisture content for harrowing, 13.2 percent, is close to the moisture content of 13.0 percent found for the roll out stage of the Atterberg scale for this soil.
An analysis of a four year record of field operations carried out at Coebiti and soil moisture contents calculated with the model using pertaining meteorological data gave following results. Out of 102 occurrences of ploughing 8 were carried out when calculated soil moisture was below 10.3 percent and 12 when this was higher than 13.9 percent. For harrowing there were 92 occurrences of which 16 at soil moisture contents above 13.2 percent wb. These data reflect also the need to complete operations for field

experiments in time and possibly working to less stringent standards than assumed in the reference. There is thus good reason for the established limits.

3.5 WORKABILITY OF HARVESTING

3.5.1. Criteria for combine harvesting

Because the project concerned mechanized farming, the workability of combine harvesting was investigated. Conditions governing the workability of the operation concern the weather, soil and the product.

- Weather conditions should not interfere with the operation.
- The soil should allow movement of the combine and product transport equipment.
- The material to be harvested should allow mowing or picking, threshing and separation within the relevant limits for loss and damage of the product and wear of the machine.
- The moisture content of the product should be within the limits for direct safe storage or the relevant post harvest drying capacity.

Trafficability is usually not considered specifically in harvesting studies, in most cases it is implicitly assumed that soil conditions are not limiting operations when crop conditions allow harvesting.

The moisture content of the material to be harvested is the main variable determining workable time for harvesting. The moisture content of the grain relates specifically to quality and damage of the product, the moisture content of the straw influences mainly product loss and wear of the machinery.

For agricultural planning purposes many authors have tried to calculate from weather data when a specific crop reaches the desired moisture status for harvesting.

The simpler simulation models consider changes of moisture content of grains in the field caused by rain and drying. Moisture change is modelled according ambient temperature drying, in which grain moisture content approaches the equilibrium moisture content under prevailing conditions following an exponential time function. Crampin and Dalton (1971) apply a constant drying rate parameter in simulations of moisture content of standing grain, Smith et al. (1981) use a temperature dependent parameter. In simulations of groundnut drying in the windrow Steele and Wright (1980) made the drying parameter a function of the groundnut moisture content. Rotz and Chen (1985) set the drying parameter as function of the sum of the solar radiation and vapour pressure deficit in a model for alfalfa drying.

Grain moisture change affected by rain is calculated from simple equations with amount and or duration of rain as independent variables.

Van Kampen (1969) related the course of moisture content of harvestable grain

to an exponential function of solar radiation. For workable time calculations pre determined periods directly after rain or in the morning after dew are treated as unworkable irrespective of other variables.
Van Elderen and van Hoven (1973) modelled the drying of the grain and straw in the field according the evapotranspiration process of living plants using functions developed by Rijtema. Rain and dew are collected around plant parts in the so called reservoir, the moisture content of this reservoir decreases by evaporation and by diffusion into the grain or other plant parts. The diffusion is influenced by moisture deficiency defined as maximum minus actual moisture content. The presence of a reservoir is included as a limitation for harvesting and represents the after effect of rain and dew.
Thomson (1981) studying the field drying of hay introduced additionally the concept of the equilibrium moisture content of the material and adjusted the Penman-Monteith combination equation for evapotranspiration accordingly.

3.5.2. Experimental

Field experiments were carried out to obtain information on the course of the moisture status of grains to be harvested. This information and pertaining meteorological data were to serve in the development of a simulation model relating grain moisture status and climatological circumstances.
At Coebiti maize, sorghum, groundnut, cowpea and soyabean were planted and hand harvested for grain moisture determinations as follows.

crop	planting date	harvest period dap*	grain moisture measurements
maize	18-11-82	104-117	28
	24-11-82	104-121	46
	21-12-82	118-129	27
sorghum	18-11-82	83- 98	36
	24-11-82	90-107	44
	21-12-82	93-108	23
soya bean	18-11-82	104-145	27
	24-11-82	112-127	29
cowpea	18-11-82	70- 78	31
	24-11-82	68- 92	36
	21-12-82	71- 86	38
groundnut	18-11-82	97-114	51
	24-11-82	105-121	46
	21-12-82	111-119	53

* days after planting.

Fields measured 20 X 6 m for the first planting series and 30 x 8 m for the later ones. Distance between rows was 0.5 m and in row distance 0.25 m for maize and 0.1 m for other crops. Conventional tillage was applied and fertilizer application was in accordance with recommendations (paragraph 2.2). At the sampling time, grain carrying parts were collected on a row length of 2 m at two randomly selected locations in a field. Grains were seperated by hand or with a small threshing machine in the case of maize and collected in air tight bottles. Moisture contents were determined in duplo on samples of both locations by drying 24 hrs at 105 ^{o}C. Each of the measurements listed in the table above refers to an average of such four determinations. Samplings were carried out between 7.30 and 18.00 hr. with a frequency of up to 6 times a day.
At the sampling time observations were made regarding the moisture status of the plant parts to be harvested as follows.

- Presence of free water from rain or dew.
- No free water visible but moist.
- Dry.

The course of moisture content of groundnut pods was measured on windrowed material. The moisture content of cowpea showed in the second planting relatively large variability reflecting uneven ripeness of the crop. It was therefore decided to sample from february 8 onwards only those pods which showed discolouration due to maturity. It is realised that these data do not reflect true average moisture of the grains but will be more worthwile in respect of discriminating between workable and non workable conditions.
On the data it is observed that the moisture contents of the grains of sorgum, cowpea and soyabean move daily with climatological circumstances (figure 18). The moisture contents of groundnut pods and maize are not so directly related to the daily climatological changes.

3.6 GRAIN MOISTURE MODEL

3.6.1 Description

To estimate workable hours for combine harvesting and required grain drying capacity a model was developed relating crop moisture status in the harvesting period with climatological data. Because time and amount of rain have relatively large influence on the moisture status of a crop and because of the frequent occurrence of dew a model calculating with a reservoir was considered to be most appropriate. Moisture change of grains was simulated to fit the moisture contents measured in the experiment.
The model calculates moisture contents of the grains and the reservoir and distinguishes periods with and without reservoir. Moisture content of the reservoir increases by rain and condensation and decreases by evaporation and by diffusion into the grains. The moisture content of the grains changes because of diffusion into the grains, exchange with the ambient air and because of radiation.

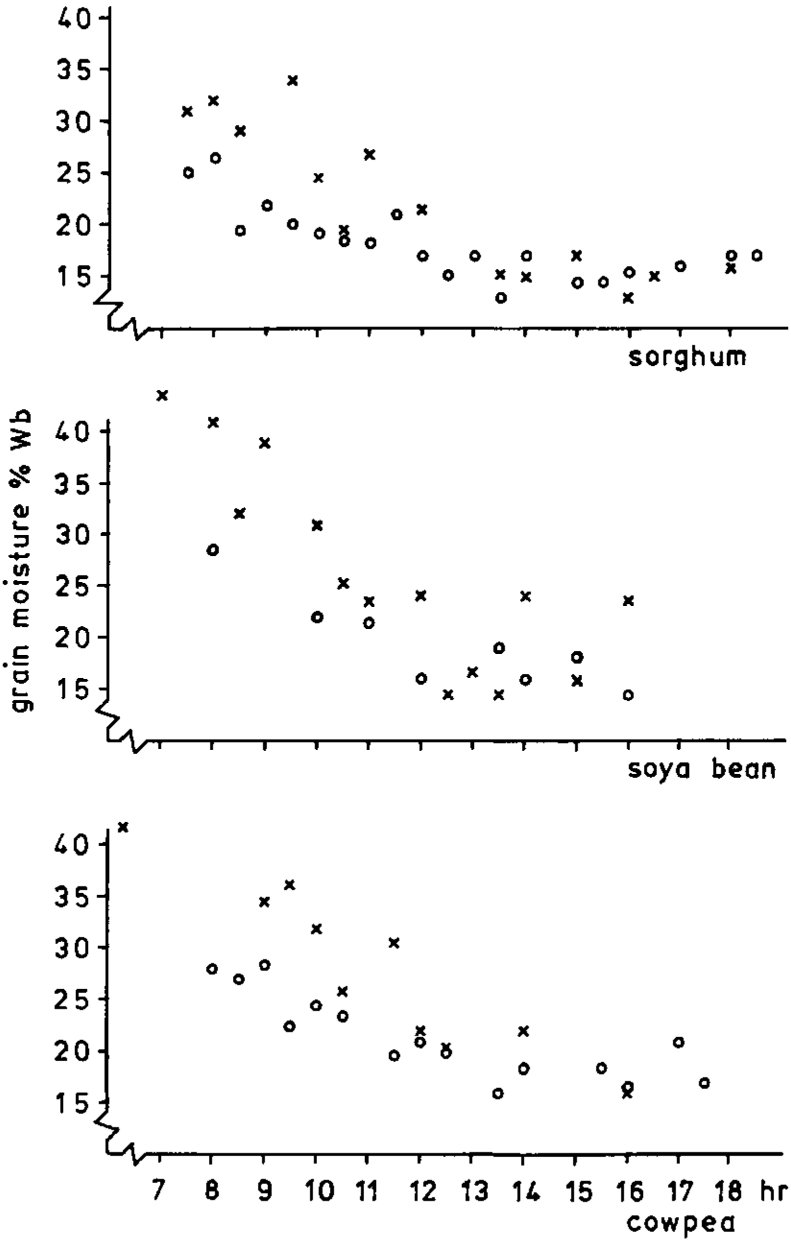


Figure 18. Course of grain moisture content during dry days, o previous day rain ≤ 3 mm, x previous day rain > 3 mm. Averages of observations at different days.

Moisture content of the reservoir.

It is assumed that rainfall of 1 mm or more is evenly distributed in the hour this rainfall is recorded. Rainfall less than 1 mm is assumed to fall with an intensity of 1 mm hr^{-1} starting at the beginning of the hour.
The fraction rainfall intercepted by the considered plant parts, R_i, is represented by a crop specific interception factor k_1.

$$R_i = k_1 \times \text{rainfall} \quad \text{mm hr}^{-1} \qquad 3.6$$

Intercepted rain is added to the reservoir and is limited by a crop specific maximum reservoir capacity. Surplus rain drips from the ears or pods.

Evaporation from and condensation into the reservoir are calculated for periods without rain as fraction of the free water evaporation calculated per hour with the Penman equation (appendix A).

$$E_{rp} = k_2 \times E_o \quad \text{mm hr}^{-1}$$
$$E_{rn} = k_3 \times E_o \quad \text{mm hr}^{-1} \qquad 3.7$$

E_o = free water evaporation mm hr^{-1}
E_{rp} = evaporation from the reservoir mm hr^{-1}
E_{rn} = condensation into the reservoir mm hr^{-1}
k_2 = crop specific fraction for evaporation
k_3 = crop specific fraction for condensation.

Moisture content of the grain.

Diffusion of moisture from the reservoir into the grain is influenced by moisture deficiency of the grain, the reservoir content, the fraction of the grain surface active in moisture exchange with the reservoir and the crop specific moisture flow.

$$M_{t+\Delta t} - M_t = (M_m - M_t) \times (1 - e^{-k_4 \times \Delta t}) \times (R/R_m \times R_s) \quad \text{kg kg}^{-1} \qquad 3.8$$

$$R/R_m \times R_s \leqslant 1$$

M_t = grain moisture content at time t kg kg^{-1}
M_m = crop specific maximum grain moisture content kg kg^{-1}
Δt = elapsed time hr
k_4 = crop specific parameter for moisture flow hr^{-1}
R = reservoir content mm
R_m = maximum capacity of the reservoir mm
R_s = crop specific fraction of the grain surface active in moisture exchange.

Exchange of moisture from the grain with ambient air through the surface not in active moisture exchange with the reservoir, depends on the difference between equilibrium moisture content and actual moisture content of the grain.

$$M_{t+\Delta t} - M_t = (M_e - M_t) \times (1-e^{-k_5 \times \Delta t}) \times (1- R/R_m \times R_s) \quad kg\ kg^{-1} \quad 3.9$$

M_e = equilibrium moisture content kg kg^{-1}
k_5 = crop specific parameter hr^{-1}.

The equilibrium moisture content is calculated with the Chung equation for which the crop specific parameters of the five crops used in the experiment are obtained from the ASAE Yearbook (ASAE, 1980).

$$M_e = E - F \times \ln(-(T+C) \times \ln(RH)) \quad kg\ kg^{-1} \quad 3.10$$

T = temperature ^oC
RH = relative humidity, decimal
C, E and F are crop specific parameters.

Allowing only ambient air drying as formulated above, the drying rate is underestimated in periods of high radiation incidence, specifically for cowpea, soya bean and sorghum. The use of a constant drying factor may well be a reason for this as well as the use of ambient air temperature and humidity as measured at the meteorological station, which do not reflect adequately conditions around the grain. To obtain a representation comparable with measured data, drying because of radiation during periods without a reservoir was allowed parallel to ambient air drying as follows.

$$E_g = k_2 \times E_o \times (M_t^2/k_6) \quad mm\ hr^{-1} \quad 3.11$$

k_6 = crop specific parameter.

For maize this equation was made time dependent to obtain a better representation of the grain moisture content during days further beyond the maturity date of maize

$$E_g = k_2 \times E_o \times (M_t^2/(1-0.1 \times dam \times k_7) \quad mm\ hr^{-1} \quad 3.12$$

dam = days after maturity of maize d
k_7 = crop specific parameter d^{-1}.

Input for the model comprises grain dry matter ha^{-1}, maximum grain moisture content, coefficients for calculating grain equilibrium moisture content and hourly meteorological data. The time step for the calculations is one hour except for periods with an evaporating reservoir, the time step then being 0.1 hour.
The model provides hourly data on grain moisture and reservoir status. Small amounts of rain evaporated within the hour the rain is recorded, are not presented in the output as a reservoir.

3.6.2. Calibration and evaluation.

With the grain moisture contents measured in the experiments described in paragraph 3.5.2 and pertaining hourly meteorological data the model was calibrated and the specific parameters were determined for each crop. The hourly meteorological data as measured at Coebiti were used, except hourly data for windspeed and cloudiness during the night which were obtained from Zanderij station.
The model was evaluated with measurements obtained in the harvest date experiments carried out in 1981 from july 29 till september 23 (chapter 4.6.).
Results obtained with model development and evaluation are presented in table 22 and 23.

Table 22. Coefficients a and b in equation y=a+bx, correlation coefficient r and root mean square difference (rms) between the measured (y) and the calculated (x) grain moisture content % wb.

	crop	n	range % wb	a	b	r	rms % wb
model development	maize	99	20.0-32.7	0.6	0.98	0.82	1.8
	sorghum	102	11.7-37.5	0.6	1.00	0.92	3.4
	soya bean	56	14.3-37.5	-2.0	1.07	0.83	4.4
	cowpea	96	13.8-37.5	0.8	0.97	0.86	3.3
	groundnut	146	14.0-52.0	-3.5	1.12	0.92	3.2
evaluation	maize	365	9.0-36.0	-6.2	1.30	0.92	3.1

Table 23. Prediction of the reservoir in model development.

crop	observed and simulated	observed not simulated	not observed simulated
maize	36	8	3
sorghum	20	4	2
soyabean	23	2	1
cowpea	23	5	6
groundnut	52	4	11

Young (1977) reports rms values between 2.1 and 6.5 % wb obtained in development of a model for drying groundnuts in windrows. Similarly Steele and Wright (1981) report 4.3 - 5.5 % db in model development and 4.4 % wb for

a validation. Smith et al. (1981) report values between 3.0 and 6.3 % db for validation of a model for field drying of wheat and barley.
Van Elderen and van Hoven (1973) report for an explanatory model applied to field drying of wheat values for $\underline{a}$ between -2 and 8, for $\underline{b}$ between 0.66 and 1.08 and for the correlation coeffient $\underline{r}$ 0.83 - 0.96.
From the above it would appear that the developed model and the models referred to are of comparable accuracy in the sense that the errors as measured by the indicators used are comparable.
It is thus concluded that the model, recognizing that it was made by fitting equations to field data, which limits applicability to crops and circumstances as used for the model development, may be used for the simulation of the course of moisture status of harvestable grains as required for estimating workable time for combine harvesting.

3.7. WORKABLE TIME FOR COMBINE HARVESTING

3.7.1. Basic data and criteria

Moisture contents of harvestable grains were calculated with the model for a period of 25 years from 1958 till 1982 using the meteorological records of Zanderij station. Weekly periods start for each year at january 1, week 52 has 8 or 9 days. Crops are assumed to be mature at the beginning of each weekly period. At that time the grain moisture content of cowpea, soya bean and sorghum is set at 26 percent wb. Groundnuts are assumed to be lifted at the beginning of the week with a pod moisture content of 45 percent wb. The moisture content of maize is taken at 31 percent wb at 98 days after planting.
Further criteria were:

- Available time. This was set as in paragraph 3.4.1.
- Weather. Hours with 0.5 mm hr^{-1} or more rain were considered unworkable.
- Trafficability. It was assumed that if the soil was too wet for ploughing, soil moisture above 13.9 percent wb, the soil would also be too wet for combine harvesting.
- Soil moisture. Groundnut combining was not possible when the soil moisture content of the 0.0-0.20 m soil layer of a ploughed field was above 13.2 percent wb.
- Reservoir. If a reservoir was present at the beginning or at the end of the hour, such hour was considered unworkable.
- Grain moisture. If grain moisture was above 24 percent wb for cowpea, groundnut, sorghum and soya bean and above 28 percent wb for maize, conditions were considered unworkable.

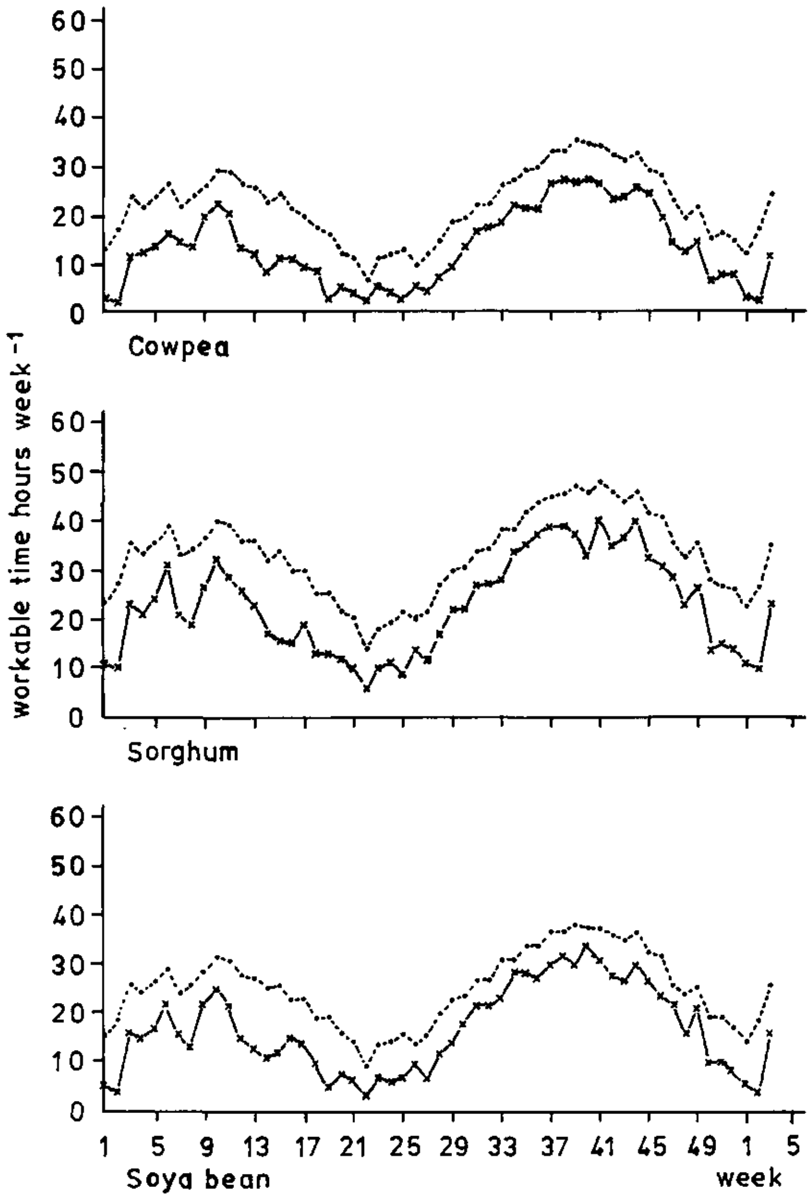


Figure 19 a,b,c. Average (•--•) and p-20 (x—x) workable hours per week for harvesting.

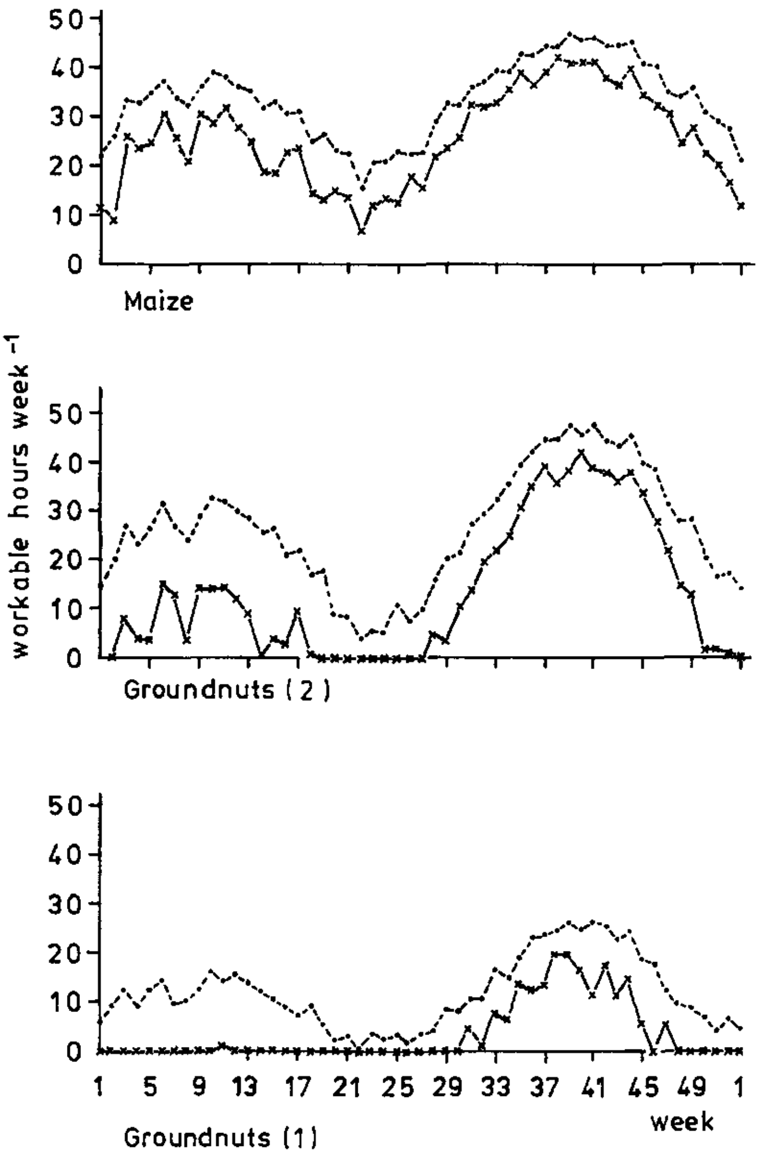


Figure 19 d,e,f. Average (•---•) and p-20 (x—x) workable hours per week for harvesting.
(2) Groundnuts second week in the windrow.
(1) Groundnuts first week in the windrow.

Table 24. Effect in average number of workable hrs wk^{-1} for harvesting, because of a change of one percent wb in the limiting value of grain moisture content.

crop	range % wb	SRS	SDS	LRS	LDS
maize	26-30				
first week after maturity		1.0	0.6	0.9	0
second week after maturity		0.1	0	0.1	0
sorghum	24-26	0.8	0.6	1.0	0.4
soya bean	24-26	1.6	1.3	1.6	1.4
cowpea	24-26	1.4	1.1	1.4	1.2
groundnut	24-26				
first week after maturity		1.9	2.0	2.1	2.0
second week after maturity		1.8	1.4	2.3	0.4

3.7.2 Workable time.

The average number of workable hours per week and the dependable level for 20 out of 25 years, p-20, are presented in figure 19. The sensitivity to the limiting values of the grain moisture content is presented in table 24.
Workable time for harvesting is low during the LRS. In this season workable time for maize harvesting is higher than for the other crops. A significant number of workable hours for groundnut combining in the first week after digging occurs only in the LDS.
The grain moisture limits used are at the high end of those experienced and advisable in practice. Post harvest drying of the grains will be necessary. Workable hours for combine harvesting allowing these moisture contents are thus about the maximum possible in this area.

CHAPTER 4

TIMELINESS

4.1. INTRODUCTION

Timeliness of an operation is defined as the ability to perform an activity at such a time that quality and quantity of product are optimised (ASAE). The economic significance is measured by the timeliness function, this relates the loss of crop value as compared to the maximum possible crop value for each day a given operation is advanced from or delayed beyond the operating date at which maximum crop value would be obtained.

For a crop planted at a certain day there are optimum times for subsequent field operations for that crop. In practice it will not be possible to carry out all the work at the optimum time and a balance has to be made between the cost of carrying capacity and timeliness cost of an operation. If a crop can be planted in different timeperiods, operating capacity and or timeliness cost can be reduced, however also planting has timeliness in seasonal climates. For agricultural planning the timeliness function of field operations relating recoverable value with time is essential. As such information was not available for the Zanderij area, experiments and calculations as described hereinafter were carried out to obtain estimates of such functions for planting of maize and harvesting of groundnuts, maize, sorghum and soya beans.

4.2. PLANTING

The available experimental data relating planting date and yield of crops do not cover a sufficiently long period to obtain timeliness functions for planting.

This relationship can be approximated with a model of physical crop production, provided sufficient specific information on the crop is available. For maize there was sufficient experimental information to obtain the crop specific parameters to be used in a model. The information on groundnuts appeared to be insufficient for the calculation of the crop specific parameters and a satisfactory model representation could not be obtained. For cowpea, sorghum and soya bean there was no information to obtain crop specific parameters.

4.2.1. Crop production model

For the calculation of a timeliness function of maize planting use was made of the model of physical crop production, WOFOST, as used by the Centre For World Food Studies. It is a so called summary model and originates from comprehensive models developed by a Wageningen working group (Penning de Vries and Van Laar, 1982). The model is in detail described by Wolf et al. (1986) and simulates crop growth for the first two of the four production situations as described by De Wit (1982; 1986):

1- Irradiance, temperature and day length determine crop growth.
2- As for situation 1 and additionally soil moisture availability may influence crop growth.
3- As in 2 and the availability of nitrogen can also limit crop growth.
4 - As in 3 also the availability of other nutrients as phosphorus and potassium may reduce growth.

The model simulates dry matter production in time steps of one day in dependence of total irradiation and air temperature. Gross CO_2 assimilation of a closed canopy (LAI 5) is an input into the model and is calculated from gross CO_2 assimilation under clear conditions by multiplication with a factor dependent on;

- actual radiation fraction of radiation on a perfectly clear day,
- gross CO_2 assimilation under overcast conditions fraction of gross CO2 assimilation under clear conditions.

Gross CO_2 assimilation of a closed canopy for clear and overcast days for any day and geographical latitude for rates of leaf photosyntheses at light saturation of 10-70 kg CO_2 ha^{-1} hr^{-1} were established by Goudriaan and Van Laar (1978).
Daily radiation on a perfectly clear day (R_c) is calculated in accordance with above mentioned reference from;

$$R_c = 1280 \int_{t=sunrise}^{t=sunset} \sin b_t \, e^{-.1/\sin b_t} \quad J\ m^{-2}\ s^{-1} \qquad (4.1)$$

b_t = solar declination at time t.

Actual radiation R_s is calculated from extraterrestrial radiation and relative sunshine duration as described in appendix A.
Gross CO_2 assimilation for the particular crop during development is

calculated from the value for a closed canopy by multiplication with the fraction of light interception

$$F_i = 1.0 - e^{-1.0 \times k_e \times LAI} \qquad (4.2)$$

k_e = the extinction coefficient of photosynthetic active radiation for the crop.

Part of the gross photosynthesis, expressed in glucose (CH_2O) is used for maintenance respiration and this is calculated with temperature dependent, organ specific factors as a function of living dry matter. The remaining photosynthates are converted into structural plant material for which organ specific conversion factors are used which depend on the chemical composition of the material to be formed.
The total growth of the crop is partitioned between roots, stems, leaves and storage organs in accordance with partitioning factors which are a function of the development stage. Development stage, 0 at emergence, 1 at flowering and 2 at maturity is a function of temperature sum and for daylight sensitive crops also of the daylength in the period before flowering.
Leaf area of the canopy follows from the growth and dying off rates of leaves and from the specific leaf area, the latter is also a function of development stage. In the available version of WOFOST it is assumed that all leaves formed have the same life span. This procedure was however changed in such a way that the life span of leaves was calculated as a function of the development stage (vide below). The dying off rate of leaves increases under moisture stress and is then also a function of the transpiration coefficient.

For calculations in production situation 2, where the availability of soil moisture can influence crop production, the gross CO_2 assimilation is corrected with the transpiration coefficient.
The soil water model included calculates with one soil layer equal to the depth of the root system of the crop. On the basis of observations in the field the rooting depth for maize was set at 0.30 m. Soil parameters are in accordance with those applied in the soil moisture model as described in chapter 3. The model distinguishes between evaporation from the soil surface and crop transpiration. Actual evaporation is calculated from potential evaporation as described in chapter 3 and potential evaporation E_p is here set equal to potential evapotranspiration of the reference crop (ET_r) as calculated with the formula proposed by Doorenbos and Pruitt (1977), vide appendix A.

The potential evapotranspiration of a crop with full canopy, ET_pfc is obtained from ET_r by multiplication with a crop factor, 1.2 for maize. The potential transpiration of the crop at full canopy is calculated from

$$T_pfc = ET_pfc - 0.1 \times E_p \qquad (4.3)$$

E_p = potential evaporation.

timeliness

The potential transpiration of the crop with less than full canopy is obtained by multiplication of $T_p$fc with the fraction of light interception, F_i. The transpiration coefficient is obtained from figure 20 where this coefficient is presented as a function of available soil moisture and the potential transpiration of the crop at closed canopy. Available soil moisture is defined as the difference in moisture content at pF 2.0 and pF 4.2.

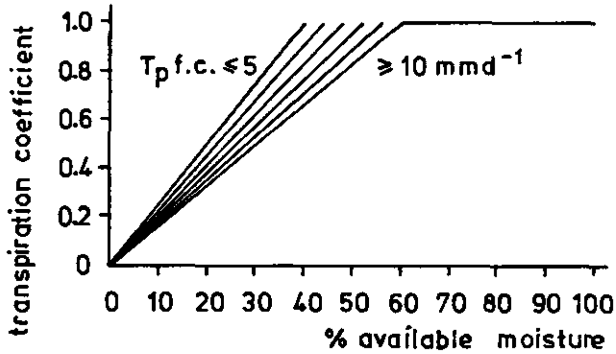


Figure 20. Transpiration coefficient as function of potential transpiration and percentage available moisture.

4.2.2 Specific parameters for maize

As the model was not provided with physiological parameters for maize grown in the Zanderij area some of these were adjusted with observations made on five maize growing experiments i.e., Wienk-Celos, Paramaribo 1969; Bakema, Kabo-Zanderij 1981 and Van den Hengel, Slaats and Ukkerman, Coebiti-Zanderij 1982. The growing period of the maize variety was 105 days except for the experiment in Paramaribo where a variety with a growing period of 120 days was used. (Wienk, 1969; Slaats and Ukkerman, 1983; Van den Hengel, 1982; Bakema, 1981).

Leaf senescence

Measured values of leaf area index LAI were plotted against the number of days after planting (dap) assuming that maximum LAI is reached halfway the growth period. The life span of leaves is estimated from those curves as the difference in dap at which a measured increase in LAI is matched by an equal decrease. These life span estimates referred to the dap of the measured decrease in LAI are presented in figure 21 together with data calculated from information on observations in Texas USA (Stapper and Arkin, 1979). The presented graph is the development dependent parameter for leaf senescence used in the model application.

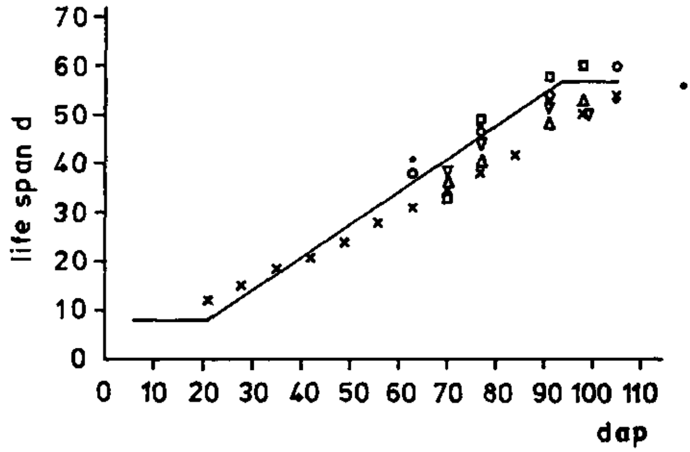


Figure 21. Life span of leaves of maize as function of dap at senesence. x Stapper, • Wienk, o Bakema, ▽ △ Slaats and Ukkerman, □ v. d. Hengel.

Specific leaf area

The specific leaf area SLA measured at intermediate harvests are averages for the leaf mass at that time. These measured values are referred to the development stage, dvs, at which half of that leaf mass was formed according to an idealized growth curve. The experimental data, figure 22 refers, cover only the period between 17 and 47 dap. The SLA in the early growth period is discussed hereafter.

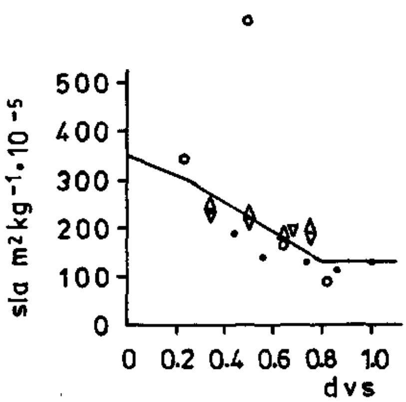


Figure 22. Specific leaf area of maize as function of development stage. • Wienk, o Bakema, △ ▽ Slaats and Ukkerman.

timeliness

Partitioning

In the field experiments no information was obtained on partitioning of dry matter to the roots. Partitioning of accumulated dry matter between above ground plant organs is presented in figure 23. Storage organ in this case comprises the total ear, and kernel yield is calculated as a fraction thereof. The measurements are referred to the dvs at which half of each increment was obtained. Partitioning to leaves and stems ceases at growth stage 1 and 1.3 respectively. The data from the Kabo experiment fall outside this pattern which may have been caused by poor crop development observed in the very wet early growth period.

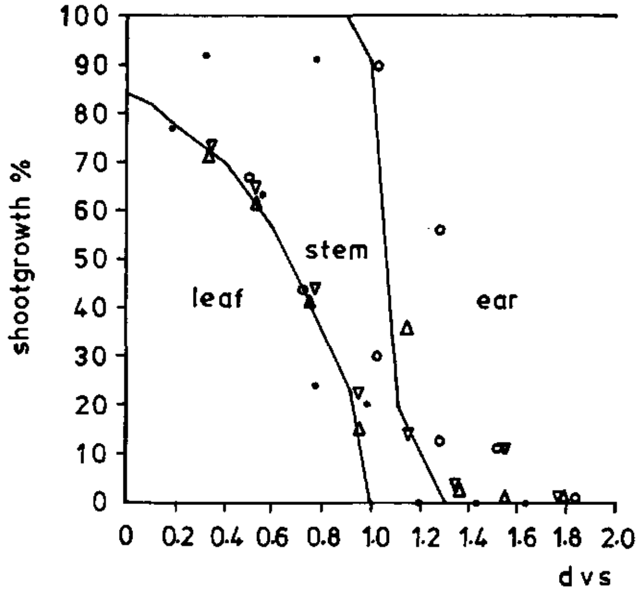


Figure 23. Partitioning of dry matter among shoot organs for maize as function of development stage. • Wienk, o Bakema, ▽△ Slaats and Ukkerman.

Early growth

Where the observations on the field experiments did not include information on the early growth period supplemental information was obtained from a pot experiment (Janssen 1973) carried out at Celos, Paramaribo. The amount of above ground dry matter as observed in this experiment is presented in figure 24. These data were used as a reference in model simulations for the same planting date for the years '78-'82, allowing no moisture stress, to obtain

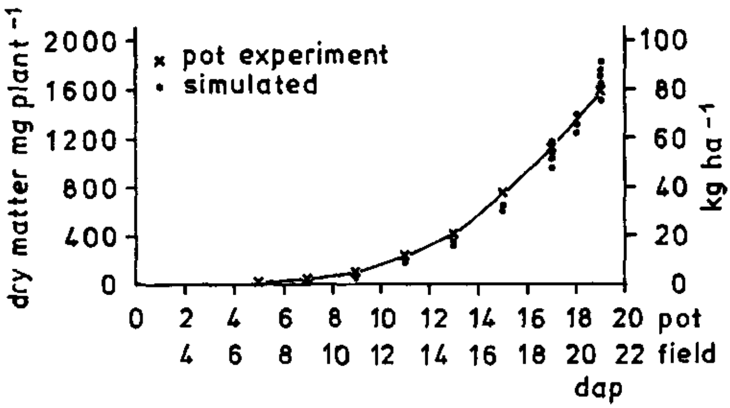


Figure 24. Above ground dry matter production for maize as function of dap as observed in pot experiments and simulated.

parameters for the early growth period.
Thus initial partitioning to the roots was set at 0.7 decreasing to 0.3 at growth stage 0.5, starting weight at emergence was set at 3.5 kg ha^{-1} and initional SLA at 0.0035 m^2 kg^{-1}.

From model simulations with the dry matter production as observed in the field experiments at Coebiti in 1982 for which also pertaining meteorological data observed at Coebiti station were available, the extinction coefficient was estimated at 0.6 and the maximum CO2 assimilation at light saturation at 60 kg ha^{-1} hr^{-1}. The simulated production and the actual production are compared in figure 25. Actual kernel yield in the experiments was 5250 kg ha^{-1} 12 percent wb. The observed kernel - ear ratio of 0.82 was used in further calculations.

4.2.3. Evaluation of the model.

For verification of the model and parameters obtained from experiments as described hereinbefore, simulations were made for planting dates in the period of june 78 - july 79. In this simulation the pertaining meteorological data for Coebiti, as obtained following the procedures described in chapter A, were applied. The calculated yields were compared with yields obtained in the planting date experiments carried out at Coebiti during the same period (unpublished data, Wienk).
The results are presented in figure 26. There is good agreement in the seasonal yield trend between experiment and calculation, but relatively large positive and negative differences occur between calculated and observed yields. The model tends to overpredict in the lower yield range as observed for growing periods in which severe moisture stress occurs.

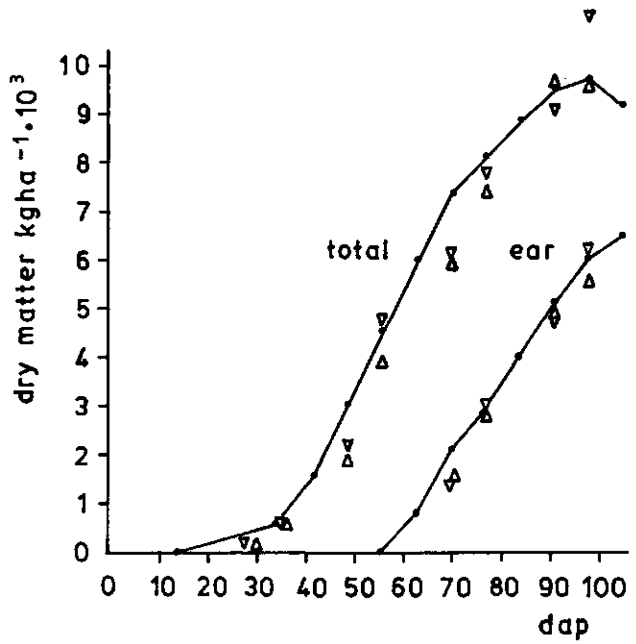


Figure 25. Maize dry matter production, experimental and simulated in model development.
Slaats and Ukkerman Δ ∇ ,simulated • .

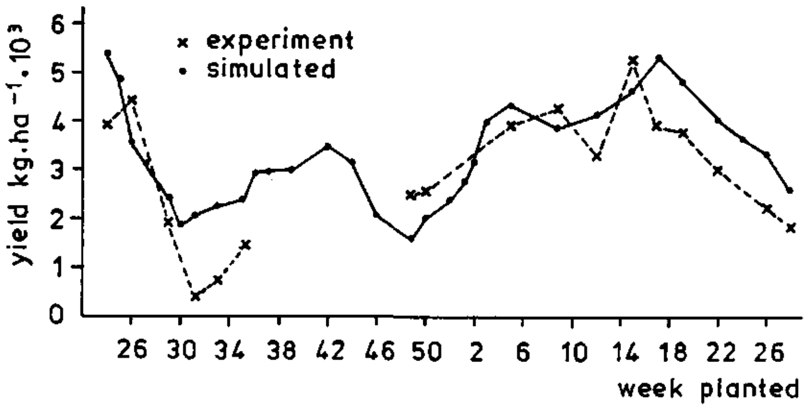


Figure 26. Maize yields obtained in a planting date experiment and as calculated.

Considering this overprediction the sensitivity of the model regarding aspects of the moisture balance were evaluated as follows:

- A rooting zone of 0.25 m instead of 0.30 m.
- Available soil moisture as the difference in soil moisture between pF 2.0 and pF 3.7 in stead of pF 2.0 and pF 4.2.
- Class-A pan evaporation, E_{pan}, instead of evapotranspiration of the reference crop ET_r according $E_{pan} = 1.75 \times ET_r - 3.50$. mm d^{-1} as established in appendix A. The effect of this change is decreased evapotranspiration at the lower levels and increased evapotranspiration at the higher levels.

With reduced rooting depth the calculated yields are lower than for the base case. The difference between the two cases varies between -20 and -330 kg ha^{-1} and does not appear to correspond with yield level. A similar picture is obtained for lower available moisture. The differences vary between -20 and -425 kg ha^{-1} but are on average larger in the lower yield range than in the higher yield range. With the modified evapotranspiration the simulated yields differ from +20 to -400 kg ha^{-1}. Also in this case the differences are on average larger for the lower yield ranges than for the higher yields. This analysis indicates that the parameter values applied in the base case limit yield at some stage for each of the planting dates. The overprediction for growing periods with severe moisture stress is not too specifically affected by adjusting one of the above parameters. As such change of parameters cannot be supported with observations or experiments, it is decided to use the model with the parameters as in the base case.

The model includes only the level of irradiance and soil moisture as production restraining factors. This condition is not always obtained in field experiments and is also reflected in the parameters derived from such experiments. Without being complete in identifying incidental or systematic factors which cause differences between calculation and experiments it is observed that notwithstanding fertilizer applications deemed adequate for crops and soil, constraints in nutrient availibility can well have occurred because with heavy rains on the Zanderij soils incidental leaching out of applied fertilizer is likely.

Recognizing the limitations of the model the agreement obtained between simulation and experiment is considered to be sufficient to allow further use of the model to obtain information on the relationship between the planting date and yield of maize.

4.3 RESULTS

Simulations of maize growing were carried out with the model as described for the 25 years between 1958 - 1983 using the Zanderij station meteorological

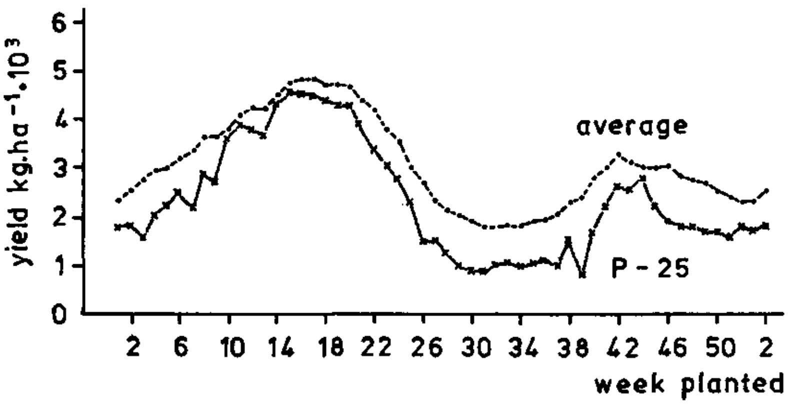


Figure 27. Maize yields as function of week of planting, simulated for the 25 year period 1958-1982. Average yields (•—•) and p-25 yields (x—x).

records for that period. The average obtainable maize yields in kg ha^{-1} 12 percent wb and the 25th percentile (p-25) as function of planting date are presented in figure 27.

The yield curve shows two different maxima and minima in accordance with the seasons and the yield decrease because of delayed planting in the wet season can run as high as 400 kg ha^{-1} $week^{-1}$. The average obtainable yield is highest for plantings around the beginning of the long rainy season, nominally occurring in week 16. Also the relative difference between the average yield and p-25 yield is smallest for that planting period. For plantings around the beginning of the SRS, nominally occurring at week 48, the average yield level is 60 percent of plantings around the beginning of LRS.

4.4 HARVESTING

The yield of grain crops is at its maximum when the stage of physiological maturity is reached. For crops with a deterministic growth habitat and a uniform growth physiological maturity is reached for all grains of that crop within a timespan of a few days and for such crops as for instance maize, sorghum and wheat the yield decreases from then onwards. Grains for such crops as groundnuts, cotton and vignii varieties, do not mature all at the same time on one plant . The maximum yield obtainable with one harvest operation occurs when additions to maturing grains are balanced by losses in mature grains. Higher yields are obtainable with selective harvesting as can be practised with cotton and mungbean.

Definition of terms.
Harvesting - concerns the operations involved in collecting, separating and cleaning of the product in the field.
Pre harvest loss - The difference between maximum potential yield and the harvestable yield at time of harvest.
Machine yield - the quantity of product collected in the harvesting machine storage bins.
Harvest loss - the difference between harvestable yield at time of harvest and the machine yield.
Apparent yield - the sum of machine yield and measured losses.
Post harvest loss - the loss during transport from the field, processing and storage.

Pre harvest losses occur because of lodging, scattering, wildlife activity, respiration of the grains or interrupted dry matter accumulation. Loss can be quantitative as well as qualitative, the latter in the form of damaged, discoloured, mouldy or germinated grains. Direct quantitative determination of these losses is not possible.
Harvest losses occur because with the harvesting system applied not all harvestable product can be collected, for instance cutter bar or picking losses when combining grain crops and digging losses when lifting groundnuts. Once collected, losses occur because separations are not complete in the threshing and cleaning operations . Also qualitative losses occur in the form of cracking and breakage of kernels. Direct quantitative determination of these losses is mostly possible.
The timeliness function as used here relates time of harvesting with the machine yield obtained when applying a certain harvesting system, properly adjusted and operated for prevailing circumstances.
Within the LH/UvS 02 project experiments were carried out to obtain insight in the timeliness of harvesting for maize, groundnuts, sorghum and soya beans.

4.5 MAIZE HARVESTING

4.5.1 Experimental

In 1981 harvest date studies for maize were carried out at the Coebiti experimental farm. For this purpose maize was planted on march 17, april 22 and may 13 in four replicates in randomly selected adjacent plots, measuring 21 x 140 m with 28 rows at 0.75 m row distance. Maize was harvested from around the time of physiological maturity at about weekly intervals over a period of six weeks. The maize planted was an open pollinating variety SMS-04 of Brazilian origin, selected for relatively good performance on the acid soil of Coebiti. Conventional tillage was applied and fertilization and weed control were carried out in accordance with procedures described in chapter 2.2.

timeliness

A Laverda M84 combine with a three row picking table was used, the available secondary thresher and cleaner were not used as such, the after cleaner was adjusted to serve as bagging device for the machine yield.
Loss determinations were carried out as follows; all combine refuse was collected in a box mounted on a rail attached to the combine over a three row area 10 m long. The material collected was analysed, loose kernels were attributed to cleaning loss and kernels attached to spills were attributed to cylinder loss. The area over which the catching device was in operation was searched for loose kernels (negligible) ears and parts of ears with kernels. This material contains the picking loss which is a harvest loss and also some pre harvest loss in so far as ears detached before harvesting were still in good condition. In the table this collected material is referred to picking loss. At each harvesting date three adjacent rows were combine harvested. The fourth row on the inside was used for control purposes. Each area to be harvested at a certain date, 3 rows over a length of 120m, was divided in three subplots of 40 m length. On each of these the machine yield was determined and on 10 m of each subplot, when the machine was on steady load, the losses were determined. The combine settings were not changed during the experiment, the cylinder speed was 700 rpm, cylinder clearance was 25 mm in front and 15 mm at the rear. Different speeds, 3.5, 5.1 and 8.0 km hr^{-1} were used on the successive subplots. The machine yields were analysed for moisture in duplo, breakage and debris. Quantities were standardized to clean product with a moisture content of 12 percent wb. Loss quantities were threshed, cleaned and corrected to standard moisture content assuming that the moisture content was the same as of the machine yield. On the control rows, the number of plants, lodged plants and kernel moisture content were determined.

4.5.2 Results

Experimental data which are averages of 12 subplots for each harvest date are presented in tables 25 a,b and c.

Table 25a. Maize harvesting at different dates, planting date 17-3-81.

date of harvest		2-7	7-7	16-7	23-7	29-7	5-8	11-8	sign
days after planting		107	112	121	128	134	141	147	
rainfall mm d^{-1} since previous harvest		6.0*	13.1	6.1	9.6	3.5	5.3	0.4	
machine yield	kg ha^{-1}	3502	3185	2548	2407	2580	2382	2393	
picking loss	,,	110	232	274	284	268	718	260	
threshing/cleaning loss	,,	62	39	34	23	16	10	9	1%
apparent yield	,,	3674	3456	2856	2714	2864	3110	2662	
plants x1000 ha^{-1}		48.4	44.6	43.4	47.8	40.3	51.1	37.3	
lodged plants %		21	41	55	67	68	70	72	
moisture machine yield %wb		24.3	22.6	17.3	18.3	12.1	12.8	12.2	1%
breakage %wt of machine yield		7.1	5.7	4.2	4.0	3.3	5.0	4.3	

Table 25b. Maize harvesting at different dates, planting date 22-4-81.

date of harvest		28-7	5-8	11-8	18-8	27-8	2-9	9-9	sign
days after planting		97	105	111	118	127	133	140	
rainfall mm d^{-1} since previous harvest		2.5*	6.2	.4	1.9	2.0	2.5	.9	
machine yield	kg ha^{-1}	1898	2081	1760	1540	1820	1617	1640	
picking loss	,,	113	194	107	161	122	134	285	
threshing/cleaning loss	,,	18	26	23	24	8	4	4	1%
apparent yield	,,	2029	2301	1890	1725	1950	1755	1929	
plants x1000 ha^{-1}		45.8	48.2	41.5	38.2	44.2	43.3	46.5	
lodged plants %		19	18	32	32	29	54	44	
moisture machine yield %wb		31.3	23.0	18.6	15.2	11.9	11.1	9.7	1%
breakage %wt of machine yield		13.1	4.1	4.6	4.3	3.5	4.5	4.8	

Table 25c. Maize harvesting at different dates, planting date 13-5-81.

Date of harvest		18-8	27-8	2-9	9-9	16-9	23-9	30-9	sign
days after planting		97	106	112	119	126	133	140	
rainfall mm d^{-1} since previous harvest		1.9*	2.0	2.5	.9	1.9	.7	1.0	
machine yield	kg ha^{-1}	1578	1738	1865	1718	1852	1897	1925	
picking loss	,,	230	182	343	267	243	210	162	
threshing/cleaning loss	,,	37	32	25	9	5	6	7	1%
apparent yield	,,	1845	1952	2233	1994	2100	2113	2094	
plants x1000 ha^{-1}		57.6	53.7	53.7	52.8	54.2	54.5	55.7	
lodged plants %		12	17	41	45	31	36	35	
moisture machine yield %wb		27.4	21.0	12.1	11.5	11.6	9.6	9.7	1%
breakage %wt of machine yield		5.0	4.3	3.6	4.1	4.3	2.8	4.5	

*Average daily rainfall six days before first harvest.

It was intended to start harvesting a few days before the 105 dap as is done in practice. Harvesting for the crop planted march 17 was delayed because of adverse weather conditions. A statistical analysis of the data indicates a significant difference in yields among the three planting dates. As reasons different environmental conditions, possible differences in nutrient availability caused by leaching and effectiviness of weed control may be mentioned.

A systematic difference between the subplots within replications was also observed. The centre plots, where during land clearing operations a windrow had been located and burnt showed the highest machine yields. On the western plots the yields were higher than on the eastern plots. Interaction between yield level and harvest date on the machine yield was present. A significant difference in machine yield among harvest dates was observed on the centre plot (1%) and western plot (5%) of the first planting and on the centre plot

timeliness

(10%) of the second planting. On the other plots no significant relation between harvest date and machine yield was observed.
On the aforementioned plots of the first planting the machine yield decreased with about 100 kg d^{-1} ha^{-1} during the first two weeks after the first harvest. In the later delay period the decrease was less. An analysis of the data indicates that the decrease of the machine yield per day of postponement of harvesting decreases with grain moisture content. However the grain moisture content depends also on the time passed since maturity and the weather.

The collected pre harvest and picking losses increase in the early delay time of the first experiment, no such distinctive trend is apparent in the two other experiments. These losses moved in a narrow band around 10 percent of apparent yield as harvesting was further delayed. Lodging increased in the initial harvest period in all three experiments but to different levels. Statistical analyses showed interaction between harvest delay and yield on the degree of lodging.
Waelti et al. (1969) report, from harvest date studies in Iowa, that losses in above mentioned category increased rapidly as kernel moisture content decreased below 25 percent and varied with variety. Losses between 8 and 18 percent of apparent yield are reported for a harvest delay of three weeks beyond the date at which grain moisture reached a level around 25 percent. Johnson et al. (1963) report the same range for this loss and mention differences between locations and relation with lodging.

Collected threshing and cleaning losses are relatively small and vary between 0.3 and 2 percent of machine grain intake. These losses decrease as harvesting is further delayed. A statistical analysis of the data showed that these losses correlated with harvested quantity per hour and with grain moisture content as measured at the time of harvest and this can be expressed as

$$\%\ loss = -1.20 + 0.366M - 0.008M^2 - 1.14\ 10^{-3}G + 2.01\ 10^{-7}\ G^2 \quad (4.4)$$
$$(r=0.49)$$

M = moisture % wb of the kernels at the time of harvest
G = machine grain intake kg hr^{-1} 12%wb.

Johnson et al. (1963) report from observations in Ohio, separation losses of 0.1-0.35 percent and threshing losses of 0-1.5 percent of apparent yield decreasing with decreasing grain moisture content.
The percentage broken kernels in the machine yield decreases with decreasing kernel moisture content, however below kernel moisture contents of 25 percent the decrease in breakage is insignificant. Breakage was determined by manual selection and the reported data are not comparable with U.S. Grade sieve determinations.
The changes in the apparent yield with delay in harvesting, especially in the first and second harvesting date experiment suggest invisible preharvest

losses.
In the initial harvest stages of the second and third planting this loss may contain also maturity losses, considering grain moisture contents at the first harvest dates. Harvesting started at 97 days after planting, in practice a growing period of around 105 days is observed to reach an acceptable grain moisture content, around 25 percent, for harvesting. Other invisible losses occurred mainly because detached and fallen ears were overlooked in the weed vegetation or not collected because of unacceptable quality. In this respect it is noted that harvesting for the first planting date was carried out under wet conditions and for the third under dry conditions.
Information on invisible preharvest losses, other than related to dry matter accumulation, is scarce and qualitative. In comprehensive harvest date studies as reported in aforementioned references such losses are not observed or not quantified. They measured however collected pre harvest losses and picking losses higher than in this investigation. It may well be that in the environment of the experiments in references detached or fallen ears did not deteriorate to invisible losses as occurred during the wet periods in the first two experiments.

4.5.3. Conclusions

The experimental results do not point to a simple timeliness function for maize harvesting, crop stand and weather are important variables. Under wet conditions machine yield reductions of up to 100 kg ha^{-1} d^{-1} were observed in the initial delay period beyond physiological maturity. Preharvest/picking losses form the main part of the losses, threshing and cleaning losses are relatively small and decrease with grain moisture content.
In literature variety and site specific circumstances are mentioned as important variables in the timeliness function.

4.6 SORGHUM HARVESTING

4.6.1 Experimental

Harvest date studies were carried out on the Coebiti experimental farm with sorghum planted on october 30, november 24 and december 15, 1981 and january 12, 1982. An earlier planting on october 15 was abandoned because dryness caused poor and irregular germination. The field was replanted on october 30, this time germination was considered just sufficient. The sorghum cultivar IS2745 was used, a combine variety originating from Icrisat, India. Conventional tillage was applied, the sorghum was planted at a row distance of 0.50 m and fertilization and weed control were as described in chapter 2.2. The crop was harvested with a Laverda M84 combine with a working width

timeliness

Table 26a. Sorghum harvesting at different dates, planting date 30-10-81.

								sign.
date harvest 1982		27-1	4-2	10-2	18-2	23-2	3-3	
days after planting		89	97	103	111	116	124	
rainfall mm d^{-1} since previous harvest		4.4*	6.9	4.7	1.9	6.9	0.8	
eastern subplots								
machine yield	kg ha^{-1}	3705	3435	2821	3179	2918	2857	ns
mowing loss	,,	76	37	88	150	76	91	ns
threshing/cleaning loss	,,	163	50	124	101	110	31	ns
apparent yield	,,	3944	3522	3033	3430	3104	2979	
plants x1000 ha^{-1}		87	131	110	126	110	50	1%
lodged plants %		0	0	1	11	3	0	ns
moisture machine yield % wb		27.2	33.2	25.9	19.4	21.3	17.1	1%
moisture MOG# %wb		77.5		77.4	69.1	71.2	68.6	10%
MOG kg ha^{-1} dry matter		1446		1089	1520	1194	1400	
western subplots								
machine yield	kg ha^{-1}	3039	3081	2976	2018	1511	1375	1%
mowing loss	,,	66	70	94	330	525	422	5%
threshing/cleaning loss	,,	34	41	36	81	14	14	ns
apparent yield	,,	3139	3192	3106	2429	2050	1811	
plants x1000 ha^{-1}		82	146	127	151	116	70	1%
lodged plants %			4	3	14	11	9	ns
moisture machine yield % wb		26.0	33.2	24.2	21.1	20.3	17.3	1%
moisture MOG % wb		77.8		72.3	72.2	73.1	65.6	1%
MOG kg ha^{-1} dry matter		1198		1024	969	778	1121	

* Average daily rainfall six days before first harvest
# MOG = Material other than grain.

of 3.20 m. The cylinder speed was set at 640 rpm and cylinder-concave clearance was 0.5 cm in front as well as in the rear, these settings were maintained throughout the experiments.
Plantings were done in three replicates measuring 24x95 m each. The eastern half of the replications covered an area where during land clearing a windrow had been located and burnt. This results in higher soil fertility and to account for this inhomogenity each replication was devided in an eastern and western subplot measuring 24 x 40 m net.
At harvest date six plant rows from the centre of an eight row area were harvested on each replication with a combine speed of 3.1 and 4.2 km hr^{-1} on the subplots. The machine yield was measured on each subplot, analysed in duplo for moisture and standardized to 12 % wb moisture. Also the combine refuse was collected on each subplot from a six row area 10 m long, following the precedure as described in chapter 4.5.1. This same area was searched after passage of the combine and heads with seeds in good condition were

Table 26b. Sorghum harvesting at different dates, planting date 24-11-81.

								sign.
date harvest 1982		18-2	23-2	3-3	8-3	19-3	24-3	
days after planting		86	91	99	104	115	119	
rainfall mm d^{-1} since previous harvest		1.5*	6.9	0.8	1.5	8.9	9.1	
eastern subplots								
machine yield	kg ha^{-1}	3514	2754	2930	2313	1737	1709	1%
mowing loss	,,	70	62	158	165	300	423	10%
threshing/cleaning loss	,,	200	230	63	30	32	102	ns
apparent yield	,,	3784	3046	3151	2508	2069	2234	
plants x1000 ha^{-1}		198	168	200	170	195	130	5%
lodged plants %		0	1	0	5	15	20	ns
heads with germination %		0	0	0	0	81	60	1%
moisture machine yield % wb		26.7	30.0	19.5	15.1	20.3	18.2	5%
moisture MOG % wb		76.1	69.4	68.2	66.6	66.0	72.6	ns
MOG kg ha^{-1} dry matter		1448	1769	965	965	1069	1088	
western subplots								
machine yield	kg ha^{-1}	2578	2477	2422	2032	911	839	1%
mowing loss	,,	42	70	262	394	383	354	5%
threshing/cleaning loss	,,	64	59	20	9	20	23	ns
apparent yield	,,	2684	2606	2704	2435	1314	1216	
plants x1000 ha^{-1}		195	190	157	164	150	108	1%
lodged plants %		0	1	9	9	28	49	5%
heads with germination %		0	0	0	0	40	19	1%
moisture machine yield % wb		31.4	32.5	19.7	19.5	16.4	25.3	1%
moisture MOG % wb		71.6	70.0	69.3	65.8	70.7	73.8	ns
MOG kg ha^{-1} dry matter		1248	1232	879	1050	974	1059	

collected. Both these quantities were weighed and bagged, the material was dried, weighed again and threshed. The grains obtained from the combine refuse were attributed to threshing and cleaning loss and those from the heads collected on the field to mowing loss. The combine refuse was threshed and analysed for moisture. On each subplot the number of plants, lodged plants and plants with germinated heads were determinated on a length of 2 m of rows to be harvested. Harvesting started on january 27 and proceeded regulary till march 9, 1982. From then onwards rain interfered with the work and planned harvest dates could not be maintained.

4.6.2 Results

In tables 26a, b and c the obtained data, averages of three replications, are reported for each subplot.

Table 26c. Sorghum harvesting at different dates.

planting date		15-12-81				13-1-82			
date harvest 1982		9-3	19-3	13-4		14-4	22-4	26-4	
days after planting		84	94	119		91	99	103	
rainfall mm d^{-1} since pr. harvest		1.3*	9.9	13.6		0.7	6.2	25.7	
					sign				sign
eastern subplots									
machine yield	kg ha^{-1}	2430	1967	722	1%	1265	1432	904	ns
mowing loss	,,	26	42	129	5%	55	50		ns
threshing/cleaning loss	,,	110	202	31	ns	14	53	56	ns
apparent yield	,,	2566	2211	882		1334	1535		
plants x1000 ha^{-1}		176				191	171	150	ns
lodged plants %		0				2	1	6	ns
heads with germination %		0				17	0	11	ns
moisture machine yield % wb		36.7	27.8	15.3	5%	21.2	23.7	30.3	ns
moisture MOG % wb		83.6	75.3	76.7	ns	74.1	71.9	71.5	ns
MOG kg ha^{-1} dry matter		1097	1438	927		974	1021	936	
western subplots									
machine yield	kg ha^{-1}	1674	1399	621	5%	1227	1082	574	5%
mowing loss	,,	22	38	98	ns	31	48		ns
threshing/cleaning loss	,,	33	45	9	ns	10	29	26	ns
apparent yield	,,	1729	1482	728		1268	1159		
plants x1000 ha^{-1}		151				180	203	138	ns
lodged plants %		24				1	1	21	1%
heads with germination %		0				8	0	0	ns
moisture machine yield % wb		36.4	23.7	14.9	1%	23.1	20.0	28.8	ns
moisture MOG % wb		80.4	74.0	68.2	1%	73.7	70.0	72.0	ns
MOG kg ha^{-1} dry matter		870	922	1088		889	1002	681	

A statistical analysis shows that machine yield, mowing loss as percentage of apparent yield and percentage lodged plants differ significantly (1, 10 and 10 %) with planting date and between eastern and western subplots (1, 5 and 10 %). The course of yield with planting date is qualitatively in line with expectations for this season, however in the third and fourth planting foliar diseases were observed from mid february onwards and the first harvest of the fourth planting was delayed beyond maturity.

Multiple regression analyses showed that the machine yield diminished linearly with postponement of harvesting at a rate between 38 and 52 kg ha^{-1} d^{-1}. ($r = 0.88$)

Germination of the sorghum to be harvested occurred from about mid march onwards and in such case quality loss must also be considered. The course of machine yield with harvest date and rainfall in this period are presented in figure 28.

The mowing loss at the first harvest date is in the order of one percent of

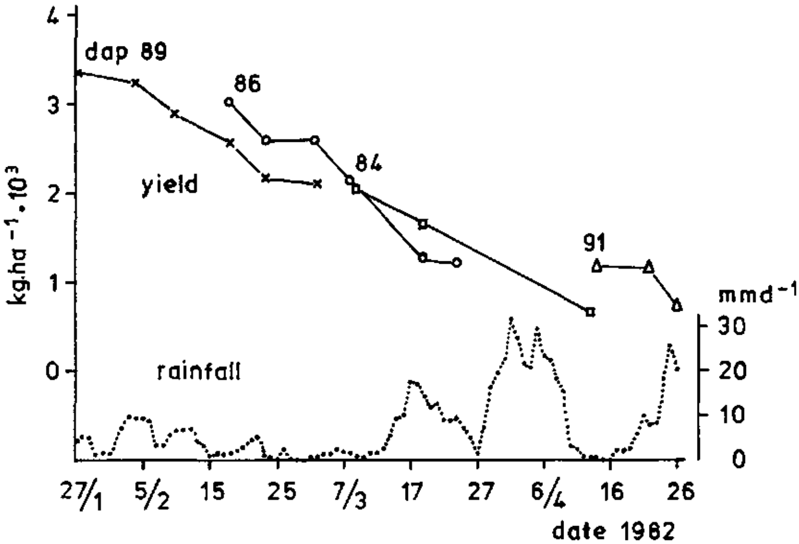


Figure 28. Sorghum, machine yields for different plantings as function of harvest date and five day moving average rainfall during the harvest period.

apparent yield and increases with delay time up to 30 percent depending on conditions. This loss correlates with lodging (L) as follows;

$$\text{mowing loss \%} = 3.9 + 0.78\ \%L - 0.007\ \%L^2 \qquad (r = 0.64) \qquad (4.5)$$

The threshing and separating losses vary with few exceptions between 1 and 5 percent of machine grain intake. A multiple regression analysis of the experimental data showed that this loss can be presented by the following, rather impractical, relation;

$$\text{loss \%} = -10.0 + 0.166\ M - 8.88\ 10^{-4}\ G + 1.77\ 10^{-6}\ MOG^2 \quad (r = 0.76) \quad (4.6)$$

MOG = material other than grain kg hr^{-1}, dry matter
M = moisture content MOG % wb
G = machine grain intake kg hr^{-1}, 12 % wb.

The observed reduction of the apparent yield with postponement of the harvest indicates that there is a considerable invisible preharvest loss which is not directly measurable.

Sorghum harvesting losses reported from experiments in the USA show large variation. Fairbanks et all, 1979 report for one harvest date study carried out under excellent conditions a total loss including preharvest loss of 5

timeliness

percent of total yield at 14 and 21 days after the first harvest date whilst grain moisture content was around 14 percent wb. In an other experiment the mowing loss increased from 6.8 to 8.4 percent and threshing and cleaning loss from 6.1 to 7.7 percent of total yield in a harvest period of 21 days. During this period grain moisture content decreased from 30 to 16 percent wb. They concluded that grain moisture content had a significant influence on the losses. Wealti et al, 1977 report from experiments where lodging occurred. The threshing and cleaning loss increased from 2.1 to 6.0 percent and mowing loss from 12.7 to 47.5 percent of total yield in a harvesting period covering 23 days with grain moisture contents decreasing from 25 to 15 percent wb. The authors do not discuss explicitly invisible pre harvest losses and the course of obtained machine yield with harvest date.

4.6.3 Conclusions

In the first three experiments an average decrease of the machine yield of respectively 1.0, 1.5 and 1.9 percent of the initial machine yield per day of harvest postponement is observed. Crop stand was good for the first two experiments and relatively poor for the later experiments. Weather conditions in terms of rainfall were favourable till the first half of the second experiment from then onwards heavy rains occurred and considerable germination of the grains to be harvested was observed. For sorghum the timeliness cost of harvesting is relatively small under favourable weather conditions. High timeliness cost occurs during wet periods specifically in terms of quality of the grain.

4.7 SOYA BEAN HARVESTING

4.7.1 Experimental

A soya bean harvesting date study was carried out at the Coebiti experimental farm. Soya beans, variety Jupiter, were planted on march 17 and april 13 1983, a third planting in this season was no more possible because of too wet conditions. Conventional tillage was applied and fertilization and weed control were as described in chapter 2.2. Planting with a row distance of 0.50 m was carried out in three replicates of 24 x 100 m, and each of these were devided into two subplots of 24 x 40 m net. Harvesting was done with a Laverda M84 combine equiped with a standard rigid cutterbar. Harvesting started at complete defoliation, and at each harvesting date the six centre rows of an eight row area were harvested. The machine yield obtained at each subplot was analysed for moisture in duplo and standardized to 12 pecent wb moisture. The combine refuse was collected from a six row area 10 m long and weighed. This material was dryed, weighed and threshed. The obtained seed was

attributed to threshing and cleaning loss, and the moisture content of material other than grain (MOG) was determined. From each area where the combine refuse was collected an area of 6 m^2 was searched and pods and loose seeds in good condition were collected. The seeds obtained from this material were attributed to mowing loss.
The first planting resulted in a good clean crop stand. The second planting occurred under wet conditions and the applied pre emergence weed control with allachlor was not fully effective. Crop stand was moderate and weed growth, mainly grasses, was such that machine harvesting at the chosen speed was no more possible after the fourth harvest date.

4.7.2. Results

The experimental data as are presented in tables 27a and b, are averages for two subplots in three replications .
A statistical analysis showed a significant difference in yield and percentage threshing and cleaning loss between the two planting dates (1 and 5%).
During a period of about two weeks after the first harvest the machine yield remains rather constant. Further delays show a decreasing machine yield with about 30 kg d^{-1} ha^{-1}. Threshing and cleaning loss varies between 0.7 and 3.8 percent of apparent yield. A multiple regression analysis shows that this loss correlates with the moisture content of grain and MOG and with the grain and MOG throughput per hour of the machine. The best fit ($r = 0.70$) is obtained with a quadratic, impracticable, function. The mowing loss shows an increasing trend with postponement of harvesting from about 3 percent of apparent yield to about 5 percent at 14 days after first harvest. A loss of 11.8 percent was observed at 29 days after the first harvest for the first planting. The increase of mowing loss with delay time may be caused by lodging so pods escape the cutterbar. Shattering because of cutterbar action increases with decreasing grain moisture. The latter moves irregular with time in the experiment and influences the time - mowing loss relation.

Table 27a. Soya bean harvesting at different dates. Planting date 17-3-83.

harvest date		18-7	21-7	26-7	3-8	10-8	16-8	sign
days after planting		123	126	131	139	146	152	
rainfall since previous harvest mm d^{-1}		8.9*	6.4	2.5	4.8	5.4	.9	
machine yield	kg ha^{-1}	3089	2925	2910	2646	2500	2236	1%
mowing loss	,,	106	103	188	150	130	318	5%
threshing and cleaning loss	,,	65	21	28	69	97	40	1%
apparent yield	,,	3260	3049	3126	2865	2727	2594	
moisture machine yield % wb		17.2	19.8	13.2	21.6	29.6	15.0	1%
MOG kg ha-1 dry matter		1879	1344	1474	1621	1362	1374	1%
moisture MOG % wb		44.1	43.3	38.7	50.2	58.9	53.0	1%

timeliness

Table 27b. Soya bean harvesting at different dates. Planting date 13-4-83.

harvest date		16-8	22-8	25-8	30-8	
days after planting		125	131	134	139	
rainfall since previous harvest mm d^{-1}		.9*	3.4	.7	3.0	
machine yield	kg ha^{-1}	2037	2073	2077	2275	ns
mowing loss	,,	68	178	130	111	ns
threshing and cleaning loss	,,	70	49	22	46	10%
apparent yield	,,	2175	2300	2329	2332	
moisture machine yield % wb		14.7	15.2	17.1	15.8	ns
MOG kg ha^{-1} dry matter		1289	1637	1308	1731	10%
moisture MOG % wb		67.4	58.3	63.9	60.4	ns

* Average daily rainfall six days before first harvest.

Pre harvest losses appear to be insignificant for the first two weeks of harvesting but increase with further delay as reflected also in the apparent yields.

In literature it is mentioned that harvest losses increase with time after maturing and with decreasing moisture content of the grain. Quick and Buchele (1974) measured header losses of about 4 percent at 13 percent wb moisture and 10 percent loss at 10 percent wb moisture.

A study at Ohio State University over the five year period 1956-1960 revealed average harvest losses of 13.7 percent of total yield of which 0.4 percent was pre harvest loss, 1.8 percent threshing and cleaning loss and 11.5 percent mowing loss. Byg and Johnson (1970) report a reduction of the average losses to around 10 percent because of the introduction of improved machinery with floating cutterbars.

4.7.3. Conclusions

The observed timeliness loss for soya bean harvesting was relatively small specially in the first weeks after crop maturity. It is reported that cutterbar (mowing) loss increases rapidly as grain moisture content decreases. Grain moisture moves considerably during a day, paragraph 3.5.2 refers. Harvesting during certain hours of a workable day might well be unattractive because of the high cutterbar losses occuring.

4.8 GROUNDNUT HARVESTING

Groundnut is an indeterminate crop and pod production continues as long as the vines are healthy. Mechanized harvesting is carried out in two stages and includes digging, shaking and windrowing in the first stage and threshing with a pick up combine in a second stage. The optimum time for digging is determined by the time course of the physiological maturing in conjunction with the conditions of the vines and the soil, and the weather during curing. A system that fully evaluates all factors is not available. A practical rule to predict optimum digging time is to dig when 75 percent of the pods show dark colouration at the inside of the hull. This method was also used in the field experiments discussed hereinafter.

4.8.1 Experimental and results

Three series of groundnut harvest date studies were carried out at the Coebiti experimental farm with the cultivar Matjan, this is a spanish type groundnut with relatively large leaves and seeds. This cultivar is usually harvested around 95 dap. Conventional tillage was applied and fertilization and weed control were in accordance with procedures described in chapter 2.2. Mechanical planting was done in a four row pattern as developed in the USA for mechanical harvesting. A Lilliston digger shaker 5500 was used for digging of groundnuts in the first two experiments, and in the third a KMC digger shaker inverter was used. The expected better plant orientation such that pods were mostly at the top of the windrow was however not obtained with the latter machine, possibly because the machine was not designed for the groundnut variety used. A Lilliston combine was used in the first two studies, in the third a locally made stationary groundnut thresher, similar to a Cecocco machine, was used as the combine was no more available.

Experiment 1979

Groundnuts were planted on may 7, may 17 and may 30. Each planting covered 28 beds with four plant rows and a length of 55 m. From each planting 3 to 5 rows were used for running in and adjustment of the harvesting machinery. Weed control with alachlor was not adequate in this experiment, specially Cenchrus Echinatus L. and Echininochloa Colonum L. escaped this treatment and these grasses hampered digging operations. To control early leafspot, Cercospora Arachidicola HORI and late leafspot Cercosporidium personatum (Berk. and Curt.) Deighton., benomyl 0.25 kg ai ha^{-1} was applied in week 4 and week 8 after planting. Additionally Cuprooxichloride 2.0 kg ai ha^{-1} was applied in week 6 and 10. In an effort to prevent rust caused by Puccinia Arachides SPEG., zinkcarbamate 3.2 kg ai ha^{-1} was applied in week 11 in the first two plantings. Notwithstanding foregoing leafspots and rust developed rapidly from 75 dap and this resulted in an almost dead foliage at 85 and 90 dap for the first respectively second and third planting.
The first digging of 6 or 7 beds per planting were carried out at 92, 93 and 92 dap. The starting date was mainly determined by the dying off of the crop. Subsequently three further diggings were carried out for each planting at intervals of 4, 3 or 2 days. Combining occurred at between 0 and 12 days

after digging. The combine yield as determined on each bed was analysed for moisture in duplo and standardized to 12 percent wb. In each bed after passage of the digging machine a bed length of 1 m was dug by hand and the digging loss was determined, excluding germinated and deteriorated pods.

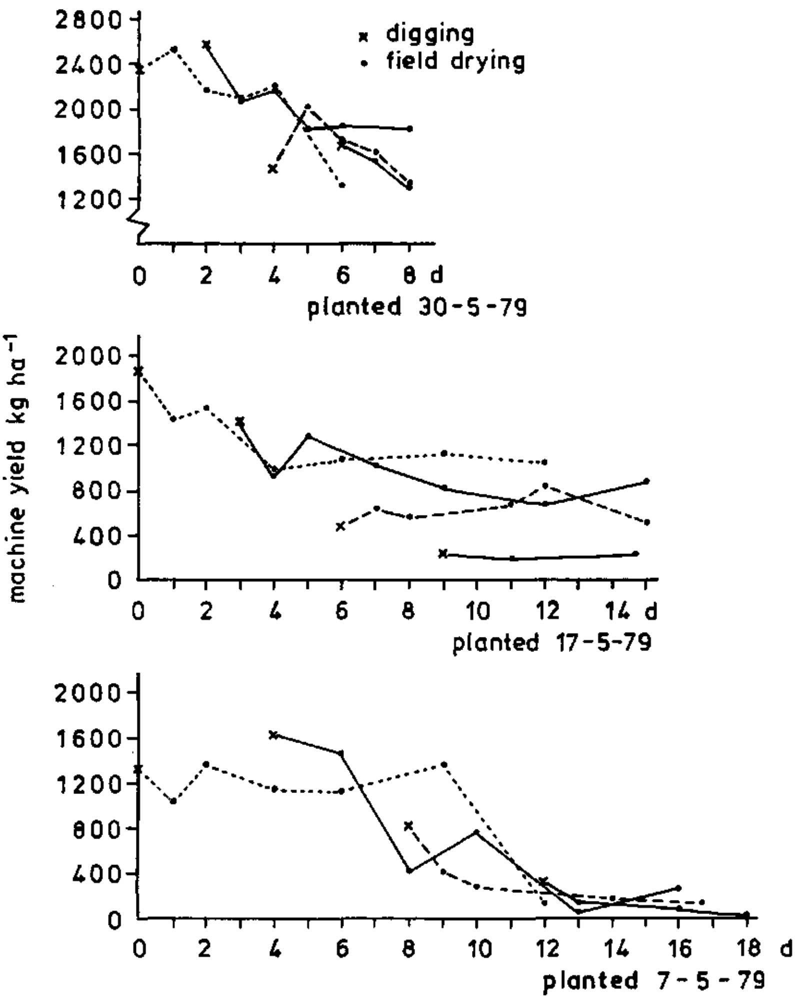


Figure 29. Groundnuts, machine yield as function of postponement of digging and field drying time.

Results

The obtained machine yields are presented in relation to time of digging and days field curing in figure 29. A multiple regression analyses of the data shows significant influence of planting date , date of digging, days field curing and interaction between planting date and days field curing. vide table 28.

Table 28. Groundnut, relation between machine yield, digging delay and days field curing, r=0.94.

		7 may	17 may	30 may
planting date 1979		7 may	17 may	30 may
initial harvest dap		92	93	92
initial machine yield	kg ha^{-1}	1605	1434	2421
Average yield reduction by:				
postponement of digging	kg ha^{-1} d^{-1}	112	112	112
	percent d^{-1}	6.9	7.8	4.6
field curing	kg ha-1 d^{-1}	82	33	107
	percent d^{-1}	5.1	2.3	4.4

In the experiment yield reductions because of postponement of digging are calculated from differences between machine yields obtained at different dates and thus include the difference in machine loss occured at those dates. The collected digging losses, as reported in table 29, are high and increase with postponement of digging in the time period investigated.
The collected digging losses were standardized to 12 percent wb moisture assuming that the moisture content of the pods were equal to the moisture content of the harvested pods from plants dug and combined at the same day.

Table 29. Groundnut, collected digging loss, kg ha^{-1}, at different digging dates.

planting date 1979		7 may	17 may	30 may
digging at dap	92	396		553
	93		594	
	94			796
	96	692	640	1033
	98			1213
	99		1041	
	100	1575		
	102		2118	
	104	1067		

timeliness

Experiment 1980

On a 2 ha field of groundnuts not specifically planted for this experiment, a harvest date study was carried out. The field was planted on july 17, 1980, weed control with alachlor was effective and with a biweekly application of 3.5 l ha Bravo 500 ec, a.i. 40 % chlorotalonil, a healthy foliage was maintained until the end of the harvest. On the field 16 blocks of 55 x 11.5 m were marked off. On each block 4 out of 24 plant rows were lifted at 89, 91, 93, 96, 98 and 100 dap. The plants were left between 2 and 4 days on the windrow before combining.

Results

The machine yields, averages for sixteen blocks are presented in table 30. In this experiment the machine yield decreases with less than 0.5 percent d^{-1} digging delay in a delay period of 10 days.

Table 30. Groundnut, machine yield in relation to date of digging and combining.

digging			field drying			
date	dap	delay d	d	average rainfall mm d^{-1}	machine yield kg ha^{-1}	s.d. kg ha^{-1}
20-10	89	0	4	4.2	2120	277
22-10	91	2	2	0.0	2193	333
24-10	93	4	3	0.6	2013	232
27-10	96	7	2	2.5	2047	183
29-10	98	9	2	0.0	2052	222
31-10	100	11	4	0.0	2010	274

Experiment 1983.

Groundnuts were planted on november 14 and december 3, 1982 in three replicates each with seven beds of four plant rows, 90 m long. One bed in each replication was reserved for adjusting and running in of the harvesting machinery. Weed and disease control as practised in the experiment of 1980 were adequate.
It was intended to dig one bed in each replication at weekly intervals, because of adverse weather conditions this scheme could not be maintained. Each bed of windrowed plants was divided into four subplots to allow further differentiation in field curing time. Threshing was done with a Cecocco type machine mounted on a wagon and plants were lifted by hand with a fork from the windrow and moved into the machine. Weather conditions and limitations of

the machine regarding handling green foliage did not allow to follow the intended field curing periods of 4 and 11 days. To determine the digging loss a length of 1 m of each bed was dug by hand and searched after passage of the digging machine.
Harvesting was started february 21, 99 dap, and march 18, 105 dap, for the first and second planting respectively. The experiment was abandoned around mid april because of adverse, too wet, conditions.

Results

The machine yield and digging losses are presented in table 31.

With multiple regression analyses allowing

days digging postponement	dd
days in the windrow	dw
planting date	p1, p2
and subplot number	f1, f2, f3, f4

as independent variables the following relationship was obtained.

Table 31. Groundnut, average machine yields and digging losses, experiment 1983.

digging date	dap	delay days	field drying days	rainfall* mm d^{-1}	machine yield kg ha^{-1}	s.d. kg ha^{-1}	digging loss kg ha^{-1}	s.d. kg ha^{-1}
21 feb	99	0	8	11.3	2818	458	280	23
			9	10.8	2748	443		
24 feb	102	3	6	8.3	3067	379	306	40
			12	9.4	2088	235		
4 mar	110	11	4	2.7	2659	627	571	106
			12	2.2	2724	558		
11 mar	117	18	5	.9	2366	860	379	87
			17	4.1	848	486		
18 mar	124	25	10	6.3	2510	615	496	112
			19	6.8	879	521		
28 mar	134	35	9	7.5	1063	599	1271	212
18 mar	105	0	10	6.3	2693	17	479	173
			19	6.8	1867	654		
			26	8.1	362	33		
28 mar	115	10	9	7.5	3247	460	617	344
			16	9.4	2614	101		

* average rainfall during field drying period.

timeliness

$$\text{machine yield} = 3312 - 1.18\ dd^2 - 4.78\ dw^2 + (511\ p2 - 87.9\ f2 - 212\ f3 - 606\ f4)\ \text{kg ha}^{-1} \quad (4.7)$$

$$r = 0.84$$

$$rms = 542.3\ \text{kg}$$

The collected digging losses increase linearly with digging delay during the early delay period.

4.8.2 Conclusions

When harvesting a diseased crop , the machine yield decreases rapidly with postponement of digging and during field curing. Such crops should be harvested as soon as significant dying off occurs. For a crop not affected by foliar diseases initial postponement of digging beyond the date at which 75 percent of pods show dark colouration at the inside of the hulls results in minor yield reductions. This finding is also confirmed by results of planting date experiments carried out at Coebiti when plots were divided in two parts and harvested at an interval of one week (unpublished data, Wienk). The data

Table 32. Groundnuts, relative machine yields at different digging delays.

digging delay days	0	10	20
		relative machine yield %	
Young	100	96	86.8
experiment 1980	100	95	
experiment 1983 *	100	95.6-96.9	82.6-87.2

* calculated with formula 4.4

obtained in the latter two groundnut harvesting experiments are comparable with average data reported by Young et al (1982) from harvesting studies with Florigiant and NC5 varieties in the USA, vide table 32.
The data reported by Young also show that the highest yield can only be obtained within a short period and that too early diggings result in yield losses comparable to those occuring when digging is postponed. With the recommended field curing period of two days (C.E.S 1979) losses during curing will be insignificant. A rapid increase with time was observed in the 1983 experiment. The very wet conditions during this experiment, apart from the amount of rain there were only 7 dry days in the experimental period from february 21 till march 13, are possibly the significant reason.

CHAPTER 5

PROSPECTS FOR MECHANIZED FARMING

The investigations reported in foregoing chapters concern important aspects for consideration in the planning of mechanized farming activities in the Zanderij area. To obtain information on prospects for mechanized farming of rainfed crops in this area a simple two crop system was formulated. This system was evaluated in a linear programming model, applying the information obtained in the investigations.

5.1 DESCRIPTION OF THE MODEL

The model describes a hypothetical farm in the Zanderij area growing maize and groundnuts. The farm is fully mechanized and the farmer carries out all the field work without additional labour, except for combine operations. The model maximizes the difference between revenues and costs and the size of the farm is a result of the maximization. The activities and state reports are based on periods of one week.

Cultural practice

For the growing of maize conventional tillage, permanent no tillage and incidental no tillage are allowed. An incidental no-tillage cycle for maize can only be applied after groundnuts or maize under conventional tillage. Groundnuts are grown under conventional tillage and only in rotation with maize. The cultural practices for the cropping system as included in the model are presented in table 33 and reflect experience obtained in the LH/UvS research project.

Workable time

The available working time of the farmer is limited to 63 hr wk^{-1}, this includes overtime and work on saturdays. National holidays are accounted for.

Table 33a. Cultural practice for growing maize under conventional tillage.

cultural practice	operation	time of application
stubble tillage	mowing	maximum one week before ploughing
primary tillage	disc ploughing	maximum one week before harrowing
secondary tillage	harrowing	in the same week as planting
planting	planting	
weed control	spraying	in the same week as planting
fertilizing	side dressing	with planting
	broadcasting	2 and 4 weeks after planting
pest control	spraying	2 weeks after planting
harvesting	combining	15, 16 or 17 weeks after planting
	transport	
drying	drying	immediately after harvesting

Table 33b. Cultural practice for growing maize under no-tillage.

cultural practice	operation	time of application
stubble tillage	mowing	maximum one week before planting
planting	planting	
weed control	spraying	in the same week as planting
fertilizing	side dressing	with planting
	broadcasting	2 and 4 weeks after planting
pest control	spraying	2 weeks after planting
harvesting	combining	15, 16 or 17 weeks after planting
	transport	
drying	drying	immediately after harvesting

Table 33c. Cultural practice for growing groundnuts.

cultural practice	operation	time of application
stubble tillage	mowing	maximum one week before ploughing
primary tillage	disc ploughing	maximum one week before harrowing
fertilizing	broadcasting	in the same week as planting
secondary tillage	harrowing	in the same week as planting
planting	planting	
weed control	spraying	in the same week as planting
disease control	spraying	4, 6, 8, 10 and 12 weeks after planting
harvesting	digging	14, 15 or 16 weeks after planting
	combining	0, 1 or 2 weeks after digging
	transport	
drying	drying	immediately after harvesting

Any of these hours can be spent on a field operation if conditions are workable for that operation. As the farmer is the only operator, field operations are carried out one by one, except for combining and grain transport.

The model recognizes three main workability classes in respect to moisture content of the 0-0.20 m soil layer.

Class I, soil moisture content of a stubble field is below 10.3 percent wb, under this condition it is too dry for disc ploughing and on the basis of practical experience it is also considered to be too dry for groundnut digging. Planting, although possible, is not allowed under this condition to avoid the risk of unsatisfactory germination. Other field operations are possible in respect to soil moisture content.

Class II, soil moisture content of a stubble field is equal or higher than 10.3 percent wb and of a ploughed field equal or lower than 13.2 percent wb. When this condition applies all field operations are possible as far as soil moisture content is concerned.

Class III, soil moisture content of a ploughed field higher than 13.2 percent wb and of a stubble field equal or lower than 13.9 percent wb. In this workability class conditions are too wet for harrowing and based on practical experience, planting on a tilled soil and combining of groundnuts are considered not to be possible. Other operations including direct planting are possible as far as soil moisture content is concerned.

The limiting values of soil moisture content for the workability classes are those discussed in paragraph 3.2.4. and 3.4.1.

The workable hours per week in a class are calculated on the basis of a 25 year meteorological record as discussed in paragraph 3.4.1 and 3.4.2. The average workable time per week for an operation is the sum of the workable hours in those classes wherein the operation can be carried out. For calculations with percentils the procedure is as follows. For class II, in which all field operations can be performed as far as soil moisture content is concerned, the x-percentil value (p-x) is calculated for the 25 year period. Harrowing can be done in class I and II and (p-x) is calculated for the combination of these classes. For ploughing and operations with the same limitation for soil moisture, (p-x) of the combination of classes II and III is calculated. The percentil values for workable hours in the three main workability classes I, II and III as used in the model are

$$p\text{-}x(I+II) - p\text{-}x(II) \ ,\ p\text{-}x(II) \text{ and } p\text{-}x(II+III) - p\text{-}x(II).$$

Within the three main workability classes workable time for the harvesting operations occurs. The average number of workable hours per week for combine harvesting of maize in the first week and in the second week after maturity are comparable with differences not larger than 1 hour per week. The same holds true for the p-20 values. It is therefore possible to treat combine harvesting of maize in different weeks after maturity as one workability class, this also limits the size of the model.

There are separate workability classes for the combining of groundnuts in the first and in the second week after digging, because the numbers of workable

hours in these periods differ too much. Workable hours in these classes are also suitable for maize harvesting.
The three main workability classes in respect to soil moisture are each divided in subclasses A, B, C and D for harvesting. In subclass A all combine operations are possible, in subclass B maize can be combined and also groundnuts in the second week after digging. In subclass C only maize can be combined and in subclass D combining is not possible.
The percentil values of workable time for harvesting are calculated for the three main workability classes following the same procedures as for tillage operations.
On the basis of foregoing there are ten workability classes for a farm where maize and groundnuts are grown. The field operations considered in the model and the workability classes in which they can be performed are presented in table 34.

Table 34. Field operations and their respective workability classes.

	workability class									
	I				II				III	
field operation	A	B	C	D	A	B	C	D	C	D
mowing	*	*	*	*	*	*	*	*	*	*
fertilizer spreading	*	*	*	*	*	*	*	*	*	*
spraying	*	*	*	*	*	*	*	*	*	*
harrowing	*	*	*	*	*	*	*	*		
ploughing					*	*	*	*	*	*
no-tillage planting					*	*	*	*	*	*
groundnut digging					*	*	*	*	*	*
planting on tilled soil					*	*	*	*		
maize combining	*	*	*		*	*	*		*	
groundnut combining 1)	*	*			*	*				
groundnut combining 2)	*				*					

1) 2) one respectively two weeks after digging.

Timeliness of planting

A timeliness function for maize planting was obtained as is described in paragraph 4.3. In the model the p-25 yield level as function of planting time was used and this reletionship is shown in figure 27. Efforts to obtain a timeliness function for groundnut planting with a crop production model were not successful. Groundnut yields obtained in various experiments in the LH/UvS project were therefore evaluated to obtain a representation for a planting date yield relation. The data in figure 30 refer to experiments done in the years 1979-1983 when adequate control of foliar diseases was practised. The experiments show that the yield of groundnuts planted during the SRS can be as high as for plantings in the LRS. There are no data

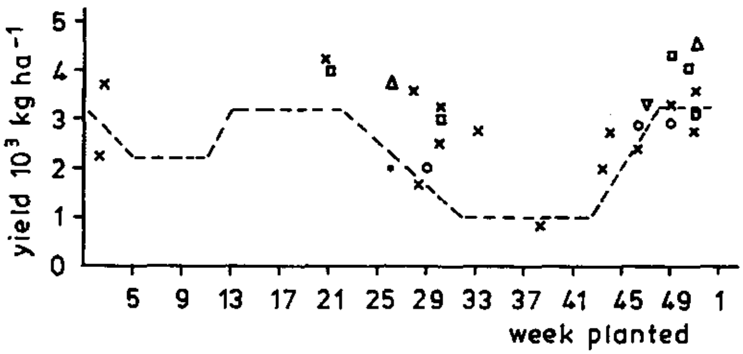


Figure 30. Groundnut yields obtained in experiments at Coebiti 1979-1983. Unpublished data, x J.F. Wienk, • R.L. Poels, □ K.E. Neering, o D.Goense, △ A.P. Everaarts, ▽ O. Boxman.

available for plantings in the SDS. Considering the sensitivity of groundnuts to dryness in the early growth stage, lower yields are expected for that planting period (Boote et al.,1982; Gillier and Silvestre, 1969; Weiss, 1983). With this limited information the planting date yield relation was approximated as presented in figure 30.

Timeliness of harvesting

The timeliness function for maize harvesting was calculated indirectly from the course of grain moisture content with time. The grain moisture content

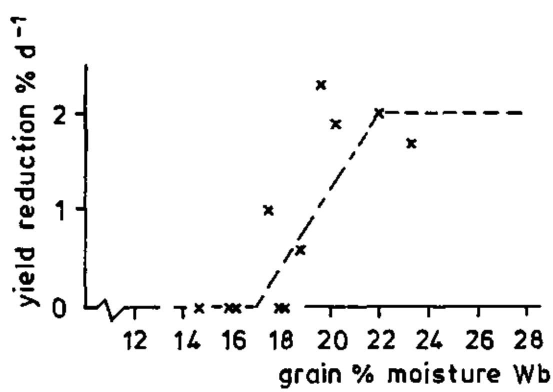


Figure 31. Maize harvesting, reduction of machine yield in % of initial yield, per day of postponement, as function of the grain moisture content.

during the first two weeks after maturity was calculated as described in paragraph 3.6.2. The relationship between average grain moisture content and the average daily decrease in machine yield for harvesting intervals was obtained from experiments reported in paragraph 4.6.2. and is shown in figure 31. The yield reductions for each day obtained with this relation, were accumulated for periods of one week and averaged for the 25 year period. The average yield reduction for the first and second week after maturity for each of 52 weeks were included in the model to represent the timeliness function for maize harvesting.
Timeliness of groundnut harvesting was presented with the relationship described in paragraph 4.7.

Farm equipment

The equipment available to operate the farm is detailed in table 35. Equipment is owned by the farmer with the exception of combines and grain drying equipment which are available from a service organisation.

To perform the field operations at the appropriate time a gang or combination of gangs must be available. A gang is defined as a set of elements, consisting of men and machinery (Van Elderen, 1977). Field operations are, with exception of harvesting operations, carried out by the farmer and

Table 35. Farm equipment, estimated capital cost, useful life and maintanance cost.

machine	list price[1] Sfl	useful life[2] years	operating hrs	life repair[2] % list price
2 wheel drive tractor 55 kW	30,000	10	10,000	120
mower	6,000	10	2,000	150
plough	4,000	12	2,000	150
spring tooth harrow	4,000	12	2,000	80
groundnut planter	10,000	12	1,200	80
maize planter	18,000	12	1,200	80
fertilizer spreader	2,500	10	1,200	120
tractor mounted sprayer	8,000	10	1,500	70
digger shaker[3]	11,000	10	2,000	60
wagon	8,000	15	3,000	80
combine for maize	125,000	10	2,000	50
groundnut combine	45,000	10	2,000	50

1) Suriname 1983
2) ASAE, 1986
3) estimated

appropriate equipment. Harvesting is done with one combination of two gangs, the combine and operator, and the farmer and grain transport equipment.
Task times are calculated for fields measuring 100 x 300 m, the average distance between fields and farm is taken at 500 m and between fields and the drying bins at 3500 m (table 36).
The fuel consumption of a tractor operating under heavy load conditions like ploughing is comparable with the fuel consumption at fifty percent of maximum load as measured in tractor tests (Hauck et al., 1983). Taking this as a reference, average tractor loadings for other operations were estimated and the fuel consumption per operating hour was obtained from the fuel consumption - engine load characteristic of a typical 55 kW tractor. The fuel consumption per hour task time was obtained by multiplication of above mentioned value with the fraction engine running time - task time. Lubricating oil is not accounted for separately but included in the fuel price.
For owned equipment straight line depreciation over the life time of the equipment is included in the model as a fixed yearly charge. Maintenance costs are charged at hourly rates in accordance with the data in table 35. The model does not allow limitations in the availability of machinery owned by the farmer.
Service charges for harvesting include labour, maintenance and fuel cost per hour as derived from tables 34 and 35. Combine capacity to be available for the farmer results from the maximization and depreciation is charged accordingly. Contractor overhead is charged at a rate of 10 percent on the depreciation and maintenance charges.

Table 36. Farm equipment capacities and fuel consumption.

gang			effective working width m	working speed km hr^{-1}	task[1] time hr	fuel consumption l tasktime hr^{-1}
farmer	+ tractor	+ mower	1.8	7	1.32	7.4
,,	+ ,,	+ plough	0.9	6	3.29	8.2
,,	+ ,,	+ harrow	2.8	7	0.92	6.9
,,	+ ,,	+ m planter	3.0	6	1.51	5.9
,,	+ ,,	+ g planter	2.0	6	2.01	5.6
,,	+ ,,	+ sprayer	12.0	6	0.69	4.0
,,	+ ,,	+ spreader	8.0	6	0.72	3.7
,,	+ ,,	+ digger	2.0	5	1.80	6.8
,,	+ ,,	+ wagon (g)			0.93	2.9
operator	+ ,,	+ g combine	2.0	5	2x2.42	6.4
farmer	+ ,,	+ wagon (m)			0.55	2.7
operator		+ m combine	3.0	6	2x1.52	10.5

1) IMAG56: Task times for field work, IMAG-Dataservice, Wageningen

prospects for mechanized farming

Grain drying

The model calculations show that the maize and groundnuts as harvested need to be dried for safe storage. It is assumed that bin drying is applied. This method is used in Suriname for rice drying and is recommended for groundnut drying.
If available drying capacity should not limit harvesting operations and allowing 48 hours drying time, the drying capacity available at the service organisation should equal two days maximum production per combine,

maize 2 x 10 x 4600 x 1/1.5 = 61.333 kg combine^{-1}, bin surface 175 m^2
groundnut 2 x 10 x 3250 x 1/2.4 = 27,083 kg combine^{-1}, bin surface 90 m^2

Investment costs for drying are estimated at Sfl. 1000,- m^{-2} (Suriname 1983). The yearly charge to cover depreciation and maintenance is calculated at Sfl. 118 m^{-2}. Drying capacity to be available for the farmer results from the maximization and depreciation is charged accordingly.
The energy required for drying is calculated in terms of dieseloil in dependence of moisture content and charged per quantity of product. For drying of groundnuts to 10 percent wb energy requirements are calculated according Blankenship and Chew as quoted by Young (1982) .

$$TEU = 1.786\ m_o - 17.536 \quad kWh\ Mg^{-1}$$
$$TGU = 2.994\ m_o - 21.902 \quad l\ Mg^{-1}$$

TEU = total electricity used
TGU = total LP gas used
m_o = initial moisture content.

For maize drying to 15.5 percent wb energy requirements are calculated from data presented by Loewer et al. (1984) for medium speed batch in bin drying.

Initial moisture content	MJ kg^{-1} water
30 %	4.08
26 %	4.15
22 %	4.38
18 %	5.26

Cost and sundries

It is assumed that materials handling, upkeep of field borders and buildings, and maintenance of machinery, in as far as not included in the task times for field operations, are carried out by the farmer when no field work is possible or available.
Prices and costs, excluding product prices, as used in the model are based on conditions in Suriname in 1983.

Costs of seed, fertilisers and chemicals		
to grow maize under conventional tillage	Sfl.	807.-- ha^{-1}
to grow maize under no tillage	Sfl.	857.-- ha^{-1}
to grow groundnuts	Sfl.	1109.-- ha^{-1}
Operating labour of the service organisation	Sfl.	9.40 hr^{-1}
Diesel fuel including surcharge for lubricating oil	Sfl.	0.70 l^{-1}

Land rent Sfl. 50 ha^{-1}

5.2 RESULTS

The linear programming model maximizes the difference between proceeds from sales of dried maize and groundnut and the cost of production. The production cost includes all variable costs, land rent and depreciation charges for equipment and drying facilities. The obtained balance is available for interest on employed capital, overhead costs and income of the farmer and taxes. The effects of variations in certain parameters on the operation and obtained balance of the model farm are established in comparisons with a reference case. The parameters considered are, product prices, yield of maize under no tillage, timeliness cost of harvesting, land rent and available workable time.

Reference case

The reference case is calculated with the description and data as discussed before and:
- Price for maize: Sfl. 0.50 kg^{-1}.
- Price for groundnuts: Sfl. 0.90 kg^{-1}.
- Yield of maize produced under incidental no tillage: 85 percent of the yield obtained under conventional tillage.
- Yield of maize produced under continuous no tillage: 75 percent of the yield obtained under conventional tillage.
- Workable time: 20 percentil values.

Table 37. Main characteristics of the reference case.

area ha				combines		drying	balance
maize ct	maize nt	grndn	land	maize	grndn	capacity m^2	Sfl yr^{-1}
7.2	25.1	32.2	34.4	0.17	1.00	64	31,469

grndn = groundnut
maize ct = maize under conventional tillage
maize nt = maize under incidental no-tillage

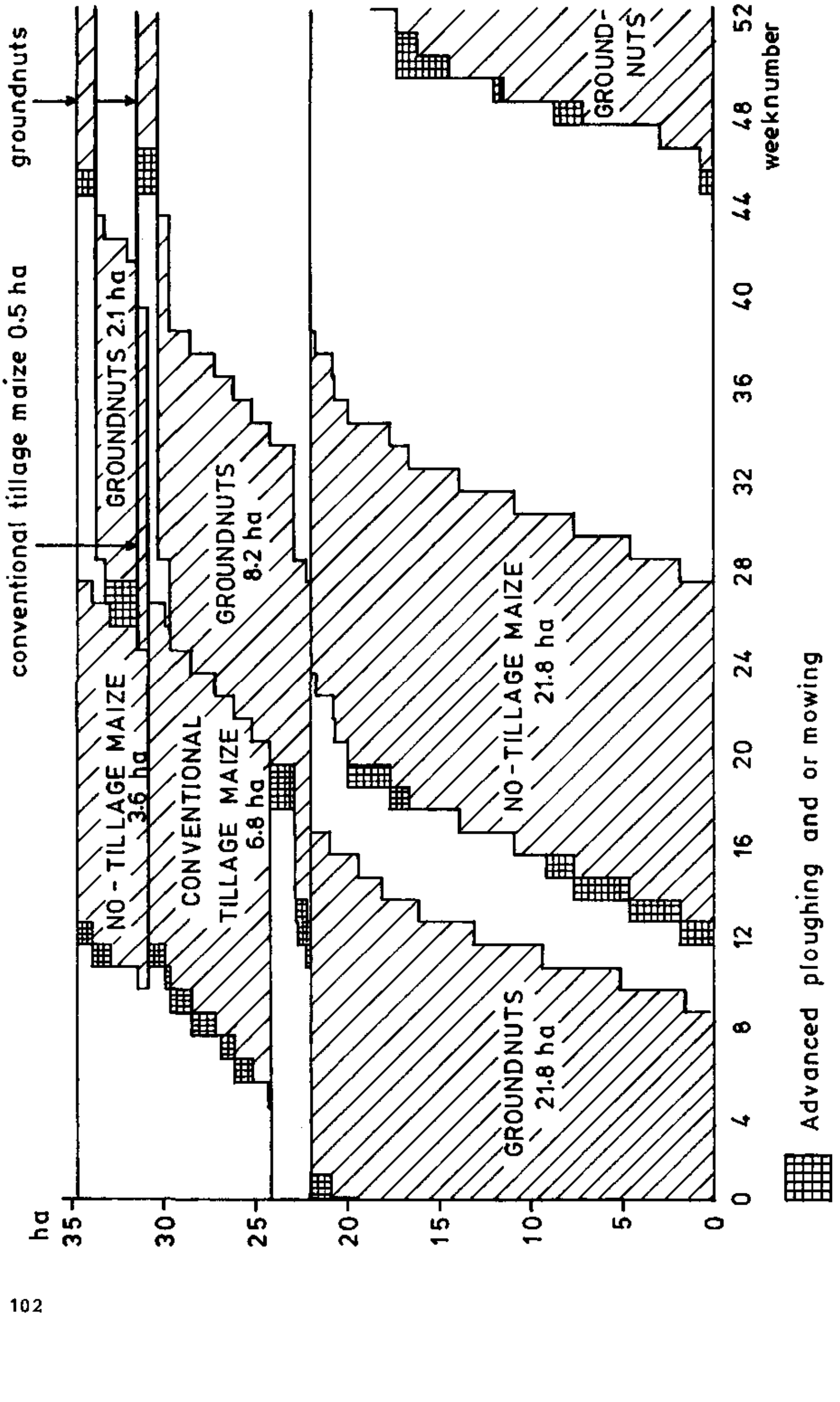


Figure 32. Land utilization for the reference case.

Table 38. Shadow prices for workable hours per workability class and per week for the reference case.

	class									
week	IA	IB	IC	ID	IIA	IIB	IIC	IID	IIIC	IIID
1	-	-	0.0	0.0	-	-	246.6	246.6	0.0	0.0
2	-	0.0	0.0	0.0	-	-	-	143.7	0.0	0.0
9	-	0.0	0.0	0.0	-	-	77.1	77.1	77.1	77.1
10	-	0.0	0.0	0.0	-	-	84.1	84.1	84.1	84.1
11	-	0.0	0.0	0.0	-	-	85.5	85.5	85.5	85.5
12	-	0.0	0.0	0.0	-	-	85.5	85.5	85.5	85.5
13	-	90.1	90.1	90.1	-	-	133.6	133.6	133.6	133.6
14	-	98.1	98.1	98.1	-	-	98.1	98.1	98.1	98.1
15	-	189.9	154.0	154.0	-	-	154.0	-	154.0	154.0
16	-	154.0	154.0	154.0	-	-	154.0	154.0	154.0	154.0
17	-	151.0	151.0	151.0	-	-	151.0	151.0	151.0	151.0
18	-	147.4	147.4	147.4	-	-	147.4	147.4	147.4	147.4
19	-	-	152.4	152.4	-	-	152.4	152.4	152.4	152.4
20	-	-	152.8	-	-	-	152.8	152.8	152.8	152.8
21	-	-	-	-	-	-	180.3	180.3	143.1	143.1
22	-	-	-	-	-	-	240.8	240.8	117.8	117.8
23	-	-	-	-	-	-	243.8	243.8	87.2	87.2
24	-	-	-	-	-	-	254.7	254.7	45.2	45.2
25	-	-	-	-	-	-	12.9	12.9	12.9	12.9
39	0.0	0.0	-	0.0	-	417.7	-	417.7	-	-
42	0.0	0.0	-	0.0	-	-	-	295.6	-	-
43	0.0	0.0	0.0	0.0	-	-	-	275.9	-	-
44	0.0	0.0	0.0	0.0	-	-	-	123.4	-	-
45	0.0	0.0	-	0.0	-	-	70.8	70.8	-	-
46	0.0	0.0	0.0	0.0	-	-	116.8	116.8	-	-
47	0.0	0.0	0.0	0.0	-	-	116.8	116.8	116.8	116.8
48	0.0	0.0	-	0.0	-	-	55.2	55.2	55.2	55.2

Weeks with shadowprices equal 0.0 in all classes are omitted, - indicates no shadow price is calculated because constraints without workable hours were omitted from the LP matrix.

prospects for mechanized farming

The farmer can cultivate 34.4 ha of land with a cropping index of 1.88. The average yield for groundnuts is 2840 kg ha^{-1} and 3470 kg ha^{-1} for maize. The use of land is schematized in figure 32. Groundnuts are mainly grown in the short rainy season and maize in the long rainy season. Maize is planted under both conventional tillage and incidental no tillage. The option to plant maize under continuous no tillage is not used. Available workable time in the opportune periods is limiting the operation of the farm, as is shown by the shadow prices for incremental workable hours presented in table 38.
Maize is harvested in the first week after maturity. Groundnut digging is postponed for 2.2 ha, 9.4 ha are combined in the first week after digging and 22.8 ha in the second week after digging. The farmer uses 1.0 combine for groundnuts, 0.17 combine for maize and 64 m^2 drying floor capacity.
The farmer is 795 hrs occupied with field operations proper, the distribution of these hours over the year is shown in figure 33.

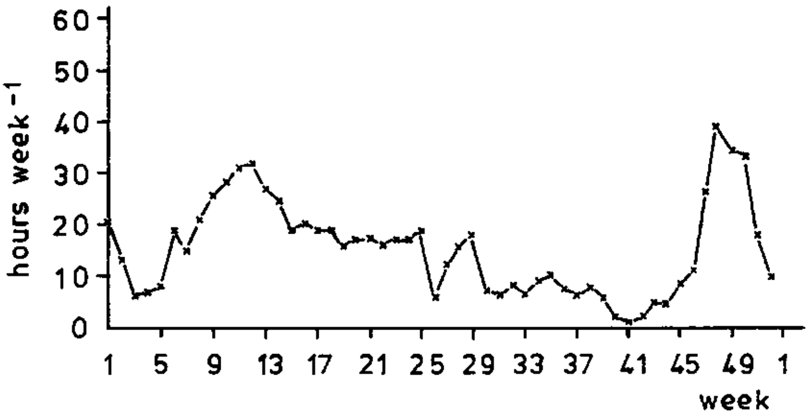


Figure 33. Hours per week spent by the farmer on fieldwork on the model farm with p-20 values for workable time.

Prices for maize and groundnuts

The prices obtainable for maize and groundnuts will be based on objectives and considerations that are no part of this study. Sensitivities regarding product prices in a practical range were therefore carried out.

The area planted with groundnuts decreases with lower groundnut prices. The restriction that groundnuts can only be grown in rotation with maize determines the area planted with maize as long as the price of groundnuts is relatively high. At a relatively low price of groundnuts more maize is planted and relatively more under conventional tillage.

Table 39. Effect of product price changes.

prices Sfl kg^{-1} maize	grndn	area ha maize ct	maize nt	grndn	land	cropping index	balance Sfl yr^{-1}
.65	1.35	20.1	19.1	39.4	37.6	2.09	93,519
.50	1.00	7.8	26.0	33.5	33.9	1.98	40,781
*.50	.90	7.2	25.1	32.2	34.4	1.88	31,469
.50	.80	11.4	28.8	21.9	39.7	1.56	23,348
.40	.80	9.6	17.7	27.3	32.9	1.65	12,568

* reference case

Maize yield under no tillage

In the reference case the yield of maize under incidental no tillage was taken at 85 percent of the yield under conventional tillage. The effect of decreasing this to 80 and 75 percent respectively is presented in table 40. Relatively lower yields for no tillage maize production result in a shift

Table40. Effect of change in the yield of maize under no tillage.

yield[1)] %	maize ct wks	maize ct ha	maize nt planted wks	maize nt planted ha	groundnuts wks	groundnuts ha	land ha	balance Sfl yr^{-1}
* 85	6-14	6.8	10-24	25.1	13-14	0.9		
	25	0.5			20-25	6.6		
					28-29	2.8		
					46- 2	21.9		
total		7.2		25.1		32.2	34.4	31,469
80	5-15	10.7	11-19	18.6	13-14	1.1		
	25	0.6	22-24	2.2	18-25	7.8		
					28-29	2.8		
					46- 2	20.4		
total		11.3		20.8		32.0	34.2	29,002
75	5-17	16.0	13-15	4.9				
	25	0.5	19-23	5.4	18-25	9.7		
	44-45	1.4			28	1.7		
	50	0.2			47- 2	17.2		
total		18.1		10.3		28.6	30.1	27,424

1) yield of maize under incidental no tillage as percentage of the yield under conventional tillage.

* reference case

towards conventional tillage for maize. The increase in time required to plant an area with maize forces reduction of the total cropped area. Under the given circumstances incidental no tillage planting of maize continues to be applied, but growing of groundnuts in the short rainy season is reduced because harvesting of these groundnuts is competing for workable time with planting of maize.

Timeliness of maize harvesting

The option to delay harvesting of maize is not chosen in the reference case, where the timeliness cost for harvesting is as discussed in the model description. The results with lower timeliness costs for maize harvesting are shown in table 41.

Table 41. Effects of timeliness cost of maize harvesting.

timeliness	area ha				combines		harvest	balance
cost[1)]	maize ct	maize nt	grndn	land	maize	grndn	delay ha	Sfl yr^{-1}
* 1.0	7.2	25.1	32.2	34.4	0.17	1.00	0.0	31,469
0.5	7.5	24.9	31.9	35.1	0.17	0.78	1.9	31,501
0.0	6.8	25.9	32.4	37.1	0.19	0.78	29.9	32,401

* reference case
1) as fraction of the value in the reference case

Maize combine capacity is not used more efficiently when the timeliness costs for maize harvesting are reduced by 50 percent and the area of maize that is harvested with one week postponement is only 1.9 ha. With minor adjustments of the planting schedules, less groundnut combine capacity is required. There is more flexibility for maize harvesting when timeliness costs for this operation are nihil. The calculations show that in that case 29.9 ha maize are harvested one week late, but changes in cropped area, planting periods and balance are small. The timeliness costs of maize harvesting is of minor influence on the two crop system studied here.

Timeliness of groundnut harvesting

In the reference case 22.8 ha groundnuts are combined in the second week after digging because workable hours for groundnut harvesting in the first week after digging are limited. A lower penalty for postponement of harvesting as compared to the reference case results in a relatively large change in the balance. Changes in planting schedule are small.

Table 42. Effect of timeliness costs of groundnut harvesting.

timeliness costs[1]	area ha maize ct	maize nt	grndn	land	combines maize	grndn	area ha d.d.[2]	c.d.[3]	balance Sfl yr^{-1}
* 1.0	7.2	25.1	32.2	34.4	0.17	1.00	2.2	22.8	31,469
0.5	6.6	25.9	32.5	34.3	0.16	1.00	2.2	24.4	33,461
0.0	6.7	25.8	32.5	34.1	0.15	1.00	2.2	30.3	35,639

* reference case
1) fraction reference case
2) digging delayed
3) combining delayed

Land rent

An increase in the land rent reflects in the balance and results in a more efficient utilization of land. A small shift from no tillage to conventional tillage for the planting of maize occurs, impact of land rent in the investigated range on the cropping pattern is small.

Table43. Effects of change in land rent.

rent Sfl ha^{-1}	area ha maize ct	maize nt	grndn	land	cropping index	balance Sfl yr^{-1}
* 50	7.2	25.1	32.2	34.4	1.88	31,469
200	8.7	24.2	32.5	32.5	2.01	26,389

* reference case

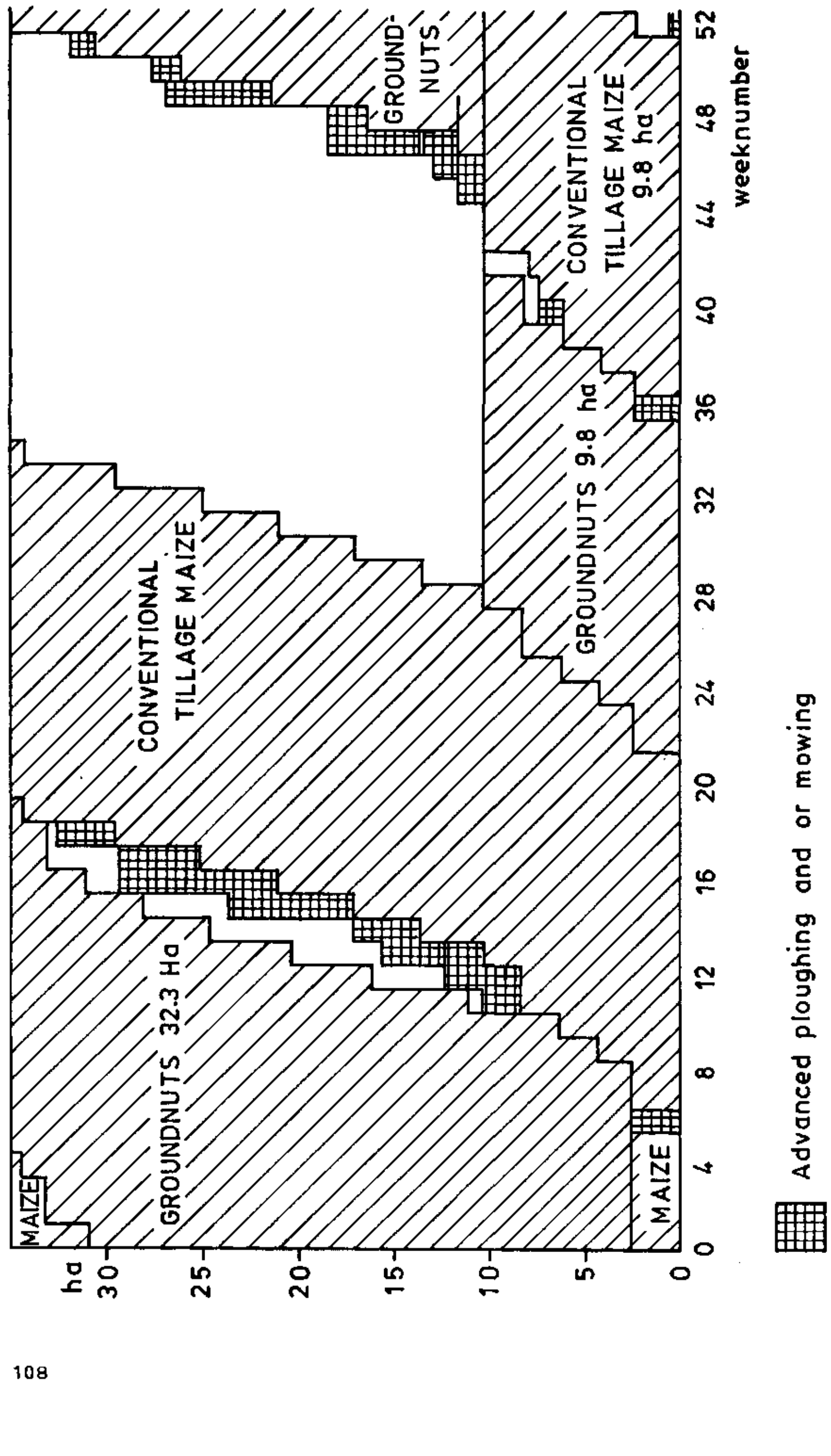
Workable time

Data presented so far are based on the p-20 values for workable time. Results with more workable time, p-50 values, and allowing the same area of land as in the reference case are shown in table 44.

Table 44. Effect of workable time.

workable time	area (ha) maize ct	maize nt	grndn	land	combines maize	grndn	drying capacity m^2	balance Sfl yr^{-1}
* p-20	7.3	25.1	32.2	34.4	0.17	1.00	64	31,469
p-50	43.8		42.1	34.4	0.16	0.45	32	63,876

* reference case



Figrue 34. Land utilization with p-50 values for workable time.

The use of land is presented in figure 34. The cropping index is increased from 1.88 to 2.50. The average yield for groundnuts is 2920 kg ha^{-1} and for maize 3630 kg ha^{-1}. Both are somewhat higher than in the reference case. Groundnuts are mainly grown in the short rainy season and maize in the long rainy season. Compared to the reference case the area grown with groundnuts in the SRS is increased with 10.5 ha of which 9.8 ha are planted after maize, which was planted in the long dry season when low yields are obtained. The main reason for planting maize in this season is the constraint that groundnuts can only be grown in rotation with maize.
With the applied p-50 values, workable time is no longer limiting the cropping system. The shadow pricė for incremental workable hours is 0.0 for all workability classes in all weeks. No tillage planting for maize is no more applied. Maize is harvested in the first week after maturity, groundnut digging is postponed for 0.6 ha and 21.5 ha are combined in the first week after digging and 20.6 in the second week after digging.
More efficient use of contractor services occurs.
The farmer is occupied 1195 hrs for field operations proper.

5.3 CONCLUSIONS

In the reference case with workable time as can be expected in 20 out of 25 years a farmer growing maize and groundnuts in rotation can cultivate about 35 ha land. Maximization calculations indicate that in those years a cropping index of at least 1.9 can be obtained, with average yields of 2840 kg ha^{-1} groundnuts and 3470 kg ha^{-1} maize. This lower limit of the cropping index is determined by the availability of workable time in the opportune periods.
The higher limit of the cropping index is 2.5, and can be obtained with workable time as can be expected in 13 out of 25 years. Average yields obtained in this case are 2920 kg ha^{-1} groundnuts and 3630 kg ha^{-1} maize. The higher limit of the cropping index is not limited by available workable time.

The farmer will be employed 800 - 1200 hr yr^{-1} in field operations proper, this is an acceptable workload, however short term peeks will occur in the SDS and SRS. The utilization of the owned tractor is 800 - 1200 hr yr^{-1}. Utilization data in comparable regions are not available, De Lange (1971) uses for arable farming in the Netherlands standard values of 700 and 1300 hr yr^{-1} respectively for low and high intensity use.

Incidental no tillage planting of maize is useful in alleviating operational constraints because of limitations in workable time.

Timeliness costs of maize harvesting can largely be avoided. A significant part of the groundnuts is however harvested in the second week after digging and timeliness costs are incurred.

prospects for mechanized farming

The farmer operates without foreknowledge of the weather and available workable time. He will therefore not always succeed to reach the minimum crop index and yield as resulting from the maximization. The reported planting schemes provide information for plans and programs. In general the farmer should aim to plant the maximum possible area with groundnuts in the SRS before week 52. Later plantings result in harvesting during a period when workable time can be critical and interference with maize planting can occur. Discipline should be observed with planting of maize before week 11 as available time for harvesting can be limited.

It is concluded that judged by the parameters considered the model type farm is a practicable proposition for the growing of maize and groundnuts in the central part of the Zanderij area in Suriname, provided that socio-economic circumstances allow. A high standard of management is required for the planning and timing of field operations.

SUMMARY

The reported investigations concern aspects of mechanized farming for the production of rainfed crops on the loamy soils of the Zanderij formation in Suriname and in particular, the effect of tillage on crop yield and soil properties, workability of field operations and timeliness of field operations. The results were evaluated as to their effect on prospects for mechanized farming in this area.
The work was carried out within a joint research project of the Agricultural University Wageningen and the University of Suriname.
The soil in the area of investigation is characterized by a low fertility and high acidity. Natural drainage is good but the water holding capacity is low. The climate in the area is classified as Af according to Köppen, the average rainfall is 2234 mm per year.
Experiments carried out on the Coebiti experimental farm during a 9 year period, covering 22 cropping cycles, showed that with continued application of conventional tillage consisting of disc ploughing and harrowing, average crop yields were higher than with successive applications of shallow or no tillage. The yield differences varied with crop and conditions, the yield obtained under no tillage was on average about 75 percent of the yield under conventional tillage for maize, sorghum and cowpea. For soya bean this was 85 percent and for groundnuts 90 percent. Shallow tillage like rotavating showed intermediate results. Comparable results were obtained at the Kabo experimental farm covering 4 cropping cycles. Chisel and disc ploughing showed here little difference. With the applied mechanized farming system soil compaction occurs which can be alleviated by soil tillage. The distribution of added fertilizer in the soil reflects the tillage treatments applied. Periodic deep tillage such as ploughing is required to incorporate lime to the appropriate depth to allow deep rooting. From a series of 6 cropping cycles at Coebiti it is concluded that the yield of a no tillage treatment when alternated with conventional tillage can be higher than those obtained under successive application of no tillage. This indicates possibilities for the application of incidental no tillage when workable time for planting is limited. It is concluded that in a mechanized cropping system on these soils, the approach to soil tillage should be flexible. Disc or chisel ploughing, as well as shallow or no tillage can be selected appropriate to crop and prevailing circumstances of field, weather and work progress.

The limits for workability of disc ploughing and harrowing were determined by measuring the performance of the operations and relating the results to the moisture content of the 0.0-0.20 m soil layer. The maximum soil moisture content for disc ploughing was found to be 13.9 percent wb and for rotary harrowing 13.2 percent wb. It appeared to be too dry for disc ploughing when the moisture content was lower than 10.3 percent wb.

The measured soil moisture contents and pertaining meteorological data were used in development of a soil moisture model formulated with physical proces descriptions from literature. Expectations of workable time for field operations in so far as limited by rain and soil moisture content were calculated with the model on the basis of a 25 year record of meteorological data at Zanderij station.

Workability of grain harvesting is governed by the grain moisture status. In field experiments the course of the grain moisture content and attached moisture was determined for maize, groundnut, soya bean, cowpea and sorghum.
A practical grain moisture model to calculate the grain moisture status in dependence of the weather was formulated and developed with the experimental data and pertaining meteorological data. The hourly course of grain moisture status after maturity was calculated for the 25 year period, allowing calculations of expectations of workable time for harvesting operations with the appropriate limits for grain moisture content.

The timeliness function for maize planting was calculated with an available model of physical crop production (WOFOST). Available data from maize growing experiments in the area were used for calculating site specific parameters and evaluation of the model. With this model yield expectations were calculated on the basis of the 25 year meteorological record.

Harvest date experiments were carried out to establish timeliness functions for harvesting of maize, groundnut, soya bean and sorghum. It appeared that crop stand and weather influenced these functions. For maize timelineness costs of up to 100 kg per day were observed under wet conditions in the initial delay period. Under dry conditions timeliness costs were insignificant for the periods considered. For a healthy groundnut crop timeliness costs could be presented by a quadratic function of delay time. Postponement of digging results initially in minor yield reductions per day, the losses per day in the windrow are about four times as high. On a diseased crop losses were much higher. For sorghum observed timeliness costs were between 1.0 and 1.9 percent of initial machine yield per day of postponement of harvesting beyond the date of maturity. The timeliness costs for soya bean harvesting were small in the first two weeks after maturity and increased sharply with further delay.

The effect of the results of the investigations on the prospects for mechanized farming in the Zanderij area was evaluated with a linear programming model. The evaluation was done for a farm for the cultivation of maize and groundnuts. This farm, equipped with machinery matching a 55 kW tractor, was operated by the farmer on his own except for harvesting operations. Maximization showed that with p-20 values for workable time an area of 35 ha can be cultivated with a cropping index of 1.9. Workable time is limiting farm operations at opportune times and no tillage planting for maize has to be applied for the long rainy season.
The timeliness costs of harvesting had only small effect on the cropping plan. With p-50 values for workable time a cropping index of 2.5 is obtained

in the maximization, in this situation workable time is not limiting farm operations and the option for no tillage planting of maize is not used.
Workable time is a limiting factor for mechanized farming in the Zanderij area and quantified information is essential for planning. The evaluation provides sufficient indications for strategies to follow to make a mechanized farming system practicable.
It is concluded that the model type farm is a practicable proposition, provided socio-economic circumstances allow. A high standard of management is required for the proper planning and timing of the field operations.

SAMENVATTING

Deze studie heeft betrekking op aspecten van gemechaniseerde teelt van niet geïrrigeerde gewassen in het Zanderij gebied van Suriname. Hierin is speciaal aandacht besteed aan systemen voor grondbewerking, het bepalen van werkbare tijd voor het uitvoeren van veldwerk en het effect van het uitvoeringstijdstip van enige veldwerkzaamheden op de gewasopbrengsten.
Het onderzoek is uitgevoerd in het kader van een gemeenschappelijk project van de Landbouw Universiteit Wageningen en de Universiteit van Suriname.
De bodem van het Zanderij gebied wordt gekenmerkt door een geringe bodemvruchtbaarheid en een lage pH. De natuurlijke drainage is goed, maar het waterhoudend vermogen gering.
Het klimaat in dit deel van Suriname, met een gemiddelde neerslag van 2234 mm per jaar kan volgens de klassificatie van Köppen gekarakteriseerd worden als Af, een tropisch regenklimaat.
In een grondbewerkingsproef op de proefboerderij Coebiti, uitgevoerd over een periode van 9 jaar met 22 gewasoccupaties zijn drie systemen van grondbewerking ononderbroken toegepast. Hierin bleek dat bij het continu toepassen van conventionele grondbewerking, bestaande uit schijvenploegen en eggen, de gewasopbrengsten hoger zijn dan met het zonder onderbreking toepassen van ondiepe grondbewerking of vastegrondzaai. De verschillen varieerden met gewas en omstandigheden. De opbrengsten van gewassen met vastegrondzaai waren voor mais, sorghum en cowpea gemiddeld 75 procent van die waarbij diepe grondbewerking werd toegepast. In het geval van soja was dit 80 procent en voor aardnoot 90 procent. De resultaten van ondiepe grondbewerking in de vorm van frezen lagen tussen die van beide eerder genoemde vormen van grondbewerking in.
Vergelijkbare resultaten werden gevonden op de proefboerderij Kabo in een serie van vier gewasoccupaties. In deze proef was er weinig verschil in opbrengst tussen diepe grondbewerking met een schijvenploeg en met een vaste tand cultivator. Met het toegepaste systeem van gemechaniseerde landbouw treedt er compactie van de grond op, die door grondbewerking voor enige tijd kan worden opgeheven. De verdeling van meststoffen in het profiel weerspiegelt de toegepaste vorm van grondbewerking. Om een diepe beworteling mogelijk te maken moet kalk tot op de gewenste diepte worden ingewerkt door zo nu en dan een diepe grondbewerking als ploegen toe te passen. Een serie van 6 gewasoccupaties op Coebiti heeft aangetoond dat de opbrengsten bij vastegrondzaai wanneer dit afgewisseld wordt met diepe grondbewerking, hoger kunnen zijn dan bij continue toepassing. Dit betekent dat er plaats is voor het toepassen van vastegrondzaai op een incidentele basis, wanneer werkbare tijd beperkend is. Er kan geconcludeerd worden dat voor landbouw in het Zanderij gebied een flexibele benadering van de grondbewerking nodig is. Zowel ploegen en cultivateren als ondiep of helemaal niet bewerken kan worden toegepast, afhankelijk van het gewas, de omstandigheden van het perceel, het weer en de voortgang van het werk.

Grenzen voor werkbaarheid van ploegen en eggen zijn bepaald door de kwaliteit van deze bewerkingen te waarderen en de resultaten te vergelijken met gemeten vochtgehaltes van de grond tussen 0,0 en 0,20 m. Als maximum vochtgehalte voor schijvenploegen is 13,9 procent wb gevonden en voor eggen 13,2 procent. Het bleek te droog voor ploegen bij vochtgehaltes beneden 10,3 procent. Met uit de literatuur beschikbare beschrijvingen van het vochttransport in de bodem is een bodemvochtmodel geformuleerd. De waarden voor specifieke parameters zijn met behulp van de gemeten vochtgehaltes en de van toepassing zijnde meteorologische waarnemingen bepaald.

Met het model zijn de bodemvochtgehaltes berekend voor een stoppel en geploegd land over een periode van 25 jaar, gebruik makende van de meteorologische gegevens van het station Zanderij. Op basis van deze bodemvochtgehaltes en uurlijkse meteorologische gegevens zijn verwachtingen voor werkbare tijd geformuleerd voor ploegen, eggen en andere bewerkingen waarvan de werkbare tijd door het bodemvochtgehalte wordt beinvloed.

De werkbare tijd voor het oogsten van granen en peulvruchten wordt bepaald door het korrelvochtgehalte en aanhangend vocht. In proeven met mais, aardnoot, soja, cowpea en sorghum is het verloop van het korrelvochtgehalte en van aanhangend vocht bepaald. Er is een eenvoudig model geformuleerd voor het berekenen van de vochttoestand van het gewas als afhankelijke van de optredende weersomstandigheden. Hierbij zijn de specifieke parameters bepaald door gebruik te maken van de eerder genoemde bepalingen en de meteorologische gegevens uit de waarnemingsperiode. Met het model is voor de vijf gewassen het verloop van het korrelvochtgehalte en aanhangend vocht per uur berekend over een periode van 25 jaar. Aan de hand hiervan zijn verwachtingen opgesteld voor de werkbare tijd voor oogstwerkzaamheden.

Het effect van de zaaidatum op de opbrengst van mais is bepaald met behulp van een beschikbaar gewasgroeimodel (WOFOST) en de meteorologische gegevens over een periode van 25 jaar. Gegevens van in het Zanderij gebied uitgevoerde proeven met mais zijn gebruikt om de voor dit gebied specifieke gewasparameters voor het model te bepalen.

Tijdigheidsfuncties voor het oogsten van mais, aardnoot, sorghum en soja zijn bepaald door het uitvoeren van oogstproeven. Het weer en de stand van het gewas waren van invloed op deze functies. Voor mais werden onder natte omstandigheden aan het begin van de oogstperiode verliezen tot 100 kg per dag gemeten. Onder droge omstandigheden was de toename van de verliezen onbetekenend in de periode waarover de proeven werden uitgevoerd. Voor een gezond gewas aardnoot kan het opbrengstverloop worden weergegeven door een kwadratische functie van het tijdstip van oogsten. Uitstel van het rooien in de eerste weken na afrijping heeft geringe dagelijkse opbrengst verliezen tot gevolg. De verliezen per dag zijn in het zwad ongeveer 4 maal zo groot. Bij een gewas dat was aangetast door ziekten waren de verliezen zeer hoog. De opbrengstverliezen bij uitstel van het oogsten van soja zijn in de eerste weken gering, maar nemen daarna snel toe. Voor sorghum was de opbrengst 1 tot 1,9 procent lager voor elke dag dat oogsten wordt uitgesteld.

De consequenties van de hiervoor genoemde onderzoeksresultaten voor gemechaniseerde landbouw in het Zanderij gebied zijn geëvalueerd door middel van berekeningen met een lineair programmerings model. Hierbij is uitgegaan van een bedrijf voor de verbouw van mais en aardnoot met een machinepark dat is afgestemd op een trekker met een vermogen van 55 kW waarbij de boer alle bewerkingen, behalve oogsten alleen uitvoert. Berekeningen uitgevoerd met hoeveelheden werkbare tijd per week die in 20 van 25 jaar voorkomt geven aan dat 35 ha beteeld kan worden met een gewasindex van 1,9.

De werkbare tijd is in een groot aantal weken een beperkende factor en daarom wordt vastegrondzaai van mais toegepast in de eerste helft van de grote regentijd.
De omvang van de tijdigheidskosten bij oogstuitstel is van geringe invloed op het teeltplan, evenals de hoogte van de grondlasten.
Als bij het zelfde bedrijfsoppervlak wordt gerekend met de werkbare tijd die in 13 van de 25 jaar voorkomt, wordt de mogelijkheid van vastegrondzaai niet meer in het teeltplan opgenomen en wordt de gewasindex 2,5.
Werkbare tijd is een beperkende factor voor een gemechaniseerde bedrijfsvoering in het Zanderij gebied en gequantificeerde informatie is essentieel voor de planning. Deze evaluatie geeft voldoende aanwijzing voor een te volgen strategie die een efficiënte bedrijfsvoering mogelijk maakt.
Er kan geconcludeerd worden dat het landbouwbedrijf zoals beschreven in het model een realistische mogelijkheid is, er van uitgaande dat dit past binnen de sociall economische omstandigheden. Er worden echter hoge eisen gesteld aan de kwaliteit van de bedrijfsvoering voor de planning van de werkzaamheden.

REFERENCES

Anon (1968). Klassificatie der seizoenen. Ministerie van Bouwwerken Verkeer en Waterstaat. Meteorologische Dienst, serie 2, no. 6.

Bandy, D.E. and Sanchez, P.A. (1982). Continuous crop cultivation in acid soils of the Amazon Basin of Peru. In Wienk, J.F. and de Wit, H.A. (eds) Management of low fertility acid soils of the American humid tropics. San José, Costa Rica, 153-175.

Bakema, R.J. (1981). Influence of splitting and rate of fertilizer application on growth and nutrient uptake by maize. Celos rapporten 133, Paramaribo.

Bennema, J. (1982). Acid soils of the humid tropics of South America with special reference to the well drained soils of the old alluvial sediments. In Wienk, J.F. and de Wit, H.A. (eds) Management of low fertility acid soils of the American humid tropics. San José, Costa Rica,105-126.

Byg, D. M. and Johson, W. H. (1970). Reducing soya bean harvest losses. Ohio Rep. Res. Dev. 55:17-18.

Boote K.J.; Stansell, J.R.; Schubert, A.M.; Stone, J.F. (1982). Irrigation, water use and water relations. In Pattee, H.E. and Young, C.T. (eds) Peanut science and technology. Yoakum, American Peanut Research and Education Society.

Cannel, R.Q. (1985). Reduced tillage in N.W. Europe, A Review. Soil Tillage Res. 5:129.

C.E.S. (1977) Growing peanuts in Georgia; a package approach. Cooperative extension service, Georgia.

Crampin, D.J. and Dalton, G.E. (1971). The determination of the moisture content of standing grain from weather records. J. agric. Engng. Res. 16:83.

Curfs, H.P.F. (1976). Systems development in agricultural mechanization with special reference to soil tillage and weed control. Mededelingen Landbouw Hogeschool, Wageningen, The Netherlands 76-5.

De Wit, C.T. and Penning de Vries, F.W.T. (1982). L'analyse des systèmes de production primair. In: La Productivité des pâturages Saheliens. Agr. Res. Rep. 918, Pudoc, Wageningen, 20-23.

De Wit, C.T. (1986). Introduction. In Van Keulen, H. and Wolf, J. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen.

Doorenbos, J. and Pruitt, W. O. (1977). Guidelines for predicting crop water requirements. FAO, Rome.

Driessen, P.M. (1986). In Van Keulen, H. and Wolf, J. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen.

FAO (1981). Agriculture: Toward 2000. Economic and social development series 23 FAO.

Fairbanks, G.E.; Johnson W.H.; Schrock M.D. and Surya Nath. (1979). Grain sorghum harvesting loss study. Transactions ASAE, 22: 246-250.

Fortanier, E.J. (1962). Onderzoek naar mogelijkheden van verbouw van tweede gewassen en boomcultures voor het Wageningen project Suriname.

references

Gillier, P. and Silvestre, P. (1969). l'Arachide. Paris, G.P. Maisonneuve and Larose.

Gonzalez, E. Kamprath, G.C., Naderman, C.C. and Soares, W.V. (1979). Effects of depth of lime incorporation on growth of corn on an oxisol of Central Brasil. Soil Sci. Soc. Amer. Proc. 43: 1155-1158.

Hauck, D.D.; Kucera, H.L.; Salseng, E.G. (1983). North Dakota tractor use study. ASAE paper, 83-1064.

Hokke, G. and Tanis, T. (1978). Onderzoek naar werkbare dagen voor veldwerkzaamheden op akkerbouwbedrijven. IMAG publication 109, Wageningen.

Jansen, B.J. (1973) Een oriënterend onderzoek naar de geschiktheid van mais voor de bepaling van het sufficiency coëfficiënt. CELOS rapporten 76, Paramaribo.

Johnson, W.H.; Lamp, B.J.; Henry, J.E. and Hall G.E. (1963). Corn harvesting performance at various dates. Transactions ASAE, 6: 268-272.

Kamprath, E.J. (1980). Soil acidity in well drained soils of the tropics as a constraint to food production. In priorities for alleviating soil related constraints to food production in the tropics, IRRI, Los Banos, Philippines, 171-188.

Kmoch, H.G. (1961). Die Bestimmung der Luftdurchlässigkeit des Bodens und ihre Bedeutung für einige ackerbaulige Probleme. Bornträger, Berlin.

Koopmans, R.W.R. and Vochteloo, J.J. (1973). Evapotranspiration measurements with a weighable lysimeter in Surinam. De Surinaamse landbouw 21, 2, 62-69.

Lal, R. (1983). No tillage farming. Monograph 2, IITA Ibadan, Nigeria.

Lenseling, K.J. and van der Weert, R. (1973). Estimating free water evaporation in Surinam. De Surinaamse landbouw, 21:2.

Link, D.A. (1962). Research needs for farm machinery scheduling. ASAE publ. Proc. 468.

Lucas, Y. and Boulet, R. (1982). Acid soils of French Guyana. In Wienk, J.F. and de Wit, H.A. (eds) management of low fertility acid soils of the American humid tropics. San José, Costa Rica, 37-48.

Maurya, P.R. and Lal, R. (1979). Effects of bulk density and soil moisture on radicle elongation of some tropical crops. In Lal, R. and Greenland, S.J. (eds). Soil physical properties and crop production in the tropics. Chichester, Wiley and Sons.

Nicou, R. and Chopart, J.L. (1979). Root growth and development in sandy and sandy clay soils of Senegal. In Lal, R. and Greenland, D.J. (eds). Soil physical properties and crop production in the tropics. Chichester, Wiley and Sons.

Penning de Vries, F.W.T. and Van Laar, H.H. (1982). (eds) Simulation of plant growth and crop production. Pudoc Wageningen.

Perdok, U.D. and Hendrikse, L.M. (1982). Workability test procedure for arable land. In Proceedings ninth ISTRO conference Osijek.

Portiek, J.H. (1978). Discussienota. In symposium werkbaarheid en bedrijf te Wageningen, IMAG rapport 1.

Priestley, C.H.B. and Taylor, R.J. (1972). On the assesment of surface heat flux and evaporation using large scale parameters. Mon. Weath. Dev. 100, 21-92.

Quick, G.R. and Buchele, W.F. (1974). Reducing combine gathering losses in soya beans. Transactions ASAE, 17: 1123-1129.

Rijtema, P.E. (1969). An analysis of actual evapotranspiration. Agricultural research reports 659, Pudoc, Wageningen.

Ritchey, J.T. (1972). Model for predicting evaporation from a row crop with incomplete cover. Water Resources Res. 8: 1204.

Rosenberg, S.E.; Rotz, C.A.; Black, J.R. and Muthar, H. (1982). Prediction of suitable days for field work. ASAE paper 82-1032.

Rotz, C.A. and Yi Chen (1985). Alfalfa drying model for the field environment. Transactions ASAE 28-1686.

Ruthenberg, H. (1980). Farming Systems in the tropics. Oxford, Clarendon Press.

Rutledge, P.L. and McHardy, F.V. (1968). The influence of the weather on field tractability in Alberta, Can. Agr. Eng., 10: 70.

Sanchez, P.A. and Cochrane, T.A. (1980). Soil constraints in relation to mayor farming systems of tropical America. In Priorities for Alleviating Soil related constraints for Food Production in the Tropics. IRRI, Los Banos, Philippines, 107-139.

Sanchez, P.A., Nicholaides, J.J. (1982). Plant nutrition in relation to soil constraints in the developing world. Technical advisory committee, FAO.

Selirio, I.S. and Brown, P.M. (1972). Estimation of spring workdays from climatological records, Can. Agr. Eng. 14: 79.

Seubert, C.E. Sanchez, P.A. and Valverde, C. Effects of land clearing methods on soil properties and crop performance in an ultisol of the Amazon Jungle of Peru. Trop. Agric. 54, 307-321.

Slaats, J.J.P. and Ukkerman, H.R. (1983). Influence of split application on uptake and leaching of N and K on maize growth. Internal report, Dept of soil science and plant nutrition, Agric. Univ. Wageningen.

Smith, E.A.; Bailey, P.H. and Ingram, G.W. (1981). Prediction of the field moisture content of mature barley and wheat by commonly used drying equations. J. Agric. Eng. Res. 26: 171.

Stapper, M.; Arkin, G.F. (1979). Simulating maize dry matter accumulation and yield components. ASAE paper 79-4513.

Steele, J.L. and Wright, F.S. (1980). Computer simulation of peanut drying in a windrow. ASAE paper 77 - 3535.

Stengel, P.; Douglas, J.T.; Guérif, J.; Goss, M.J.; Monnier, G. and Cannell, R.Q. (1984). Factors influencing the variation of some properties of soil in relation to their suitability for direct drilling. Soil Tillage Res., 4: 35-50.

Ten Holte, L. (1982). Effects of zero tillage on soil characteristics and crop yields. In Proceedings of the ninth ISTRO conference Osijek.

Thomson, N. (1981). Modelling the field drying of hay. J. Agric. Sci. Camb. 97, 214-260.

Tulu, M.Y. (1974). Timeliness costs and available working days - shelled corn. Transactions ASAE, 17: 798.

Van Elderen, E. (1977). Heuristic strategy for scheduling farm operations. Pudoc, Wageningen.

Van Elderen, E. and Van Hoven, S.P.J.H. (1973). Moisture content of wheat in the harvesting period. J. agric. Engng. Res. 18: 71.

Van den Hengel, J.F.M. (1982) Influence of N, K and Mg application on yields of annual crops. Internal report CELOS.

Van Kampen, J.H. (1969). Optimising harvesting operations on a large scale grain farm. Thesis Wageningen.

Van der Sar, T. (1978). Grondbewerking gericht op de permanente teelt van droge eenjarige gewassen in Suriname, proef in de Stipris proeftuinen te Coebiti. In CELOS rapporten 102, 115 en 125, Universiteit van Suriname.

Vyn, T.J. (1982). Effect of reduced tillage systems on soil physical properties and maize grain yields in Ontario. In Proceedings of the ninth ISTRO conference, Osijek.

Wealti, H.; Buchele, W.F. and Farell, M. (1969). Progress report on losses associated with corn harvesting in Iowa. J. agric. Engng. Res., 14: 134-138.

Waelti, H.; Turnquist, P.K. and Matter, V.E. (1971). Harvesting techniques for reducing grain sorghum losses. Transactions ASAE, 14: 797-800.

Weiss, E.A. (1983). Oil seed crops. Tropical agricultural series, Longman, London.

Wienk, J.F. (1969). A growth analysis of maize and soya bean. Internal report CELOS, Paramaribo.

Williams, D.L. (1978). Field work days in Iowa. Cooperative extension service. Iowa State University, Ames, Iowa.

Wolf, J.; Rijsdijk, F.H.; Van Keulen, H. (1986). A FORTRAN model of crop production. In Van Keulen, H. and Wolf, J. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen.

Young, J.H. (1977) Simulation of peanut drying in inverted windrows. Transactions ASAE, 20: 782.

Young, J.H.; Person, N.K.; Donald, J. and Mayfield, W.D. (1982). Harvesting curing and energy utilization. In Pattee, H.E. and Young, C.T. (eds) Peanut science and technology. Yoakum, American Peanut Research and Education Society.

APPENDIX A

Meteorological data

Meteorological data based on observations at the "klima" station Zanderij are available for the 25 year period from 1958 - 1982. This station is located respectively 42 and 80 km east of the experimental farms Coebiti and Kabo. Meteorological data are also recorded at Coebiti since 1971 and at Kabo since 1979. A comparison between average monthly rainfall at Coebiti and at Zanderij station in the period 1971 - 1983 shows good agreement in seasonal pattern, but average rainfall at Coebiti was lower during the months may - october (figure a1). The rainfall measured in the period 1980 - 1983 at Kabo was not much different in quantity and pattern from the rainfall observed at Coebiti. In this period average rainfall at Zanderij was higher than at Coebiti and Kabo during the months may-august. Rainfall at Kabo was higher than at Coebiti and Zanderij for the months february and march (figure a2).
Considering this comparison and also the fact that comparable suitable data are not available from other stations in the Zanderij area for a long period, it was decided to use the Zanderij station data in long term simulations for the area. Regarding the agricultural experiments carried out at Coebiti use was made of meteorological data observed at the site stations, except for windspeed which was taken from Zanderij station.

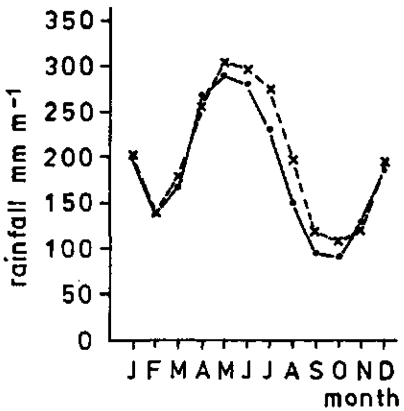


Figure a1.
Average rainfall in mm month^{-1}, 1971-1983.
•——• Coebiti, x--x Zanderij

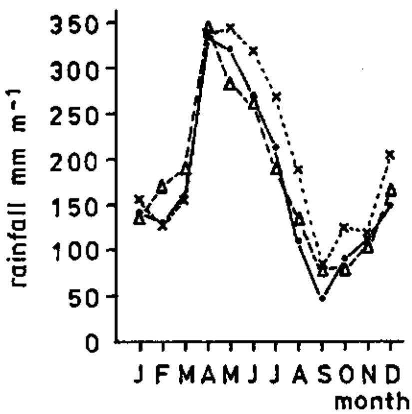


Figure a2.
Average rainfall in mm month^{-1}, 1980-1983.
•——• Coebiti, x--x Zanderij, Δ–Δ Kabo

Treatment of meteorological data

Observations at Zanderij station are normally made at 8.00, 14.00 and 18.00 hr local time as follows;
- wet bulb temperature °C
- dry bulb temperature °C

appendix A

- percentage cloudiness
- precipitation mm
- wind speed (Beaufort)
- wind direction

at 8.00 hr

- maximum temperature previous 24 hrs °C
- minimum temperature previous 24 hrs °C
- sunshine previous 24 hrs, Campbell-Stokes
- class A-pan evaporation mm d^{-1} since 1973.

Averages for temperature, relative humidity, cloudiness and windspeed as presented by the Meteorological Service of Suriname are based on the three observations per day and are thus not averages for a 24 hour day.

For calculations concerning workability of mechanized field operations it is desirable to have hourly data. Such data were not available in an accessible form. For the purpose of this exercise hourly data and 24 hour averages are reconstructed from the available 25 year records with the aid of characterisations of the course of climatological phenomena from hourly observations over short periods.

Temperature

To approximate the average daily temperature and hourly temperatures it is assumed that the minimum temperature occurs at 6.00 hr and the maximum temperature at 13.00 hr. This assumption is in agreement with observations made at Coebiti in the period january - april 1983 (figure a3). The average temperature is then calculated from

$$(7T_{min} +3.5T_8 +3T_{max} +2.5T_{14} +8T_{18})/24 \qquad (a1)$$

Hourly values between measurements are obtained by linear interpolation.

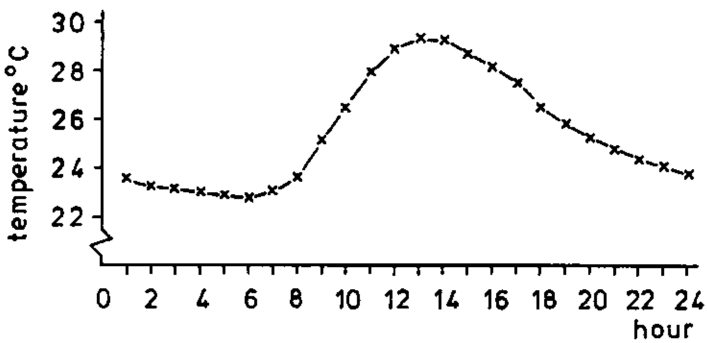


Figure a3. Average hourly temperature, Coebiti january-april 1983.

Relative humidity

Observations at Coebiti during the period january-april 1983 indicated that the minimum relative humidity is reached at 12.00 - 13.00 hr. The maximum relative humidity is about 96 percent and is reached at 24.00 hr and remains at that level till 7.00 hr (figure a4). To calculate an average relative humidity for a 24 hour day the maximum is assumed at 96 percent while it is also assumed that the value measured at 14.00 hr is already reached at 12.00 hr. The average relative humidity is calculated from

$$(10.5RH_{max} + 2.5RH_8 + 6RH_{14} + 5RH_{18})/24 \qquad (a2)$$

Hourly values are obtained by linear interpolation between measured and assumed values as mentioned above.

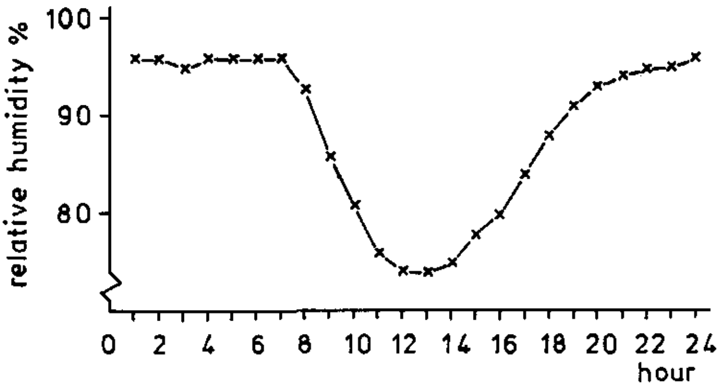


Figure a4. Average hourly relative humidity, Coebiti january-april 1983.

Wind velocity

The wind velocity (W) is calculated from estimates in Beaufort (W_B) according

$$W = 0.83 \times W_B^{1.5} \text{ m s}^{-1} \qquad (a3)$$

From an evaluation of Zanderij data for 1983 it is concluded that the maximum wind velocity is reached at 10.00 hr and continues at this level till 16.00 hr. Hourly wind velocities are calculated from available observations as follows:

06.00 - 08.00	linear interpolation between	0.25 ms^{-1}	- W_8
08.00 - 10.00	,,	W_8	- W_{14}
10.00 - 16.00		W_{14}	
16.00 - 18.00	linear interpolation between	W_{14}	- W_{18}
18.00 - 24.00	,,	W_{18}	- 0.25 ms^{-1}
24.00 - 06.00		0.25 ms^{-1}	

appendix A

Rainfall

To establish hourly rainfall data from the three observations per day a disaggregation procedure is used. For each period between observations the number of hours with 0.1 mm or more rainfall is estimated from cumulative distribution functions. These functions are based on a record of hourly rainfall data for Zanderij station from 1973 - 1980 and are established for eight classes of total rainfall within each period.
The distribution of the number of estimated hours with rainfall over a period is based on the probability of rain for these specific hours. The amount of rain in a period is distributed between the established rain hours proportional to average rainfall in these hours. The differences between the number of recorded rain hours and the number of generated rain hours per day between 07.00 - 18.00 hr show a normal distribution, whilst hours with 0.5 mm rain or more are slightly overpredicted (figure a5, a6).

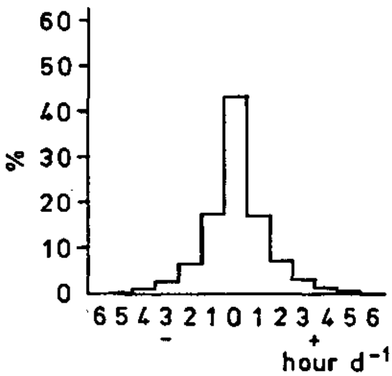


Figure a5. All rain hours

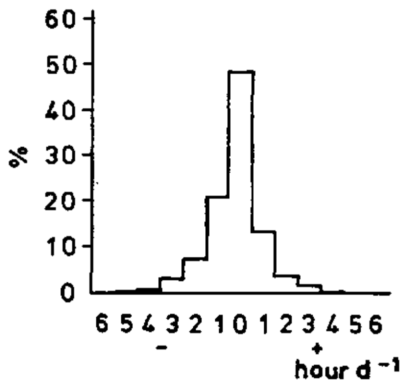


Figure a6. Rain hours $\geq$ 0.5 mm.

Frequency distribution of the difference between observed and generated hours with rain per day between 7.00-18.00 hr., dry days excluded.

Solar radiation

Solar radiation (R_s) is not measured on a routine basis in Suriname, but the relative duration of sunshine is measured according Campbell-Stokes and reported for the ten hour period between 7.00 - 17.00 hr as n/N.
R_s is calculated with the Angström-Prescot formula as follows

$$R_s = (a + b \times n/N)\, R_a \qquad J\ m^{-2}\ s^{-1} \qquad \text{(a4)}$$

R_a = extraterrestrial radiation $J\ m^{-2}\ s^{-1}$
a = 0.28
b = 0.42.

The values for the site specific constants a and b are those determined by Lenselink and van der Weert (1973) for Paramaribo. R_a is calculated for 5^o 36' NL using a solar constant of 1353 J m^{-2} s^{-1}, corrected for seasonal variation in the distance between the earth and the sun.
For disaggregation of the daily values of relative sunshine duration into hourly values it is assumed that there is no sunshine in hours with rain and sunshine duration is equally distributed between the remaining hours without rain. Hourly values of n/N between 17.00 and sunset are assumed to be equal to the average value between 15.00 and 17.00 hr and between sunrise and 7.00 hr equal to the value between 7.00 and 9.00 hr. The fraction cloudiness from sunset-24.00 hr is assumed equal to 1-(n/N 15.00-17.00 hr) and values between 24.00 and sunrise equal to 1-(n/N 7.00-9.00 hr).

Evaporation and evapotranspiration

Several methods are available to calculate free water evaporation, E_o, and potential evapotranspiration of a vegetation, ET_p, from meteorological data. Four such formulae were evaluated for application in the work described in this report. These formulae vary in complexity and meteorological information required. As estimates of windspeed were not available at Coebiti, the formulae proposed by Lenselink and Van der Weert and Priestley and Taylor were included as these do not use windspeed.

Lenselink and Van der Weert (1973)

$$E_o = 2.59 + 4.58 \times n/N \quad \text{mm d}^{-1} \qquad (a5)$$

This equation was obtained by regression analyses of measured values for n/N and values for E_o calculated with the Penman formula. Mean monthly meteorological data for Paramaribo over a 30 year period were used. Application of this formula requires only measured sunshine duration.

Priestley and Taylor (1972)

$$E_o = d/(d+g) \times R_{nt}/59 \quad \text{mm d}^{-1} \qquad (a6)$$

R_{nt} = net radiative flux = $R_s \times (1-r) - R_{nl}$ cal d^{-1} cm^{-2}
59.0 = latent heat of water evaporation cal g^{-1}
r = reflection coefficient (0.05 for water)
R_{nl} = net long wave radiation and calculated with
R_{nl} = $S \times (T+273)^4 (0.56 - 0.092\, e_a^{0.5}) \times (0.1 + 0.9\, n/N)$ cal d^{-1} cm^{-2}
S = 118.10^{-9} cal cm^{-2} day^{-1} $^oK^{-4a}$
T = temperature ^oC
e_a = actual vapour pressure mm Hg
d = slope saturation vapour pressure curve T mm Hg $^oC^{-1}$
e_s = saturated vapour pressure at T mm Hg
g = psygrometer constant 0.485 mm Hg $^oC^{-1}$

The empirical multiplier is set at 1. This method requires in addition to relative sunshine duration temperature and humidity data.

Penman (1956)

The Penman formula is built up of two parts, of which the radiation term is as described above for the Priestley-Taylor formula with in addition an aerodynamic term

$$E_o = d/(d+g) \times R_{nt}/59 + g/(d+g) \times 0.35(0.50 + 0.54W) \times (e_s - e_a) \text{ mm d}^{-1} \quad (a7)$$

W = windvelocity m s^{-1}

Application of the Penman formula requires information on temperature, humidity, sunshine and windspeed.

Doorenbos and Pruitt (1977)

Doorenbos and Pruitt developed two formulae for calculating potential evapotranspiration of a reference crop, ET_r.

The Penman formula with different factors for calculating R_{nl} and a different wind function. (a8)

As above, but with an overall correction factor which is a function of average day wind speed, the ratio of day and nigth wind speed, maximum humidity and evaporative demand from short wave radiation. (a9)

The reference crop is defined as an extensive surface with a 0.08-0.15 m tall grass cover of uniform height, actively growing, completely shading the ground and not short of water, with a reflection factor of 0.25.

Evaporation was calculated with the above mentioned methods and compared with class A pan evaporation data. The calculations were made for the period 1973-1980 with meteorological data from Zanderij station which for that period included class A pan data. Calculated and measured values for a day were each averaged for seven day periods and compared for the following cases.

- 1 Lenselink and van der Weert according a5.
- 2 Priestley Taylor according a6 with average data as reported by the meteorological service.
- 3 Penman according to formula a7
    - 3a with average data as reported by the meteorological service.
    - 3b with average data for a 24 hour period
    - 3c with hourly data.
- 4 Doorenbos and Pruitt
    - 4a according a8 with average data for a 24 hour period
    - 4b according a9 with average data for a 24 hour period.

Table a1. Results of regression analyses between the calculated evaporation, y, and the measured class A pan evaporation, x. Root mean square difference, rms, between the calculated evaporation and the measured A Pan evaporation.

	intercept mm d^{-1}	slope	r	rms mm d^{-1}
1 Lenselink and Van der Weert	3.1	0.48	0.73	1.06
2 Priestley-Taylor	2.8	0.35	0.73	0.80
3a Penman	2.7	0.53	0.78	0.91
3b Penman	2.8	0.45	0.77	0.79
3c Penman	2.8	0.50	0.78	0.87
4a Doorenbos and Pruitt	2.2	0.44	0.78	0.78
4b Doorenbos and Pruitt	2.0	0.57	0.79	0.67

The resuls of these comparisons are presented in table a1. The comparisons were made for 254 periods of 7 successive days for which class A pan evaporation was available. Class A pan values varied between 2 and 7 mm d^{-1}.

Compared with class A pan, the formulae overestimate evaporation in the lower range and underestimate in the higher range, specifically the Priestley and Taylor formula. The better correlations are obtained with the Penman and Doorenbos-Pruitt formulae. The correlations obtained with the Penman equation using average daytime data, average 24 hour data or hourly data are comparable.

Upon this review, appreciating that the evaporation formulae were not intended for periods shorter than one week, it was decided to calculate the hourly course of evaporation with the Penman equation and the hourly weather data as described, for use in calculations concerning workability for tillage and harvesting operations. For calculations with a crop growth model, where time steps of one day are used, the evapotranspiration formula as proposed by Doorenbos and Pruitt with average meteorological data for 24 hours is used.

The area of land occupied with a crop CR:

$$CR_i - \underset{i'}{\text{sum}}\ ZACR_{i'} - \underset{n}{\text{sum}}\ MDCR_{n,i+n} = 0 \quad \text{for all CR,i}$$

i' = i-p , i-p+1 , ... , i
p = length of the growing period of crop CR
$ZACR_{i'}$ = area of crop CR planted in period i'
for n = 0,1,2
n = periods of postponement of harvesting (weeks)
$MDCR_{n,i}$ = area of crop CR harvested in period i

The area of stubble originating from crop CR:

$$STCR_i - STCR_{i-1} - MDCR_i + PLCR_i = 0 \quad \text{for all CR,i}$$

Mowing of a stubble has to be carried out in the same week or n weeks in advance of plowing or no tillage planting.

$$PLCR_i + \underset{CR'}{\text{sum}}\ ZA_{nt}CR'_i - \underset{n}{\text{sum}}\ MOCR_{n,i-n} = 0 \quad \text{for all CR,i}$$

n = 0,1
n = the number of periods that mowing advances the following operations (restricted to 1 week)
CR' is restricted to those crops that can be grown after crop CR
$ZA_{nt}CR$ = area of crop CR planted no-tillage

Ploughing, to be done in the same period or n periods in advance of harrowing.

$$TCCR_i - \underset{n}{\text{sum}}\ PLCR_{n,i-n} = 0 \quad \text{for all CR,i}$$

n = 0,1
n = the number of periods that ploughing advances the following operations (restricted to 1 week)
TCCR = Harrowing of a ploughed field originating from crop CR

Harrowing, to be done in the same period as planting.

$$\underset{CR}{\text{sum}}\ ZACR_i - \underset{CR}{\text{sum}}\ TCCR_i = 0 \quad \text{for all i}$$

and

$$ZACR_i - \sum_{CR'} TCCR'_i \leq 0 \qquad \text{for all } CR, i$$

CR' is restricted to those crops that can be followed in rotation by crop CR

Spraying of a crop.

$$ZACR_i - SPCR_{n,i+n} = 0 \qquad \text{for all } CR, i, \text{specified } n$$

n = number of periods after planting, crop CR has to be sprayed.

Fertilizing of a crop.

$$ZACR_i - KNCR_{n,i+n} = 0 \qquad \text{for all } CR, i, \text{specified } n$$

n = number of periods after planting, crop CR has to be fertilized.

Combine harvesting

$$ZACR_i - \sum_{n} MDCR_{n,i+p+n} = 0 \qquad \text{for all } CR, i$$

MDCR = combine harvesting of crop CR
p = length of normal growing period
n = periods of postponement of harvesting (n = 0,1,2)

Groundnut digging

$$ZAPI_i - \sum_{n} DIPI_{i+p+n} = 0 \qquad \text{for all } i$$

DIPI = digging of groundnut
p = length of the growing period
n = period of postponement of digging (n = 0,1,2)

Groundnut combining

$$DIPI_i - \sum_{n} COPI_{i+n} = 0 \qquad \text{for all } i$$

COPI = Combining of groundnut

n = period of postponement of groundnut combining (n = 0,1,2)

Constraints for combinations

$$\sum_{n}\sum_{CR'} FOCR'_{n,i} - \sum_{l}\sum_{m} WFO_{l,m,i} = 0 \quad \text{for all } i$$

FO = field operation

WFO = combination for field operation FO

l = type of combination

m = workability class in which the combination is available

m is restricted to relevant workability classes (table 34)

Constraint for drying capacity

$$\sum_{CR}\sum_{n} MDCR_{n,i} \times RDR - UDR \leqslant 0 \quad \text{for all } i$$

RDR = required dryer capacity (chapter 5.1)

Constraints for elements

$$TAFO_l \sum\sum WFO_{l,m,i} - WH_{m,i} \times EL \leqslant 0$$ for all i, all relevant m, all EL of the combination

$WH_{m,i}$ = workable hours in workability class m in period i

EL = element

$TAFO_l$ = task time for combination FO_l hr ha^{-1}

Constraints for depriciation of machinery

$$\sum_{EL} EL \times CJEL - TKUE = 0$$

CJEL = fixed cost of machine EL Sfi. yr^{-1}

Energy cost of drying

$$\sum_{i} \sum_{n} \sum_{CR} MDCR_{n,i}\ YICR_{n,i-p-n}\ FU_{cr,mci}\ CFU - TKDR = 0$$

FU_{mci} = fuel required for drying 1 kg grain of crop CR, with moisture content mci

CFU = cost of one unit fuel

Operating cost of machinery

$$\sum_{i} \sum_{l} \sum_{m} WFO_{m,l,i} \times CFO_{l} - TCFO = 0$$

CFO = variable cost of combination

CURICULUM VITAE

The author was born in Blijham in 1950. Upon completing secondary school at the St Dominicus college in Nijmegen, he studied at the Agricultural University in Wageningen and graduated in 1976 with agricultural machinery as main subject and engineering and mathematics as secondary subjects. After working one year with Essochem Belgium he joined the Department of Agricultural Engineering of the Agricultural University in Wageningen in 1977. From april 1978 till the end of 1983 the author was assigned to the research project "Permanent cultivation of rainfed annual crops on the loamy soils of the Zanderij formation" in Suriname. The author is now lecturer at the Agricultural University of Wageningen in the Department of Agricultural Engineering.