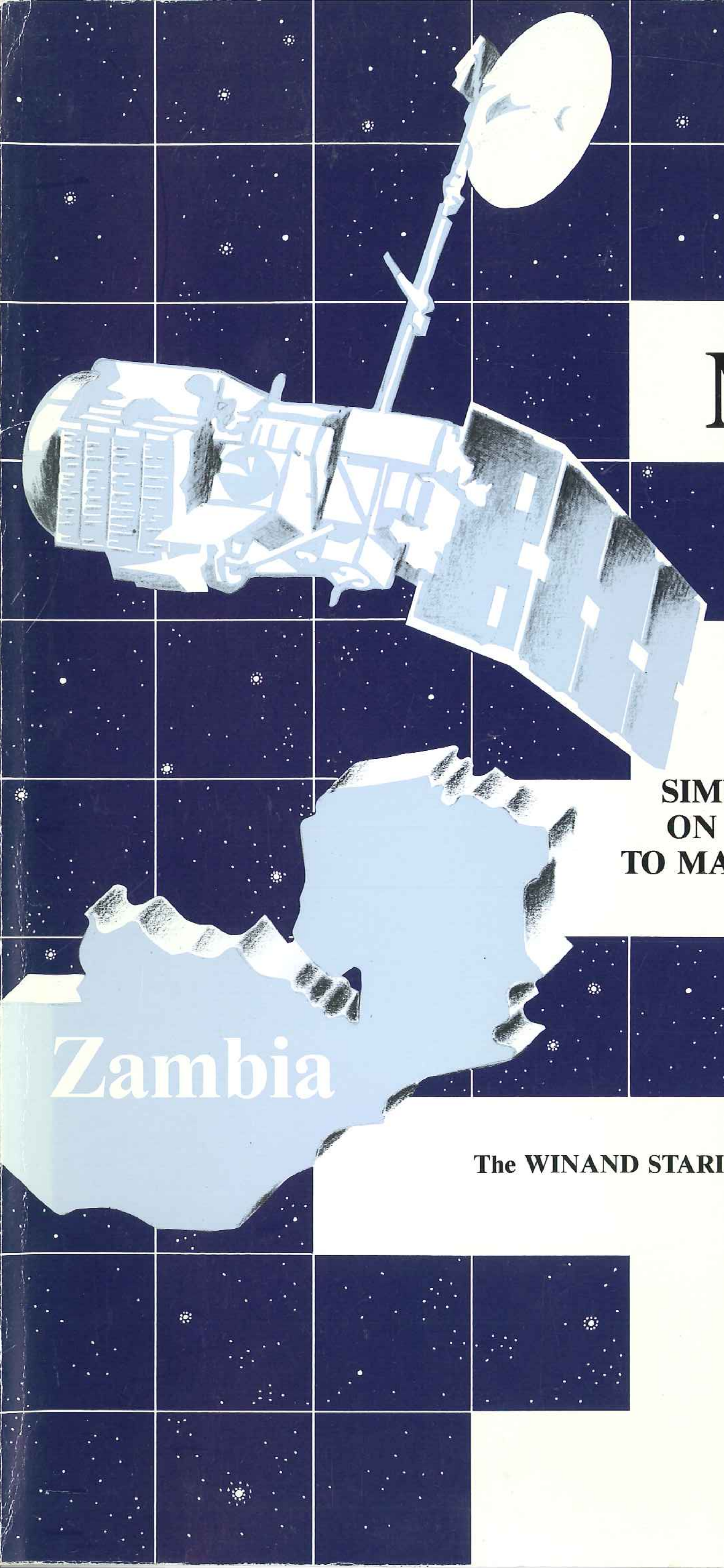


MARS

Monitoring Agro-ecological Resources with Remote sensing & Simulation

SIMULATION STUDIES ON THE LIMITATIONS TO MAIZE PRODUCTION IN ZAMBIA

REPORT 27

The WINAND STARING CENTRE, Wageningen (The Netherlands), 1990

Simulation studies on the limitations to maize production in Zambia

14158

Simulation studies on the limitations to maize production in Zambia

J. Huygen, editor

Contributing authors:

C.A. van Diepen
C.H. van Immerzeel
H. van Keulen
F. de Koning
K. Nijhof
C. Rappoldt
J. Wolf
J.C. van de Zande

Report 27

The WINAND STARING CENTRE, Wageningen (The Netherlands), 1990

ABSTRACT

Huygen, J. (editor), 1990. Simulation studies on the limitations to maize production in Zambia. Wageningen, the Netherlands, The Winand Staring Centre. Report 27.
99 p; 4 maps; 38 tab.

A crop growth simulation model has been used to assess the potential for maize production in Zambia under various crop management systems, ranging from low input subsistence farming to large scale commercial farming using high input cropping technologies.
The report focusses on the risks involved with the adoption of improved cropping practices by small scale farmers that impede a widespread transition to commercial farming.
Modern cropping technologies however are a necessity to arrive at the desired significant higher level of productivity of food and cash crops.

Keywords: Zambia, maize production, crop growth simulation, risk computation, linear programming

ISSN 0924-3062

The WINAND STARING CENTRE is continuing the research of: Institute for Land and Water Management Research (ICW), Institute for Pesticide Research, Environment Division (IOB), Dorschkamp Research Institute for Forestry and Landscape Planning, Division of Landscape Planning (LB), and Soil Survey Institute (STIBOKA).

Project 370.50 470wn/09.90

CONTENTS Page

PREFACE

The studies presented in this report form part of MARS (Monitoring Agro-ecological Resources using remote sensing and Simulation), a demonstration research project on the combined use of simulation models, earth observation satellite and meteorological satellite data on behalf of a National Early Warning System in Zambia.
MARS was initiated in 1986 by the Centre for World Food Studies (CWFS) and the Institute for Land and Water Management Research (ICW). At present MARS is executed by the Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, the Netherlands.

This report consists of three sections and the content is a compilation of the work of several people. Most of it has been performed at the CWFS and also has been or will be published separately:

SECTION 1

- Chapter 1.1: Diepen, C.A. van, J. Wolf, H. van Keulen and C. Rappoldt, 1989. WOFOST: a simulation model of crop production. Soil Use and Management 5 (1989), 1:16-24;
- Chapter 1.2: Wolf, J., C.A. van Diepen and C.H. van Immerzeel, 1987. A study on the limitations to maize production in Zambia using simulation models and a geographic information system. Wageningen, the Winand Staring Centre. Annex 6 in MARS definition study: results of the preparatory phase;

SECTION 2

- Chapter 2-7: Koning, F. de, B. de Leeuw and K. Nijhof, 1989. Risk computation with crop growth simulation models: a case study on the commercialization of maize production in Zambia. Wageningen, Centre for World Food Studies;

SECTION 3

- Chapter 8: Zande, J.C. van de , 1990. Yield analysis in relation to the availability of farm labour and equipment. Wageningen, Agricultural University, Soil Tillage Laboratory (in preparation).

SUMMARY

In section 1 the crop growth simulation model WOFOST is introduced. WOFOST is a tool to estimate the influence of weather, crop characteristics and soil physical and chemical properties on crop yields. The description of WOFOST is followed by a study to apply WOFOST on a national scale that was carried out for Zambia. The results indicate that in years with low rainfall in the southern part of Zambia and only on fertile soils water shortage may limit the yield of a fertilized maize crop, but generally the availibility of nutrients determines the maize yield.

In section 2 a study concerning simulation of maize growth in eastern Zambia (Petauke) is presented. The main goal of this study is to determine the appropriateness of crop growth simulation models for the calculation of risks of maize cultivation. The study focusses on a comparison of the risks of maize cultivation with "improved" (i.e. high input) cropping technologies and low input cropping technologies under smallholders' conditions. These improvements include the application of high-yielding varieties, fertilizer and "improved" crop protection methods. Risks are often supposed to be a major constraint for the adoption of "improved" cropping practices among Zambian smallholders, but experimental data are lacking. Such data will probably not be available soon as risk-studies require long observation periods by their nature. Simulation studies concerning risks might therefore be a valuable source of information.
Various approaches have been developed for the assessment of risks. The safety-first models are considered as most suitable for this study. Risks are defined as the probability that the returns of maize cultivation fall below a specified disaster-level in these models. Thus, risk calculations are based on the probability distribution of the returns of the various cropping technologies. It has been assumed that these returns are normally distributed for reasons of simplicity. WOFOST has been used to determine maize yields for ten successive growing seasons in Petauke. Returns and variation in returns have subsequently been determined using information on costs of the various inputs. With the safety-first method, the risks accepted by farmers have to be determined first and subsequently the disasterlevel is maximized. The risks accepted by farmers has been estimated using information from literature.
The WOFOST model can provide good estimates for the level of crop yields, but usually not on the variation in crop yields, especially when crops are hardly fertilized. The hierarchy of the WOFOST-model has therefore been slightly changed to allow comparison of this variation for the various cropping technologies.
The calculations indicate that a well balanced combination of several innovations pays better off than intensification of separate agronomic practices.

In conclusion, the prospects of risk assessment with simulation models are promising, and in this way crop growth simulation models can provide an attribution to the understanding of smallholders' behavior. Unfortunately, precipitation at the examined location is usually adequate, and the risks of maize cultivation and its intensification are therefore small. For verification, this method should be applied in more drought prone

Zambian regions, and the results should be compared with the local smallholders' behavior.

The objective of the study presented in section 3 is to analyze the variation in maize yield due to management effects. The impact of timeliness of the various field activities caused by limited resource availability has been emphasized. The quality and nature of the data available, together with the straightforward character of the production-decision problem, suggested that it would be both practical and sensible to use linear programming techniques to identify mechanical and organizational innovations which will maximize crop yields for farmers in eastern Zambia.

SECTION 1

1 A STUDY ON THE LIMITATIONS TO MAIZE PRODUCTION IN ZAMBIA, USING A CROP GROWTH SIMULATION MODEL, A SOIL FERTILITY EVALUATION SYSTEM AND A GEOGRAPHICAL INFORMATION SYSTEM

1.1 Introduction to the crop growth simulation model WOFOST

WOFOST is the acronym for WOrld FOod STudies. It is the name of a model for simulating the growth of crops and was developed by the Centre for World Food Studies (CWFS) in Wageningen, the Netherlands.

WOFOST calculates crop yields under three principal growth constraints. This results in three theoretically defined Production Situations (PS) which are hierarchically ordered according to increasing analytical complexity. They are:
PS1 = potential production: crop growth is limited by light and temperature regime only. Water and nutrient supply are taken to be optimum.
PS2 = water-limited production, where moisture supply may limit crop growth. Nutrient supply is taken to be optimum.
PS3 = nutrient-limited production where the soil nutrient supply is introduced as a growth limiting factor. Nitrogen, phosphorus and potassium are considered as the most growth constraining macro-nutrients.

Other factors could be introduced such as the influence of weeds, pests and diseases and the effectiveness of farm operations on crop yields. However, WOFOST does not yet describe the effects of these factors. PS1 indicates the production ceiling for irrigated farming, PS2 for rainfed farming and PS3 for farming without fertilizer application. PS2 also indicates whether irrigation or drainage is needed to realize a potential yield. Running PS2 for different water management scenarios gives an evaluation of their effects on crop yields. Finally, PS3 indicates how much fertilizer should be applied to realize the PS1 and PS2 yields.

Actual yields on farms are usually lower than calculated theoretical yields. This difference may be due to the influence of growth conditions and limitations not considered in the model.

The WOFOST model simulates the growth of a crop from emergence to maturity. The basis for the calculation of dry matter production and yield is the rate of gross CO_2 assimilation of the green canopy, determined by the level of irradiance, the green area of the crop capable of intercepting the incoming radiation, the photosynthetic characteristics of the crop species and the prevailing temperature. A part of the assimilates is used by the crop for respiratory processes to provide energy for its own maintenance. The remainder of the assimilates is available for increase in structural dry matter. The increase in total dry weight of the crop is partitioned over the roots, leaves, stems and storage organs, whereas the partitioning is a function of phenological development stage, which in turn is a function of the prevailing temperature and/or daylength. The conversion efficiency of primary photosynthetic products into structural plant material depends on the chemical composition of the material and is defined for each organ separately. The crop growth curve and resulting yield are found by integrating the daily dry matter increase, partitioned to the plant organs, over the total crop growth period.

Transpiration is the loss of water from the plant to the atmosphere through the open stomata in the leaves. The transpiration losses are replenished with water taken up by the roots from the soil. Within the optimum soil moisture range for plant growth these losses are fully compensated, and transpiration and assimilation proceed at their potential rates. Outside that range the soil can be either too dry or too wet. Both conditions lead to reduced water uptake by the roots, desiccation of the plant and hence reduced growth: in a dry soil due to water shortage, in a wet soil due to oxygen shortage. Soil moisture content in the root zone follows from the water balance based on rainfall, runoff, soil surface evaporation, transpiration and percolation beyond the root zone.
Potential production will only be attained if throughout the growth cycle the moisture content in the root zone remains within the optimum range. Actual growth is calculated by multiplying the potential growth with a reduction factor defined as the ratio of actual over potential transpiration.

The nutrient-limited production is calculated on the basis of information on natural fertility, provided by the user, and the harvest index (which is dry weight of storage organs divided by total above-ground dry weight) resulting from the crop growth simulation (PS1, PS2). Next the amounts of fertilizer needed to reach potential and water-limited yield are calculated, making use of the fertilizer recovery fraction (the fraction of the fertilizer nutrient actually taken up by the crop), also supplied by the user. Contrary to crop growth and the soil water balance which are described with a time resolution of one day, the nutrient uptake is calculated for the whole growing season at once. The present knowledge of the dynamics of nutrients in the soil unfortunately does not permit a more detailed approach.

1.1.1 Input data

Data requirements comprise site specific information such as the starting date, initial moisture conditions, physical properties of the soil surface, such as surface water storage capacity and more general data on climate, crop and soil.

Climate data
As climate data the model needs mean monthly data, i.e. minimum and maximum air temperature, irradiation, humidity and wind speed and monthly or daily rainfall data. In case of monthly rainfall data also the number of rainy days must be specified.

Crop data
Crop specific data include initial dry weight, life span of leaves, parameters that determine assimilation and respiration rates, rate of phenological development, death rates, response to moisture stress, fractions of assimilates partitioned to plant organs and the minimum and maximum nutrient concentrations per plant organ.

Soil data
Soil data requirements can be divided into soil physical data and soil fertility data.

The calculation of the water-limited production is based on the dynamic simulation of the soil water balance, for which the soil's water retention and water transport properties and the bottom boundary condition must be specified. One soil layer (functionally divided into rooting zone and subsoil) is distinguished.

Data on soil fertility include the base uptake of nitrogen, phosphorus and potassium from unfertilized soil and the recovery fractions of N-, P-, and K-fertilizers. They have to be specified by the user. The base uptake is the nutrient uptake by a reference crop (for instance maize) with a growth cycle of 120 days. For other crops the base uptake is related to the length of their growth cycle. Fertility data can be derived from detailed fertilizer experiments or estimated from chemical soil data according to the so called QUEFTS system (Quantitative Evaluation of the Fertility of Tropical Soils, Janssen et al., 1989).

1.1.2 Output

For a given combination of soil, crop and climate the output is split up by production situation. For the potential production situation, reporting takes place after ten day periods until the end of the growth cycle. The variables listed are dry weights of living leaves, stems and storage organs, leaf area index, development stage, rooting depth, crop transpiration rate, gross assimilation rate, maintenance respiration rate and total above ground biomass. For the water-limited production situation, the list of crop variables is followed by components of the soil water balance such as actual transpiration and evaporation rates, soil moisture content, surface water storage, amount of water stored in the soil and the situation at the bottom of the system. After finishing the simulation of water-limited production, two summarized water balances are given, one for the whole system, and one for the root zone only. Finally, a summary is given of the calculated potential, water-limited and nutrient-limited yield, harvest indices and fertilizer needs.

The modelling procedure itself takes no account of geographical scale as it is applied basically as a point analysis.

For applications on regional or national scale a GIS, a Geographical Information System, is an indispensable tool. The GIS provides the facilities to input, combine, extract and display spatial data. The GIS can be used to select all unique soil-climate combinations in a country. These can be sent to the simulation model to run simulations for all combinations for a given crop and to produce country maps of calculated yield levels for that crop. This procedure has been followed for a study on the limitations to maize production in Zambia using simulation models and a geographical information system.

1.2 Regional crop growth simulation and the organization of geo-referenced information

Grain yields of maize, the principal food crop, are calculated for a number of land units as defined along agro-ecological criteria. Four levels of maize production are distinguished with an increasing number of constraints to crop production: the potential yield, the water-limited yield, the nutrient-limited yield and the actual yield.

Only the High Yielding Variety (HYV) cultivar MM752 with a growth cycle of about 150 days is considered. In areas with high temperatures its growth cycle decreases to about 120 days.

As a first step three maps have been digitized: the map of mean annual rainfall, the map of mean annual temperature and the soil map. Digitization of irregularly shaped mapping units into a rectangular grid pattern has been done by assigning to each grid cell the number of its dominant map unit. In this study each cell represents 150 sq.km.

The agro-climatic zonification is assumed to be based on two components: mean annual temperature and mean annual rainfall. So for Zambia agro-climatic zones are derived by stratification of the map of mean annual rainfall with the map of mean annual temperature. The result is a new map with 9 agro-climatic zones (map 1) and for each zone a representative weather station has been selected for the calculations of the crop production.

Soil information includes the geographical distribution of soils and their chemical properties. For this study the 1 : 2 500 000 soil map of Zambia (Brammer, 1973) was used, supplemented by more detailed information from soil survey reports. The soil map is of a rather general nature, with a small number of soil units distinguished. This causes a large variability in soil characteristics within one soil unit. In general, the type of data required for the quantitative analysis used in this study cannot be derived directly from the definitions of the soil units. In fact, such data must be obtained through careful interpretation and comparison with data from other sources. For this study the units of the soil map were regrouped on the basis of inherent soil moisture characteristics (map 2).

The potential and the water-limited yields of maize are calculated with the dynamic crop growth simulation model WOFOST.

1.2.1 Potential yields

The potential yields depend on solar radiation and temperature only, as it is assumed that the supply of water and nutrients is optimum and no losses due to weeds, pests and diseases occur.

Table 1 Crop growth cycle characteristics and potential grain yields of maize HYV for some locations in Zambia.

Crop	Location, province	Date of emergence	Anthesis	Maturity	Potential yield
Maize HYV	Samfya, North.	Dec. 1	63	131	10.4
idem	Mpika, ,,	Dec. 1	71	153	12.3
idem	Solwezi, West.	Dec. 1	69	147	11.7
idem	Kabompo, West.	Nov.15	60	124	10.2
idem	Kaoma, ,,	Dec. 1	60	127	10.4
idem	Sesheke, ,,	Dec. 1	54	114	9.5
idem	Kawambwa, Luap.	Dec. 1	68	141	10.9
idem	Lundazi, East.	Jan. 1	64	145	11.0
idem	Livingstone, South.	Dec.15	55	118	9.2

anthesis, maturity : days after emergence
potential yield : dry matter in grains (*1000 kg/ha)

Thus potential yields have been calculated for the nine climatic zones in Zambia and they range from 9 tons/ha to 12 tons/ha (table 1). The cooler zones allow longer growth cycles and higher yield levels.

1.2.2 Water-limited yields

Water-limited yields of maize have been computed for 21 climate-soil combinations (map 3). The analysis has been done for maize cultivated on well-drained upland soils only and as a consequence, water-limited production refers to drought effects only. Soils that are insufficiently drained and/or flooded during the wet season, are not suitable for maize production and are therefore left out of the analysis. Such areas are generally used for grazing or kept under natural vegetation.

The water-limited yield is strongly influenced by the rainfall pattern which is characterized by a strong interannual variation. Therefore, the water-limited yield is calculated as the average of a series of simulated yields over 20 years for each combination. The required 20 years of daily rainfall data are obtained via a random-number generator on the basis of available mean monthly rainfall data. A fixed date of crop emergence, usually 1 December, has been used. The variability in yield between individual years is reflected in the coefficient of variation (the standard deviation as a percentage of the mean yield). In most cases yield reductions due to water shortage are small, i.e. less than 10 percent and also the yield variability (map 4) is small, even though the interannual variability of the generated rainfall is usually as high as 20 percent. In zones receiving roughly less than 800 mm during the growing season reduction due to water stress becomes more pronounced. This is the case in Livingstone, Sesheke and Lundazi. In these zones the water-holding capacity of the soil is a factor that influences the average water-limited crop yield. In the high-rainfall areas this factor has little influence and the calculated water-limited yields are approximately similar for all soils, irrespective of their water-holding capacity. The average yields shown (table 2) are calculated for soils where the rootable depth is set at 50 cm. In that way possible occurrence of crop stress by drought is indicated more clearly than with yield calculations for deeper soils. The results indicate clearly the increase in yield reduction and in yield variability with decreasing rainfall. The favourable effect of a larger water-holding capacity in heavier soils is partly offset by greater evaporation losses from the soil surface, especially during the period of crop establishment. This leads to very low yields in some years with an unfavourable rainfall distribution, which reduces the average yield level and results also in a higher yield variability. In most years however, the yield on clay soils is higher than on sand.

Editor's note: Evaporation was not modelled correctly at the time of this study, so these high losses might be unrealistic!

1.2.3 Nutrient-limited yields

Nutrient-limited yields are determined by QUEFTS, which is fully integrated in WOFOST. The QUEFTS system comprises a number of successive steps.

First, the quantities of nitrogen, phosphorus and potassium that are potentially available for uptake by a maize crop during one growth cycle, are estimated using empirical relationships between chemical soil properties and nutrient uptake. Most useful as diagnostic properties appeared to be pH-H_2O, organic Carbon, P-Olsen and exchangeable potassium.

The second step is the calculation of the actual uptakes of N, P and K as fractions of the potential supplies determined in step 1. The relationships between the potential supply and the actual uptake of a nutrient are based on the following considerations. The nutrients are first compaired in pairs. Thus the relation between the actual uptake and the potential supply of nitrogen is calculated twice: as depending on the potential supply of phosphorus and as depending on the potential supply of potassium. Likewise, the actual uptake of phosphorus is calculated as depending on the potential supplies of nitrogen and potassium, and that of potassium as depending on the potential supplies of

Table 2 Calculated potential and water-limited yields of maize HYV for some selected soil-climate combinations in Zambia.

Station	Soil type	ASM (%)	Rainfall		Pot. yield	Water-limited yield	
			(mm)	cv(%)	(kg/ha)	(kg/ha)	cv(%)
Solwezi	red clay	12.5	1120	12.7	11700	11600	2.7
	loamy sand	8.0				11400	4.1
	sand	5.0				11000	6.2
Kabompo	red clay	12.5	819	20.3	10200	9800	6.0
	loamy sand	8.0				9700	7.2
	sand	5.0				9300	10.4
Sesheke	red clay	12.5	557	21.9	9500	7100	31.1
	loamy sand	8.0				7200	18.0
	sand	5.0				6900	14.9

ASM : volume fraction of Available Soil Moisture
rainfall : average rainfall during growth cycle
cv : coefficient of variation
yields : average yields in kg/ha dry matter in grains
Rootable depth of soil is set at 50 cm.

nitrogen and phosphorus. This results in two estimates of the actual uptake for each of the three nutrients. The lower of the two estimates is considered the more realistic.

In step 3 yield-ranges as functions of the actual uptakes of nitrogen, phosphorus and potassium determined in step 2 are calculated using empirical uptake - yield relations. These relations have been established for each element separately both for the situation that the nutrient is completely diluted and for the situation that the nutrient concentration is maximum. These ranges in yield often differ considerably, but they usually have an overlap. In step 4 finally these ranges are narrowed to one yield estimate by systematic comparison of the possible yields determined in step 3.

The response of maize to fertilizer application is also calculated with the QUEFTS system. But in this case data on the fraction of fertilizer nutrient taken up by the crop (called recovery fraction) have to be collected from fertilizer trials. The QUEFTS system uses the maximum value for the recovery fraction, which only depends on the soil and water regime specific losses by leaching, precipitation etc. but which is not restricted by a limiting soil supply of other nutrients. The amount of fertilizer nutrient applied is multiplied with the recovery fraction to find the additional uptake which is added to the potential uptake of the unfertilized soil. Steps 2, 3 and 4 are the same as described before.

For the kinds of soil that are of importance for maize production in Zambia, chemical soil data are collected that are probably representative for these soils (table 3). These data are used to calculate the potential supply by maize of soil nitrogen, phosphorus and potassium and the corresponding yield (table 4). These nutrient-limited yields range from about 800 kg/ha on Barotse sands in the Western province to about 1400, 2000 and 3800 kg/ha on Sandveldt soils, red brown loams and red clays respectively that are found mainly in the Central, Eastern and Southern provinces. According to these calculations phosphorus is the nutrient that mainly limits the maize yields. Comparing the water-limited yields with these nutrient-limited yields, the scope for yield improvement by fertilizer application appears to be large.

In the leached soils in the Northwestern and Northern provinces the pH is so low that maize production is almost impossible. Therefore yields are calculated both for the original pH and for a pH of 5.5 attained by liming. In these provinces shifting cultivation is mainly practised, part of the forest is cleared and chopped branches and trunks are collected and burnt on the cultivated area. This has the same effect as liming and it enlarges the amounts of phosphorus, potassium and other nutrients that are taken up by the maize crop. In such systems the maize yields will be much higher than the nutrient-limited yields calculated for the leached soils. For more permanent cropping on the leached soils liming is required.

Table 3 Chemical soil data representative for some of the kinds of soil occurring in Zambia, without and with liming to a pH equal to 5.5.

Soil	PH-H_2O	Organic C (g/kg)	P-Olsen (mg/kg)	Exch. K (mmol/kg)
red clays	6.2	22.0	3.0	6.0
leached red clays	4.5	15.0	2.0	3.0
idem after liming	5.5	15.0	2.0	3.0
red brown loams	5.7	10.0	2.0	4.0
leached red brown loams	4.4	10.0	1.5	2.0
idem after liming	5.5	10.0	1.5	2.0
Sandveldt soils	5.6	7.0	1.5	3.0
leached Sandtveldt soils	4.3	7.0	1.0	1.5
idem after liming	5.5	7.0	1.0	1.5
Barotse sands	5.5	6.0	0.5	0.5

1.2.4 Actual yields

The actual yields obtained in agricultural practice are the result of intricate interactions among the availability of water and nutrients, competition by weeds, occurrence of pests and diseases and the actual management practices. Because the availability of nutrients appears to be the most constraining factor in Zambia, the actual yields of maize are mainly a function of the natural soil fertility. The nutrient-limited yields will practically always be higher than the actual yields, because part of the yields may be lost. These losses vary strongly, depending on crop cultivar, yield level, growing

Table 4 Soil supply of nitrogen, phosphorus and potassium to a maize crop, calculated from chemical soil data representative for a number of soils occurring in Zambia, the corresponding grain yields of maize HYV and the nutrient that mainly limits crop yield.

Soil	Soil supply (kg/ha)			Yield (kg/ha)	Nutrient limiting
	N	P	K		
red clays	119.7	9.1	63.3	3843	PK
leached red clays	38.3	1.0	77.4	360	P
idem after liming	63.8	5.6	58.1	2384	P
red brown loams	45.9	4.3	101.8	2047	P
leached red brown loams	23.8	0.8	74.5	210	P
idem after liming	42.5	3.8	54.6	1655	P
Sandveldt soils	30.9	3.0	104.8	1384	P
leached Sandtveldt soils	15.5	0.5	75.9	60	P
idem after liming	29.8	2.6	54.2	1165	P
Barotse sands	25.5	2.1	20.3	791	P

Grain yields with 12% moisture and without correction for losses.

conditions, type of weed, severity of infestation by pests and deseases and the level of control. Harvest losses will also occur.

The average amount of fertilizer used per hectare of maize is still small, because large part of Zambia is used for traditional subsistence farming. Only commercial farmers, mainly found in the Central, Eastern and Southern provinces, apply large amounts of fertilizer. According to a food strategy study by Admiraal (1981) in traditional subsistence farming (which is called level 1) no fertilizer is used. Small-scale emergent farmers (level 2) apply 43(N)-20(P_2O_5)-10(K_2O) kg/ha, medium-scale commercial farmers (level 3) apply twice as much and large-scale commercial farmers (level 4) apply three times as much.
For the main soil units in Zambia values are collected for the recovery fractions of applied fertilizer nitrogen, phosphorus and potassium. For the three application levels of fertilizer nutrients, corresponding with management levels 2, 3 and 4, the grain yields of maize HYV and the increase in grain yield by

Table 5 Grain yields of maize HYV growing on some kinds of soil occurring in Zambia, without and with liming to a pH of 5.5, for specified levels of fertilizer application, increases in grain yield as a result of the fertilizer application and the nutrient that mainly limits the yield of the fertilized crop.

Soil	Amounts of fertilizer nutrients (kg/ha)						Nutrient limiting
	$N-P_2O_5-K_2O$ 43 20 10		$N-P_2O5-K_2O$ 86 40 20		$N-P_2O_5-K_2O$ 135 70 35		
	yield	incr.	yield	incr.	yield	incr.	
red clays	4345	502	4833	990	5508	1665	PK
leached rc	892	532	1398	1038	2096	1736	P
+ liming	2926	542	3453	1069	4166	1782	P
red brown loams	2662	615	3252	1205	4041	1994	P
leached rbl	731	521	1237	1027	1925	1715	P
+ liming	2220	565	2769	1114	3496	1841	P
Sandveldt soils	1872	488	2315	931	2911	1527	P
leached S	426	366	780	720	1292	1232	P
+ liming	1582	417	1984	819	2524	1359	P
Barotse sands	1163	372	1520	729	1997	1206	PK

Grain yields and increases in grain yield with 12% moisture and without correction for losses (kg/ha).

fertilizer application are calculated for the different soil units, using the QUEFTS system (table 5). Phosphorus is still the main limiting factor for the yields of the fertilized maize crops.

The actual yield levels that can be attained at the different soil units with the different levels of management, with and without application of the specified amounts of fertilizer are given in table 6. The yield losses are based on information by Admiraal (1981) about the crop protection at the different management levels and based on other studies. At management level 4 weeds, pests and diseases are completely controlled by use of herbicides and pesticides and soil tillage and sowing find place in time, so that the fraction lost will be small, about 5%. At level 3 crop protection is less complete because often no herbicides are used and sometimes less pesticides, so that losses will on the average be higher, about 10%. At level 2, weed control is done only with oxen or by hand and only a small amount of pesticides is used. The timeliness of soil tillage and sowing is often less optimum, because oxen or a tractor are not always available at the right time. This may result in a later date of crop emergence and in losses as a result of waterstress at the end of the growth cycle of maize. The total yield reduction for this level is estimated at about 20%. At level 1 there is only a limited degree of weed control, no fertilizers are applied, local maize varieties are used and the timeliness of farm operations is far from optimum because most activities are done by hand. So at this level the yield reduction is estimated at 30%. If shifting cultivation is practised, actual maize yields may be much higher

Table 6 Estimated grain yields of maize HYV at four management levels, without and with four levels of fertilizer application for some kinds of soil occurring in Zambia and corrected for losses during harvest and by pests, diseases and weeds.

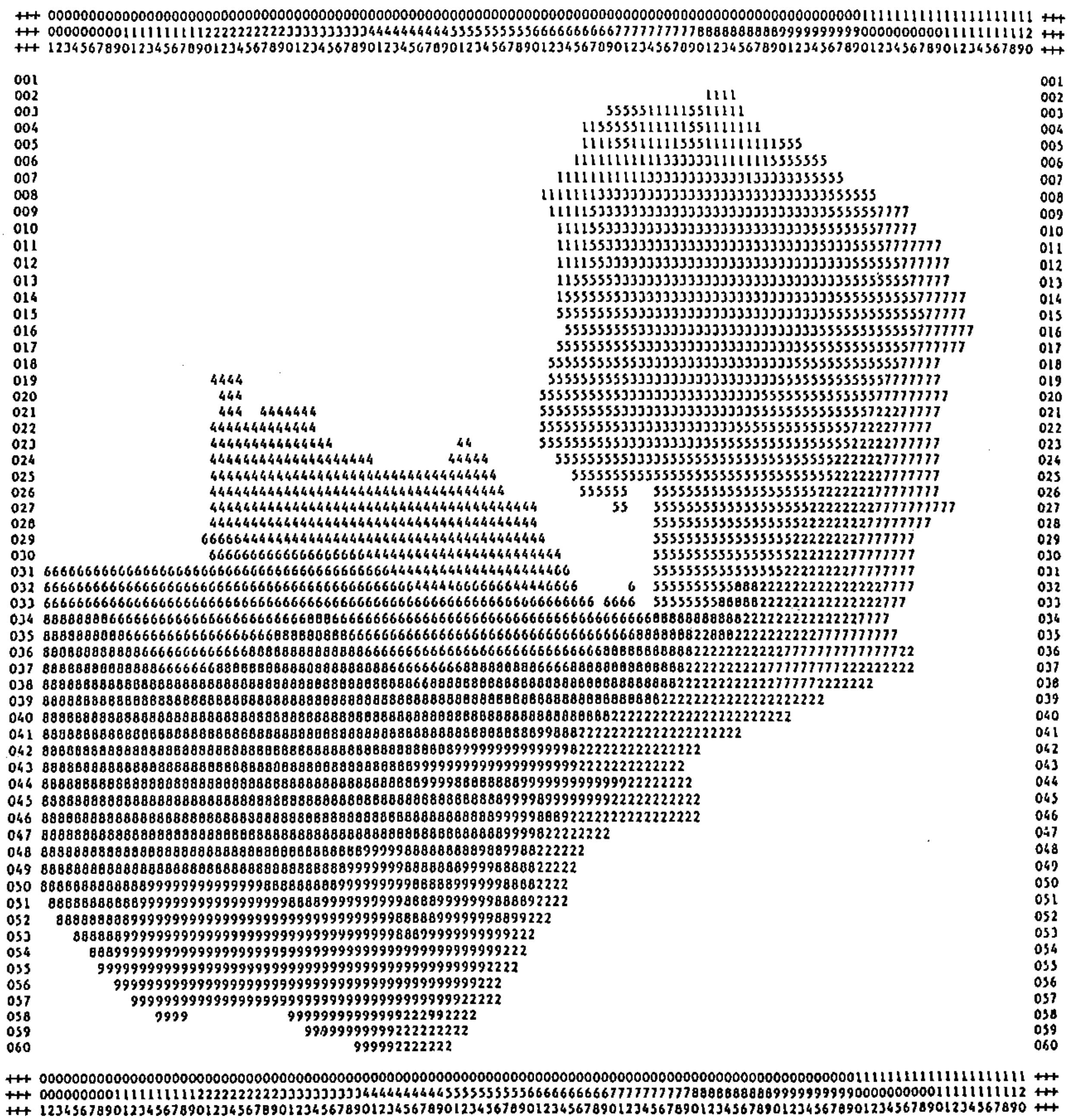
Soil	Yield at management level (kg/ha)						
	I	II		III		IV	
	unfert.	unfert.	fert.	unfert.	fert.	unfert.	fert.
red clays	2356	3074	3476	3459	4350	3651	5234
leached rc	221	288	714	324	1258	342	1991
+ liming	1461	1907	2341	2146	3108	2265	3958
red brown loams	1255	1638	2130	1842	2927	1945	3839
leached rbl	130	168	585	189	1113	200	1829
+ liming	1015	1324	1776	1490	2492	1572	3321
Sandveldt soils	848	1107	1498	1246	2084	1315	2765
leached S	37	48	341	54	702	57	1227
+ liming	714	932	1266	1049	1786	1107	2398
Barotse sands	485	633	930	712	1368	751	1897

- Grain yields with 12% moisture.
- Management level I (= traditional subsistence households): yield losses estimated at 0.30, local maize variety, no fertilizer application.
- Management level II (= small scale emergent farmers): yield losses estimated at 0.20, high yielding maize variety, fertilizer application of 43(N)-20(P_2O_5)-10(K_2O).
- Management level III (= medium-scale commercial farmers): yield losses estimated at 0.10, high yielding maize variety, fertilizer application of 86(N)-40(P_2O_5)-20(K_2O).
- Management level IV (= large-scale commercial farmers): yield losses estimated at 0.05, high yielding maize variety, fertilizer application of 135(N)-70(P_2O_5)-35(K_2O).

than expected for the specified type of soil, for reasons explained before.

On the fertile red clays, grain yields of about 5500 kg/ha (without losses) may be attained at the highest management level, which is near the water-limited yield. This indicates that in years with low rainfall in the southern part of Zambia and only on fertile soils water shortage may limit the yield of a fertilized maize crop, but that generally the availability of nutrients determines the maize yield.

A major problem in this study posed the rather general nature of the soil map from 1973. The number of soil units distinguished is rather small, resulting in a large variability in soil characteristics within one soil unit. This probably has consequences for the accuracy of the presented results. The new, more detailed version of the soil map of Zambia from 1983 was not yet available at the time of this study. The methodology presented is universally applicable and the same approach for studying the limitations to maize production can also be applied to other crops.



85 ZCLIM2 Represent. Agroclimatic Areas ZAMBI

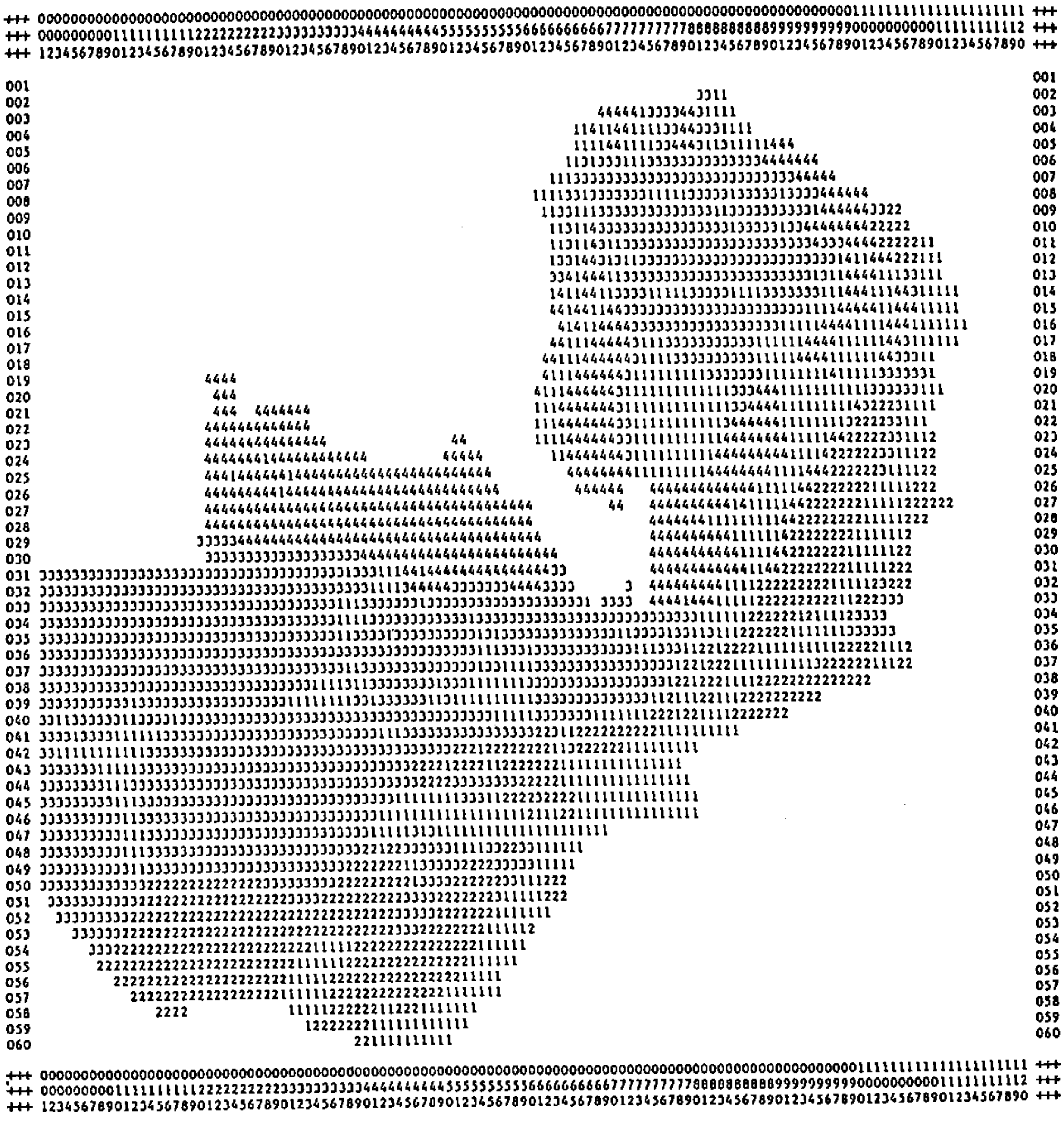
				coverage		
		0	. . .	3540 cells		49.2%
1	1111	1	Kawambwa	105 cells	1.5%	
2	2222	2	Livingstone	373 cells	5.2%	
3	3333	3	Samfya	383 cells	5.3%	
4	4444	4	Solwezi	313 cells	4.3%	
5	5555	5	Mpika	508 cells	7.1%	
6	6666	6	Kabompo	376 cells	5.2%	
7	7777	7	Lundazi	203 cells	2.8%	
8	8888	8	Kaoma	941 cells	13.1%	
9	9999	9	Sesheke	458 cells	6.4%	

Map 1 Map of representative agro-climatic areas

78 ZSOIL Soil Map of Zambia ZAMBI

					coverage	
		0	. . .	3540 cells		49.2%
1	1111	1	Red Clays (Moist.: 12.5%)	28 cells	0.4%	
2	2222	2	Leached Red Clays (Moist.: 12.5%)	9 cells	0.1%	
3	3333	3	Red Brown Loams (Moist.: 12.5%)	68 cells	0.9%	
4	4444	4	Leached Red Brown Loams (Moist.: 12.5%)	2 cells	0.0%	
5	5555	5	Sandveldt (Moist.: 8%)	484 cells	6.7%	
6	6666	6	Leached Sandveldt (Moist.: 8%)	1010 cells	14.0%	
7	7777	7	Barotse Sands (Moist.: 5%)	889 cells	12.3%	
8	8888	8	Kafue Clays (-)	43 cells	0.6%	
9	9999	9	Kafue Basin Alluvium (Moist.: 12.5%)	28 cells	0.4%	
A	AAAA	10	Flood Plain Soils (-)	109 cells	1.5%	
B	BBBB	11	Seasonally Waterlogged soils (-)	28 cells	0.4%	
C	CCCC	12	Solon. Grey Clays and Sandy Clays (-)	28 cells	0.4%	
D	DDDD	13	Valley Soils (Moist.: 12.5%)	209 cells	2.9%	
E	EEEE	14	Rock and Rubble (-)	597 cells	8.3%	
F	FFFF	15	Swamp (-)	82 cells	1.1%	
G	GGGG	16	Water (-)	46 cells	0.6%	

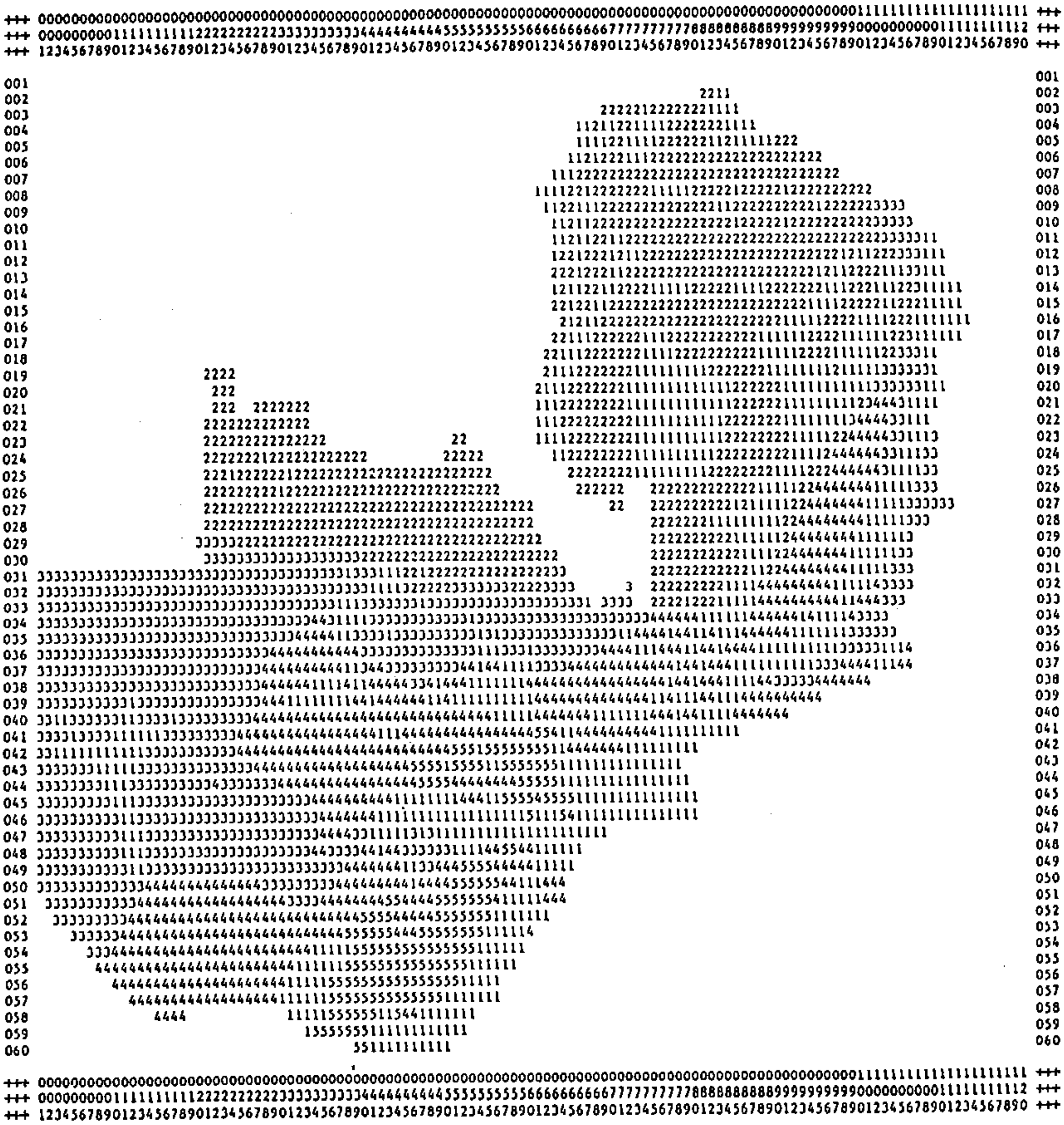
Map 2 Map of soil types and related volume fractions of available soil moisture



92 ZMAIZE Water Limited Yields of Maize ZAHBI

				coverage		
		0	. . .	3540 cells		49.2%
1	1111	1	No estimates	933 cells	13.0%	
2	2222	2	7 - 9 (T/ha)	617 cells	8.6%	
3	3333	3	9 - 11 (T/ha)	1475 cells	20.5%	
4	4444	4	11 - 13 (T/ha)	635 cells	8.8%	

Map 3 Map of water-limited yields of maize (dry matter in grains)



93 ZHVARI Maize Yield Variability ZAHBI

		0	. . .	3540 cells		49.2%
1	1111	1	No estimates	933 cells	13.0%	
2	2222	2	0 - 5 %	951 cells	13.2%	
3	3333	3	5 - 10 %	886 cells	12.3%	
4	4444	4	10 - 15 %	721 cells	10.0%	
5	5555	5	15 - 40 %	169 cells	2.3%	

coverage

Map 4 Map of variability in water-limited grain yields of maize

SECTION 2

2 INTRODUCTION TO RISK COMPUTATION WITH CROP GROWTH SIMULATION MODELS AND CHOICE OF THE STUDY AREA

2.1 Introduction to risk computation with crop growth simulation models

Agricultural development policies in the developing countries usually aim at a higher level of productivity of both food and cash crops. In this way it is tried to alleviate rural poverty. For the production of staple foods, one of the prime instruments in agricultural development programs is the encouragement of the diffusion of Green Revolution technologies, together with development of rural infrastructure, institutional credit and rural public services (technical assistance, education etc.). This policy is expected to provide small farmers with incentives to shift from subsistence into the institutions of capitalist society and incorporate them into the market because small farmers would be attracted by the profitability of this modern cropping technology (De Janvry, 1981). However, in many instances, small farmers seem to favor their traditional technology above modern technologies, even if the latter appear to be highly profitable. One of the explanations for the rejection of the Green Revolution-like technology is based on the riskiness of agriculture, particularly under marginal circumstances, and the risk-aversive behaviour of small farmers. Risks are particularly burdensome to small farmers in the developing countries, whose primary aim is to secure the continuity of their production system, even if this leads to underinvestments and consequently to a sacrifice of some potential cash income (Hazell, 1986a). Risky innovations, that could jeopardize the continuity of production systems, such as the purchase of chemical fertilizers are therefore avoided, because small farmers usually lack the financial resources to bear losses in bad years (De Janvry, 1972). In this explanation Green Revolution-like technologies are assumed to be perceived as more risky by small farmers.

Risks can be attributed to either unstable yield levels or unstable producer prices. Price risks of the staple food crops are not of major importance for small farmers, whether subsistence- or market-orientated, because a relative large proportion is consumed at home and only the surplus, if any, is sold. Therefore, we intend to be primarily concerned with yield risks in this study. While the assumption of risk aversive behaviour of small farmers is generally accepted, there is still debate about the riskiness of new agricultural technology, such as the technology generated in the Green Revolution (Hazell, 1986b). This is partly due to the lack of reliable data on long term comparisons of current and improved agricultural technologies at farmers level. According to Binswanger (1979) this can be attributed to the following reasons:

1 Before a new practice is adopted anywhere, the information available is from experiment station data. These experiments are conducted under conditions far superior to those at the average farm so that they largely overestimate the expected response of yield to inputs as fertilizers. Only recently agricultural research tends towards more and prolonged

experimentation in farmers fields.

2 The most frequently used approach to derive probability distributions of yields is to assume simply that aggregate regional or district level data correctly reflect yield variabilities at farmers' field levels. However, internal compensation causes aggregate regional data to underestimate the year to year variability in farmers' fields.

3 Farm level data for both traditional and new practices over many years are almost non-existent in developing countries because few farm record schemes have been in operation long enough. Furthermore, one cannot derive data on new practices from recorded historical farm level data.

2.2 Choice of study area and crop

The Centre for World Food Studies has developed simulation models for crop growth, in which the influence of weather, crop characteristics and soil physical and chemical properties on crop yields can be estimated (Van Keulen and Wolf, 1986). As experimental data on crop yields and their variability under traditional and modern cropping technologies are scarce, we intend to study the suitability of these simulation models to quantify the yield risks of both cropping technologies. The study is therefore focussed on the following questions:

1 Can crop growth simulation models produce reliable data on the yields and variability under modern and traditional cropping technologies.
2 Can this variability be used to quantify the yield risks of these cropping technologies.
3 Can we quantify the relation between input use and risk.

This study is thus not concerned with the perception of risks of modern technologies by small farmers, but with the question whether the actual yield variability is increased by the adoption of modern technology or not and whether this can explain the reluctance to adoption of this technology. Thus, in this study a typical small farmer can opt for different technologies for a crop, leaving all other factors constant.

The simulation models mentioned above do not (yet) incorporate the yield reductions and their variability caused by pests, diseases, weeds and local factors, such as micro-nutrient deficiencies. Therefore, for this study, a location had to be selected where yield reductions due to pests, diseases, weeds and local factors can be expected to be relatively small compared to the influence of low and/or unreliable rainfall on crop yields, i.e. the semi-arid tropics. As the Centre for World Food Studies had previously studied crop production in Zambia at two locations (Copperbelt and the Eastern Province) and had collected data necessary for the application of crop growth simulation models, this study is concerned with the risks of food production in Zambia. Maize is the major food crop in this country in many aspects: in area cultivated, in total production, as subsistence and as commercial crop. Hence, maize is the crop studied.

Maize in Zambia is produced in a wide variety of cropping systems ranging from shifting cultivation to large scale commercial farming. Agricultural policies towards small farmers in Zambia are characterized by a a strong focus on the promotion of new agricultural technologies, such as improved maize varieties combined with appropriate fertilization, plant populations, weed control and plant protection as well as the promotion of animal traction and tractors (Anthony et al., 1979; Kinsey, 1979). Zambian farmers have shown their willingness and ability to respond quickly to new opportunities, if conditions are favorable (Anthony and Uchendu, 1970). However, most Zambian farmers have not given up their subsistence orientation, because the transition from subsistence farmer into small scale commercial (emergent) farmer is not without problems. Small scale farmers are subject to risk of low yields, resulting in seasonal malnutrition as stocks are inadequate to feed the farmers' families till the harvest of next-seasons maize. The risks on food shortages are increased for transient farmers as, because of loan obligations, much of the staple crop must be sold. In case of low yields, such farmers not only experience shortage of food and cash, but also difficulties in acquiring new credits. This increased risk is supposed to be one of the main factors that deter traditional subsistence farmers from entering the market economy in Zambia (Admiraal, 1981). Thus on the chosen locations, the questions around which this study is focussed, appear to be highly relevant.

Of the two locations, for which data were collected by the Centre for World Food Studies, the Eastern Province and more particularly, the Petauke area, was selected because more information on this district was available.

3 METHODOLOGY OF RISK ASSESSMENT

Glossary

crop yield: production of a crop at a given year, expressed in kilogram marketable product per hectare.

crop returns: gross income derived from a crop, calculated as crop yield * producer price.

modern cropping technology: cropping techniques and know-how, generated by scientific agricultural research, involving the use of high yielding varieties, fertilizer and pesticides, and which, if applied by farmers, usually promotes the market incorporation of crop production.

current cropping technology: cropping techniques and know-how based on the experience and knowledge of the farmers community. The term traditional technology has been avoided because this term may suggest a judgement of value and also may suggest that farmers' knowledge and experience cannot evolve.

Methods for modelling decision-making under uncertainty can be distinguished into two broad types: normative and descriptive models. Their main differences, according to Anderson (1979), are given in table 7.

Table 7 Differences between normative and descriptive decision-making models.

	Normative models	Descriptive models
emphasis	deductive	inductive
goal	indicate what an individual should (not) do, conditional on expressed goals and available information.	predict future actions or explain behaviour of groups or individuals.
simplifying for modelling by	- focussing on important decisions only - simplifying decision-makers' goals and planning horizons.	looking at simple, well structured, unambiguous situations in laboratory or field.

Classifications can also be based on the output of the models. Anderson (1979) distinguishes maximizing and non-maximizing models. The former methods necessarily identify a unique and optimal solution for a decision problem, while the latter may leave several options open.

The goals of this study are to explore whether yield instability of modern cropping technologies prevents their diffusion among small farmers and possibly predict whether small farmers might adopt modern technologies in the future. Other criteria (apart from yield), which might influence the adoption rate, such as the farmers' perception of the risks of modern cropping technologies, or changes in taste or cooking properties of the produce, are not taken into account. Therefore, a descriptive model seems most appropriate for this study. Moreover, we will start by confronting a hypothetical, representative small farmer with a choice between current and modern cropping technology. This is the kind of simple, well-structured unambiguous situation for which the descriptive models are developed. Given the simplification of the situation, the prime interest is in those models that provide one answer to the problem: the maximizing models. These models have received most attention and generally seem more refined than the non-maximizing models. Roumasset (1979) distinguishes six types of maximizing, descriptive models. The "safety first" models were selected as most appropriate for this study, because these are based on data of either crop yield(s), -return(s) or profit(s) over several years. This kind of information can easily be generated by the CWFS simulation models.

In the group of safety first models, it is assumed that small farmers do not primarily aim at the most profitable production level of their crops and livestock, but instead primarily aim at a productivity at which the continuity of their production system is assured and only secondarily at profitability. Risk is therefore defined as the probability that yields, returns or profits fall below a certain critical level, at which the continuity of the production system is at stake: the disaster level (d-level). This level varies among farming systems and regions. It can be a bankruptcy level, a level that just meets the minimum caloric requirements of the farmers' family, it can be determined by the need for socially important cash expenditures or can be equal to the returns that just balance the cash expenditures for fertilizers and other inputs. If, as in this study, yields are expressed per hectare, then d-levels should be expressed per hectare too. Similarly, d-levels should be expressed per farm if the yields are recorded by farm. Roumasset (1976) distinguishes three important types of safety first models:

1 - the safety principle, involving minimizing the probability that x (yield, profit, returns) falls below a specified disaster level d:

$$\min r = P(\ x<d\ ), \qquad r = \text{risk}$$

An important drawback of this method is that it does not recognize the expected average value of x as important for a choice between alternatives.

2 - the strict safety principle, where x is maximized subject to a chance constraint of the form:

$$P(\ x<d\ )\leq r,$$

Both r and d are exogenous in this method and have to be estimated prior to application. The estimation of the d-level is particularly difficult because all essential needs and expenses have to be recorded and all on- and off farm activities have to be considered.

3 - the safety first principle, where d is maximized subject to:

$$P(\ x<d\ )\leq r \qquad r = \text{specified exogenously}$$

This rule is also referred to as Kataoka's rule.
It can be assumed that d at a given r is a function of the expected value of d as well as of its variation. Thus contrary to the safety principle the expected value is taken into account as a decision rule. The d-level of a particular production system can be determined indirectly if the probability distribution and r are known.

All principles can be applied to assess the risk of a particular crop or of a production system, either at farm or at regional level. In this study we will use the crop returns to calculate risks. As this study is orientated on the risk of one crop at farm level, Kataoka's rule seems most appropriate.

Risk assessment in the safety first models is reduced to an assessment of the probability of low yields, profits or - as in this study - returns. The standard normal distribution is often assumed to approach this distribution properly, see for example Zandstra et al. (1979), Benito (1976), Moscardi and De Janvry (1977), Schweigman et al. (1981) and Pyle and Turnovski (1970). If this assumption holds, Kataoka's rule can be rewritten into:

$d = \tilde{y} - ks$

$\tilde{y}$ = sample mean
s = sample standard deviation
k = determined by the risk, r
r = the cumulative value of -k

The expected loss can also easily be calculated using the tabulated data of this distribution. An important advantage of the safety first models is that cropping systems can be compared even if the estimated yields systematically have a relative or absolute deviation from the actual yields, assuming a normal distribution. Thus, the d-level used in Kataoka's rule, does not necessarily have to represent the actual d-level, that is if the same deviation is used in the calculation of the d-level of the various cropping systems. This is a great advantage when yields are estimated by crop growth simulation.

We will now turn to some points of attention with respect to the application of the safety first model in this study. These can be categorized into points related to:
1 - the collection of information
2 - the choice of the probability function
3 - the estimation of the disaster level and acceptable risk
4 - the application of the safety first principle
5 - the drawing of conclusions

3.1 Collection of information

The information, required for the application of Kataoka's rule includes information on the prices of the in- and outputs of the farming system as well as on crop yields. The former category includes prices of the crop produced, fertilizers and pesticides purchased, the rents for credit and land etc. Depending on the available time and on the price policies of the crop in question, we can use either fixed or variable prices of the crop produced for the risk assessment. We assume that the selling prices of the current and modern varieties are equal. If crop production is primarily aimed at subsistence and not at marketing, it may be considered to calculate the crop returns based on purchasing prices rather than on producer prices. This because in that case low yields do not so much result in a low gross income but rather in the need for the purchase of supplementary food. At times of food shortages, these can be considerably higher than the producer prices at harvesting time. The information on the crop yields and their variation will be generated by the crop growth simulation models of the Centre for World Food Studies. These models account for the effects of weather, soil and crop characteristics and soil fertility on crop yield. The models can thus quantify the effects of changes in crop husbandry, varieties and fertilization on crop yields. However, these models do not (yet) incorporate the yield reduction due to pests, diseases, weeds and local factors (i.e. hurricanes, hail, flooding, soil structure, micro-nutrient deficiencies). The calculated yields are therefore usually higher than the observed actual yields. If the variation in crop yields caused by pests, diseases, weeds and local factors is much smaller than the variation in yields which have been calculated by the simulation models, then a simple correction for these effects seems adequate. This is usually the case in semi-arid regions. Changes in pest-, disease- and weed management should be reflected in changes in the correction factors. If, however, the variation in yield reduction by pests, diseases, weeds and local factors is considerable, then we should calculate risks with yield distributions, in which these factors are incorporated in the simulated yields. This situation is far more complicated than the situation, in which simple correction factors can be used. It is particularly complicated if the yield reductions are interrelated to the level of the simulated yields. The yield reduction and its variability will be examined during this study.

3.2 Probability function

The second step in the application of the safety first model is the determination of the probability distribution of the simulated crop yields. We assume that the normal distribution fits, unless indications are otherwise.

The first and second step provide all information of both modern and current cropping technologies required for the application of Kataoka's rule. In this we intend to follow a rather indirect approach, which starts with establishing the risk, r, which farmers are willing to take. If r and the probability distribution of crop returns are known, we can calculate the value of the disaster level, d, of both current and modern cropping technologies. This d-level provides an indication of the returns of a crop at which farmers find their subsistence needs as well as their cash needs are covered. The d-level of the modern technology has to be compensated for the extra expenditures compared to the current technologies, for example for the purchase of seeds, fertilizer and pesticides, and possibly for credit, new farm equipment and hired labour. Kataoka's rule implies that farmers will opt for modern technology only if its compensated d-level is higher than that of their current cropping technology.

Table 8 Some acceptable risk values, as found in literature.

Source	Mean	Range
Scandizzo (1979)		
Brasil; owners	0.040	0.000-0.500
sharecroppers	0.006	0.000-0.500
Roumasset (1979)		
Philippines		0.001-0.100
Moscardi (1979)		
Mexico	0.130	0.023-0.500
Benito (1976)		
Mexico	0.150	

In this study the risk r, which farmers are willing to accept, is estimated from information from literature. Obviously this is a bottleneck and requires a thorough literature review. A primary review resulted in the following data (table 8).

These figures reflect the accepted risk in a peasants' staple crops: maize and - for the data of Roumasset - rice. It is doubtful whether these figures can be transferred to the regions, which will be studied here. The r reflects the penalties, one is subjected to at a failure to meet the disaster level. If the penalty is acute hunger, then r will be very low. Kumar (1987) has shown that child malnutrition can occur in rural areas under Zambian conditions. He also states that "traditional farmers in Zambia characteristically rely little on the purchase of food grains". These two observations imply that Zambian smallholders can accept a low risk only, probably lower than most of the means of the data presented above.

3.3 Disaster level and acceptable risk

In the approach of risk assessment outlined above, the risk of crop production is estimated irrespective to the size of the farmers holding. The data of Benito (1976), Moscardi (1979), Feder (1981), Gerhart (1975), Humberto (1975) and Zandstra et al. (1979) among others indicate that the rate of adoption of modern technologies increases with the size of the holding. This is usually ascribed to the extended possibilities to compensate crop failures and the better access to agricultural services, such as credit provisions, of the farmers with larger holdings. In this study we intend to explain differences in the behaviour of small and larger farmers by differentiating the level of r and interest rates for credit for both categories of farmers. Many other factors, which also influence the adoption of modern technologies, such as education, access to extension services, age, other on- and off-farm activities, are thus ignored. The influence of these factors on technology adoption is indirect, less predictable and thus difficult to quantify.

3.4 Application of the safety first principle

The application of the safety principle is rather straightforward as all necessary information has been collected in the preceding steps. This can be illustrated using the data of Zulberti et al. (1979) for potatoes and maize in Columbia. A normal distribution is assumed for both crops. For maize three technologies are distinguished: traditional, new and modified; for potatoes two: traditional and new. The main characteristics and the results of the application of Kataoka's rule are presented in table 9. In this example the d is specified as the returns minus the extra cash costs for increased input use.
The differences in d-levels at a given r in maize between new and traditional technologies are small compared to the differences in potato. The introduction of new potato technology results in d-levels that are several hundreds of dollars higher. The introduction of new maize technology only results in higher d-levels if the farmer is willing to accept risks of more than 1%. Moreover, these increases are rather small. This is, according to Zulberti et al. (1979) one of the reasons that the enthusiasm for the adoption for new technology was less for maize compared

to potato. The d-levels of the modified maize technology, which designed to overcome this lack of enthusiasm are clearly much higher then the d-levels for both other types of maize technology.

3.5 Drawing of conclusions

We now arrive at the last step in the application of the safety principle: the drawing of conclusions. The preceding steps enabled us to indicate whether modern technology does or does not increase cropping risks since the d-levels and expected losses have been determined. We should now consider the question whether our risk measures can explain adoption behaviour. Therefore, we need to collect information on the diffusion rate of modern cropping technologies among the various categories of farmers and verify our risk-based expectations.

Table 9 Examples of the calculation of disaster levels using Kataoka's rule.

A - Maize

Technology	Traditional	New	Modified
mean returns ($)	145	438	283
standard deviation ($)	106	187	±98
cash costs ($)	21	142	31
extra cash costs ($)	0	121	10
d-level ($) at risk of			
10%	9	77	147
5%	-29	9	112
2.5%	-63	-50	81
1%	-101	-118	45

B - Potato

Technology	Traditional	New
mean returns ($)	790	937
standard deviation ($)	680	529
cash costs ($)	285	313
extra cash costs ($)	0	28
d-level ($) at risk of		
10%	-82	231
5%	-329	39
2.5%	-543	-128
1%	-792	-321

(Source: Zulberti et al., 1979)

4 FARMING SYSTEMS OF THE PETAUKE DISTRICT

The Zambian economy is dominated by copper mining and this industry has strongly influenced agricultural development. The relatively well paid jobs in the mining and related sectors have stimulated many Zambians to rural-urban migration. Having 40% urban population in 1976, Zambia has the biggest urban population of tropical Africa. It left the rural villages with only 40-60% of the young men to perform agricultural tasks (Marchand et al., 1983). The necessary food is traditionally produced on (semi) commercial farms near the line-of-rail, which was constructed to transport the mining products. Agricultural policies traditionally served the interests of the urban population and of the mining sector and thus focussed on the area's near the line-of-rail. The agricultural and infrastructural development outside the Copperbelt and line-of-rail were discouraged and staggered (Marchand et al., 1983). These areas were to provide the mines with cheap labour. The Zambian government started to aim at better regional equity in its rural development efforts only recently. Minimum floor prices for maize were introduced throughout the country in the seventies and fertilizer pricing became more uniform (Kinsey, 1979). Still, differences in farming systems and farm sizes are large.

Zambian farmers are often classified into three categories: subsistence, emergent and commercial farmers. Of course, such a crude classification does not pay respect to all possible variations in farming systems but is practical for descriptive purposes. Commercial farmers usually cultivate 40 ha or more and market most of their production. Most labour is supplied by hired labourers, contrary to the other sectors, where the family labour constitutes a major proportion in the total labour force. Commercial farmers are important in terms of products delivered to the marketing organizations, but the number of commercially farming families is only small. Emergent farmers cultivate smaller acreages than commercial farmers, but sell more than 50% of their products. Subsistence farmers have the smallest farms and sell surpluses only. The subsistence sector is most important with respect to the number of families involved, while the emergent farmers are important because they are, together with the commercial farmers, responsible for most of the deliveries to the marketing organizations. In all three farming systems, maize is an important crop. This situation also applies to the area studied in the Eastern Province, which is the third largest maize producing province in Zambia (Kumar, 1987). The second most important crop in the Eastern Province, also grown either as cash or as food crop, is groundnut. The Petauke area is located on a plateau, where red clays and sandy loams are common as well as loamy sands (Brammer, 1973). The red soils have good physical and chemical qualities as they are less leached than the soils in the northern parts of Zambia. The Petauke area is considered to be one of the regions with high agricultural potentials. We did not come across any indications in the literature that shifting cultivation is still practiced in the Petauke area and therefore we did not consider this farming system in this study.

Table 10 Main characteristics of farming systems of the Eastern Province of Zambia.

Farming system	Subsistence	Emergent small	Emergent medium		Commercial
power source	hand	hand/ oxen	oxen	tractor	tractor
family size *	3.5	4.6	4.5	4.6	-
total acreage (ha)	0.8	2.4	15	33	335
maize acreage (ha) **	0.66	1.7	14	25	127
local varieties (%)	93	68	51	0	0
maize yields (bags/ha)	10	22	27	37	55
D-compound rate ***	-	2	3	4	7
amm.nitrate rate ****	-	2	3	4	6
lime rate (kg/ha)	-	-	-	-	375
stalkborer protection	-	+	+	+	+
soil-pest protection	-	-	+	+	+
herbicides	-	-	-	-	+
planting equipment	-	-	+/-	+/-	+

(Source: compilation of De Toro, 1984 and Admiraal, 1981)
All data refer to the cultivation of hybrid maize except for those given for the subsistence sector. Maize yields are expressed in 90 kg bags of air-dry grain.

* in labour units (man-years/year)
** including the acreage of other cereal subsistence crops
*** D-compound: NPKS 10.20.10.10, rate in bags (50 kg)/ha.
**** ammonium nitrate: 33-34% N, rate in bags (50 kg)/ha.

4.1 Subsistence agriculture

The most prominent features of the various farming systems are summarized in table 10. Maize cultivation in the subsistence sector is characterized by the use of land and labour as sole inputs. Cash inputs, such as chemical fertilizers, hybrid seeds, pesticides, hired labour or farm machinery are seldom applied. All activities are performed by the family. The soil is prepared after the onset of the rainy season with hoes (Dequin, 1970). The exact way in which soils are prepared will be discussed in chapter 5. This preparation is very labour-consuming and delays the planting date of maize. Moreover it competes with the time available for another laborious task: the weeding of the crops. Maize yields are low, among others due to the late planting which results in more severe attacks by pests and diseases, more waterstress and more leaching of nutrients before and during the initial stages of maize growth (Acland, 1971). Yields are also low because of nutrient deficiencies, intense weed competition and the absence of chemical pest management. Moreover, local varieties are planted, which have a lower genetic potential than the hybrid varieties. In dry years, yields are often too low to store enough maize to feed the family during the subsequent planting and weeding season (Kumar, 1987). No maize is sold apart from surpluses and cash income is acquired from other sources: off-farm work and sale of beer, vegetables and fish (Admiraal, 1981). The activities, which should be performed after the onset of the rainy season (soil preparation, planting, weeding) are so time-consuming that most families do not succeed in planting all available land, hence some land is left fallow. The amount of land left idle strongly depends on the physical condition of the farmers family, which in turn strongly depends on the supply of stored maize of the previous year (Kumar, 1987). Therefore, the labour available to the families of this group is below potential. One more hectare would commonly be cultivated if food supplies would be adequate. Thus, if subsistence farmers are willing and able to extend their cultivated acreage, they can bring new land under cultivation at will in the Eastern Province (Kumar, 1987) as well as in the Northern, Central and Southern Provinces (Due, 1978). Both authors suggest that at least half the subsistence farmers' holding is left fallow. Even so, it has been observed that often some land is cropped continuously with maize, while other parts are continuously left fallow (Kumar, 1987).

The acreages cultivated by subsistence farmers as indicated in table 10 include the acreages of farms, run by old people, who are less able to prepare large areas. Moreover, these old farmers may partly depend on their children for additional maize supply and therefore feel little incentive to cultivate large area's. Small plots, in or near the cities, used for homegardening, have been included too. Also female farm households, which are also included in the table, are often smaller than male farm households (Due, 1987), because females have to combine farming tasks with household tasks. We feel that changes in cropping systems are most likely to be made by complete, young and physically strong families. The acreages, that such subsistence farming families cultivate are most probably slightly underestimated in table 10 even if the farmers are not in optimal conditions due to insufficient food supplies. We therefore assume that they cultivate about 10% more land.

The possibilities of subsistence farmers to increase the output of their farming system is limited by their lack of capital and lack of access to credit from official agents. Smallholders in Africa are supplied with credit through informal channels: moneylenders, traders, farmers, relatives, etc. They generally provide small loans on a short notice, often require little or no collateral and tend to place few if any restrictions on how funds can be used (Eicher and Baker, 1982). Credit of this type is often used for the purchase of seeds and fertilizer in Zambia (Miracle et al., 1980). Moneylenders are often accused of charging excessive interest rates, up to 150% annually, or even more, specially in West Africa (Miracle et al., 1980). These high interest rates are partly due to extra costs made by the moneylenders. Research in Sierra Leone by Linsenmeyer (1976) has revealed that, although the effective annual interest rate was 168%, the actual interest received by moneylenders was only 43% after deducting for late payments and defaults. Commercial moneylenders are not the only source of credit for smallholders. Hyden (1981) has stressed the importance of reciprocal ties within African communities and these ties can provide subsistence farmers with credit at low interest rates (Eicher and Baker, 1982). Rotating savings and credit associations with a few members are said to be abundant in Zambia (Miracle et al., 1980). The collective deposit of such an association, which is allocated to one of its members, can only be small because the resource base of the members, subsistence farmers, is small. If farmers wish to increase the productivity of their farming system, they probably need supplementary commercial credit. If we assume that smallholders rely both on informal commercial and informal non-commercial credit, the average interest rate can be arbitrarily established at 30%, while government charges 12% interest in the Eastern Province (De Toro, 1984).

4.2 Emergent farmers' agriculture

Emergent farmers can be distinguished from the subsistence farmers because they apply some cash-requiring technology. We distinguish two types of emergent farmers: the small scale and the medium scale farmers. The farming systems of the small scale emergent farmers show considerable variation, but the general pattern is as follows in the Eastern Province (De Toro, 1984). The farmers of this group cultivate a larger area than the subsistence farmers, up to 10 ha. For this purpose, they either hire a pair of oxen to prepare the soil after the onset of the rainy season and afterwards weed the crops or they make use of the larger labour force that the family can supply due to its larger size. Many of the small scale emergent farmers own cattle, which is possible because the tse-tse fly is absent at the Petauke plateau. Oxen husbandry is a problem however. Work rotation and supplementary fodder is seldom given and consequently the working capacity of the oxen is low. Small scale emergent farmers allocate some of the maize acreage to local varieties for home consumption. Hybrid varieties, supplied with fertilizer and pesticide, are grown for sale. It has been observed that the local varieties are planted first, followed by the hybrids. This practice is sometimes used as an insurance against crop failure. The local varieties though low-yielding tend to combine some drought resistance and drought escaping qualities (SADCC, 1987). Yields are considerably higher than in the subsistence sector, but are still relatively low, because of insufficient access to traction power for timely and effective land preparation, planting and weeding and because of uncertain supply of inputs, particularly fertilizer, which is often not delivered in time (De Toro, 1984). This problem is aggravated by the poor infrastructure in the more remote areas, where many of the small scale emergent and subsistence farmers have their residence. The poor infrastructure generates another problem to these farmers, i.e. the difficulty to transport the marketable maize to depots. As pointed out above, this is a general description of the farming system of small scale emergent farmers and considerable deviations from the general pattern are possible. Some farmers may prepare their plots with hoes, while other emergent farmers have no access to high yielding planting material and/or agrochemicals.

Medium scale emergent farmers usually own several pairs of oxen and/or a tractor and are able to increase their acreage further. Moreover, the use of tractors enables farmers to start preparing the soil before the start of the rainy season, or at the end of the previous season, permitting all maize to be planted at an optimal date. As with small scale emergent farmers, these farmers retain part of their maize production for home consumption. Local varieties are planted for this purpose. In the hybrid maize, more fertilizer and more pesticides are applied compared to the small scale farmers.

4.3 Commercial agriculture

Maize cultivation by commercial farmers is characterized by application of all modern inputs, such as chemical fertilizers, hybrid seeds and pesticides. Tractors are used for plowing and - with planting machines - planting. Crops are grown in rotation, a practice that is not common in the other farming systems. Both commercial and medium scale emergent farms are located along the line-of-rail.

The commercial and medium scale emergent farmers face the same problems. Farming equipment is hard to obtain as well as spare parts for tractors and equipment. Supplies of fertilizer, seeds, oil and fuel are often insufficient. The medium scale emergent farmers also commonly face financial problems (De Toro, 1984).

4.4 Dynamics of farming systems

The position of the medium scale emergent and commercial farmer is not that interesting for the study of risks. The decisions that these farmers make are not of such a complex nature as for small scale farmers: they only decide whether or not to apply more or less agrochemicals and whether or not to increase mechanization. Moreover, risk may not be an important criterion in these decisions, specially for the larger scale farmers because their resources are adequate to compensate for low yields. The dynamics of the farming systems of small scale emergent and subsistence farmers are more interesting because they have to make a choice from a broad spectrum of alternatives to increase the agricultural output of their farming systems. The decisions that these small scale farmers have to make are thus often of a more fundamental character and risk is an important criterion, as they lack the resources to cope with low yields. Studies on the riskiness of alternative cropping systems become increasingly important. Elliott (1983) has pointed out that for three reasons the rural poor are more and more forced to consider the adoption of modern, risky maize technologies. Firstly, he noticed that agriculture is more and more concentrating in clusters around centres of economic and social services. In these clusters, monoculture is common, resulting in a decline in soil fertility and in an increase in scarcity of wood lots, where products of wild plants can be gathered. Secondly, the rural population is faced with terms of rural/urban trade, that become more unfavourable, resulting in increasing cash expenditures for clothes and schooling. Thirdly, the agrarian communities in Zambia nowadays interact more intensively with the outside world, resulting in rising expectations and aspirations of the rural population. These findings more or less agree with those cited by Kumar (1981) that as soil fertility declines, cropping patterns change in such a way that higher yields (in kJ/ha) can be harvested. Two types of changes are cited to occur. If farmers have access to better inputs, they shift to hybrid maize. But when they don't, they shift to cassava. This latter shift is most probably relevant to the northern provinces of Zambia, but not for the Petauke area, where cassava is hardly cultivated.

Suppose a subsistence farmer trying to increase productivity has succeeded in obtaining informal credit. This farmer has several options to invest this money:
- he/she may hire additional labour to extend the acreage under maize cultivation;
- he/she may hire a pair of oxen and plowing equipment to extend the acreage under maize cultivation;
- he/she may buy a pair of oxen, to insure that traction power is available at times of peak demands, so that no time is lost waiting for a hired span;
- he/she may hire a tractor to extend the acreage under maize cultivation and ensure timely planting of the crops and sufficient opportunities for timely weeding;

- he/she can purchase hybrid seeds;
- he/she may opt for an early maturing variety and for plowing at the end of the season, so that crops can be planted right away in the next season;
- he/she can purchase chemical fertilizers to a rate applied in any of the other farming systems;
- he/she can purchase pesticides and spraying equipment;
- he/she may combine these options.

The last option is most interesting to farmers because the marginal returns to any individual component of modern maize technology (hybrid seeds, agrochemicals) are fairly low, while the marginal returns of the whole package are high (Elliott, 1983). Therefore, Zambian authorities recommend an integrated use of agrochemicals and hybrid seeds.

We have outlined that the characteristics of the farming systems of the small scale emergent farmers show more variation than those of subsistence farmers. Therefore, the options available to the small scale emergent farmer, who wishes to raise productivity and has obtained credit, depend on the details of his farming system. If the farmer follows the general pattern outlined by De Toro (1984) above, he has the following options:

- he/she may hire additional labour to extend the acreage under cultivation;
- he/she may hire an extra pair of oxen to extend the acreage under maize cultivation;
- he/she may buy a pair of oxen, instead of hiring, to ensure that traction power is available at times of peak demands, so that no time is lost waiting for a hired span;
- he/she may hire a tractor to extend the acreage under maize cultivation and ensure timely planting of the crops and sufficient opportunities for timely weeding;
- he/she may sow maize in rows instead of broadcasting or sowing behind the plow, with a planting machine. This technique results in higher maize yields;
- he/she may change to improved equipment for soil preparation, which require less tractive power;
- he/she may opt for an early maturing variety and for plowing at the end of the season, so that crops can be planted right away in the next season;
- he/she may increase the doses of chemical fertilizers;
- he/she may increase the number of pesticide-applications;
- he/she may combine these options.

If a small scale emergent farmer prepares the soil by hand, he/she has an extra option: buying/hiring a span of oxen. If a small scale emergent farmer plants local varieties he/she can switch to hybrid varieties with or without application of agrochemicals.

4.5 Risks in Zambian agriculture

In this study, risks are only computed for the options open to small scale emergent and subsistence farmers. Ideally, risks and disaster levels are calculated for the total maize acreage of a typical farm and not on a per hectare basis, because expansion of the maize acreage is one of the options open to farmers.
Data on the risks taken by Zambian farmers are scarce if not completely absent in the literature. Many authors stress the importance of risks in the decision making process in maize cultivation by Zambian and eastern/southern African farmers in general (e.g. Admiraal, 1981; Doyle, 1974; Gerhart, 1975; Wolgin,

1975), but this importance is seldom quantified. Wolgin (1975) did so, but his method is not compatible to the approach of risk-assessment in this study. Only the paper by Gommes (1985) provides useful information. He estimated that small farmers in N. Tanzania, who cultivate several crops, take a 13% risk that maize yields fall below the minimum human caloric needs. Subsistence farmers, when they primarily depend on the cultivation of one main crop, like the subsistence farmers in Petauke, would probably take a smaller risk under comparable conditions.

Risks of yields falling below a specified disaster level can also be determined if data on crop yield variation are available. These data, however, are scarce for Zambia. Regional maize yields are recorded since 1982 only and no separate records are kept for the various farming systems (Statistics Section, 1985). Information on the yield variation of maize grown under subsistence farmers' conditions is available for Zimbabwe over the period 1946-1958. (Masell and Johnson, 1966). This information indicates that the coefficient of variation of yields (cv = standard deviation divided by the sample mean) is 28.3%, assuming a standard normal distribution. This cv is used to calculate the yield variation and risks taken by farmers in maize cultivation in the Petauke region, with the data of the subsistence farming system presented above.

The procedure of the risk assessment is outlined in table 11. The first step involves an adaption of the national Zimbabwean cv to a regional cv for Petauke. The yields recorded by the Statistics Section (1985) for Zambia indicate that provincial cv 's are slightly over twice as high as the nationwide cv. However, maize yields in Zambia show less variation than the yields in Zimbabwe: the cv of Zambian maize yields is only 63% of the cv of Zimbabwe. This results in a cv of 36% for Petauke. For the determination of the disaster level, we assume that maize is hardly sold or purchased in subsistence agriculture (Kumar, 1987) and young subsistence farmers retain all maize they produce for home consumption. Surpluses are sold only in years with high yields. In that case, the total amount of maize retained can be determined by multiplication with the maize acreage, 0.66 ha + 10% = 0.73 ha * 10 bags/ha * 90 kg/bag = 653 kg/yr. This is very close to the actual maize retention for subsistence farmers in the Petauke area found by De Toro (1984): 659 kg/yr. We suppose that these 10 bags include some luxury consumption. We also suppose that malnutrition is likely if yields are 10% under their average value. Of the maize produced, only some 80% is used as food and planting material, the rest is used for brewing of beer, gifts, etc. (Adams and Harman, 1977). The disaster level will therefore be about 7 bags. This information is sufficient to calculate the risk, taken by subsistence farmers, assuming a standard normal distribution of maize yields. The result is 20%.

Table 11 Procedure of risk calculation.

1	cv Zimbabwe subsistence farmers	28.3%
2	adaptation to regional level Zambia	36%
3	mean maize yield/farm	10 bags
4	absolute subsistence level (food only)	7 bags
5	risks taken by farmers	
	$P(10 \pm 3.6\ \underline{X} \leq 7)$	20%

Both the risk established by Gommes (1985) and the risk calculated in table 11 are not very reliable. It is doubtful whether the data of Northern Tanzania are valid in Eastern Zambia and our calculations for Petauke are based on numerous assumptions.

As mentioned before, the risks taken by farmers depend on the size of the farm: the larger the size, the higher the risks taken. For commercial farmers (holdings of 40 ha or more) risk is hardly a criterion. We therefore introduced a relation between farm size and risks accepted. As we found no information on the nature of the relationship between farming system and risks accepted, we assume a linear relation. Using the value of Gommes (1985) for small scale emergent farmers and our calculated risk for subsistence farmers, we can establish:

risk accepted (%) = 11.6 + 9.6 * (farming system factor)

The farming system factor is:

0 for subsistence farming;
1 for small scale emergent farmers;
2 for medium scale emergent farmers using oxen traction;
3 for medium scale emergent farmers using tractors;
4 for commercial farmers.

5 SIMULATION OF POTENTIAL AND WATER-LIMITED MAIZE GROWTH IN EASTERN ZAMBIA

5.1 Input data for WOFOST

5.1.1 Climate

Long term mean monthly values concerning temperature, irradiation, wind speed and vapour pressure were obtained from the weather station of Petauke. Daily rainfall data for the last 10 years were obtained from the same station. Table 12 shows a summary of the rainfall figures.

Table 12 Monthly rainfall at the Petauke weather station from January 1976 until May 1986 (October 1976 is missing).

	Rainfall (mm)											
	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	ave.
Jan	202	273	199	96	171	297	302	294	177	353	353	247
Feb	359	189	272	122	232	267	248	121	153	230	199	218
Mar	243	172	326	81	244	162	53	96	194	252	183	182
Apr	48	8	89	15	107	18	41	8	16	43	69	42
May	42	0	0	0	0	0	29	3	3	45	-	12
Jun	2	0	0	2	0	0	0	0	2	0	-	0
Jul	0	0	0	0	0	0	0	0	4	0	-	0
Aug	0	0	0	0	0	0	0	0	0	0	-	0
Sep	5	0	0	0	2	0	0	0	0	0	-	1
Oct	-	1	26	11	14	23	40	0	5	15	-	15
Nov	58	154	120	170	97	83	71	60	106	108	-	103
Dec	300	193	291	144	332	87	195	156	287	171	-	216
Tot.	-	990	1323	641	1199	937	979	738	947	1217		997

ave. = average, Tot. = total

There is one growing season in Petauke. Its length depends on the defined criteria. The FAO (1984) differentiates between three periods within the rainy season: first a pre-humid period where precipitation on average ranges between half the potential evapotranspiration, calculated according to the Penman method, and Potential EvapoTranspiration (PET). Then a humid period follows during which precipitation is on average higher than PET and finally there is a post-humid period which covers the days that the precipitation is between PET and 0.5 times PET plus the number of days that accumulated soil moisture (up to 100 mm) is transpired at the potential evapotranspiration rate. The dates corresponding to these periods have been established by comparing interpolated 10 day amounts of rainfall and potential evapotranspiration. Following this description an average start of the rainy season is calculated to be on 12 November in Petauke. The humid period lasts from 28 November until 20 March and the end of the rainy season is on 3 April.

Das (1979) has defined the criterion for the commencement of sowing rain as follows: starting with any rainy day of at least 1 mm of rain, 7 consecutive days are counted and the total rain in this period should be at least 20 mm. In addition there should be at least 4 rainy days of 1 mm or more in this period of 7 days. The end of the season is defined by the last day of the last week for which the same criterion is valid. In this report another procedure has been used to determine the start of the season (section 5.2).

5.1.2 Soils

The most important soils in the area are the Sandveldt loamy sands, the Sandveldt sandy loams and the red clays. From soil-physical point of view the sandy loams and the red clays are very similar and therefore were grouped together. The amount of Available Water between field Capacity and wilting point (AWC) was estimated to be 10% for the loamy sands and 15% for the sandy loams and red clays. Surface storage was set to zero and situations with no runoff and with 15% runoff were distinguished. For all calculations a situation without groundwater was assumed.

5.1.3 Crops

The most common commercially grown improved maize variety in this area is SR-52, a hybrid. For the climatic conditions of the Petauke district, SR-52 has a growing period of about 64 days from emergence until anthesis and 131 days until maturity, when planted mid-November. The recommended number of plants in Zambia for well fertilized hybrids is 40 000 plants/ha. Running the model resulted in a potential yield of between 11 and 12 tons grains (dry matter) per hectare. This corresponds well with the results of field experiments.

Breeding programmes have been set up to develop new varieties, for example early maturing varieties that are better adapted to short growing seasons. In the crop growth simulations such a variety was introduced (hereafter referred to as M400). The crop data set of M400 was identical to that of SR-52 with the exception of the development rate. This change results in a growing period of 51 days from emergence until silking and 96 days until maturity when sown mid-November.

Subsistence farmers in Zambia usually do not use hybrids. The local maize varieties grown by traditional farmers in Southern Africa are selections from material that originates from the Caribbean and South and Middle America. For Petauke, with its short growing season, fast developing local cultivars which occur in Zambia appear the most appropriate and thus the most likely to be grown. Considering this, a rough estimate of the development rate of a hypothetical local variety has been done. The resulting growing period is 61 days from emergence till silking and 125 days till maturity when sown mid-November. The assumption that subsistence farmers plant only one local variety, is presumably an oversimplification. Most probably, they plant several varieties, which meet various demands. For the sake of simplicity, however, we only consider the hypothetical variety. Local cultivars may be better adapted to adverse conditions than hybrids but their production potential is in general lower. For this study the difference in potential production between SR-52 and a local variety was estimated at about 35%. There are a number of ways to simulate this difference by adaptations to the crop data set. Field observations often indicate that local maize varieties have a larger vegetative apparatus. Therefore, it has been decided to adjust the dry matter distribution pattern in such a way that more dry matter is invested in roots, stems and leaves, resulting in a lower harvest index. The plant density of local cultivars is about half that of hybrids (20 000 plants/ha). In this way the farmers try to reduce yield losses due to lack of water and nutrients and moreover it shortens the time needed for sowing. To take into account the extra amount of assimilates partitioned to the roots, the maximum rooting depth was increased to 90 cm (for the SR-52 and M400 this is 75 cm). Root growth may be restricted if soils are very acid. Taking this into account crop growth simulation was also conducted for a reduced maximum rooting depth which is more pronounced for SR-52 and M400 (maximum depth 50 cm) than for the local cultivar (70 cm). The latter are presumably better adapted to the locally occuring soils.

5.2 Application of the model

5.2.1 Start of the season

The critical soil moisture level to start cultivation at the beginning of the season depends on the type of soil and the employed means (tractor power, oxen or only manual labour).
In this study the soil is considered workable (whatever cultivation method is used) after a precipitation sufficient to bring the upper 15 cm of the soil to field capacity at a certain point in time. The first day after the dry season, meeting this criterion is called "start of season". The starts of seasons are calculated in subroutine START. Until the start of the rains the soil is supposed to be at wilting point. Effects of runoff have not been accounted for until the start of season. For practical reasons the daily evaporation of water from the soil (which is considered to be bare) is in this subroutine set at 0.5 times the potential evaporation (calculated according to Penman), provided that the soil moisture level does not decrease below wilting point. It is possible to set a critical date in subroutine START before which a start of season is not accepted.

5.2.2 Soil moisture and labour requirements after the start of the season

At the start of season the model is initialized. It then starts calculating the soil moisture balance. Three soil layers are distinguished: the actual root zone, the underlying part of the potential root zone and the subsoil. The initial amount of available water in the total potential root zone (moisture content above wilting point) at the start of season is distributed between the rooted zone (until field capacity is reached) and (if any water is left) the remainder of the potential root zone. Until emergence of the crop the rooted zone is supposed to be 10 cm (the initial root length). Evaporation from the soil surface without plant cover is described as a function of the soil moisture content of the root zone.

At the start of season, farmers are assumed to start cultivating their land. Depending on the type of farming system this takes a certain amount of time meaning a delay in sowing and consequently a later start of crop growth. This may affect crop yield because of the shortening of the growing period.
Evaluating labour requirements a differentiation can be made between farmers only using manual labour (hoe) and farmers using additional power like oxen or a tractor. Admiraal (1981) compared the amount of time needed for land preparation, applying different power sources (table 13).

Table 13 Comparison of manual labour, oxen traction and tractor use for land preparation (Admiraal, 1981).

	Working hours per ha		
Power source	man	span oxen	tractor
hand/hoe	240	-	-
oxen	60	30	-
tractor	6	-	6

Farmers do not plow and sow their total acreage all at once, but they divide it into sections which are cultivated successively. This results in competing labour requirements when in one section weeding is needed while the farmer and possibly other labourers are occupied with land preparation and sowing in another section. In that case the farmers decision on labour allocation depends on many factors, for example the condition and stage of a crop and the degree of weed infestation. In field experiments in the central and southern provinces of Zambia, Vernon and Parker (1983) have determined the critical period of the competition of weeds with maize, during which the crop should be kept clean. They estimated this period to be from 10 to 30 days after emergence. They state that farmers often delay their first weeding to well beyond 10 days after emergence usually due to labour shortage. Estimates of yield reductions due to weeds, related to the method and the time of weeding have been made for Zambia by Kinsey (1979) and by Vernon and Parker (1983).
The total acreage of maize and the sowing date for each section thus depends on a number of factors, such as: available area of land, use of hoe, oxen or tractor, amount of labour available, composition of labour resources (family and additional, for example hired, labour), farmer decisions and the start of the season.

5.2.3 Start of crop growth

From the calculated start of season onwards a certain period of time was supposed to be necessary for land preparation and sowing a certain section of land. These periods were set at 0, 7, 14, 21, 28, 35, and 42 days and are called "delay time" hereafter. A delay time of zero was included because sometimes seeds are sown in dry soil. Instead of the normal depth of 5 cm, seeds are then sown at 9 cm before the rains start. After sowing, seeds can only germinate if the soil is moist enough i.e. if more than one third of the maximum available amount of water is present. When, at the time of sowing, the condition for germination is not met, germination is delayed until the first day the soil moisture content in the top 10 cm exceeds this (arbitrarily set) critical soil moisture level. In addition the time needed for germination was estimated at 7 days after which crop growth is initialized. WOFOST only simulates crop growth after emergence. The germination process is not included. The date of emergence in this study is referred to as "start of crop growth". Between the start of season and start of crop growth the model was used to calculate the soil moisture balance as described in 5.2.2.

In summary: after the start of season the start of crop growth is delayed with at least the number of days required for land preparation and sowing plus 7 days needed for germination, but possibly more in case of a dry soil at the time of sowing.

For each of the ten years, model calculations for each starting date of crop growth will result in a specific potential and water-limited yield. A section of land with a certain size, depending on farming system, can be sown in each period of 7 days, with a corresponding yield. When labour pressure increases because weeding of earlier sown crops is needed, the sections sown will decrease in size. In this way an estimate of the total farm yield can be made for each farming system. Optimizing models can be used for evaluating decisions about weeding and important constraints for production.

5.2.4 Sowing methods

In the model sowing is assumed to take place after land preparation, but in reality this is not always the case. Bessell (1973) differentiates a number of methods of sowing maize that are used in Zambia:

- Broadcast sowing:
  - Hoe. The farmer goes over the field, randomly slashing the soil with a hoe. One, two or three seeds are dropped into the gash in the soil and are subsequently covered.
  - Behind plow. Seeds are dropped at irregular distances into the furrow behind an ox- or tractor-drawn plow. If ploughing is not done in reasonably straight furrows the resulting crop looks similar to the one sown with the use of a hoe.
- Rows without spacing:
  Seeds are sown in well-defined rows but there is no regular spacing between the plants. This can be done on ridges or in straight plough furrows.
- Rows with individual seed spacing:
  - Line or wire. A line or wire is stretched across the plot and seeds are placed individually in the ground at regular intervals. The seeds are placed at an even depth, provided the land has been worked well before planting.
  - Plough. Seeds are placed individually and regularly along a straight furrow.
  - Planter. With or without fertilizer at the time of planting.

These different methods result in a specific crop emergence and pattern on the field. Different plant densities affect potential crop yield and weed competition. These effects are not included in the model.

5.3 Results

5.3.1 Calculations

As explained in the preceding sections, the model was used to calculate crop growth for:

- 10 growing seasons for which daily rainfall data were available (season 1976/1977 up to and including season 1985/1986);
- 3 maize varieties (SR-52, M400 and Local);
- 2 soil types (Sandveldt loamy sand and Sandveldt sandy loam/red clay with 10% and 15% AWC, respectively;
- standard and acid soils. In acid soils maximum root depth was supposed to be restricted: for SR-52 and M400 from 75 to 50 cm and for Local from 90 to 70 cm;
- without or with 15% runoff;
- 7 periods with which sowing at a certain section of land is delayed after the start of season, as determined by the

time required at that section for soil tillage and sowing and labour requirements at other sections of land.

5.3.2 Start of season

The starting dates of the 10 seasons for both soil types as calculated by subroutine START are shown in table 14. The average starting dates for the soil types with a water holding capacity of 10% and 15% are respectively 11 November and 15 November. The difference between both soil types is because the 15% soil needs more precipitation before the start criterion is met. Early rains in October can result in an early start of season. As explained in section 5.2 this can be prevented by defining a critical date in START, for example 1 November. This restriction was not used. For the 10% soil this results in 2 early starting dates: 26 October in season 81/82 and 23 October in season 81/82. For the season 81/82 the calculated start for the 15% soil is 30 days later than for the 10% soil due to a long period with very little rain after the first rains in October. This season is the main cause of the difference of 4 days in mean starting date for the 2 soil types.

Table 14 Start of 10 growing seasons in Petauke for 2 soil types with different fractions of available soil moisture.

Season	Fractions of available soil moisture	
	10%	15%
76/77	10 Nov	10 Nov
77/78	13 Nov	13 Nov
78/79	16 Nov	16 Nov
79/80	19 Nov	19 Nov
80/81	26 Nov	27 Nov
81/82	26 Oct	24 Nov
82/83	23 Oct	23 Oct
83/84	26 Nov	30 Nov
84/85	11 Nov	11 Nov
85/86	7 Nov	7 Nov

5.3.3 Germination

When the delay time is set to zero (i.e. sowing in dry soil before the start of season), the moisture content of the soil at the start of season allows immediate germination. In case of postponed sowing, however, drying of the soil may prevent this. The occurrence of delayed germination is shown in table 15. Long periods during which the seeds cannot germinate are most evident when the start of season is very early (seasons 81/82 and 82/83 at the 10% soil and season 82/83 at the 15% soil). In season 76/77 the last two weeks of November were dry. In 78/79 the start of the season was followed by a period of 13 days without any precipitation. Runoff mainly affects the date of germination on the 15% soil and when delay time is 21 days. It results in an average start of crop growth 1 day later than without runoff. Because of delayed germination, the intervals between starting dates of crop growth for the different delay times are not exactly 7 days.

5.3.4 Potential production

On the 10% soil, potential production of SR-52 is 11,426 kg/ha grains dry matter when the delay time is zero. With delayed sowing, the yield slightly declines: it amounts to 10,819 kg/ha when the delay time is 42 days, a reduction of 5%. The coefficient of variation for the yields during 10 seasons is low (1%-2%). For the two other maize varieties growing on the 10% soil the same pattern emerges but the levels of production are lower: the average yields of Local range from 7697 kg/ha to 7242 kg/ha (a difference of 6%) and those of M400 range from 8936 kg/ha to 8639 kg/ha (a difference of 3%).
Compared to the 10% soil the average start of crop growth at the 15% soil is delayed. This results slightly lower potential yields. Crop phenology depends on variety and date of emergence. For SR-52 and Local the average period between emergence and maturity on both soil types is 8 days longer when the delay time is 42 days, compared with a delay time of 0. For M400 that difference is 5 days on the 10% soil and 4 days on the 15% soil. The reason for the physiological slower development of the 3 maize varieties when emergence occurs later, is the decrease in average temperature towards the end of the season.

Table 15 Occurrence and number of days of delayed germination due to dry soil conditions after sowing, for each delay time and for 2 soils types, with and without a fraction of rainfall lost by runoff (ro).

Delay of planting (days)	10% soil			15% soil		
	season	ro=0	ro=15%	season	ro=0	ro=15%
		delayed germination (days)	(days)		delayed germination (days)	(days)
0	-	-	-	-	-	-
7	78/79	7	7	78/79	7	7
	81/82	10	10			
	82/83	24	24	82/83	25	26
14	76/77	12	12	76/77	12	24
	81/82	3	3			
	82/83	17	17	82/83	18	19
	85/86	-	1	85/86	1	1
21	76/77	5	5	76/77	5	7
	81/82	9	9	81/82	4	11
	82/83	10	10	82/83	11	12
	85/86	5	5			
28	81/82	2	2	81/82	4	4
	82/83	3	3	82/83	4	5
35	-	-	-	-	-	-
42	79/80	1	1	-	-	-
	81/82	2	2			

5.3.5 Water-limited production

A presentation of the averages of the water-limited yields related to the delay time, together with the coefficients of variation, is given in table 16.

In table 16-A both for SR-52 and for Local, water-limited yields on the 10% soil decrease with increasing delay time. This effect is both absolutely and relatively stronger if these varieties grow on an acid soil. Water-limited yields are very close to potential yields (+/- 2%) when delay time is zero. Compared to these water-limited yields, for a delay time of 42 days yield reductions amount to 32%, 42%, 29% and 37% for the crop varieties SR-52, SR-52A, Local and LocalA respectively. When the average yields decline, their variability increases. Observing individual seasons, yield reductions due to an increasing delay time are most extreme when the start of the season is late. In season 1980/81 for example with such a late start, the yield reduction of SR-52 at a 10% soil (not acid) with no runoff, is 83% due to water shortage.

M400 shows another pattern. At a delay time of 0 days, the water-limited production is 8% below the potential level. At a delay time of 7 days the yield has increased to the potential level, after which it slightly decreases with further increasing delay time. At a delay time of 42 days the yield compared to the potential yield is reduced with 5%, due to water-limitation. Acidity has more effect when the maize crop is sown later. Reduction due to acidity of the water-limited yield at a delay time of 42 days is 9%. As for the varieties SR-52 and Local, variability increases with decreasing yields.

If, due to late sowing, water availability is strongly limiting, other factors restricting the amount of water available for the crop also affect yields more pronouncedly. This is illustrated for acid soils in table 16-A. The effect of runoff is similar (table 16-B). Runoff hardly affects yields at the earliest start of crop growth, but reductions in water-limited yields due to runoff at a delay time of 42 days amount to 7%, 7%, 8%, 8%, 2% and 4% for SR-52, SR-52A, Local, LocalA, M400 and M400A, respectively.

For the 15% soil roughly the same pattern can be observed. There are some differences though. First, a situation without runoff will be analysed (table 16-C). Compared to the 10% soil, water-limited yields at a delay time of 0 are slightly lower for the 15% soil. For SR-52, SR-52A, Local and LocalA varieties, from a delay time of 7 days onwards, water-limited yields for the 15% soil are higher than for the 10% soil with a maximum difference at the latest sowing time of 13%, 17%, 14% and 16%, respectively. For M400 and M400A this effect is less pronounced: yields at a delay time of 42 days are only 2% and 3% higher, respectively, at the 15% soil.

Runoff affects yields of SR-52 and Local for the 15% soil (table 16-D) in the same way as for the 10% soil. There is hardly any effect at a delay time of 0 but at a delay time of 42 days water-limited yields of SR-52, SR-52A, Local and LocalA are reduced due to runoff with 6%, 9%, 7%, and 8%, respectively. Yields of M400 and M400A are hardly affected by runoff (2% or less).

5.4 Discussion

5.4.1 Discussion of the simulation results

The calculated average start of season in Petauke (11 November on the 10% soil and 15 November on the 15% soil) is close to the beginning of the season in Petauke according to the FAO (1984) who mentions 12 November. The average start of the 10 seasons according to the criterion of Das (1979) does correspond fairly well too (18 November) but the separate values for some seasons differ substantially. This is especially the case for the seasons 1981/82 and 1982/83 for which in this study an early start in

Table 16 Water-limited crop yield (grains dry matter, kg/ha), related to delay time for 3 maize varieties on a standard or an acid soil (A added) for several combinations of water holding capacity and percentage of runoff. Averages of 10 seasons with their coefficients of variation.

A - Water holding capacity of 10%, no runoff.

Delay of planting (days)	Crop variety					
	SR-52	SR-52A	Local	LocalA	M400	M400A
0	11586	11236	7751	7754	8228	8265
7	11166	10476	7628	7494	9201	9100
14	10761	9915	7354	7151	9144	9016
21	10011	9028	6785	6428	9024	8847
28	9519	8474	6436	6044	8888	8558
35	8811	7580	6008	5505	8653	8147
42	7846	6493	5491	4914	8216	7460
	Coefficient of variation (%)					
0	6	8	9	9	27	25
7	7	11	5	8	2	2
14	11	15	10	14	2	2
21	18	23	19	26	2	3
28	24	30	26	33	4	8
35	32	37	32	41	9	14
42	40	46	41	48	15	23

B - Water holding capacity of 10%, 15% runoff.

Delay of planting (days)	Crop variety					
	SR-52	SR-52A	Local	LocalA	M400	M400A
0	11410	11013	7680	7582	8030	8006
7	10822	10159	7507	7212	9202	9100
14	10403	9569	7233	6858	9138	8983
21	9580	8607	6586	6124	8983	8737
28	9092	8033	6181	5752	8827	8390
35	8369	7121	5656	5163	8591	7899
42	7260	6034	5067	4499	8042	7144
	Coefficient of variation (%)					
0	7	10	10	10	31	29
7	11	14	7	13	3	4
14	13	17	11	17	2	3
21	21	26	20	29	2	5
28	29	34	29	37	5	10
35	36	42	38	46	9	16
42	46	52	48	53	16	26

C - Water holding capacity of 15%, no runoff.

Delay of planting (days)	Crop variety					
	SR-52	SR-52A	Local	LocalA	M400	M400A
0	11149	10517	7586	7422	8089	7783
7	11265	10511	7794	7579	9000	8594
14	10946	10133	7590	7297	9059	8652
21	10580	9729	7357	7018	8938	8492
28	10176	9293	7101	6673	8852	8320
35	9688	8671	6782	6315	8705	8076
42	9022	7832	6368	5848	8415	7694
	Coefficient of variation (%)					
0	10	13	15	16	30	30
7	5	13	4	8	3	4
14	7	17	3	10	3	5
21	12	21	7	16	4	12
28	17	27	14	24	5	15
35	23	34	20	31	5	17
42	32	43	28	40	10	23

D - Water holding capacity of 15%, 15% runoff.

Delay of planting (days)	Crop variety					
	SR-52	SR-52A	Local	LocalA	M400	M400A
0	11110	10482	7529	7372	8153	7874
7	11140	10198	7744	7474	9104	8801
14	10750	9701	7488	7140	9103	8775
21	10118	9164	7107	6676	8876	8427
28	9665	8701	6818	6269	8815	8278
35	9173	8082	6432	5878	8646	7997
42	8460	7138	5953	5376	8309	7504
	Coefficient of variation (%)					
0	12	13	17	18	31	30
7	6	15	4	10	3	4
14	18	19	4	12	3	4
21	16	26	11	20	6	16
28	21	34	17	29	6	16
35	28	41	24	37	7	19
42	38	50	34	47	13	26

October is found. To bring the upper 15 cm of the 10% soil to field capacity a shower of 18 mm on one day (15 mm plus approximately 3 mm to compensate for evaporation) is sufficient. For the 15% soil this is 25.5 mm. When more days are involved additional precipitation is required because of soil evaporation. In season 1981/82 precipitation is 13.1 mm on 24 October and 8.2 mm on 25 October. In season 1982/83 precipitation is 27.8 mm on 22 October. These showers are just large enough to meet the criterion.

Potential yields depend on temperature and the level of solar radiation and thus vary depending on the date of emergence. The calculated potential yields give an indication of the productive potential of the agro-climatic zone around Petauke. Wolf, Van Diepen and Van Immerzeel (1987) have calculated a potential grain yield for MM752 (identical to SR-52 but with an improved seed quality) of about 11 tons (dry matter) per hectare for Lundazi which is also located on the easthern plateau. That estimate corresponds well with the yields found in this study.

Water-limited yields are in some cases higher than potential yields. This is the result of moderate moisture stress before anthesis. The resulting reduction in weights of leaves and stems causes maintenance respiration during grain filling to be lower. When the LAI (Leaf Area Index) during the grain filling period is still high enough to ensure complete light interception, the reduced respiration rate may result in higher grain yield.
The lower average water-limited yields of SR-52 and Local with delayed sowing is obviously the result of the lower amount of precipitation during the crop growing period, even though the length of the growing period increases. From January onwards average monthly rainfall decreases and in March and April it is very low (table 12). The yields of SR-52 are slightly more affected than those of Local.

Very important is the increasing variability with delayed sowing. On sections of land, where a farmer is forced to sow late, risks of severe yield losses are high, especially when the season has started late. The yield reductions of M400 with late sowing are less pronounced. At the 10% soil this variety performs even better than SR-52 when the delay time is 42 days, even though the potential yield is about 20% lower. The variability is also much lower. Varieties with a shorter growing period seem to be interesting for farmers when they are forced to sow late, because of the reduced risks. For subsistence farmers it is important that there are varieties with this feature that also perform reasonably well under low input conditions. In the model calculations, moisture stress after anthesis has a direct effect on grain yield because water shortage causes a reduction in transpiration and hence in assimilation during the filling of the kernels. This is not the case when drought occurs before anthesis. Then a lower LAI may result during the post-anthesis period but as explained at the beginning of this section, that does not imply a proportional reduction in grain yield. Therefore, the average yields of M400 at the first sowing period, though these are reduced due to water shortage before anthesis, are not additionally affected by acidity and runoff (tables 16-A and 16-B). When sowing is later, water shortage during grain filling of all 3 varieties occurs at an increasing number of days. Acidity and runoff increase the number of stress days and the intensity of the stress. This results in an increasing effect of acidity and runoff with an increasing delay time, both relatively and absolutely, for all 3 varieties.

The lower average yields at the 15% soil compared to the 10% soil if the delay time is 0, are mainly caused by the results of season 1982/83. In that season at the end of the dry period after sowing and germination a longer period of time is required on the 15% soil before the soil moisture content attains the level that allows assimilation. This results in a lower LAI at anthesis than at the 10% soil. When sowing is late, the yields on the 15% soil are less reduced by water shortage because of the higher water holding capacity of this soil, which consequently remains moist during a longer period at the end of the season.

M400 with its short growing period is less sensitive to late sowing but the average yields are lower at the first sowing period. This is mainly due to the seasons for which a start in October has been calculated (seasons 1981/82 and 1982/83 at the 10% soil, and season 82/83 at the 15% soil). As explained in section 5.3, these early starts are followed by prolonged dry periods. At longer delay times, germination after sowing is postponed due to drying of the soil during the time needed for tillage and sowing. When delay time is 0, however, seeds will germinate immediately and the seedlings suffer from moisture stress. Because of the short growing period until anthesis, M400 has insufficient time to recover and to restore the low LAI which is the result of the drought during the beginning of the growing period.

5.4.2 Additional discussion

The period between sowing and emergence is not included in the WOFOST simulation model. Germination is a very crucial period though and because of the small root that just starts to grow, a seedling is sensitive to drought. In this study the critical soil moisture content for germination was set at a rather arbitrary value and when the criterion is met, germination starts immediately on that day. Drought during the subsequent days is not accounted for. After the start of germination, drying of the soil may prevent further development though. This is a complex process: some seedlings may be able to grow fast enough to reach soil layers that are still moist and others, which have germinated 1 or 2 days later may not be able. In a model thin soil layers have to be distinguished to simulate these processes. Dying of seedlings results in uneven plant density in the field or in a total loss of the crop. In some cases farmers will have to sow again. To model these processes, more information should be collected about the sensitivity of maize seedlings to moisture stress during the different stages of germination. Then an estimate can be made of the probability of a certain plant density on the field, depending on rainfall distribution and/or soil moisture content of the upper soil layers after sowing.

Likewise more information is needed about the degree of stress a maize plant can resist before it dies, in relation to its growth stage. Even when a plant does not die it may need some time before assimilation processes are normal again, damage has been restored and new leaves have been formed. In the present model such effects have not been included. Other effects of severe moisture stress which have been recorded for some crops but for which relevant data are lacking, are: rolling of leaves, changes in development rate, change in partitioning of assimilates and effects on photosynthesis characteristics. Neither process is simulated in the present version of WOFOST. De Koning et al. (1989) have evaluated the additional effect of drought during critical periods such as pollination and silking, on the reduction in grain yield.
Sowing in dry soil is risky because the first rains are early in some seasons. When a long period of drought follows, yields could be severely reduced. In those cases resowing will be necessary. According to the Ministry of Agriculture and Water Development of Zambia (1983) sowing in dry soil can be advised if soil tillage is done at the end of the preceding growing season and if seeds are planted at a depth of 9 cm. This prevents the seeds from germinating after light showers.

Late sowing affects yields of both subsistence and commercial farmers. In general, the latter group operates at a relatively high level of mechanization and has more options to arrange optimal timeliness of farm operations. Subsistence farmers can advance the date of sowing by reducing the required amount of human labour per hectare, for example by increasingly using oxen or by hiring a tractor. The socio-economic feasability of such measures has to be evaluated however. To what extent actual yields are lower than the water-limited yields, for example due to weeds, nutrient-limitation, pests and diseases, has been estimated in chapter 6. Optimization models can be used to evaluate what are the main constraints for agricultural production (Van de Zande, 1990) and to estimate what are the consequences of certain decisions of farmers, for example about the distribution of labour over different agricultural operations.
One should be aware of the fact that a lack of means (inputs, cash, credit etc.) and/or knowledge can be important constraints on the application of innovative technological measures.

6 PESTS, DISEASES, WEEDS AND OTHER FACTORS INFLUENCING MAIZE YIELDS

Maize yields in Zambia can to a large extent be reduced by the occurrence of pests, diseases and weeds and by other, local factors. For the sake of simplicity, we will use "pests" to refer to all biological factors that reduce crop yields: insects, weeds, fungal and viral diseases, nematodes etc.
If yields are reduced by several pests, the final relative yield should be assessed by multiplying the relevant relative yields, where relative yield is defined as:
yield infested crop / yield healthy crop * 100%

If the interyear variation in pest incidence in maize is limited, then losses in grain yield and/or other crop parts of maize would be stable and can be assessed by stable reduction factors. This is probably realistic for the occurrence of weeds (Van Heemst, 1985) as well as for soil-borne pests, of which the incidence is mainly determined by cultural practices. However, it seems an oversimplification for air-borne pests such as stalkborer. The cumulative effect of all maize pests can nevertheless be stable if their occurrence is complementary, i.e. if sudden outbreaks of some pests are compensated by reduced incidence of other pests and vice versa. Compensation can occur: for example because the sizes of the populations of crop pests are mutually dampened by antagonistic interaction, such as competition for the energy produced by a crop. Whether this results in stable yield reductions is unclear, as crop losses do not only depend on the population size of a pest agent but also on the harmfulness of an infection. We have not been able to check the assumption of complete complementarity, because we did not come across long-term records of the incidence of all major maize pests in southern Africa. However, we find some support in the observations of Das (1973). He related maize yields over many years in Zambia to meteorological data, with a correction for the technological trend. The correlation coefficient he obtained was extremely high: 99.7%. That could indicate that interannual variation in maize yields can almost completely be explained by interannual variation in rainfall and temperature and crop losses due to pests can be considered as almost constant.
The relative yields of maize in maize/weed stands have mainly been derived from the information provided by Kinsey (1979), which seems to refer to row-planted maize. In such a regular plant arrangement, intrarow weed competition is limited, as will be discussed below. Kinsey's data can be transformed into figures that represent the relative yield if maize is not weeded during particular periods. These figures, which have slightly been corrected for the information provided by Vernon and Parker (1983), are represented in table 17 for maize planted in rows.

According to Ntlhabo (1985) maize yields are reduced to 67% if maize is not planted in rows but broadcasted or sown behind the plow. This reduction is caused by the irregularity of such stands, which makes crop cover of the soil less complete and weeding more difficult. The effect of weed competition seems to be more important than the incomplete cover as the data of Vernon and Parker (1983) indicate that without interrow weeding, weed competition causes a drop in relative yields to approximately 70%. This implies that if no weeding is practiced at all, the differences in yields between row-planted maize and broadcasted maize/maize sown behind the plow should be small. This yield gap increases with the intensity of weed control to a maximum of 15%. This 15% (indicated in table 17 as additional reduction) has been chosen because we assume that weeding normally involves an interrow cultivation plus some intrarow hoeing, specially on badly infested spots.

Table 17 Relative grain yield of maize in Zambia in absence of protection against various pests.

Pest	Yield (%)
stalkborer (median value)	80
soil pests/nematodes/maize beetle	80 (rel. yield)
(relative population density)	70
leaf diseases + MSV	90
weeds:	
A - maize planted in rows	
no weeding during 15-24 days after planting	80
no weeding during 25-44 days after planting	89
no weeding during 45-65 days after planting	92
B - broadcasted/sown behind the plow	
no weeding during 15-24 days after planting	83
no weeding during 25-44 days after planting	93
no weeding during 45-65 days after planting	96
additional reduction due to irregular stand	85

rel. yield = relative yield. Thus soil pests/nematodes/maize beetle reduce population density of the maize stand as well as the yield.
MSV = maize streak virus

The resulting relative yields for various intensities of weeding are presented in table 18:

Table 18 The influence of weeding on the relative yields of maize in Zambia.

Weeding system	Maize in rows	Broadcasted maize
no weeding	66	63
1 weeding (15-24 DAP) *	74	68
1 weeding (25-44 DAP) *	82	76
2 weedings (15-24 + 25-44)	92	82
3 weedings	100	85

* DAP = Days After Planting

6.1 Modelling crop losses due to pests

For modelling purposes, Boote et al. (1983) classified crop pests into 7 categories, according to their effect on the carbon flow processes:
- stand reducers, such as damping-off;
- photosynthetic rate reducers, e.g. some fungal and viral diseases;
- leaf senescence accelerators, e.g. leaf fungi;
- light stealers, e.g. weeds;
- assimilate sappers, e.g. sucking insects and nematodes;
- tissue consumers, e.g. chewing insects like foliage, root or grain feeders;
- turgor reducers, like soil-borne pests and diseases.

Of course, a single pest can fall into more than one category. For the purpose of this study, we have further simplified Bootes classification. The effects of soil-borne pests are according to Boote, a combination of stand and turgor reduction, assimilate sapping and root tissue consumption. These effects can be simulated by lowering plant density and rooting depth plus reducing nutrient availability. Light stealing is primarily caused by weeds. We assume that weeds grow in the same way as maize, i.e. with the same growth rate, transpiration coefficient and nutrient concentrations, but they yield no economic product. The simplification of Bootes classification results in three categories of maize pests:

1 those that reduce grain yields but have little or no influence on the rate of and development of the crop;
2 the pests that affect the leaves of maize;
3 the soil pests.

1 Those that reduce grain yields but have little or no influence on the rate of growth and development of the crop. In their presence, the Harvest Index is reduced, while the Leaf Area Index (LAI), water and nutrient uptake remain unchanged compared to uninfected crops. The yield loss can simply be assessed by multiplying the relative yield with the water-limited grain yield. The various relative yields should be multiplied, if several pests are present. The total reduction caused by stalkborers and weed competition at 15-24 and 45-65 days after planting in a broadcasted crop would thus be: 80% * 83% * 96% * 85% = 56%. The pests we have classified in this group are:
   - stalkborers, because we assume that their damage is confined to the cobs only;
   - cobrot, because of the same reason;
   - weeds, because we assume weeds to grow maize-like and therefore the LAI, water and nutrient uptake of a crop/weed stand are simular to that of a weed free crop;
   - the effect of irregular stands due to broadcasting or planting behind the plow, because we suppose that this results in more severe weed competition.

2 The pests that affect the leaves of maize. Their action can involve a reduction in the life span of the leaves. The resulting LAI reduction induces lower yields as well as lower transpiration rates. Leaf diseases such as maize streak virus and others typically belong to this group. It has been observed, however, that some leaf diseases also cause a yield reduction by decreasing the rate of photosynthesis (Buchanan et al., 1981). This is the case for some viral and most obligate fungal diseases. At the pest + water-limited yield level (see below), nutrients are supposed to be abundantly available and infections by obligate parasites are likely. We will therefore suppose that some of the leaf diseases cause a reduction in the photosynthesis, although we have no information about the photosynthesis reducing properties of Zambian leaf diseases. For the sake of simplicity, we will attribute about half the yield loss to a reduction in the lifespan of the leaves and half the loss to a reduction in the rate of photosynthesis. The effect of the decline in this rate will be simulated with a constant factor.

3 The soil pests. These pests attack maize during its initial stages, resulting in reduced plant density. Later, they can also reduce the expansion of the rooting system. The first effect can be introduced straightforwardly in the simulation models by reducing the plant density of maize, while the latter can be simulated by a reduction in the rooting depth. Also, nutrient uptake can be reduced due to infestations with soil pests.

   The influence of nematodes and other soil pests on the rooting depth of maize has not yet been thoroughly examined in tropical

regions. For temperate countries, some information is available. Scholte and 's Jacob (1983) found that the most serious soil pest of monocropped maize in the Netherlands is *Pratylenchus neglectus* and that this nematode mainly feeds on the primary roots of maize. During the later stages, secondary (crown) roots develop and these roots take over the functions of the primary roots. As these secondary roots are not so severely attacked by *P. neglectus,* a normal rooting depth is achieved at a somewhat later stage. In South Africa more species of *Pratylenchus* are involved and it is uncertain whether these species have feeding habits similar to *P. neglectus* in the Netherlands (Louw, 1982). Generally, the numbers of nematodes are higher in warmer regions (Agrios, 1969). Agrios (1969) states that feeding by *Pratylenchus* species not only results in root weight reduction, but also in root rot caused by secondary infections by fungi etc., that finally result in root pruning and slough of roots. Therefore, Pratylenchus-infested crops are unable to absorb adequate amounts of water and nutrients. The illustrations of maize root systems provided by Shurtleff (1980) seem to indicate that the rooting depth of soil-pest infested maize from a non-specified region is ± 60% of that of healthy maize and the rooting depth of Pratylenchus-infested maize is ± 75% of that of the healthy crop. Some quantitative information is available for other crops. Boote et al. (1983) have calculated that soybeans will show a reduction in pod yield and transpiration of 70-83% and 60-80%, respectively, if half the root-mass is taken away. The reduction in rooting depth will in that case be about 79%, if we assume that root growth is reduced in all three dimensions to an equal extent (the 3rd power of .79 is .50).
In our calculations, soil pests reduce the rooting depth as well as the rate of vertical extension of the rootsystem.

6.2 Application

The approach to crop growth modeling applied by the CWFS is hierarchic. At the highest level, the potential level of crop yields, crop growth is only limited by solar radiation and temperature. At the second level, moisture availability is introduced as a possible limiting factor and at the third level, the availability of macro nutrients determines crop yield. Finally, at the fourth level, crop losses due to pests and local factors are considered (Wolf et al., 1987). We will refer to this fourth level as "actual yield". In the approach followed by the CWFS, variation in crop yields is small at the highest level, but - in the case of Zambia, where rainfall is erratic - variations in crop yields occur at the second level. If farmers, as is the case in Zambia, apply little fertilizer, then crop yields would be determined only by nutrient availability. In that case, all variation, due to variations in severity and timing of drought, will be lost. That is not in accordance with the findings of Das (1973), who established a strong relationship between rainfall and maize growth (see above). Also other authors mention yield variability of maize, even at low soil fertility and this variation is normally attributed to variations in rainfall patterns (e.g. Wood, 1985). Therefore, we have modified the hierarchy slightly in order to save some of the variation. We start by calculating the potential, water-limited and nutrient-limited yields according to the "normal" CWFS-procedure. Yield losses due to pests are introduced at two levels, both for water- and for nutrient-limited yields.

6.2.1 Pest+water-limited yield

A pest+water-limited yield is introduced to simulate actual yield in abundance of nutrients. This level is calculated by reducing the water-limited yields to a level established in table 17, following the method described in points 1-3 (sect. 6.1) above. The pest+water-limited yield level fluctuates as the water-limited yields show variations. Yields of maize, grown in the absence of plant protection, planting devices and with one medium late weeding, are approximately reduced to 40% (= 80% * 80% * 90% * 83% * 96% * 85%) of the water-limited yield. We expect this reduced yield to be slightly above the actual yields. We have no direct proof for this expectation, but we derive some support from the official recommendations for maize production by Zambian smallholders. These recommendations include the application of pesticides as well as of chemical fertilizers and improved varieties (National LIMA Fertilizer Programme, 1985). Clearly, pesticides are only necessary if the pest+water-limited yields are just a little above the actual yields. If the pest+water-limited yields would be at a higher level, that would suggest that only fertilizer is required to achieve a large increase in actual yields. If the pest+water-limited yields would be at a level below the actual yields, that would suggest that fertilization would not be effective at all. Both situations, with the pest+water-limited yields set too high or too low, are not conform the official Zambian recommendations. Another indication of the pest+water-limited yield level is provided by De Toro (1984). He observed that farmers started to apply pesticides if fertilization had increased the grain yields over 2250 kg/ha but before 3150 kg/ha was reached. The pest+water-limited yield level should be within this range (approx. 2000-2800 kg dry matter/ha). The modification of the approach of crop growth modelling can be represented as shown in table 19.

Table 19 Modified versus "normal" approach of crop modelling.

Grain yield (tons/ha)	Modified approach		"Normal" CWFS approach
10	– ———	potential yield	——— –
8	| ———	water-limited yield	——— |
6	–		–
4	–		
	| ———	pest+water-limitated yield	
2	– ———	nutrient-limited yield	———
	———	actual yield	———
0			

–
|
– crop yield variation of water-limited and pest+water-limited yields

In this hypothetical example actual and nutrient-limited yields are equal in both approaches. Differences will develop at increasing fertilizer rates. In that case, the actual yield level will approach the pest+water-limited yields. This results in a decreasing response to fertilizer application because the actual yields cannot "pass" the pest+water-limited yields. Moreover, at increasing fertilizer rates, actual yields will start to show variation because this yield level "enters" the lower tail of the probability distribution of the pest+water-limited yields. In the "normal" CWFS approach actual yields will show no variation at higher fertilizer rates, except for very high rates, at which water-limited yields are approached. Thus the consequences of the introduction of this additional pest+water-limited yield level are:

- application of fertilizer results in higher and more variable yields;
- high fertilizer rates in the absence of plant protection are ineffective because of pest+water limitation.

6.2.2 Pest+nutrient-limited yield

Pest+nutrient-limited yields are determined in the same way as nutrient-limited yields, but the effect of pests, that interact with the nutrient uptake of crops, is taken into account as well. The effect of pests on the level of the pest+nutrient-limited yields depends on the mobility of the nutrient involved and on the nature of the pest, i.e. soil pest or weed.
We distinguish mobile nutrients, such as N, and immobile nutrients, such as P. Immobile nutrients can only be derived from the immediate surroundings of the roots. A crop can only be assured of a continuous influx of immobile nutrients, if the roots are growing continuously. The "effective feeding area" of the root system for mobile nutrients is not confined to the actual soil area contacted by the roots, but includes all the area within the - relatively large - diffusion range of these nutrients. Therefore, competition between weeds and maize for N will be as severe as for water. Earlier, we have assumed that weeds grow in the same way as maize. This implies that the reduction in crop yield, established in table 17, should be equal to the reduction in N-uptake if N is limiting crop growth. Soil pests, on the other hand, mainly limit the size and expansion of the root system. They only reduce N uptake in prolonged dry periods, during which the soil is too dry to allow N to diffuse towards the root system. The data of Anthony and Uchendu (1970) indicate that this is seldom the case and soil pests generally do not reduce N-uptake.

Their data also indicate that the P-response (increase in crop yield/increase in P-application) of monocultured maize is only 70% of the P-response of rotated maize in Magoye. Although we are not certain, we have assumed that soil pests decrease the P-recovery in Magoye to 70% too. It is not clear whether this percentage can be transferred directly to the situation in the Petauke area because the Kafue clays of Magoye are very poor in P (Brammer, 1973). Presumably, the reduction in P uptake is less pronounced in other parts in Zambia, where more P is available. Weed competition for P is less likely than for N, because plants only compete for P if the rooting systems of the crop and weed population contact (Kurtz et al., 1952). This is only likely for weeds that grow in the near vicinity of the crop, i.e. within the rows. Weeds that grow at larger distances from the maize rows will mostly feed on P that cannot be utilized by maize. Thus, weeding will hardly increase P-availability to maize and conversely, on a badly weeded plot, P-availability will hardly be reduced. We therefore feel no need for an adjustment of the P uptake caused by the occurrence of weeds between the rows. If uptake of this element by the crop in a mixed maize/weed stand is reduced, it is most probably the result of competition for other factors, such as a low N-uptake, rather than that it has been caused by direct competition.

Wolf et al. (1987) estimated that the actual yields are approximately 70% of the nutrient-limited yields and calculated that P is generally the limiting nutrient for crop growth. As our information on crop losses at low input conditions is limited, we intend to follow them. Then, P-uptake would be reduced to around 70% because of soil pests and weeds. We have chosen for reduction to 85% due to weeds within the row, equal to the reduction caused by broadcasting/sowing behind the plow. The relative uptake caused by soil pests is consequently 82% (=70/85).

For potassium, the third nutrient involved in the determination of nutrient-limited production, no such information was found. However, that is not very serious because K deficiency is unlikely in Eastern Zambia (Prior, 1976). As the mobility of K is between those of N and P, we have assumed that the reduction in K uptake is between those of N and P (table 20). Thus, the recovery of P can only be increased by row planting or by rotation and/or chemical protection against soil pests. The recovery of N however is fully dependant on the intensity with which the crop is weeded.

Table 20 Relative nutrient uptake of maize in Zambia in the absence of protection against soil pests and weeds.

Pest	Relative nutrient uptake (%)		
	N	P	K
soil pests	100	82	91
weeds:			
A - maize planted in rows			
no weeding during 15-24 DAP	80	100	89
no weeding during 25-44 DAP	89	100	94
no weeding during 45-65 DAP	92	100	96
B - broadcasted/sown behind the plow			
no weeding during 15-24 DAP	83	100	91
no weeding during 25-44 DAP	93	100	96
no weeding during 45-65 DAP	96	100	98
extra reduction	85	85	85

DAP = Days After Planting

6.3 Results and discussion

Crop data have been adapted to simulate the effect of leaf diseases and soil-borne pests. These adaptations have been calibrated in such a way that the resulting relative yields were at the desired level (table 17). For this calibration we have focussed on the maize variety SR-52 with a normal rooting depth (= no acidity hampering root growth), growing in an area without runoff and with the crop planted two weeks after the onset of the rainy season.

We have indicated that about half of the effect of leaf diseases can be attributed to a reduction in the life-span of the leaves. At a reduction from 40 to 34 days, a relative yield of 94% is obtained for SR-52 at the conditions described above (table 21). Consequently, the constant factor expressing the decline in rate of photosynthesis is 96% (90/94). The coefficient of variation declines if the life span is reduced, which indicates that the crop becomes less sensitive to drought. This can be explained by the reduced LAI which causes a decline in transpiration, thus reducing water shortage. The results indicate that the local varieties are less influenced by a reduction in the life span, probably because they produce a relatively large number of leaves. M400 is also little influenced, presumably because its yield is mainly determined by the short reproductive period, rather than by environmental stress.

The effects of soil pests are simulated by reducing the plant density, maximum rooting depth and RRI (rate of vertical extension of the rootsystem). The maximum rooting depth at a plant density of 70% had to be reduced to 40%, i.e. from 75 cm to 30 cm, for variety SR-52, growing under the conditions described above to attain a yield reduction to 80%. The accompanying reduction in transpiration is 16%. The large discrepancy between our calculated reduction in the rooting depth to achieve the desired reduction in crop yields (table 17) and the one deduced from Bootes data for soybeans (see 6.1) is partly explained by the insensitivity of the WOFOST model to changes in plant density, such as the stand reduction caused by soil-borne pests. This insensitivity of the WOFOST-model results from the assumption that crop plants are distributed regularly, but this is not the case if soil pests reduce the plant density. Therefore, we have assumed that the losses caused by soil-borne pests should only for 50% be attributed to a reduction in the rooting depth and for 50% to other causes. These other causes include, amongst others, a reduction in the density of the maize stand and the excretion of harmful substances by nematodes. Such effects may result in enhanced weed growth. The yield loss caused by these effects can thus be assessed in a way similar to that of stalkborer and weeds, i.e. with a constant factor.

The reduction in rooting depth to achieve the desired yield reduction (table 17) is 40%, i.e. from 75 to 45 cm for variety SR-52 growing under the conditions described above. This 40% is in reasonable accordance with the information provided in 6.1. As the relative yield of maize infested by soil pests is 80% and the reduction caused by the change in maximum rooting depth is ± 91%, the fixed reduction factor should be 88% (.80/.91). Crop yields of SR-52 and the local variety are reduced to the same extent by a reduced maximum rooting depth, but M400 is less affected, presumably because it matures before the onset of the longer dry periods during which infested crops are highly sensitive. In all varieties the coefficient of variation increases, as the crop becomes more drought prone.

The relative yields of maize variety SR-52 infested by both pests is close to 72%, the expected value (80% * 90%, see table 21). The yield losses due to both pests are relatively small for M400, while the losses for the local variety are in between.

SR-52, with its adaptations for leaf diseases and soil-borne pests is more drought sensitive than healthy SR-52. This is shown in the decline in grain yields of maize due to delayed planting, as presented in table 22. A delay in planting time of 35 days results in relative yields of 65 - 83% for healthy maize and 63 - 69% for diseased maize. The latter figures are close to the relative yield found by Kinsey (1979), which was 60% at a delay of 35 days.

Table 21 Crop yields (pest+water-limited) (kg dry grains/ha) of maize varieties infested with various pests. The coefficient of variation is given between parentheses. Maize is planted after a delay of 14 days.

Maize varieties	Yield of healthy maize	Crop yields with various pests			
		leaf diseases	soil-pests	leaf diseases + soil-pests	idem + runoff
life span leaves:	40 days	34 days	40 days	34 days	34 days
rooting depth:	100%	100%	60%	60%	60%
RRI *	100%	100%	50%	50%	50%
runoff:	0%	0%	0%	0%	15%
reduction factor	100%	96%	88%	84.5%	84.5%
loamy sand (10% water holding capacity)					
SR-52	10761	9740	8613	7926	7131
	(11%)	(9%)	(15%)	(14%)	(24%)
SR-52A	9915	9102	7673	7060	6464
	(15%)	(13%)	(19%)	(17%)	(27%)
Local	7354	6994	6014	5739	5090
	(10%)	(9%)	(18%)	(18%)	(28%)
LocalA	7151	6812	5639	5381	4804
	(14%)	(14%)	(22%)	(21%)	(31%)
M400	9144	8776	7970	7648	7333
	(2%)	(2%)	(3%)	(3%)	(10%)
M400A	9016	8655	7450	7150	6872
	(2%)	(2%)	(7%)	(7%)	(14%)
sandy loam/red clay (15% water holding capacity)					
SR-52	10946	9782	8784	7926	7288
	(7%)	(6%)	(18%)	(17%)	(21%)
SR-52A	10133	9108	7806	7084	6476
	(17%)	(15%)	(23%)	(22%)	(25%)
Local	7590	7214	6199	5888	5356
	(3%)	(3%)	(17%)	(17%)	(24%)
LocalA	7297	6935	5846	5557	4900
	(10%)	(10%)	(22%)	(22%)	(31%)
M400	9059	8695	7577	7270	7335
	(3%)	(3%)	(7%)	(7%)	(5%)
M400A	8652	8304	7062	6779	6748
	(5%)	(5%)	(11%)	(11%)	(10%)

* RRI - rate of vertical extension of the root zone

Table 22 Maize yields of SR-52 in kg dry grains/ha infested by leaf diseases and soil pests and with runoff at various planting times.

Delay of planting (days)	Maize infested by soil pests and leaf deseases			
	loamy sand		sandy loam/red clay	
	SR-52	SR-52A	SR-52	SR-52A
0	8121	7444	8371	7609
7	7667	7019	7851	7041
14	7131	6464	7288	6476
21	6683	6009	6750	6012
28	6243	5624	6262	5511
35	5592	4965	5398	4765

Delay of planting (days)	Healthy maize			
	loamy sand		sandy loam/red clay	
	SR-52	SR-52A	SR-52	SR-52A
0	11410	11013	11110	10482
7	10822	10159	11140	10198
14	10403	9569	10750	9701
21	9580	8607	10118	9164
28	9092	8033	9665	8701
35	8369	7121	9173	8082

Control treatments are recommended for soil pests and stalkborer. We have little information on the yield losses of treated maize crops. Soil pests appear to be effectively controlled by pesticides (Louw, 1982) and therefore the yield losses of a treated crop is assumed to be zero. The data of Walker (1960) indicate that the effect of stalkborer under Zambian conditions can be as follows:

- no spraying: relative yield 80%;
- 1 spray: relative yield 93%;
- 2 sprays: relative yield 97%;
- 3 sprays: relative yield 100%.

7 RISK OF CROPPING PRACTICES

In the preceding sections the major yield determining and yield reducing factors have been examined and we are provided with means to predict the effects of agronomic practices such as fertilization, choice of variety, crop protection and planting method. In this section we will use this information to calculate expected yield levels for various combinations of agronomic practices. Moreover, this information will be used to establish how these practices can be optimally applied in risk averse and risk neutral farming systems. We will frequently use the term crop management system, which we define as a specific combination of agronomic practices.

To determine the risks of the application of agronomic practices we have to:

- simulate yields under various crop management systems;
- determine the most adequate probability distribution for the simulated crop yields;
- determine the optimum crop management system using d-levels or returns for risk averse and risk neutral farmers, respectively.

7.1 Simulations

Yields are determined using the WOFOST and QUEFTS models. The WOFOST model is run for 10 years as described in chapter 5 with the adaptations for pests and other factors as described in chapter 6 and with 15% runoff. Although the soils in the Petauke area are not particularly leached and acid, we have used the reduced rooting depths (SR-52A, LocalA and M400A) as we assumed that this reduction is caused by soil disturbances rather than by acidity. Clay soils can contain sheet laterite and on Sandveldt soils gravel inclusions are common (Brammer, 1973). Such disturbances cannot be corrected by liming. The yield reduction caused by drought at the flowering stage (De Koning et al. 1989) has been included in the simulations. The resulting yield losses of local varieties are set at a 10% lower level compared to the hybrid varieties because the sensitivity of the heterogeneous local varieties is expected to be lower. The QUEFTS model is applied in a similar way as in earlier CWFS-studies on Zambia (Wolf et al., 1987). Reductions in nutrient uptake caused by soil pests and weeds described in chapter 6 are included. We will consider two soil types only: red clay and Sandveldt loamy sand. Fertility on red brown loams, which are also common in the Petauke area, is in between those of red clay and loamy sand. Therefore, the returns and risks of agronomic practices are presumed to be between those on the other two soil types.
We are primarily interested in a comparison between the performance of local varieties and SR-52, as these are the most widespread varieties in Zambia. We have included some calculations of M400 as well, to demonstrate the potential usefullness of early maturing varieties under Zambian conditions. M400 is not widespread yet and it is mostly planted by commercial and emergent farmers (both small and large scale). Their holdings are concentrated on red clay soils, and therefore we calculated yields of M400 for red clay soils only.

7.2 Yield distributions

The probability distribution of the water-limited yields turns out to be rather skewed, specially if maize is planted late (table 23).

Table 23 The probability distribution of water-limited maize yields on loamy sand and red clay soils, for the planting dates of 35 + 42 days (combined) after the onset of the rainy season.

	Yield (grain dry matter, tons/ha)									
	1	2	3	4	5	6	7	8	9	10
loamy sand	0.10		0.15		0.15		0.20		0.40	
red clay		0.20		0.20				0.15		0.45

Yields are commonly close to the potential as precipitation is normally adequate and yields are only occasionally considerably lower. This asymmetry is also observed for the pest+water-limited yield. The skewness is greatly increased if nutrient limitation is taken into account, especially if little or no fertilizer is applied. In that case, yields often reach the maximum level that is allowed by nutrient availability.

Following Zandstra et al. (1979), we assume that the normal distribution, although not skewed at all, is adequate to describe the outer left part of the yield distribution. This implies that Kataoka's rule can be rewritten into:

$d = \tilde{y} - ks$ where: $\tilde{y}$ = mean yield
s = standard deviation of yield
k = determined by the risk accepted

Thus, d-levels increase if yields increase and/or standard deviations decrease. D-levels decrease if yields decrease and/or standard deviations increase.

7.3 Determination of optimum crop management systems

In this section we will distinguish three kinds of agronomic practices:

- agronomic practices that require little additional labour but increase yields. Chemical crop protection, fertilization and choice of variety belong to this group. The costs of these practices can be expressed on a per hectare basis, which does not necessarily apply to the other kinds of agronomic practices.
- agronomic practices that reduce the labour requirement while the yield level is only marginally affected. The mechanization level of a crop management system is included in this category as well as the application of herbicides instead of manual weeding, because herbicides are assumed to be as effective as an early plus a middle late round of weeding (Parker and Vernon, 1982).
- agronomic practices that both affect the labour requirements and have an influence on the yield level. Weeding is a laborious task that clearly increases yields. The intensity of weeding (i.e. the number of weedings) therefore belongs to this group as well as the use of planting machines versus other planting methods.

The attractivity of agronomic practices to risk averse and risk neutral farmers will be evaluated in the following way. First the costs and benefits of the practices of the first group are considered. The combinations of practices that yield the highest returns or d-levels are determined for the various soil types, weeding methods, planting methods, planting dates and types of farmers. We simplify these results by combining our findings for the various weeding systems. This is done by taking the mean returns and the d-value of the d-levels of the various weeding methods (i.e. the number and timing of weeding) at a given soil type, planting method and date and type of farmer. The two selected combinations (highest returns, highest d-level) plus a base line combination are used at the second stage: the evaluation of the agronomic practices of the second and third group. This is done by maximizing either the returns or the d-levels of all maize cultivated in a farming system, using linear programming, with labour availability of the farmers' family as major constraint. In this way we are able to determine the optimal allocation of labour to major tasks such as soil preparation and weeding and consequently the acreage cultivated. The attractivity of the various alternatives for soil preparation and weeding can be calculated and evaluated by comparing the costs with the gains (returns * acreage or d-levels * acreage). The linear programming model has to be run separately for each of the soil types, types of farmers and planting methods. By comparison the most attractive planting method can be determined. Some additional assumptions have to be made to run the linear programming model, such as:

- the maximum area to which a farmer can increase his maize acreage;
- the maximum fertilizer rate;
- the availability of oxen and tractors for hire.

Because of lack of time, we focus on the agronomic practices of the first group. The results of the linear programming exercise are represented in chapter 8.
The costs of agronomic practices, necessary to calculate the returns and d-levels are represented in table 24.

Table 24 Costs of agricultural inputs (K).
1 K(wacha) = $ 0.26 (1979).

producer maize price	K 16/bag (90 kg air dry grains) = K 0.2/kg grain (dry matter)
hybrid seed (SR-52; 20 kg)	K 20
open pollinated seed (M400; 20 kg)	K 10
carbofuran 10 (12 kg)	K 49
endosulfan 5 % (2 kg)	K 10
primagram 50 (4 l)	K 36
ammonium nitrate	K 10/bag (50 kg)
d-compound	K 12/bag (50 kg)
interest	30% (subsistence farmers) 12% (small scale emergent farmers)
transport surplus maize	K 2.5/year
knapsack sprayer	K 15/year at 30% interest K 11/year at 12% interest
oxen rent (plowing + harrowing)	K 78/ha
tractor rent (plowing + harrowing)	K 78/ha
price oxen (pair)	K 237/year at 30% interest K 167/year at 12% interest
price ox implements (plow, harrow, ridger, cart)	K 193/year at 30% interest K 150/year at 12% interest
price ox-drawn planter	K 79/year at 30% interest K 53/year at 12% interest
price tractor	K 6500/year at 12% interest
price tractor implements (trailer, cultivator, plow, harrow)	K 3500/year at 12% interest
price tractor drawn planter	K 529/year at 12% interest

(Sources: Admiraal, 1981, De Toro, 1984 and Kinsey, 1979)

7.4 Results of calculation of returns and d-levels

Wolf et al. (1987) collected soil chemical data for some Zambian soils. The corresponding supply of nutrients from natural sources and the nutrient limited grain yields were calculated using the QUEFTS system (table 25).
As explained in chapter 6 the nutrient supplies to the crop are reduced in the presence of weeds and soil pests, resulting in lower nutrient limited yields. The nutrient-limited yields of the local varieties was set at 87.5% of the yields of hybrid varieties, because the latter have higher harvest indices. This value was also used by Wolf et al. (1987). The actual yields in a given year are assumed to be equal to the (reduced) nutrient-limited yields, if the latter are lower than the pest+water-limited yields, while the actual yield is equal to the nutrient-limited yields irrespective of the pest+water-limited yields, if the latter are lower. The yields have not been established for all crop management systems. The control of soil pests on red clay soils for example is very attractive, both to risk averse as well as risk neutral farmers. Therefore, yields of maize in the absence of soil pest control have been calculated for a few cases only.

Table 25 Supply of nitrogen, phosphorus and potassium to a maize crop (kg/ha) and the corresponding grain yields (kg/ha dry matter, without correction for losses).

Soil	Soil supply (kg/ha)			Grain yield (kg/ha)
	N	P	K	
red clay	119.7	9.1	63.3	3431
loamy sand	30.9	3.0	104.8	1231

(Source: Wolf et al, 1987)

Before determining the optimum crop management systems, we will consider the effects of several agronomic practices such as date of planting, choice of variety, rate of fertilizer application, and control of pests, on the performance of maize. These effects are most clearly demonstrated at a rather high level of fertilization and a rather low level of pest control. In table 26 the yields of hybrid, open pollinated and local varieties are illustrated for various planting dates, together with the variation in these yields, expressed in cv's (coefficient of variation = standard deviation/average in %).
The table indicates that yields decline if planting is delayed, both on loamy sand and red clay soils, although it should be realized that this decline is less pronounced at lower fertilizer rates and with more pest control. The decrease in yields in table 26 is not as sharp as the decrease in water-limited yields because these yields are mainly determined by nutrient availability at the early planting dates, specially on loamy sand soils. The yields of SR-52A are high if maize is planted early but are more affected by a delay in planting than those of the local variety as is shown by the decrease in yields at late planting dates and the increase in cv's. The local variety, with its deeper rooting system and higher development rate seems to be less sensitive to drought. The yields of M400A, although low at the first planting date, seem to be hardly influenced by the date of planting, and its short growth cycle seems adequate to escape drought, even at late planting dates. The variation in yield of M400A is also clearly much lower.
Returns have been calculated by subtracting the costs (expressed in kg/ha grain dry matter) from the yields and these

are presented in table 27 for subsistence farmers.

Table 26 Actual yields of hybrid and local maize varieties at various planting dates on red clay and loamy sand soils (broadcasted; fertilization rate: 86; soil pests controlled; stalkborer not controlled; no weedings) and their coefficients of variation.

Delay of planting (days)	Actual yields (kg/ha)				
	on red clay			on loamy sand	
	SR-52	M400	Local	SR-52	Local
0	3207	2943	2720	1554	1360
7	3188	3207	2795	1554	1360
14	3161	3207	2770	1554	1360
21	3064	3107	2664	1554	1349
28	2907	3107	2508	1537	1311
35	2770	3056	2340	1481	1251
42	2409	2932	2179	1370	1157
	Coefficient of variation (%)				
0	0	28.4	9.6	0	0
7	1.9	0	1.4	0	0
14	4.7	0	4.0	0	0
21	9.9	10.2	11.6	0	2.5
28	16.3	10.2	19.9	3.6	11.7
35	25.6	11.5	28.5	15.6	17.8
42	43.7	18.8	40.7	26.4	29.4

Table 27 The returns of maize varieties on red clay soils and loamy sand soils and their d-levels.

Delay of planting (days)	Actual yields (kg/ha)				
	on red clay			on loamy sand	
	SR-52	M400	Local	SR-52	Local
0	2311	2104	1940	658	577
7	2292	2368	2010	658	577
14	2265	2368	1995	658	577
21	2168	2268	1880	658	566
28	2011	2268	1730	641	528
35	1896	2217	1560	585	468
42	1585	2093	1390	474	374
	D-level (kg/ha grain dry matter)				
0	2311	1102	1610	658	577
7	2219	2368	1950	658	577
14	2089	2368	1880	658	577
21	1806	1888	1510	658	525
28	1443	1888	1100	575	343
35	990	1790	720	308	200
42	250	1431	305	41	-34

The highest returns on red clay are provided by M00A at all planting dates except at a delay of 0 days. The margin between the returns of SR-52 and local varieties is smaller than the margin between their yields as the costs of planting material have been included. This margin is particularly small when maize is planted late: the returns of SR-52A are only 100-140 kg/ha above the returns of the local variety at a 42 days delay in planting. The margin at this planting date between SR-52 and local varieties is further reduced if d-levels are considered: +75 kg/ha on loamy sand soils and -76 kg/ha on red clay soils. These data indicate that risk averse subsistence farmers should

Table 28 The effect of fertilization and pest control on the simulated maize yields on red clay soils. Maize is not weeded. (N:0, N:43, N:86 = chemical fertilizer rate of 0 kg N, 43 kg N and 86 kg N per ha respectively.)

Delay of planting (days)	Fertilization			Pest control	
	N:0	N:43	N:86	yes(N:43)	no(N:43)
0	2548	2889	3207	2889	2516
7	2548	2889	3207	2889	2479
14	2548	2889	3188	2899	2414
21	2538	2810	3064	2885	2293
28	2469	2717	2907	2806	2114
35	2324	2529	2780	2658	1959
42	2014	2219	2430	2298	1781

Table 29 Optimal input use for risk neutral subsistence farmers (maximizing returns) and risk averse subsistence farmers (maximizing d-levels).

Delay of planting (days)	Highest returns (kg/ha)		Highest d-level (kg/ha)	
A - loamy sand soil, maize broadcasted/sown behind the plow				
0	H+86+:	786	H+86+:	733
7	H+86+:	786	H+86+:	733
14	H+86+:	786	H+86+:	733
21	H+86+:	786	H+86-:	733
28	H-86+:	758	H-86-:	649
35	H+65+:	696	L+0+:	546
B - loamy sand soil, maize planted in rows				
0	H-129+:	1102	H+129+:	982
7	H-129+:	1102	H+129+:	982
14	H-129+:	1102	H+129+:	982
21	H-129+:	1102	H+86-:	888
28	H-129+:	1059	H-86-:	741
35	H-129+:	985	L+0+:	593
42	H-129-:	804	L+0+:	480
C - red clay soil, maize broadcasted/sown behind the plow				
0	H-86+:	2554	H-86+:	2334
7	H-86+:	2589	H-86+:	2374
14	H-86+:	2533	H-86-:	2273
21	H-86-:	2463	H-43-:	2192
28	H-86-:	2388	H-0-:	1875
35	H-65-:	2229	H-0-:	1569
42	H-0-:	1855	L-0-:	914
D - red clay soil, maize planted in rows				
0	H-129+:	3182	H-129-:	2723
7	H-129-:	3158	H-86-:	2648
14	H-129-:	3118	H-65-:	2577
21	H-129-:	3033	H-43-:	2440
28	H-129-:	2886	H-0-:	2077
35	H-65-:	2640	H-0-:	1731
42	H-43-:	2177	L-0-:	978

variety : H = hybrid seed (SR-52), L = local variety
soil pests : + = present, - = controlled
fertilization : chemical fertilizer rate:

0 = 0 kg N/ha, 0 kg P_2O_5/ha, 0 kg K_2O/ha
43 = 43 kg N/ha, 20 kg P_2O_5/ha, 10 kg K_2O/ha
65 = 65 kg N/ha, 30 kg P_2O_5/ha, 15 kg K_2O/ha
86 = 86 kg N/ha, 40 kg P_2O_5/ha, 20 kg K_2O/ha
129 = 129 kg N/ha, 50 kg P_2O_5/ha, 30 kg K_2O/ha

stalkborer : + = present, - = controlled.

prefer a local variety above SR-52 on red clay soils at this rate of fertilization and this system of pest control.

The effects of fertilization and pest control on the yields of a maize hybrid on red clay soils are presented in table 28. The differences in yield for the various fertilizer rates tend to decrease at the later planting dates, indicating that fertilization is less advantageous if planting is delayed. The margins between the three fertilizer rates are reduced if the returns are considered instead of the yields, and even more if d-levels are considered similar to the observations above. Maize yields with and without pest control seem to diverge slightly if planting is delayed. The returns also show an increasing profitablility of pest control at later planting dates: from 40 kg grains/ha at a 0 days delay to 185 kg grains/ha at a 42 days delay. The d-levels show an even larger margin, as pest control reduces the variability of yields: from 151 kg/ha at a 0 days delay to 390 kg/ha at 42 days.

Such effects for the choice of variety, control of pests and the rate of fertilization exist in various degrees for all systems of crop management. We are primarily concerned with a comparison between local and SR-52 varieties because these are the most widespread varieties and are most familiar to Zambian farmers. The calculations for M400 are included to demonstrate the potential usefulness of early maturing varieties only. Table 29 indicates that the optimum crop management system (excluding M400) shows a declining rate of fertilization if planting dates are delayed, specially if d-levels are maximized. Local varieties appear to be favourable for risk averse subsistence farmers, only if maize is planted very late. The system of pest control does not show a clear relation with planting date. The management systems selected after optimization of returns show in comparison to the systems selected after optimization of d-levels, lower fertilizer rates and more emphasis on local

Table 30 Comparison of the performance of M400 to the other varieties. Maize is broadcasted on red clay by subsistence farmers.

A - maximizing returns

Delay of planting (days)	Optimal input use *	Returns (kg/ha)	Relative returns
0	M-86+	2333	(= 91.3% of H-86+)
7	M-86+	2611	(= 100.8% of H-86+)
14	M-86+	2611	(= 103.1% of H-86+)
21	M-86+	2527	(= 102.6% of H-86-)
28	M-86+	2527	(= 105.8% of H-86-)
35	M-86-	2500	(= 112.2% of H-65-)
42	M-86-	2384	(= 128.5% of H-0-)

B - maximizing d-level

Delay of planting (days)	Optimal input use *	D-level (kg/ha)	Relative d-levels
0	M-0+	1267	(= 54.3% of H-86+)
7	M-86+	2391	(= 100.7% of H-86+)
14	M-86+	2391	(= 105.2% of H-86-)
21	M-0-	2164	(= 98.7% of H-43-)
28	M-0-	2164	(= 115.4% of H-0-)
35	M-0-	2137	(= 136.2% of H-0-)
42	M-0-	1915	(= 209.5% of L-0-)

* representation of crop management system as in table 29
M stands for maize variety M400.

varieties. In this comparison we have set the maximum rate of fertilization at 86 kg/ha N, if maize is broadcasted and slightly higher (129 kg/ha N) for farmers, who own sufficient resources to apply planting machines.

SR-52A and the local variety are clearly outyielded, both with respect to returns as well as to d-levels by M400 at all, except the first planting date (table 30).

This variety reaches maturity so early that it is not necessary to adjust the fertilizer rate to the planting date to achieve high returns, contrary to the other varieties. High rates of fertilizer application are optimal for high returns at all planting dates for M400.

The returns and d-levels of the various crop management systems of small scale emergent farmers have been calculated for red clay soils only, because these farmers are concentrated on these soils. The management systems that are optimal for emergent farmers are to a large extent similar to those of subsistence farmers (table 31). The optimum fertilizer rates are slightly higher than those for subsistence farmers, because we assumed higher maximum fertilizer rates, lower interest rates for credit and higher risk acceptance.

The mean differences in the returns and d-levels of the broadcasted maize and the maize planted in rows give an indication of the attractivity of the application of planting machines, assuming that maize is planted in 7 weeks. The costs of planting in rows to subsistence farmers are K 79 for the machinery (table 24) and K 11/ha for the rent of oxen (5 hours/ha at 2 K/hour, exclusive interest for credit, Admiraal, 1981). For small scale emergent farmers, with their own oxen, the costs are only K 55. The acreages, at which the costs balance the benefits for the various crop management systems are shown in table 32.

Table 31 Optimal input use for risk neutral (maximizing returns) and risk averse small scale emergent farmers (maximizing d-levels). Maize is planted on red clay soils. (codes: see table 29)*

Delay of planting (days)	Highest returns (kg/ha)	Highest d-level (kg/ha)
A - broadcasting/ sowing behind the plow		
0	H-129+: 2724	H-129+: 2527
7	H-129+: 2706	H-86+: 2524
14	H-129+: 2672	H-129-: 2429
21	H-129-: 2605	H-65-: 2328
28	H-129-: 2492	H-0-: 2059
35	H-65-: 2296	H-0-: 1820
42	H-0-: 1897	H-0-: 1239
B - planting in rows		
0	H-129+: 3270	H-129-: 2954
7	H-129+: 3246	H-129-: 2896
14	H-129-: 3209	H-86-: 2780
21	H-129-: 3124	H-43-: 2628
28	H-129-: 2977	H-0-: 2254
35	H-86-: 2713	H-0-: 1885
42	H-86-: 2240	H-0-: 1109

The acreage at which planting machines become attractive to risk averse small scale emergent farmers is much smaller than the average acreage that these farmers cultivate. Consequently, the purchase of such equipment does not jeopardize the continuity of the small farmers' farming system. The application of planting machines is not attractive to risk averse subsistence farmers, unless they substantially increase their acreage under maize.

Table 32 Acreage, at which the costs of planting machines equals the gains.

Type of farmer	Soil	Attitude to risk	Acreage (ha)
subsistence	loamy sand	neutral	1.70
		averse	4.03
	red clay	neutral	0.86
		averse	2.19
small scale	red clay	neutral	0.55
emergent		averse	1.17

7.5 Discussion

Simulation of the variation in maize yields has been hampered by:
1 our inability to apply an appropriate model for the probability distributions of crop yields;
2 the static character of the QUEFTS model.

1 Our inability to apply an appropriate model for the probability distributions of crop yields.
A Pearson type 1 distribution seems more suitable for the kind of distributions observed. This type 1 distribution can be bell shaped, which is appropriate for the water-limited yields, or J-shaped, which is appropriate for the nutrient-limited yields. The calculations, required to determine the parameters of this distribution functions, are not particularly difficult because the range of possible yields is well defined: from zero to potential for water-limited yields and from zero to the actual yield for the actual yields. However, manipulation of the Pearson type 1 equations is rather complicated because comprehensive tables are lacking and calculations are laborious. Therefore we assumed that the normal distribution, although not skewed at all, is adequate to describe the outer left part of the yield distributions.

2 The static character of the QUEFTS model.
We have found that in most years yields are mainly limited by nutrient availability, even at the highest fertilizer rates. Yield levels therefore tended to be stable as we assumed that the soil chemical properties remained stable over the period examined. Yields are particularly stable at early planting dates, when water+pest-limited yields are still high. Under such conditions, maize yields show no variation and are not influenced by the level of precipitation. This seems an oversimplification as nutrient-limited yields are affected by the weather too. Drought for example reduces N-availability and affects dry matter distribution of maize.

The analysis of yield risks will most certainly benefit from a more dynamic simulation model for nutrient-limited yields, in which the effects of drought are incorporated. Such a model would be particularly relevant for farming systems in infertile areas and/or for low rates of fertilization. We feel that a period of 10 years is rather short to calculate variation in yields. M400, for example, is strongly affected in a dry year (1982/1983). In spite of these shortcomings, we arrived at some conclusions.

Conclusion 1: Generally, the results indicate that there is a clear relation between the riskiness of maize cultivation and the attractivity of intensification of the crop management system. We have found high correlation coefficients between input use (in this case fertilizer rate in kg/ha for risk averse subsistence farmers) and riskiness of maize production (expressed in d-levels for maize without weeding in kg/ha, grain dry matter) under various conditions (i.e. planting dates): R = + 0.89 for red clay soils and R = + 0.82 for Sandveldt loamy sands. This is in accordance with the findings of Zandstra et al. (1979), who found that maize yields in Columbia, contrary to potato yields, are most stable with low input management systems. Thus, we may expect that farmers are averse of high input systems if maize is cultivated under risky climatological conditions.

Conclusion 2: The calculations clearly show that the optimum crop management systems of risk averse farmers differ from those of risk neutral farmers (table 29). The optimum systems for risk neutral farmers involve more inputs, such as improved varieties and fertilizer, compared to those of risk averse farmers, specially if maize is planted late.

Conclusion 3: The calculations also show that the more extended resources and the higher risk acceptance of small scale emergent farmers result in higher levels of input use. Local varieties, for example, are attractive to subsistence farmers (if maize is planted late), but not to small scale emergent farmers. Planting machines also seem attractive to small scale emergent farmers, while this is still doubtfull for subsistence farmers.

Conclusion 4: A change in a sole agronomic practice is often hardly attractive; it should be combined with changes in other practices. This is in accordance with observations in which it has been stressed that in (semi)-commercial maize cultivation various agronomic practices should be jointly intensified (e.g. Ministry of Agriculture, 1983). The calculations indicate that the returns of the combination of a hybrid variety with fertilization and soil pest control are especially high, while stalkborer control seems somewhat less important. This result is a consequence of the imperfections of the simulation models used. In our calculations, stalkborer control is only necessary if the water+ pest-limited yields drop to a level below or slightly above the nutrient-limited yields, i.e. if maize is planted late. In practice, it is recommended to control stalkborer even if maize is planted early.

Conclusion 5: The returns that we have found, suggest that at Petauke intensification of maize cultivation is attractive, on both soil types tested, if several aspects of the crop management system are intensified in combination. The characteristics of local varieties have been defined in such a way that these varieties are less prone to drought. However, the rainfall in the Petauke area is usually adequate and therefore the lower sensitivity of local varieties is not sufficient to compensate for the disadvantages of their low harvest indices. Water limitation to maize yields was most severe at a 42 days delay in planting, resulting in high coefficients of variation of maize yields. At this date, local varieties, which are less prone to drought, are attractive to risk averse subsistence farmers. At the other planting dates, hybrids are more attractive. The optimum fertilizer rates for these farmers gradually decrease from the maximum permitted rate at planting without delay to 0 kg/ha at a delay of 42 days. Early maturing varieties, such as

M400, seem very promising, both to risk averse and risk neutral farmers.

These conclusions contrast with the literature on Zambian agriculture in some aspects. Admiraal (1981) has suggested that risk is a major constraint to intensification of maize cultivation, while our calculations did not completely confirm this. Our results are also somewhat contrary to the observation that local maize varieties are planted first, as an insurance against crop failure, while hybrid varieties are planted later on (SADCC, 1987). Our results suggest that the opposite sequence would be more attractive. Such differences can be due to several causes. An obvious cause for the differences between our results and literature observations would be that we have set some parameters at wrong levels. For example, we have used the minimum floor prices in our calculation. However these prices are not always paid to farmers, specially in the more remote area's. Surprisingly, this change in farm gate prices hardly affects the selection of optimal systems of crop management (table 33).

Another parameter that could have been set at a too high level is the risk accepted by subsistence farmers. We have indicated that the risks accepted by farmers are among the least documented parameters. Consequently, it has been set at a rather arbitrary level. The optimum systems of crop management for subsistence farmers that would take 6% risk instead of the assumed 11.6 %, are presented in table 34. This change hardly influences the selection of optimal crop management systems.

Table 33 Optimal input use for risk neutral and risk averse subsistence farmers at two maize prices. Maize is broadcasted on red clays (codes as in table 29).*

Delay of planting (days)	Crop management system with			
	highest returns at		highest d-level at	
	K16/bag	K13/bag	K16/bag	K13/bag
0	H-86+ *	H-86+	H-86+	H-86+
7	H-86+	H-86+	H-86-	H-65+
14	H-86+	H-86+	H-86+	H-86-
21	H-86-	H-86+	H-43-	H-43-
28	H-86-	H-86-	H-0-	H-0-
35	H-65-	H-43-	H-0-	H-0-
42	H-0-	H-0-	L-0-	L-0-

Table 34 Optimal input use for risk averse subsistence farmers at various levels of risks taken. Maize is broadcasted on red clay soils (codes as in table 29).*

Delay of planting (days)	Optimal crop management system at	
	11.6 % risk	6 % risk
0	H-86+ *	H-86+
7	H-86-	H-86+
14	H-86+	H-86-
21	H-43-	H-43-
28	H-0-	H-0-
35	H-0-	H-0-
42	L-0-	L-0-

As the values of these parameters hardly seem to affect the results, a further consideration could be the adequacy of the simulation model to calculate risks. It could be possible that a model for nutrient-limited growth, in which effects due to drought are incorporated, would result in higher risks for improved varieties and lower risks for local varieties. Also the yield stability of local varieties due to their heterogeneity is hardly taken into account. On the other hand, in our study, we select the optimum system of crop management by comparing the calculated d-levels of various crop management systems to each other. The absolute value of the d-levels is only of secondary interest. Therefore, deviations, either in relative or in absolute terms, in the yields and coefficients of variation, that systematically apply to all crop management systems, do not affect the selection of the optimum system. The scope of this study has been too limited to allow a validation of the calculated risks. That would only be possible after comparing the expected behavior with the actual behavior of risk averse farmers in different regions with various climatological risks to crop production.

Calculations would probably indicate that risks of maize cultivation vary among the different Zambian regions. In northern Zambia, water-limited yields are rather high and stable, and actual yields are mainly determined by nutrient availability and acidity of the leached soils (Wolf et al., 1987). We would therefore find low but stable actual yields. Although the risks of maize production are small in these regions, we would probably conclude that the low returns are a constraint to the adoption of more intensive maize cultivation systems. In southern Zambia soils are generally fertile compared to the north, but rainfall is low. We would therefore probably find rather high nutrient-limited yields but low and variable water-limited yields, specially if maize is planted late. The actual yields will thus vary and maize cultivation would be risky under these conditions. That would result in the risks to be a major constraint to the intensification of maize production. The Petauke area is between the north and the south and it has both fertile soils and adequate rainfall. At Petauke, intensification of maize cultivation is neither seriously limited by high risks nor by low returns.

It is plausible that the observations of Admiraal (1981) that the risks of intensification are high, mainly refer to the south of Zambia and not to Zambia as a whole. That could most probably be confirmed by our calculations if more regions would be treated. We therefore expect that our procedure of risk assessment can be a valuable aid to differentiate between observations concerning risks regionally.

The observation that local varieties are planted before improved varieties by small farmers (SADCC, 1987) indicates that farmers both are averse of risks and aim at high returns (local varieties for secured food supply; improved verieties for surplus production). These are the assumptions on which the "safety first" rules are based but apparently farmers do not always act according to these rules. The behavior of small scale farmers exposed to risks should therefore be further examined and more appropriate behavioral rules should be developed.

In our opinion, crop growth simulation models can be a valuable aid in the assessment of risks. They allow easy comparison of various crop management systems, once the main parameters, required to perform the simulations and subsequent calculations, have been set. The effects of changes in ecology, cropping technology, and socio-economic environment (i.e. prices of inputs and outputs, risks accepted by farmers) can quickly be established. Such comparisons would take years if they were to be based on experiments and/or observations only. Further extensions of the crop growth simulation model adapted to the assessment of risks should be focussed on the incorporation of the effects of drought on the simulation of nutrient-limited yields, the probability distribution of crop yields, and the modelling of risk averse behavior. Such an extended simulation model can supply valuable information on the acceptance and rejection of modern agricultural technologies by small scale farmers, a phenomenon usually studied in rural sociology. In this sense, the present study has demonstrated that the range of application of simulation models extends to the field of study of rural sociologists as well.

SECTION 3

8 YIELD VARIABILITY IN RELATION TO THE AVAILABILITY OF FARM LABOUR AND EQUIPMENT

The objective of this chapter is to analyse the variation in maize yield due to management effects, with special emphasis on the impact of timeliness of the various field activities caused by limited resource availability. The quality and nature of the data available, together with the straightforward character of the production-decision problem, suggest that it would be both practical and sensible to use Linear Programming (LP) techniques to identify mechanical and organizational innovations which will maximize crop yields for farmers in Zambia (Hazell and Norton, 1986).

Labour constraints, measured in labour-hours available per week, are set to a constant value and cropping activities are specified in terms of mean per-hectare labour inputs by operation. In order to reflect the sensitivity of yield to the timing of certain operations, labour and other resources are made available over the agricultural year according to the following scheme:
A season of 7 weeks is specified during which land preparation and planting must take place if any yield is to be forthcoming. The planting season, beginning whenever precipitation has wettened the upper 15 cm of the soil up to field capacity, is subdivided into 7 discrete intervals. Yields of any maize planted during a given interval are evaluated as if all the maize were planted on the middle day. Following the planting season, there is another period of 7 weeks, in which other activities, such as weeding, can take place.

The complicated nature of the decision-making process is introduced into the LP model through the way in which cropping activities compete over time. To illustrate: maize planted in period 1 should be early-weeded in periods 3-4, medium weeded in periods 5 and 6, and late weeded in periods 7 and 8 (table 35). This means that weeding of early planted maize competes for resources with later planting, and that early, medium and late weedings compete with one another for maize planted in different periods.

Table 35 Time-table of the activities tillage, planting and weeding (weeks).

Tillage period	Planting period	Weeding period		
		early	medium	late
1	1,2	3,4	5,6	7,8
2	2,3	4,5	6,7	8,9
3	3,4	5,6	7,8	9,10
4	4,5	6,7	8,9	10,11
5	5,6	7,8	9,10	11,12
6	6,7	8,9	10,11	12,13
7	7,8	9,10	11,12	13,14

Because the returns to early weeding of early planted maize can be greater than those of the other weedings and, moreover, can be greater than the returns from late planting, the model realistically reflects the complex activity-choice problem faced by the farmer.

Based on the distribution of implements found in surveys (Kinsey, 1979,1984), the model farm can possess an equipment set consisting of a plough, a cultivator, a harrow, a planter and a weeder. Likewise, the farm can have one working ox-team unit and speci-fication is made in terms of the number of team hours available. For the maize crop under study the activity set consists of land preparation, manual or ploughing and harrowing, a number of alternative planting techniques, topdressing and insecticides application, and weeding. Harvesting, insecticide application and topdressing are not explicit choice variables. Options open to the farmers are:
- method (hence time) of preparing land, planting and weeding;
- the choice of which maize cultivar (SR-52, Local, or M400) to grow, on 2 soil types (loamy sand and sandy loam/red clay soils), each with and without runoff (15% of the rainfall lost by runoff).

In order to quantify the importance of timeliness, a yield function is used calculated with the crop growth simulation model WOFOST. Thus land planted in each of the 7 possible intervals carries a different associated yield. Planting however can only take place after land has been completely prepared and land can only be weeded (in certain periods) after it has been planted. The output of the planting and weeding activities consists both of yield, determined by time of planting, and area planted land. The interactions among techniques and time of planting, maize type, and time and intensity of weeding determine final yield. The model is made representative for different technology states as occurring in Zambia. It therefore portrays the current and dominant pattern of maize production in which a low-yielding, local maize variety is grown in the traditional completely manual way or using a characteristic set of ox-drawn implements. Modifications are made to the model to evaluate the effect of different innovations in farming practice. These are:
- maize varieties: Local, SR-52 or M400;
- introducing traditional ox-drawn implement sets (plough, cultivator, span of oxen) to the manual farming system;
- augmenting of the traditional implement set with additional ox_drawn implements:
  - adding ox-drawn weeder;
  - adding ox-drawn planter.

Another variant of the model deals not with innovation in the sense of new technology but with innovation representing a recommended change in farming practices. The practice considered involves the rescheduling of agricultural tasks so as to permit improved timeliness of operations (this is done for "winter ploughing")

8.1 Organization of the input for the LP model

8.1.1 Crop growth

The WOFOST model was used to calculate crop growth for:
- 10 growing seasons for which daily rainfall data were available (season 1976/1977 up to and including season 1985/1986);
- 3 maize varieties (SR-52, M400 and Local);
- 2 soil types (Sandveldt loamy sand and Sandveldt sandy loam/red clay with respectively 10% and 15% available water between field capacity (FC) and wilting point (WP);
- standard and acid soils (A added to variety name, e.g. SR-52A): in acid soils maximum root growth was supposed to be reduced,

for SR-52 and M400 from 75 to 50 cm and for the local variety from 90 to 70 cm;
- without or with 15% runoff;
- 7 periods of required labour time after the start of season until sowing has been completed: 0, 7, 14, 21, 28, 35 and 42 days.

8.1.2 Agricultural technology

When evaluating labour requirements, a differentiation can be made between farmers only using manual labour (hoe) and farmers using additional power like oxen or a tractor. A complete data set of labour requirements for all agricultural tasks for the differing farming systems in Eastern Zambia has not been found but some data of Kinsey (1979), Admiraal (1981) and Bessell (1973) are compiled and used in this study (table 36).

Table 36 Human labour (h/ha) and draft oxen power (team-h/ha) requirement for the different technology levels in the LP model.

Technology	Tillage		Planting		Weeding					
					early		medium		late	
	human	ox	human	ox	human	ox	human	ox	human	ox
MANU	252.0	-	18.0	-	103.5	-	103.5	-	103.5	-
TRMW	70.8	23.6	45.3	15.1	103.5	-	103.5	-	103.5	-
TROX	70.8	23.6	45.3	15.1	71.4	11.4	71.4	11.4	71.4	11.4
PLRS	36.6	18.3	45.3	15.1	71.4	11.4	71.4	11.4	71.4	11.4
IMPL	70.8	23.6	9.0	4.5	71.4	11.4	71.4	11.4	71.4	11.4
RSIP	36.6	18.3	9.0	4.5	71.4	11.4	71.4	11.4	71.4	11.4

(Source: Kinsey, 1979; Admiraal, 1981; De Toro, 1984)

Farmers do not plow and sow their total acreage all in once, but divide it into sections which will be treated successively. This is for example demonstrated by the division of labour over the season (Bessell, 1973). This results in competing labour requirements when in one section weeding is needed while the farmer and possible other labourers are occupied with land preparation and sowing in another section. In that case the farmers decision on where labour should be employed depends on many factors, for example the condition and stage of a crop and the amount of weeds. With field experiments in the Central and Southern Provinces of Zambia, Vernon and Parker (1983) have determined the critical period of the competition of weeds with maize, during which the crop should be kept clean. They estimated this period to be from 10 to 30 days after emergence. They state that farmers often delay their first weeding to well beyond 10 days after emergence usually due to labour shortage. Estimations of yield reductions of weeds related to the method of weeding and the moment of appliance have for Zambia been made by Kinsey (1979) and by Vernon and Parker (1983) (chapter 6, table 18). The total acreage of maize and the sowing date at each section thus depends on a number of factors, such as: available area of land, use of hoe, oxen or tractor, amount of labour available, labour composition (family and additional, for example hired, labour), farmer decisions and the start of the season.

The technology sets used for this study are:
1 subsistence farming;
2 rescheduling the ploughing task;

3 addition of an ox-drawn planter;
4 adoption of hybrid maize package.

1 Subsistence farming
An average family consists of five adults and two children. As the number of hours spent on fieldwork averages 5 a day, the amount of available labour will be 25 hours per day, for 6 days a week. When draught animals are available, most farms possess 2 yoke of working oxen (5 trained animals and 1 being trained). Only one yoke of oxen is used for harrowing, weeding and planting behind the plough, but a minimum of 2 is used as a ploughing team - and sometimes 3 or more. Oxen can be usefully employed only if equipment suited to the required task is available. The subsistence farmer owns 1 plough and 1 cultivator, which means that he can plough and weed with only 1 yoke of oxen at a time. The basic set of ox-drawn equipment consists therefore of 1 mouldboard plough, 1 spike-toothed harrow and 1 adjustable, inter-row cultivator. The subsistence farmer grows local, open-pollinated maize, without fertilizer or insecticides and he plants behind the plough, which results in poor plant stands due to irregular spacing and placing the seed too deeply in the soil.

2 Rescheduling the ploughing task
This models the practice of "winter ploughing" whereby land is ploughed near the end of the preceding rainy season rather than at the beginning of the season in which planting occurs. Ploughing would normally be done in February, March or April and the land would be left to weather until the rains begin in November, when the newly moistened, ploughed land would be harrowed, probably twice, and planted. This practice is recommended in Zambia because it results in planting nearer the critical date by shifting much of the land preparation activity to a period when there is slack labour and draft animal capacity. Moreover, ploughing then takes place at a time when there is still sufficient moisture in the soil to permit the mouldboard plough to penetrate and when oxen, with the benefit of several months good grazing, are in peak condition. Because ploughing is done at a time when there are standing crops in the fields, however, task rescheduling requires sufficient available land to permit the land to be winter-ploughed to lie idle until planting takes place.

3 Addition of an ox-drawn planter
One of the most promising equipment innovations available to the small- and medium-scale farmers is the ox-drawn planter. The major practical advantage of the planter is the speed with which planting can be done and the fact that planting and application of basal fertiliser and insecticides can all be done at one time in a single pass. This results in much lower inputs of labour and draft power.

4 Adoption of hybrid maize package
All above mentioned sets of activities can be done using hybrid maize package instead of the local maize variety seed. When planting is still done behind the plough, it is supposed that the more vigorous hybrid variety is able to overcome to some extend the adverse effects of this planting method.

The various experiments carried out with the LP model permit farmers 2 choices of techniques for land preparation (ox-plough and harrow or manual), 3 techniques for planting (manual, behind the plough and ox-drawn planter) and 2 ways of weeding (manual or using ox-drawn weeders with additional in-row manual weeding).

The possible choices have been aggregated to 6 technology levels:
1 MANU: traditional, all activities manual;
2 TRMW: ox-plough, planting behind plough + manual weeding;
3 TROX: ox-plough, planting behind plough + ox weeding;
4 IMPL: ox-plough, planting with improved planter + ox weeding;
5 PLRS: rescheduled ploughing, planting behind plough + ox weeding;
6 RSIP: rescheduled ploughing + improved planter + ox weeding.
Harvesting technology is not explored in this model.
Planting may involve local or hybrid maize (SR-52 or M400). Yield is determined by: the genetic potential of the maize variety, the time of planting, the technique of planting (main effect through timeliness) and the frequency and time of weeding. At certain time periods, the activities of preparing land, planting and weeding may all compete for the same resources, and early, medium and late weeding may compete with one another for maize planted at different times.

8.2 The linear programming model ZAMFARM

The basic structure of the model consists of a linear programming tableau which imitates a cropping system with maize as only crop. The crop requires certain periodic field operations. These can be performed following certain methods, with each method using a certain combination of human labour or draft animal power. The model is developed in such a way that the effect of different technology levels, defined as a package of activities, on maize yield can be explored. The effect of timeliness of operations is incorporated by means of yield response to time of planting and time of weeding.

An LP tableau consists of activities, constraints, and an objective function. The objective function, total farm maize yield, is maximized. Typical LP activities are: tillage, planting and weeding. Typical resource constraints are: available human labour, available oxen pair draft power and available land. Matrix coefficients (input/output coefficients) represent the demand for labour, and draft animals. The activities and resource constraints are specified by period. In the LP tableau, a number of miscellaneous restrictions and equations are included. Sequence and area balance rows ensure that farm operations are done in the proper sequence, that no more land is planted than is tilled and that no more land is weeded than is planted.

The linear programming model has been designed to portray much of the complexity of the environment at the farm level. In general the model has the following structure:

$$\text{maximize} \quad R = \sum_{i=1}^{n} \sum_{t=1}^{p} c(i,t)\, x(i,t) \qquad (1)$$

where x(i,t) = the i-th activity in the t-th period
c(i,t) = the maize yield per hectare from the i-th activity in the t-th period

Equation (1) is maximized subject to a series of constraints:

$$\sum_{i=1}^{n} \sum_{t=1}^{p} a(i,j,t)\ x(i,t) \leq b(j,t) \quad (j=1,\ldots,z;\ t=1,\ldots p) \tag{2}$$

where a(i,j,t) = the per hectare input-output coefficient of the j-th resource used or contributed by the i-th maize activity in the t-th period

b(j,t) = a vector of resource availabilities in the t-th period

The system of equations (1) and (2) describes a linear-programming problem for maize production for a representative farm. Choice of activity levels x(i,t) is constrained by the resource constraints. Maize production is described by a sequence of tasks, each of which uses a specific power-implement combination. Alternative activities in this category include land preparation and planting by oxen. The choice between alternative ways of performing tasks depends, then, upon the relative costs of the operations, the relative availability of resources used in the operations and the relative contribution of the operation to the maize yield.

8.3 Constraints handled by the LP model

Labour constraints

The first group of restrictions serves to distribute the supply of family labour (5 persons) over the cropping season. The model represents the segment of the season during which most activities take place, and this segment is broken down in 14 weeks. Average labour inputs are calculated per hectare by operation, and the family labour available is divided among the 14 periods on the assumption that there are six working days a week and 5 in-field working hours per person per working day. Harvesting is an activity excluded from the model.

Power constraints

A second group of constraints describes the distribution of animal power over the 14 weeks period. Average inputs are calculated in terms of team-hours per hectare per operation, and the animal power constraint is based on the assumption that the representative holding commands one team of working oxen. The availability of team-hours for in-field work is calculated on the same basis as for labour-hours. The services of oxen are treated as a fixed resource to the farm because of their indivisible nature and because of the complete absence of a rental market. There are 30 team-hours available per week period.

Land constraints

Maize production is assumed to be on 6 hectares, typical for farms in the area. However, parametric programming is used to vary available land from 2 to 10 ha to calculate the maximum cropable area with a given technology level. All land is assumed to have been under crops the previous season or under short fallow (two years or less). The land preparation, or tillage, activity uses one hectare of "raw" land and produces as output one hectare of prepared land, which is in turn used as an input by the planting activity. The planting activity produces as output a unit of planted land per unit activity which is made available to one of the three weeding activities.

8.4 Data inputs to the LP model

Maize yield
Crop yields for different sowing periods were calculated with WOFOST (chapter 5). Adjustment of yield for intensity of weeding has been carried out according to the methodology presented in chapter 6.

Labour and power requirement
A summary of the human labour and draft oxen power requirement for the different technology levels is given in table 36.

8.5 Results

8.5.1 MANU: traditional, all activities manual

Acreage variation
The results of ZAMFARM for the acreage variation of the tilled and planted area, early weeded, medium weeded and late weeded area is given in table 38. When all field activities are done manual no more than 3.8 ha can be planted as human labour is constrained in the first 9 periods after the first planting rain (see table 37). When more than 2.0 ha are cultivated not all weeding activities can be done anymore: at first medium and late weeding are left out in favour of early weeding which gives higher returns. The final stage is that early weeding is only done on 1.6 ha whereas medium weeding and late weeding are done on 2.1 ha and 2.9 ha resp. At the end late weeding is done on a greater area because there is no longer competition between the weeding and planting activities in the last periods of the time period under consideration.

Maize yield
Mean maize yield for the technology level MANU declines very sharp with increasing farm sizes. The competition between tillage/planting and the weeding activities results in non-optimal management of the maize crop: some parts are weeded once, other parts twice or three times or even not weeded at all. Consequently the maize yield will vary on different parts of the field. During the seven planting periods mean water-limited maize yield declines with 32%, 42%, 29%, 37%, 5% and 8% for SR-52, SR-52A, Local, LocalA, M400 and M400A resp. When planted maize acreage is expanded from 2 to 3.8 ha for this technology level on soil 10-00 (water holding capacity of 10%, no runoff) mean (= normal+acid/2) maize yield declines from 10.5 t/ha to 7.9 t/ha for SR-52, from 9.0 t/ha to 7.2 t/ha for M400, and from 7.3 t/ha to 5.5 t/ha for Local varieties (see table 38 A). For the other soil types the tendency is the same as for soil type 10-00 (table 38).

Labour productivity
Total labour requirement at full use of the available labour is 1701 labour hours resulting in a mean labour requirement of 449 h/ha for this technology. The labour productivity, measured as the quantity of maize produced per hour of labour input is between 12.2 kg/h for Local and 18.7 kg/h for SR-52.

Table 37 Periods in which constraints on human labour and draft oxen power (at the maximum cropped areas) for the different technology levels are active (*).

Tech-nology	Acre-age (ha)	Total labour (hours)	Period (week) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A - human labour																	
MANU	3.80	1701	*	*	*	*	*	*	*	*	*	-	-	-	-	-	-
TRMW	5.58	1744	-	-	-	*	*	*	*	-	*	*	*	-	-	-	-
TROX	5.44	1296	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-
IMPL	7.50	1366	-	-	-	-	-	-	-	-	*	*	*	-	-	-	-
PLRS	6.29	1198	-	-	-	-	-	-	-	*	*	-	-	-	-	-	-
RSIP	9.34	1213	-	-	-	-	-	-	-	-	*	*	*	-	-	-	-
B - draft oxen power																	
MANU	3.80	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TRMW	5.58	215	*	*	*	*	*	*	*	-	-	-	-	-	-	-	-
TROX	5.44	316	*	*	*	*	*	*	*	-	-	-	-	-	-	-	-
IMPL	7.50	333	*	*	*	*	*	*	*	-	-	-	-	-	-	-	-
PLRS	6.29	319	*	*	*	*	*	*	*	-	-	-	-	-	-	-	-
RSIP	9.34	338	*	*	*	*	*	*	*	-	-	-	-	-	-	-	-

8.5.2 TRMW: traditional oxplough, planting behind plough + manual weeding

Acreage variation

The acreage variation of technology TRMW for tilled and planted area, early, medium, and late weeded area in relation with land availability is given in table 38. The maximum area planted with this technology is 5.6 ha. Then oxen power is constrained in periods 1 to 7 and human labour in the periods 4 to 7 and 9 to 11 (table 37). When the land area under cultivation is larger than 2.0 ha, not all land can be weeded three times. Only 0.1 ha cannot be weeded (at medium or late periods) when the planted area is 3.0 ha. When the planted area is larger than 4.0 ha, early weeding also has to be dropped partly. The optimum activity distribution with maximum land planted is, 2.9 ha late weeded, 3.3 ha medium weeded and 4.5 ha early weeded.

Maize yield

For this technology level on soil 10-00 the mean maize yields decline from 7.6 t/ha to 5.9 t/ha when planted acreage is expanded from 2 to 5.6 ha for Local, and from 11.0 t/ha to 8.5 t/ha for SR-52 and from 9.1 t/ha to 7.7 t/ha for M400. The same pattern occurs for the other soil types (table 38).

Labour productivity

Total labour requirement at full use of the available labour is 1745 labour hours (table 37) and 215 oxen pair hours. This results in a mean labour requirement of 313 h/ha and a mean oxen pair hour requirement of 38 h/ha. The labour productivity expressed as the quantity of maize produced per hour of labour input is between 18.7 kg/h for Local and 28.6 kg/h for SR-52. The oxen pair productivity varies between 151.5 kg/h and 232.2 kg/h for Local and SR-52 respectively.

8.5.3 TROX: traditional oxplough, planting behind plough + ox weeding

Acreage variation

The acreage variation of technology TROX is given in table 38. Maximum area planted, with given inputs is 5.4 ha. Oxen power is then constrained in periods 1 to 7 and human labour only in period 9. Up to 3.0 ha all fields are weeded three times, and from 4.0 ha onwards no fields are weeded triple. At maximum area planted the acreage early, medium and late weeded are resp. 2.2 ha, 3.0 ha and 4.2 ha. Because of the competition for draft animal power especially at the early periods, early weeding drops down to this low acreage level. The high level of late weeding acreage can again be explained by the labour surplus in the late periods. Total acreage planted is therefor lower for TROX than for TRMW (allthough the difference is very small). The difference in maize yield however is much greater. It might be one of these aspects that shows the problems of low acceptance levels for use of oxen and tool-carriers in weeding.

Maize yield

From 4.0 ha onward the decline in mean maize yield for TROX is sharper than for TRMW, up to 4.0 ha the mean maize yield levels are the same for both technologies. Mean maize yield for technology level TROX is given in table 38 A. On soil 10-00 mean maize yield declines from 7.3 t/ha to 5.5 t/ha when planted acreage is expanded from 3 to 5.4 ha for Local variety, and from 10.6 t/ha to 7.9 t/ha for SR-52 and from 9.0 t/ha to 7.2 t/ha for M400. The same pattern occurs for the other soil types (table 38). It is clear that the decline in mean maize yield per increased ha of cropped area is greater for TROX than it is for technology TRMW. At first instance it would therefore be advisory to introduce draft animals only for ploughing. However the combination of oxen and manual weeding as suggested in the TROX input data can be changed to another ratio, that can result in completely new insights as this coefficient dictates the use of manual and oxen-pair labour. Further research can be done using new data on labour and oxen requirement on this issue, with further specification of new activities and choosing possibilities between them.

Labour productivity

Total labour requirement at full use of the available labour is 1296 labour hours and 316 oxen-pair hours (table 37). This results in a mean labour requirement of 239 h/ha human labour and 58 h/ha of oxen-pair draft hours. Labour productivity expressed as the quantity of maize produced per hour of labour input is between 22.9 kg/h for Local and 35.1 kg/h for SR-52. The oxen pair productivity varies between 93.9 kg/h and 144.1 kg/h for Local and SR-52 respectively. It is clear that at maximum output the inputs of human labour are lower and that of draft animal power are higher than of technology TRMW. Productivity reacts in the opposit way, and is in TROX higher for human labour and lower for draft animal power. However, the increase in productivity doesn't compensate the effect of acreage distribution and therefore total maize yield is smaller for TROX technology than for TRMW.

8.5.4 PLRS: rescheduled ploughing, planting behind plough + ox weeding

Acreage variation
In table 38 total acreage variation for the different field activities is given for technology PLRS. Maximum planted acreage is 6.3 ha at optimal use of labour and draft animal resources which are constrained in periods 1 to 7 for oxen power and periods 8 and 9 for human labour. Complete three times weeding can be done up to 3 ha, with larger planted area first medium weeding is holding back (from 3 ha onward) with an average weeded area around 3 ha, from 4 ha onward late weeding is not at the total area but only around 4 ha, and from 5 ha onward early weeding isn't done at full acreage. Early weeding acreage declines very sharp with increasing planted area above 5 ha. At maximum capacity of resources from the total planted area of 6.3 ha, 2.5 ha is early weeded, 3.4 ha medium weeded and 4.2 ha late weeded.

Maize yield
Mean maize yields for the different varieties with different planted acreages for technology PLRS on soil 10-00 is given in table 38 A. Mean maize yield declines from 7.4 t/ha to 5.4 t/ha when planted acreage is expanded from 3 to 6.3 ha for Local variety, and from 10.8 t/ha to 7.9 t/ha for SR-52 and from 9.0 t/ha to 7.0 t/ha for M400. The same pattern occurs for the other soil types (table 38).

Labour productivity
Total labour requirement at full use of the available labour is 1198 labour hours and 319 oxen-pair hours (table 37). This results in a mean labour requirement of 190 h/ha human labour and 51 h/ha of oxen-pair draft hours. Labour productivity expressed as the quantity of maize produced per hour of labour input is between 28.5 kg/h for Local and 43.7 kg/h for SR-52. The oxen-pair productivity varies between 106.9 kg/h and 164.0 kg/h for Local and SR-52 respectively.

The benefits from task rescheduling are large: an additional 12% of land can be planted with maize and average maize yield increases 22% (from 8.1 to 9.9 t/ha) on a 5 ha farm on soil type 10-00. However, it should be stated that if farmers are to adopt this change in practice, it implies that they will either have to halve their maize acreage in order that land may be empty to permit early tillage or that they be given access to additional land equal in area to what they can plant in any given season.

8.5.5 IMPL: traditional oxplough, planting with ox-drawn planter + ox weeding

Acreage variation
The acreage variation of technology IMPL is given in table 38. Maximum area planted, with given inputs is 7.5 ha using all oxen power in the first 7 periods and human labour in periods 9 to 11. Up to 4.0 ha, all fields are weeded three times, and from 5.0 ha onwards no fields are weeded triple. At maximum area planted the acreage early, medium and late weeded are resp. 2.4 ha, 4.2 ha and 4.2 ha.

Maize yield
Mean maize yields for the different varieties with different

planted acreages for technology IMPL on soil 10-00 is given in table 38 A. Mean maize yield declines from 7.6 t/ha to 5.4 t/ha when planted acreage is expanded from 3 to 7.5 ha for Local variety, and from 10.9 t/ha to 7.7 t/ha for SR-52 and from 9.1 t/ha to 7.0 t/ha for M400. The same pattern occurs for the other soil types (table 38).

Labour productivity
Total labour requirement at full use of the available labour is 1366 labour hours and 333 oxen-pair hours (table 37). This results in a mean labour requirement of 182 h/ha human labour and 44 h/ha of oxen-pair draft hours. Labour productivity expressed as the quantity of maize produced per hour of labour input is between 28.8 kg/h for Local and 44.2 kg/h for SR-52. The oxen-pair productivity varies between 118.2 kg/h and 181.4 kg/h for Local and SR-52 respectively.

With maize areas larger than 3 ha, the effect of speedier planting begins to manifest itself in the form of higher yields than those attainable with planting behind the plough. Even more important is the fact that a farmer using a planter is capable of increasing his maize area by 38%, from 5.4 ha to 7.5 ha.
For this technology level average maize yield increases as much as for the PLRS technology, 22% for SR-52 on soil type 10-00. However, total area that can be planted to maize is 19% larger than for PLRS and as compared to the TROX technology even 38% more.

8.5.6 RSIP: rescheduled ploughing + improved planter + ox weeding

Acreage variation
The acreage variation of technology RSIP is given in table 38. Maximum area planted, with given inputs is 9.3 ha using the total amount of available draft oxen in the first 7 periods and human labour to its maximum in the periods 9 to 11. Up to 4.0 ha all fields are weeded three times, and from 6.0 ha onwards no fields are weeded triple. At maximum area planted the acreage early, medium and late weeded are resp. 2.6 ha, 4.2 ha and 4.2 ha.

Maize yield
Mean maize yields for the different varieties with different planted acreages for technology RSIP on soil 10-00 is given in table 38 A. Mean maize yield declines from 7.6 t/ha to 5.2 t/ha when planted acreage is expanded from 3 to 9.4 ha for Local variety, and from 11.1 t/ha to 7.4 t/ha for SR-52 and from 9.1 t/ha to 6.8 t/ha for M400. The same pattern occurs for the other soil types (table 38 A,B).

Labour productivity
Total labour requirement at full use of the available labour is 1213 labour hours and 338 oxen-pair hours (table 37). This results in a mean labour requirement of 129 h/ha human labour and 36 h/ha of oxen-pair draft hours. Labour productivity expressed as the quantity of maize produced per hour of labour input is between 39.3 kg/h for Local and 60.3 kg/h for SR-52. The oxen-pair productivity varies between 141.0 kg/h and 216.5 kg/h for Local and SR-52 respectively.

The combination of both last options, rescheduled ploughing as well as introducing an improved planter, becomes very interesting for the farmer. Planted area to maize can still be increased by 25% compared to the improved planter technology system. That is a 72% increase of planted acreage compared to the TROX technology level. Mean maize yields for this "advanced" technology farming system is for the maximum field area (9.34 ha) still only 7% less than at full capacity (6.5 ha) of the TROX technology level.

Table 38 Summary of activity distribution (ha) and maize yield (kg/ha) for six technologies in relation to available land area (ha) for three maize varieties (A added when planted in acid soils).

A - Loamy sand (waterholding capacity of 10%)

Tech nolo gy	Avai lable area (ha)	Area used for (ha)				Average maize yield (kg/ha *1000)											
		t&p	weeding			crop variety - no runoff						crop variety - 15% runoff					
			e	m	l	Local	LocalA	SR-52	SR-52A	M400	M400A	Local	LocalA	SR-52	SR-52A	M400	M400A
MANU	2.0	2.0	2.0	2.0	2.0	7.4	7.3	10.9	10.2	9.1	8.9	7.3	7.0	10.6	9.9	9.0	8.8
	3.0	3.0	2.7	1.9	3.0	6.6	6.3	9.7	8.8	8.4	8.2	6.4	6.0	9.3	8.5	8.3	8.0
	4.0	3.8	1.6	2.1	2.9	5.7	5.4	8.3	7.5	7.2	7.2	5.5	5.1	8.0	7.2	7.4	7.0
TRMW	2.0	2.0	2.0	2.0	2.0	7.7	7.6	11.3	10.8	9.2	9.0	7.6	7.3	11.0	10.5	9.2	9.0
	3.0	3.0	3.0	2.9	2.9	7.4	7.3	10.9	10.3	9.1	8.9	7.3	7.0	10.6	10.0	9.0	8.8
	4.0	4.0	4.0	3.0	2.9	6.9	6.6	10.1	9.3	8.6	8.4	6.7	6.4	9.8	9.0	8.5	8.2
	5.0	5.0	4.6	3.1	2.9	6.4	6.1	9.4	8.5	8.2	7.9	6.2	5.8	9.0	8.2	8.1	7.8
	6.0	5.6	4.5	3.3	2.9	6.1	5.8	8.9	8.1	7.9	7.6	5.9	5.5	8.6	7.7	7.8	7.4
TROX	3.0	3.0	3.0	3.0	3.0	7.4	7.2	10.9	10.2	9.1	8.9	7.3	7.0	10.6	9.9	9.0	8.8
	4.0	4.0	4.0	3.5	3.0	7.0	6.7	10.3	9.4	8.7	8.5	6.8	6.4	9.9	9.1	8.6	8.3
	5.0	5.0	3.7	2.7	4.0	6.1	5.8	9.0	8.1	7.9	7.6	5.9	5.5	8.6	7.8	7.8	7.4
	6.0	5.4	2.2	3.0	4.2	5.7	5.4	8.3	7.5	7.4	7.1	5.5	5.2	8.0	7.2	7.3	7.0
IMPL	3.0	3.0	3.0	3.0	3.0	7.6	7.5	11.2	10.6	9.1	9.0	7.5	7.3	10.9	10.3	9.1	9.0
	4.0	4.0	4.0	4.0	4.0	7.4	7.2	10.9	10.2	9.1	8.9	7.2	7.0	10.6	9.9	9.0	8.8
	5.0	5.0	5.0	4.3	4.5	6.9	6.7	10.2	9.4	8.7	8.4	6.8	6.4	9.9	9.1	8.6	8.3
	6.0	6.0	5.3	3.8	4.2	6.4	6.1	9.4	8.5	8.2	7.9	6.2	5.8	9.0	8.2	8.1	7.7
	7.0	7.0	3.3	4.4	4.2	5.8	5.5	8.5	7.7	7.5	7.2	5.6	5.2	8.1	7.3	7.4	7.1
	8.0	7.3	3.0	4.0	4.2	5.5	5.3	8.2	7.4	7.1	6.9	5.4	5.1	7.9	7.1	7.1	6.8
PLRS	3.0	3.0	3.0	3.0	3.0	7.5	7.4	11.1	10.5	9.1	9.0	7.4	7.2	10.8	10.2	9.1	8.9
	4.0	4.0	4.0	3.8	4.0	7.2	7.0	10.6	9.9	8.9	8.7	7.1	6.8	10.3	9.6	8.9	8.6
	5.0	5.0	5.0	3.0	4.3	6.6	6.4	9.7	8.9	8.4	8.1	6.4	6.1	9.4	8.6	8.3	8.0
	6.0	6.0	3.4	3.3	4.2	5.8	5.7	8.6	7.8	7.6	7.3	5.7	5.3	8.3	7.5	7.5	7.2
	7.0	6.3	1.8	3.6	4.2	5.5	5.4	8.3	7.5	7.1	6.9	5.4	5.1	7.9	7.2	7.0	6.7
RSIP	3.0	3.0	3.0	3.0	3.0	7.7	7.6	11.3	10.8	9.2	9.0	7.6	7.4	11.1	10.5	9.2	9.0
	4.0	4.0	4.0	4.0	4.0	7.5	7.4	11.1	10.5	9.1	9.0	7.4	7.2	10.8	10.2	9.1	8.9
	5.0	5.0	5.0	4.7	4.3	7.2	7.0	10.6	9.9	8.9	8.7	7.1	6.8	10.3	9.6	8.8	8.6
	6.0	6.0	6.0	4.5	4.5	6.8	6.6	10.0	9.2	8.5	8.3	6.6	6.3	9.7	8.9	8.4	8.1
	7.0	7.0	6.1	4.2	4.6	6.4	6.1	9.3	8.5	8.1	7.9	6.2	5.8	9.0	8.2	8.0	7.7
	8.0	8.0	5.0	4.9	4.2	5.9	5.6	8.7	7.8	7.6	7.4	5.7	5.4	8.4	7.6	7.6	7.2
	9.0	9.0	3.5	4.2	4.2	5.5	5.2	8.1	7.3	7.2	6.9	5.3	5.0	7.7	7.0	7.1	6.8
	10.0	9.3	2.6	4.2	4.2	5.3	5.0	7.8	7.0	6.9	6.7	5.1	4.8	7.5	7.0	6.9	6.6

t&p = tillage plus planting
e = early
m = medium
l = late

B - Sandy loam/red clay (waterholding capacity of 15%)

Tech nolo gy	Avai lable area (ha)	Area used for (ha)				Average maize yield (kg/ha *1000)											
		t&p	weeding			crop variety - no runoff						crop variety - 15% runoff					
			e	m	l	Local	LocalA	SR-52	SR-52A	M400	M400A	Local	LocalA	SR-52	SR-52A	M400	M400A
MANU	2.0	2.0	2.0	2.0	2.0	7.6	7.3	11.0	10.2	9.0	8.5	7.5	7.2	10.8	9.9	9.0	8.6
	3.0	3.0	3.0	1.9	2.5	7.0	6.7	10.0	9.2	8.3	7.9	6.8	6.4	9.7	8.8	8.3	7.9
	4.0	3.8	1.6	2.1	2.9	6.1	5.8	8.7	8.0	7.2	6.8	5.9	5.5	8.4	7.6	7.2	7.0
TRMW	2.0	2.0	2.0	2.0	2.0	7.7	7.5	11.2	10.5	9.0	8.6	7.6	7.4	11.1	10.3	9.1	8.7
	3.0	3.0	3.0	2.9	2.9	7.6	7.3	11.0	10.2	8.9	8.5	7.5	7.2	10.8	9.9	9.0	8.6
	4.0	4.0	4.0	3.0	2.9	7.2	6.9	10.3	9.6	8.5	8.1	7.0	6.7	10.1	9.2	8.5	8.1
	5.0	5.0	4.7	3.2	2.9	6.8	6.4	9.7	8.9	8.1	7.7	6.6	6.2	9.4	8.5	8.1	7.7
	6.0	5.6	4.5	3.3	2.9	6.5	6.2	9.3	8.5	7.8	7.4	6.3	5.9	9.1	8.1	7.8	7.4
TROX	3.0	3.0	3.0	3.0	3.0	7.6	7.3	11.0	10.2	9.0	8.5	7.5	7.2	10.8	9.9	9.0	8.6
	4.0	4.0	4.0	3.5	4.0	7.3	7.0	10.5	9.7	8.6	8.2	7.1	6.8	10.2	9.3	8.6	8.2
	5.0	5.0	3.7	2.7	4.0	6.5	6.2	9.4	8.6	7.8	7.4	6.3	5.9	9.0	8.2	7.8	7.4
	6.0	5.4	2.2	3.0	4.2	6.1	5.8	8.7	8.0	7.4	6.9	5.9	5.5	8.4	7.6	7.3	6.9
IMPL	3.0	3.0	3.0	3.0	3.0	7.7	7.4	11.1	10.4	9.0	8.6	7.6	7.4	11.0	10.2	9.0	8.7
	4.0	4.0	4.0	4.0	4.0	7.6	7.3	11.0	10.2	9.0	8.5	7.5	7.2	10.8	9.9	9.0	8.6
	5.0	5.0	5.0	4.3	4.5	7.3	7.0	10.5	9.7	8.6	8.1	7.1	6.7	10.2	9.3	8.6	8.2
	6.0	6.0	5.4	3.8	4.2	6.8	6.4	9.7	8.9	8.1	7.7	6.6	6.2	9.4	8.5	8.1	7.7
	7.0	7.0	3.8	3.9	4.2	6.2	5.9	8.9	8.1	7.5	7.0	6.0	5.6	8.6	7.7	7.5	7.0
	8.0	7.5	2.4	4.2	4.2	5.9	5.6	8.4	7.7	7.1	6.7	5.7	5.3	8.1	7.5	7.1	6.7
PLRS	3.0	3.0	3.0	3.0	3.0	7.6	7.4	11.1	10.3	9.0	8.6	7.5	7.2	10.9	10.1	9.0	8.7
	4.0	4.0	4.0	3.8	4.0	7.5	7.2	10.8	10.0	8.9	8.4	7.3	7.0	10.6	9.7	8.9	8.4
	5.0	5.0	5.0	3.0	4.3	7.0	6.7	10.1	9.3	8.3	7.9	6.8	6.4	9.8	8.9	8.3	7.9
	6.0	6.0	3.4	3.3	4.2	6.2	5.9	9.0	8.2	7.5	7.1	6.0	5.7	8.7	7.8	7.5	7.1
	7.0	6.3	2.5	3.4	4.2	5.9	5.6	8.4	7.7	7.1	6.7	5.7	5.3	8.1	7.5	7.1	6.7
RSIP	3.0	3.0	3.0	3.0	3.0	7.7	7.5	11.2	10.5	9.0	8.6	7.6	7.4	11.1	10.3	9.1	8.8
	4.0	4.0	4.0	4.0	4.0	7.6	7.4	11.1	10.4	9.0	8.6	7.6	7.3	11.0	10.1	9.0	8.7
	5.0	5.0	5.0	4.6	4.2	7.4	7.2	10.7	10.0	8.8	8.3	7.3	7.0	10.5	9.7	8.8	8.4
	6.0	6.0	6.0	4.4	4.5	7.1	6.8	10.3	9.5	8.4	8.0	7.0	6.6	10.0	9.1	8.4	8.0
	7.0	7.0	6.5	4.2	4.2	6.7	6.4	9.7	8.9	8.1	7.6	6.5	6.2	9.4	8.5	8.1	7.6
	8.0	8.0	5.5	4.2	4.2	6.3	6.0	9.1	8.3	7.6	7.2	6.1	5.8	8.8	7.9	7.6	7.2
	9.0	9.0	3.5	4.2	4.2	5.9	5.6	8.5	7.7	7.1	6.7	5.7	5.3	8.2	7.3	7.1	6.7
	10.0	9.3	2.6	4.2	4.2	5.7	5.4	8.2	7.5	6.9	6.5	5.5	5.2	7.9	7.1	6.9	6.5

t&p = tillage plus planting
e = early
m = medium
l = late

REFERENCES

Acland, J.D., 1971. East African crops: an introduction to the production of field and plantation crops in Kenya, Tanzania and Uganda Singapore. Rome, FAO.

Adams, J.M. and G.W. Harman, 1977. The evaluation of losses in maize stored on a selection of small farms in Zambia with particular reference to the development of methodology. London, Tropical Products Institute. Report 109.

Admiraal, J.G.A., 1981. Food strategy study. Farm management. Ministry of Agriculture and Water development, Planning unit. Lusaka, Zambia. Amsterdam, KIT.

Agrios, G.N., 1969. Plant pathology. New York, Academic Press.

Anderson, J.R., 1979. Perspectives on models of uncertain decisions. In: Roumasset, J.A., J.M. Boussard and I. Singh (eds). Risk, uncertainty and agricultural development: 39-62.

Anthony, K.R. and V.C. Uchendu. 1970. Agricultural change in Mazabuka District, Zambia. Food Research Institute Studies 9: 215-267.

Anthony, K.R., B.F. Johnston, W.O. Jones and V.C. Uchendu, 1979. Agricultural change in Tropical Africa. London, Cornell University Press.

Benito, C.A., 1976. Peasants' response to modernization projects in minifundia economics. American Journal of Agricultural Economics 58: 143-151.

Bessell, J.E., 1973. Technical systems of maize production for Zambia. University of Nottingham and Zambia Agricultural Labour Productivity Investigations (UNZALPI), Sutton Bonington, UK & Lusaka, Zambia. Report no 6.

Binswanger, H.P., 1979. Risk and uncertainty in agricultural development: An overview. In: Roumasset, J.A., J.M. Boussard and I. Singh (eds). Risk, uncertainty and agricultural development.

Boote, K.J., J.W. Jones, J.W. Mishoe and R.D. Berger, 1983. Coupling pests to crop growth simulators to predict yield reductions. Phytopathology 73: 1581-1587.

Brammer, H., 1973. Soils of Zambia. Lusaka, Ministry of Rural Development.

Buchanan, B.B., S.W. Hutcheson, A.C. Magyarosy and P. Montalbini, 1981. Photosynthesis in healthy and diseased plants. In: Ayres, P.G. (ed), Effects of disease on the physiology of the growing plant: 13-28.

Das, J.C., 1973. Forecasting maize yields in Zambia using multiple regression with weather factors as predictors. Lusaka, Zambia, Department of Meteorology. Agrometeorological Report no 6.

Das, J.C., 1979. Commencement of sowing rains in Zambia. Meteorological Department, Lusaka. Meteor. Notes Series A, 18.

Day, R.H., 1965. Probability distributions of field crop yields. Journal of Farm Economics 47: 713-741.

Dequin, H., 1970. Agricultural development in Malawi. München, IFO-Institut fuer Wirtschaftsforschung, Afrika Studienstelle.

Diepen, C.A. van, J. Wolf, H. van Keulen and C. Rappoldt, 1989. WOFOST: a simulation model of crop production. Soil Use and Management 5 (1989), 1:16-24.

Doyle, C.J., 1974. Productivity, technical change and peasant production: a profile of the African cultivator. Food Research Institute Studies 13: 61-76.

Due, J.M., 1978. The allocation of credit to small farmers in Tanzania and Zambia. Illinois Agricultural Economics Staff Paper 78 E-55.

Due, J.M., 1987. Women and technology in African agriculture. Illinois Agricultural Economics Staff Paper 87 E-381.

Eicher, C.K. and D.C. Baker, 1982. Research on agricultural development in Sub-Saharan Africa: a critical review. MSU International Development Paper, no 1.

Elliott, C., 1983. Equity and growth: an unresolved conflict in Zambian rural development policy. In: D. Ghai and S. Radwan (eds), Agrarian policies and rural poverty in Africa: 155-189.

FAO, 1976. Perspective study of agricultural development for Zambia; Crop Production. Roma, FAO Country Perspective Study Team.

FAO, 1984. Agroclimatological data for Africa, Vol 2. Roma, FAO plant production and protection series 22.

Feder, G. and G.T. O'Mara, 1981. Farm size and the diffusion of Green Revolution technology. Economic Development and Cultural Change: 59-76.

Gerhart, J., 1975. The diffusion of hybrid maize in W. Kenya. Mexico City, CYMMIT.

Gommes, R., 1985. Rainfed food-crop production in East Mwanza region: a semi-quantative risk analysis. Paper presented at the Workshop on food security and nutrition education.

Hazell, P.B.R., 1986a. Introduction. In: Hazell, P.B.R., C. Pomareda and A. Valdes (eds), Crop insurance for agricultural development. Baltimore, Hopkins University Press.

Hazell, P.B.R., 1986b. Introduction. In: Hazell, P.B.R. (ed), Summery Proceedings of a workshop on cereal yield variability.

Hazell, P.B.R. and R.D. Norton, 1986. Mathematical programming for economic analysis in agriculture. New York, USA, MacMillan.

Heemst, H.D.J. van, 1985. The influence of weed competition on crop yield. Agricultural Systems 18: 81-93.

Humberto, J., 1975. Adoption of hybrid seeds and fertilizers among Columbian corn growers. Mexico City, CYMMIT.

Hyden, G., 1981. Modern cooperatives and the economy of affection in Sub-Saharan Africa. Proceedings of the symposium on traditional cooperation and social organization in relation to modern cooperative organization and enterprise.

Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf and H. van Reuler, 1989. A system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). Wageningen, the Netherlands (in press).

Janvry, A. de, 1972. Optimal levels of fertilization under risk: the potential for corn and wheat fertilization under alternative price policies in Argentina. American Journal of Agricultural Economics 54: 1-10.

Janvry, A. de, 1981. The agrarian question and reformism in Latin America. Baltimore, Hopkins University Press.

Keulen, H. van and J. Wolf (eds), 1986. Modelling of agricultural production: weather, soils and crops. Wageningen, the Netherlands, PUDOC. Simulation Monographs.

Kinsey, B.H., 1979. Agricultural technology, staple food crop production and rural development in Zambia. University of East Anglia, School of Development Studies. Monographs in Development Studies no 6.

Kinsey, B.H., 1984. Farm equipment innovations, agricultural growth and employment in Zambia. In: Ahmed, I. and B.H. Kinsey (eds), Farm equipment innovations in eastern and central southern Africa. Vermont, USA, International Labor Organization.

Koning, F. de, B. de Leeuw and K. Nijhof, 1989. Risk computation with crop growth simulation models: a case study on the commercialization of maize production in Zambia. Wageningen, the Netherlands, Centre for World Food Studies.

Kumar, S.K., 1981. Nutrition concerns in food policy for Sub Saharan Africa. IFPRI: food policy issues and concerns in Sub Saharan Africa: 81-102.

Kumar, S.K., 1987. The nutrition situation and its food policy links. In: Mellor, J.W., C.L. Delgado and M.J. Blackie (eds), Accelerating food production in Sub Saharan Africa. London.

Kurtz, T., S.W. Melsed and R.H. Bray, 1952. The importance of nitrogen and water in reducing competition between intercrop and corn. Agronomy Journal 44: 13-17.

Linsenmeyer, D.A., 1976. On cit by Eicher et al. (1983).

Louw, I.W., 1982. Nematode pests of maize. In: Keetch, D.P. and J. Heyns (eds), Nematology in Southern Africa: 69-72.

Marchand, M., E. Wisse and C.A. Drijver, 1983. Land use possibilities on the Kafue Flats, Zambia. Leiden. CES-Raport 10.

Masell, B.F. and R.W.M. Johnson, 1966. African agriculture in Rhodesia: an econometric study. Rand Report R-443 RC.

Ministry of Agriculture and Water Development, 1983. Handbooks for Agricultural Field Workers: Crop Husbandry. Lusaka, Zambia.

Miracle, M.P., D.S. Miracle and L. Cohen, 1980. Informal savings mobilization in Africa. Economic Development and Cultural Change 28: 701-724.

Moscardi, E.R., 1979. Methodology to study attitudes towards risk: the Puebla Project. In: Valdes, A., G. Scobie and J. Dillon (eds), Economics and design of small farmers technology.

Moscardi, E.R. and A. de Janvry, 1977. Attitudes towards risk among peasants: an econometric approach. American Journal of Agricultural Economics 59: 710-716.

National LIMA Fertilizer Programme, 1985. 1985 Annual Report.

Ntlhabo, P.P., 1985. Maize Research in Lesotho. In: To Feed Ourselves: Proceedings of the 1st Eastern, Central and Southern Africa Regional Maize Workshop: 37-42.

Parker, J.M.H. and R. Vernon, 1982. Maize herbicides for small scale farmers in Zambia. Tropical Pest Management 28: 259-265.

Prior, A.J., 1976. Research with fertilizers in Zambia. Report on the FAO/NORAD seminar on fertilizer use development in Zambia: 28-32.

Pyle, D.H. and S.J. Turnovski, 1970. Safety first and expected utility maximization in mean-standard deviation portfolio analysis. The Review of Economics and Statistics 52: 75-81.

Radner, R., 1972. On cit by Roumasset, 1976.

Roumasset, J.A., 1976. Rice and risk: decision making among low income farmers. Amsterdam, North-Holland.

Roumasset, J.A., 1979. Introduction in the state of arts. In: Roumasset, J.A., J.M. Boussard and I. Singh (eds), Risk, uncertainty and agricultural development: 3-21.

SADCC, 1987. Revised assessment of the impact of the 1986/87 drought in the SADCC member states. Harare.

Scandizzo, P.L. and J.L. Dillon, 1979. Peasant agriculture and risk preferences in NE Brazil: a statistical approach. In: Roumasset, J.A., J.M. Boussard and I. Singh (eds), Risk, uncertainty and agricultural development: 133-160.

Scholte, K. and J.J. 's Jacob, 1983. De betekenis van continue teelt en vrijlevende wortelaaltjes voor de opbrengst van snijmais. PAGV-verslag no 6: 12-23.

Schultz, J., 1974. Explanatory study to the land use map of Zambia, with special reference to the traditional and semi-commercial land use systems. Lusaka.

Schweigman, C., T.A.B. Snijders and F. Hagenzieker, 1981. Risk in agriculture in the developing countries caused by rainfall variability: introduction to risk computations. Groningen, University of Groningen.

Shurtleff, M.C. (ed), 1980. Compendium of corn diseases. St Paul, American Phytopathological Society.

Statistics Section, 1985. Agricultural Statistics Bulletin.

Toro, A. de, 1984. Evaluation of the mechanization systems of different groups of farmers in the Eastern Province of Zambia. Uppsala, Sweden, Swedish University of Agricultural Sciences, International Rural Development Centre. Working Paper 24.

Vernon, R. and Parker, J.M., 1983. Maize/weed competition experiments: implications for tropical small-farm weed control research. Expl. Agric. (1983): 191, 341-347.

Walker, P.T., 1960. Insecticide use on the maize stalkborer in East Africa. Bulletin Entomological Research 51: 321-351.

Wolf, J., C.A. van Diepen and C.H. van Immerzeel, 1987. A study on the limitations to maize production in Zambia using simulation models and a geographic information system. Wageningen, W. Staring Centre. Annex 6 in MARS definition study: results of the preparatory phase.

Wolgin, J.M., 1975. Resource allocation and risk: a case study of smallholder agriculture in Kenya. American Journal of Agricultural Economics: 622-630.

Wood, A., 1985. Food production and the changing structure of Zambian agriculture. In: Pottier, J. (ed), Food Systems in Central and Southern Africa: 138-168.

Zande, J.C. van de, 1990. Yield analysis in relation to the availability of farm labour and equipment. Wageningen, the Netherlands, Agricultural University, Soil Tillage Laboratory.

Zandstra, H., K. Swanberg, C. Zulberti and B. Nestel, 1979. Living rural development, chapter 12: risk. Ottawa, I.D.R.C.

Zulberti, C.A., K.G. Swanberg and H.G. Zandstra, 1979. Technology adaption in a Columbian rural development project. In: Valdes, A., G. Scobie and J. Dillon (eds), Economics and design of small farmers technology: 143-166. Ames, Iowa State University Press.