3. The Effects of Climatic Variations on Crop Yields: A Simulation Approach

3.1. Introduction

In 1978 a simulation model of the water-plant-soil type was developed by researchers of the Brazilian Agricultural Research Enterprise (EMBRAPA), (Garagorry *et al.*, 1982). This model was the main element of a computerized system for analysis of agroclimatic data, used to meet the needs of researchers of the Center for Agricultural Research in the Semi-Arid Tropics, CPATSA (located in Petrolina, State of Pernambuco). These needs were related to:

(1) The determination of the optimal planting period for annual crops in NEB.
(2) The production of risk estimations associated with the several crops.
(3) The preparation of maps of agroclimatic zones.
(4) The appraisal of potential in different projects for the use of excess water in the soil.
(5) The development of proposals for improved agricultural systems at the farm level.

The outcome of previous experiments aimed at attaining the above results had been unsatisfactory, due to the unavailability of a sufficiently large sample of years to provide the basis for estimations of the risks involved in determining the optimal time of the year for planting (SUDENE, 1967a; 1967b). On the other hand, computerized experiments with the above-mentioned model had been carried out for some time with beans (*Phaseolos*), cowpea (*Vigna Unguiculata*) which is a type of short-cycle bean (60–70) days) very resistant to moisture stress, corn and soybeans. The results of these experiments were considered satisfactory by CPATSA scientists (Garagorry *et al.*, 1982; Garagorry and Porto, 1983).

Two important aspects must be taken into consideration with respect to the use of a simulation model of the water-soil-plant type, rather than dealing simply with climate data. Firstly, the monthly average or annual precipitation data used in the more traditional studies are of little use for ascertaining what really occurs at the farm level, due to the extreme variability of precipitation in NEB. The simulation model, for instance, may be able to explain why a certain crop had a lower yield in one year than another in spite of the fact that the total amount of rainfall in the former was larger. Several examples researched with the use of the model show that these types of situations can occur quite frequently.

Secondly, the five main objectives listed above are interrelated in one way or another. Generally speaking, it is extremely difficult to devise a model which is adequate for a range of different objectives unless these objectives are closely interrelated. This section focuses on the study of agricultural systems at the farm level particularly with respect to the selection of optimal planting periods and optimal water management. The simulation model has clearly shown that the best planting period may vary significantly from one place to another, even on farms located in the same state (Garagorry *et al.*, 1982). In other words, NEB comprises several semi-arid tropic types, so an agroclimatic zonation is mandatory before any appropriate recommendations can be made to farmers.

To date, all studies of climate zoning based solely on precipitation data have given unsatisfactory results. These results are very different from the ones obtained by the use of interrelated data from climate, soil and plants. An agroclimatic zonation will be one of the model's outputs for each crop. Moreover, the model takes into account the excess or deficit of water in the soil, which provides an estimation of the risk associated to these variables, and from this a probability distribution is obtained for a yield index for each crop.

In this section we use the modeling approach described above to estimate the impacts caused by climatic variations on productivity in NEB. With this end in mind, six municipalities which are representative of the semi-arid tropic zone of NEB were selected for study, based upon historical meteorological and yield data for these locations.

Although the scenarios suggested in Section 2 of this case study were used as far as possible, it should be noted that:

(1) While the year 1983 has been characterized as a year of meteorological drought it was not necessarily a year of extensive agricultural drought. Although drought was meteorologically extreme and affected the entire NEB, in some localities the distribution of rainfall allowed for the maintenance of significant agricultural activity. That, for example, was the case for Petrolina (where CPATSA is located), which is included in the present study.

(2) While some drought scenarios have been selected from the post-1979 period, much of the climatic and yield data that were suitable for the model were available only up to the year 1978.

Because of these constraints, and some specific characteristics of the model (to be discussed later), other similar scenarios were substituted, using criteria based on the analysis of empirical data related to the agricultural years, which do not always coincide with the calendar year.

3.2. The Model and the Data

3.2.1. Outline of the agroclimatic model

This section provides an overview of the agroclimatic model for the semiarid tropic zone of NEB. The model considers not only precipitation and evapotranspiration, but also plant development as a function of the soil's capacity to retain water. For a detailed analysis using this system, it requires daily rainfall data for a series of years, and daily potential evapotranspiration data obtained from the monthly averages of potential evapotranspiration estimated by Hargreaves (1974) from the monthly averages of temperature and relative humidity. For the unit of time in the simulation analysis, the five-day period was selected as best reflecting the variations which occur in the availability of water for plants. The year is thus divided into 73 five-day periods. Precipitation and potential evapotranspiration are then expressed in terms of the 5-day totals.

The territory within the boundary of a municipality is taken as the geographical unit for the purpose of applying the model, because of the unavailability of climate data at the farm-scale level. The soil water holding capacity was estimated for the prevailing type of soil in each municipality.

For each five-day planting period being considered, the water balance is computed through the growing season for the crop started in that five-day period. To estimate the initial moisture status at planting, water balance computations are performed for the 20 preceding five-day periods. For example for a January 11–15 planting period in 1981, with a crop that would mature around June 1, the water balance would be computed for the 20 five-day periods October 3, 1980 to January 10, 1981, and then on as far as the five-day period including June 1. Note that the model would thus require precipitation data for parts of two years, 1980 and 1981, even for an analysis relating to a single planting period early in 1981.

After computing the water balance through the growing season for a crop started in a particular five-day period, the model estimates that crop's yield index, YI, which is defined as the ratio between the actual yield and the 'potential yield'. YI is computed as a function of the relative evapotranspiration (here defined as the ratio between actual evapotranspiration and the maximum expected evapotranspiration of that particular plant), and the yield response factor (estimated empirically, FAO, 1979).

More specifically the yield index (YI) used in this section is computed as follows:

$$\mathrm{YI} = \prod_{i=1}^{n} \left\{ \max \left[0; 1 - \mathrm{Ky}_i \left(1 - \frac{\mathrm{ETA}_i}{\mathrm{ETM}_i} \right) \right] \right\} \qquad (3.1)$$

where n = total number of phenological periods (here n = 4: seeding, growing, pod formation and ripening of grains);

Ky_i = yield response factor for the i-th phenological period;

ETA_i = actual evapotranspiration of the crop during the i-th phenological period;

ETM_i = maximum evapotranspiration of the crop during the i-th phenological period;

'max' function – see explanation under Equation (3.2), below.

As the equation above indicates, the yield index (YI) is estimated using the maximum and the actual crop's evapotranspiration and the associated yield response factor (Ky) for each phenological period in turn (*Figure 3.1*). The contribution to YI, in a given phenological period, is at its maximum if the plant suffers no water shortage, that is ETA=ETM. Thus, the value of YI is a function of the value of Ky and of relative evapotranspiration ETA/ETM. *Figure 3.2* provides an idea of the variation of YI as a function of relative evapotranspiration.

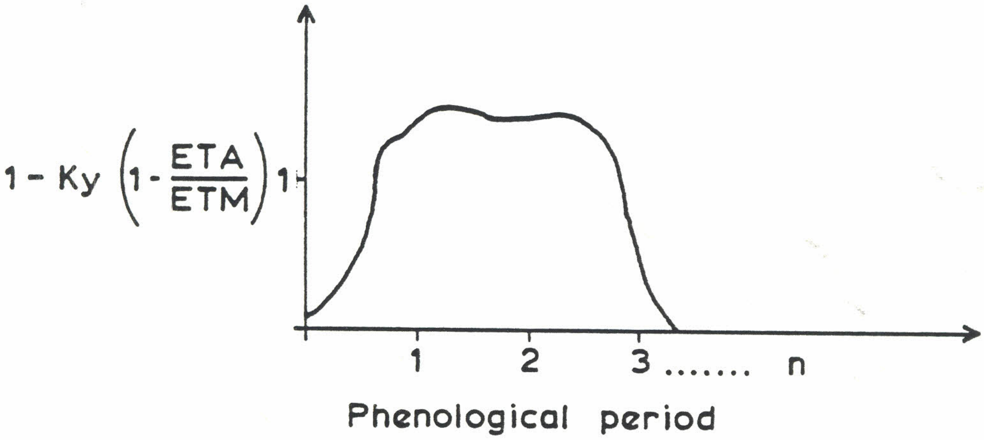

Figure 3.1. Variations of the yield index, YI, by phenological period (schematic).

It can be seen that the yield index tends to reach its maximum value if there is no water shortage, that is, when relative evapotranspiration tends to 1.

Equation (3.1) is based on the following equation derived by FAO to quantify the effect of water stress on yields:

$$(1 - YA/YM) = Ky\,(1 - ETA/ETM) \qquad (3.2)$$

where YA = actual crop yield;

YM = maximum (or potential) crop yield;

Ky = crop yield response factor;
ETA = actual crop evapotranspiration;
ETM = maximum crop evapotranspiration.

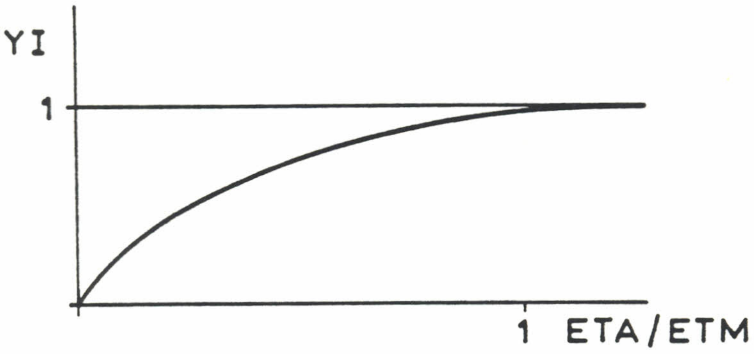

Figure 3.2. Dependence of the yield index, YI, on relative evapotranspiration.

From Equation (3.2), YI may be obtained as follows:
YI = YA/YM = 1 − Ky (1 − ETA/ETM), which was redefined in Equation (3.1) in order to specify the effects of phenological periods and to assure a positive yield index. The function 'max' gives the greater value among several values provided as arguments. For instance, given two arguments, numbers 7 and 3; then max (3; 7) will be equal to 7. Its use in conjunction with a '0' argument in Equation (3.1) avoids negative results. If Ky = (1 − YA/YM) / (1 − ETA/ETM) were greater than 1, the use of Equation (3.2) to obtain YI could give a negative result.

The program next classifies the yield index into three categories of results: 'good', 'fair', and 'poor'. This classification is done according to values supplied by the user (who has the final decision over the planting of a certain crop). For instance, the farmer may have established that for the yield index to be considered 'good', it must be equal or greater than 80%; for 'fair', equal to or greater than 50% but less than 80%; and for 'bad', less than 50%. Thus the values of 0.8 and 0.5 must be supplied to the program by the user, so that the classification can be completed.

Besides classifying the yield index for each crop growing season as 'good', 'fair' or 'poor', the program also accumulates the incidence of water excess or deficit.

After completing the calculation of yield indices and water excesses and deficits as outlined above, for each of the selected localities, over the whole series of years, on the basis of five day time periods, the program provides the relative frequency of the 'good', 'fair' and 'bad' results, and the relative frequency of acceptable results (defined as the sum of the 'good' and 'fair' results). In addition, it prints the following indicators for each five-day period:

(1) Mean value, standard deviation, and coefficient of variation of the yield index, if the 5-day period was one of the selected planting periods.
(2) A frequency distribution and mean value of water excess.
(3) A frequency distribution and mean value of water deficit.
(4) The difference between mean values of water excess and deficit.

The operation of the model is shown schematically in *Figure 3.3*. The items framed by the dotted lines are the computational elements of the model, where the water-plant-soil interrelation is quantified, through the water balance and yield index calculations, and the necessary operations for obtaining the above-mentioned statistics are performed. These procedures are carried out for the crop corresponding to each selected five-day planting period for every year of that series, and for each municipality.

3.2.2. The data

The model utilized in this study was designed primarily for ascertaining the best planting period as a function of the expected yield value, which, in turn, is computed from an 'expected' rainfall distribution. A precipitation data series of at least 15 years is necessary, in order to obtain useful results. It is essential that the data record be sufficiently long to allow for the estimation of the associated risk in determining the best planting period through the assessments of the standard deviation and the coefficient of variation of the expected yield index value.

For the climate impact analysis of the present study, a sample of six stations located in representative municipalities of the NEB semi-arid zone was chosen. Their locations, as well as the lengths of the available data series, are shown in *Figure 3.4* and *Table 3.1*. The daily precipitation data were provided by SUDENE and CPATSA. The remaining data required for the simulation were the following:

(1) Estimated monthly average potential evapotranspiration (from Hargreaves, 1974).
(2) Water holding capacity of soil (from CPATSA, unpublished).
(3) Crop coefficient for each phenological period (from FAO, 1979).
(4) Crop yield response factor for each phenological period (from CPATSA, unpublished).

The data series employed are for similar periods for 5 of the stations, the exception being Petrolina.

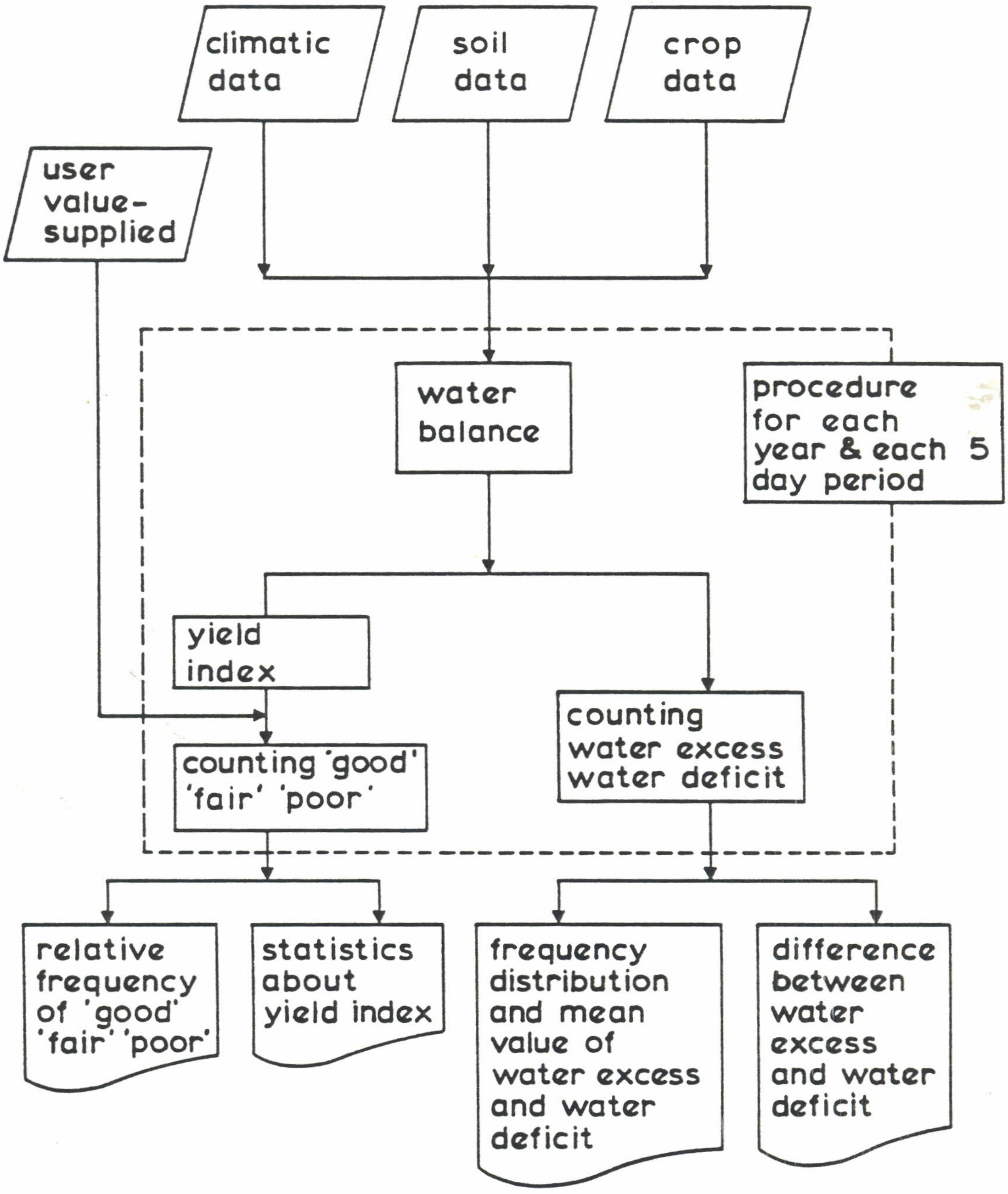

Figure 3.3. Schema of the water-soil-plant model.

3.2.3. The agricultural year

In many localities in NEB the agricultural year usually begins in mid-calendar year and ends in the following year. For instance, in some places the planting season starts in November and harvest occurs in March. Thus,

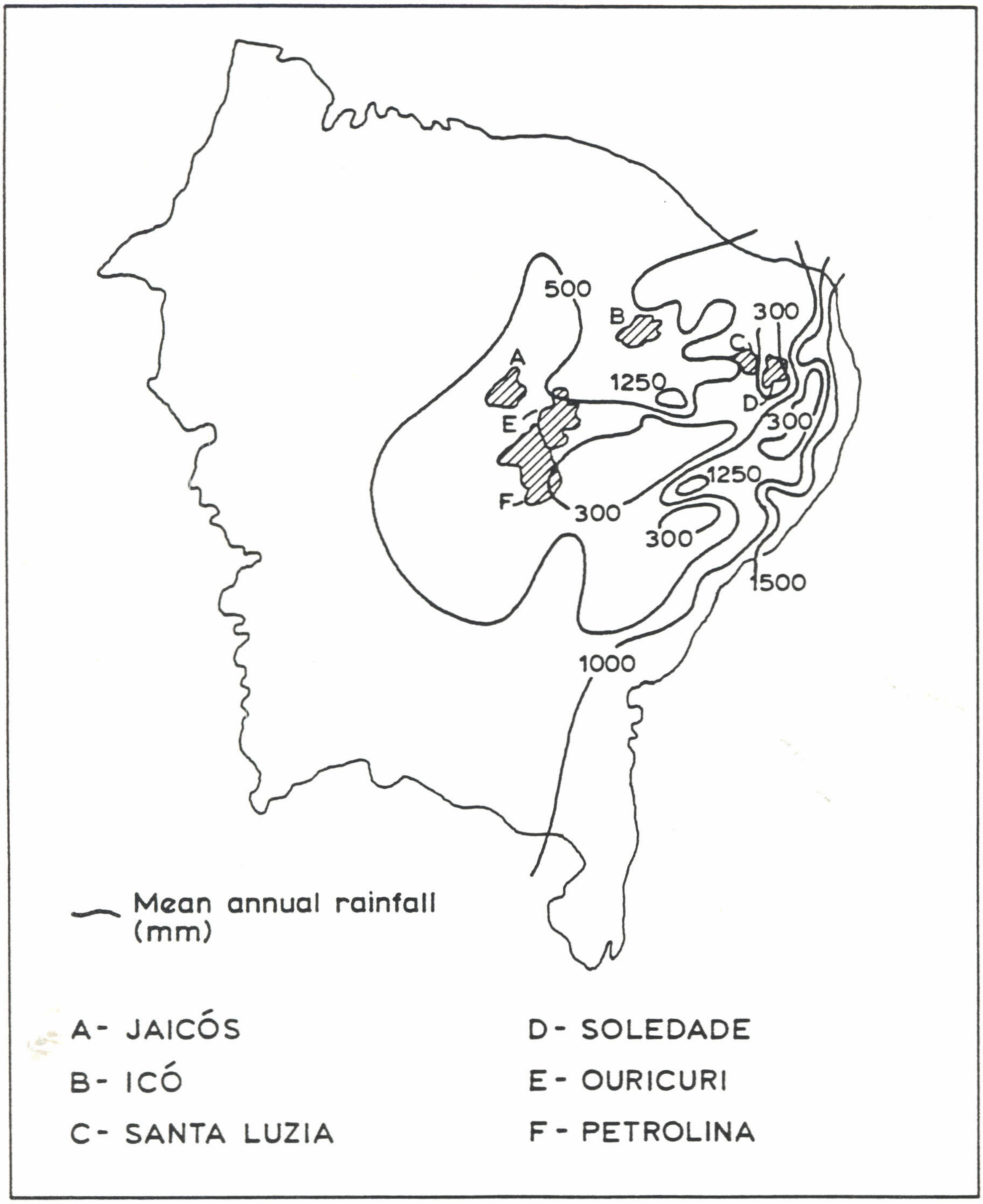

Figure 3.4. Locations of stations and municipalities referred to in the text.

Table 3.1. Locations and main climate characteristics of the stations.

	Geograhic coordinates					
Location	*Lat.*	*Long.*	*Altitude*	*Number of years (start/end)*	*Mean annual rainfall* (mm)	*Mean annual PET* (mm)
Jaicós	07° 22′S	41° 08′W	255 m	41 (1913/1977)	684	1882
Icó	06° 25′S	38° 51′W	160 m	51 (1913/1975)	720	2020
Santa Luzia	06° 52′S	36° 56′W	290 m	63 (1912/1978)	537	1811
Soledade	07° 07′S	36° 22′W	517 m	56 (1913/1980)	366	1614
Ouricuri	07° 53′S	40° 04′W	432 m	44 (1914/1978)	559	1965
Petrolina	09° 09′S	40° 22′W	355 m	20 (1965/1984)	577	2080

Source: SUDENE/CPATSA.

the total annual rainfall for a calendar year may not be a good indicator of climate conditions for rainfed agriculture in some places. This limits the utilization of scenarios based on the total annual precipitation for a calendar year, such as the year 1983. That year was considered one of widespread drought, in meteorological terms, though some reasonable agricultural yield occurred at a few places.

A very simple computer program was devised to determine the agricultural year for each locality. The procedures were as follows:

(1) For each year of the series, the month with minimum rainfall was determined (in case of a tie the last month with minimum amount of rainfall was selected).

(2) For each month (January to December), the number of times it had been selected as the minimum rainfall month in (1), above, was noted, and the month with the highest frequency was defined as the final month of the agricultural year (if there was a tie, the last month with the largest frequency was chosen).

The agricultural year is then the 12-month period ending with the final month as obtained in step 2 above. The results obtained by this method were found to be more satisfactory than those obtained by other procedures (such as, for example, simply defining the final month of the agricultural year as the month with minimum precipitation). In our case, the beginning of the agricultural year coincides with the beginning of the agricultural season in each locality. The following months were thus defined as the beginning of the agricultural years:

Icó and Soledade:	January
Jaicós:	October
Petrolina and Ouricuri:	November
Santa Luzia:	December

3.3. Simulating the Effects of Climatic Variations on Yields of Cowpea

3.3.1. Simulation design

This simulation exercise sought to analyse the possible effects on agricultural yield of a variation of ± 10% in precipitation and potential evapotranspiration (PET). To achieve this the precipitation and potential evapotranspiration data were multiplied by 0.9, 1.0 and 1.1, producing a simulation of 3 × 3 factorial, and providing the following situations:

(1) Precipitation and PET multiplied by 1.0, i.e. with unaltered original data and representing a climate called 'normal'.
(2) 'Normal' precipitation, with PET decreased by 10% (i.e. multiplied by 0.9).
(3) 'Normal' precipitation, with PET increased by 10% (i.e. multiplied by 1.1).
(4) 10% increase in precipitation, and 'normal' PET.
(5) 10% increase in precipitation, and 10% decrease in PET. This is the most favorable situation for a semi-arid climate, because it improves the moisture situation through both an increase in the supply of water and a decrease in the moisture demand as reflected by the potential evapotranspiration.
(6) 10% increase in both precipitation and PET.
(7) 10% decrease in precipitation with 'normal' PET.
(8) 10% decrease in both precipitation and PET.
(9) 10% decrease in precipitation and an increase of 10% in PET. This is the most unfavorable situation for plant growth in semi-arid regions, because the supply of water diminishes as the plant's need for water increases.

These situations may be expressed by a pair (x_1, x_2), where x_1 is the value by which the precipitation will be multiplied and x_2 is the value by which potential evapotranspiration will be multiplied. For example (1.0, 1.0) represents the first situation, described above as 'normal', whereas (1.1, 0.9) represents the most favorable situation, as described in (5) above. The simulations were performed without altering either the soil and plant data, or the procedures for calculating the yield index, water excess or water deficit.

3.3.2. Types of results obtained

In order to assess the impacts caused by climate variations, estimations for expected yield are needed. Since they are expected values, there is a degree of variability associated with them, and it is important to have an understanding of this variability. To be able to design a project for water and soil management that can respond adequately to eventual water needs at critical stages of plant growth, thus improving yield, it is necessary to have a thorough knowledge of the estimation of water excess and deficit, combined with knowledge of the expected values of the yield estimation.

Several indicators selected from the computer output are discussed below:

(1) Maximum probability (PA) of an acceptable relative yield, as indicated by the yield index defined in Section 3.2.1. PA is utilized to determine the best planting period in the following way: cut-off values at 10% intervals are assumed. When the maximum value of PA is found, the next lowest cut-off value is then selected for that case; then the five-day period corresponding to the first occurrence of a PA value greater or equal to that cut-off level is defined as the initial period for the best planting season; and the five-day period corresponding to the last occurrence of a PA value greater than or equal to that cut-off level will be the final period for the most suitable planting season. For example, if the maximum value for PA is 63.2%, the cut-off level will be 60. The initial period for the best planting season will be the one corresponding to the first occurrence of a value greater than or equal to 60; the final period will be the last one where PA is greater than or equal to 60.

(2) Maximum mean value of the crop yield index (MYI) within the best planting season, i.e. the growing season of a crop planted in the best planting period.

(3) Coefficient of variation of the crop yield index (CVMYI) corresponding to the value obtained in (2). If there is a tie in (2) for more than one five-day period, the maximum coefficient of variation will be chosen.

(4) Maximum value of the mean water excess (in millimeters) within the best planting season as defined in (2) above (EXC).

(5) Maximum value for the mean water deficit (in millimeters) within the best planting season as defined in (2) above (DEF).

3.3.3. Analysis of the obtained results

Tables 3.2–3.6 show the results obtained from the procedures described above. *Table 3.2* indicates the likelihood of obtaining acceptable relative yield (PA). These values may be seen as percentage probabilities of achieving a fair or good yield. The first three Municipalities clearly have the best chance of obtaining acceptable yields, with probabilities greater than 60% for all the simulated situations. For the other three Municipalities, the table indicates a need for supplementary irrigation under existing precipitation levels. At these locations the best chance of obtaining a good or a fair yield is at Ouricuri with the precipitation level increased by 10%, and crop demand for water through evapotranspiration decreased by 10%.

Table 3.2. Percent probabilities (PA) of acceptable yields, for each Municipality, according to the simulated climatic situation.

	Climatic Situation[a]								
Location	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Jaicós	85	90	80	90	93	85	80	88	78
Icó	88	92	86	90	92	88	88	88	86
Santa Luzia	70	75	65	73	76	68	67	71	63
Soledade	33	36	29	33	40	31	31	33	26
Ouricuri	40	49	35	45	54	38	35	35	35
Petrolina	42	47	37	42	47	42	42	42	32

[a] The simulated climatic situation is defined by pairs (x_1,x_2) in the text: Situation 1 = (0.1, 1.0); 2 = (1.0, 0.9); 3 = (1.0, 1.1); 4 = (1.1, 1.0); 5 = (1.1, 0.9); 6 = (1.1, 1.1); 7 = (0.9, 1.0); 8 = (0.9, 0.9); 9 = (0.9, 1.1).

Table 3.3 provides the values for the maximum expected yield index, for the different localities and climatic situations. One may observe that these results agree with those in *Table 3.2*, in that for all the situations yield performance is shown as better for the first three Municipalities than for the last three. The most favorable result is the expected maximum yield index of 75% for situation (1.1, 0.9) at Icó.

Table 3.3. Maximum yield index (MYI) in percent.

	Climatic Situation[a]								
Location	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Jaicós	69	72	66	69	74	68	66	66	62
Icó	70	73	67	72	75	69	68	71	65
Santa Luzia	60	63	55	62	65	57	56	60	54
Soledade	30	33	26	33	35	30	27	30	26
Ouricuri	42	46	36	43	48	40	39	43	32
Petrolina	38	42	35	40	42	36	36	40	33

[a] The simulated climatic situation is defined by pairs (x_1, x_2) in the text: Situation 1 = (1.0, 1.0); 2 = (1.0, 0.9); 3 = (1.0, 1.1); 4 = (1.1, 1.0); 5 = (1.1, 0.9); 6 = (1.1, 1.1); 7 = (0.9, 1.0); 8 = (0.9, 0.9); 9 = (0.9, 1.1).

Table 3.4 shows the values of the coefficient of variation for the maximum yield index, for the six localities and nine climate situations. Again these results are consistent with those in the preceding paragraphs, with the first three Municipalities showing the best results among the six. Their coefficients of variation are much smaller than those for Soledade, Ouricuri, and Petrolina. Soledade, which had the poorest results in *Tables 3.2* and *3.3* also presents the greatest variability in its MYI values, as indicated by the *Table 3.4* results. This suggests that crop production there would be particularly unstable.

Table 3.4. Coefficient of variation for the maximum yield index (CVMYI) in percent.

	Climatic Situation[a]								
Location	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Jaicós	36.1	35.6	38.8	34.2	31.9	36.8	40.6	32.6	41.3
Icó	33.4	31.3	34.9	31.8	30.4	33.8	34.7	33.2	36.6
Santa Luzia	48.8	45.9	52.0	47.4	44.7	50.2	51.0	47.6	54.6
Soledade	91.0	84.6	100.7	87.3	81.1	92.8	95.7	88.8	102.1
Ouricuri	64.3	58.3	69.5	61.4	55.5	66.7	67.4	61.4	72.7
Petrolina	74.3	69.1	78.5	71.5	68.6	75.8	77.3	72.1	81.3

[a] The simulated climatic situation is defined by pairs (x_1,x_2) in the text: Situation 1 = (1.0, 1.0); 2 = (1.0, 0.9); 3 = (1.0, 1.1); 4 = (1.1, 1.0); 5 = (1.1, 0.9); 6 = (1.1, 1.1); 7 = (0.9, 1.0); 8 = (0.9, 0.9); 9 = (0.9, 1.1).

As is shown in *Table 3.1*, the total annual average precipitation for Santa Luzia, Ouricuri and Petrolina are similar, although potential evapotranspiration is somewhat lower at Santa Luzia. With respect to the variability of MYI, however, Santa Luzia shows a much smaller figure than the other two (*Table 3.4*). This implies a better agricultural performance for that Municipality.

From the results of *Table 3.4* it can be seen that the variability is much smaller for the first three municipalities, which indicates more stability and reliability in the rainfall distribution from year to year for those localities. Such results are useful for agroclimatic zoning, in that they provide a means of comparing the suitability of the different locations for achieving acceptable yields. The procedures may also be seen as providing a simple type of risk analysis, because the coefficient of variation is related directly to the standard deviation of the yield index; the smaller the standard deviation, the smaller the coefficient of variation, and consequently, the smaller the risk.

Table 3.5 shows the maximum soil water excess, within the season with the best planting period, for the several localities and climatic situations. The importance of these water excess values stems from the fact that they may help to indicate the needs with respect to the management of water to improve yields. This excess water may be stored in small reservoirs, by the use of 'in situ' collecting technologies, already developed for NEB semi-arid areas by CPATSA.

It will be noted that the first three municipalities, together with Petrolina, offer the best conditions for excess water utilization, because there would be relatively large volumes of excess water during the crop season that could be saved for later use.

Table 3.5. Average water excess (EXC) in mm.

	Climatic Situation[a]								
Location	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Jaicós	185	196	176	214	229	208	153	163	144
Icó	202	206	191	237	241	226	166	177	163
Santa Luzia	164	170	156	191	200	185	135	141	126
Soledade	51	59	52	67	71	58	31	43	41
Ouricuri	93	100	87	110	117	106	74	80	56
Petrolina	102	108	96	123	130	116	88	94	83

[a] The simulated climatic situations is defined by pairs (x_1x_2) in the text: Situation 1 = (1.0, 1.0); 2 = (1.0, 0.9); 3 = (1.0, 1.1); 4 = (1.1, 1.0); 5 = (1.1, 0.9); 6 = (1.1, 1.1); 7 = (0.9, 1.0); 8 = (0.9, 0.9); 9 = (0.9, 1.1).

Table 3.6 provides the maximum values for average water deficit during the best crop season. When one compares these results with those obtained in *Table 3.5*, it can be seen that the deficit is smaller than the excess for all the municipalities except Soledade. Where this is the case it may be concluded that water management may appropriately depend solely on local rainfall. However, in the case of Soledade, where the deficit values are greater than the excess values, additional water from other sources would be needed or agricultural yields would suffer.

Table 3.6. Average water deficit (DEF) in mm.

	Climatic Situation[a]								
Location	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Jaicós	28	19	34	25	16	31	26	25	32
Icó	26	18	32	25	17	30	28	23	37
Santa Luzia	28	30	45	31	29	43	41	30	44
Soledade	56	52	73	60	50	63	55	48	76
Ouricuri	77	64	78	56	43	76	83	58	78
Petrolina	69	59	84	67	56	79	72	60	85

[a] The simulated climatic situations is defined by pairs (x_1,x_2) in the text: Situation 1 = (1.0, 1.0); 2 = (1.0, 0.9); 3 = (1.0, 1.1); 4 = (1.1, 1.0); 5 = (1.1, 0.9); 6 = (1.1, 1.1); 7 = (0.9, 1.0); 8 = (0.9, 0.9); 9 = (0.9, 1.1).

3.4. Impacts under Specified Climatic Scenarios

3.4.1. Analysis of the scenarios proposed

The selection of climatic scenarios should take the impact model's major characteristics into account. For the model used here there was a need to know the amount of water contained in the soil during the planting season, and to make yield estimations after the calculation of the water balance for all the five-day periods. These aspects, combined with the constraints mentioned on Section 3.2.2, made it inappropriate to use this model with all of the scenarios suggested in Section 2.

Of the six municipalities involved in the analyses here, only Petrolina and Soledade had daily precipitation data available after 1978. *Table 3.7* shows the results of the effects of a 'back-to-back' drought in the years 1979 and 1980. The apparent contradictory nature of the results in this table may reflect the model's sensitivity to rainfall distribution through the year, and the fact that the amount of water contained in the soil in the first five-day period in the given year is computed from the rainfall data for the previous one hundred days.

Table 3.7. Effects under the 'back-to-back' drought scenario for Petrolina and Soledade (1979 and 1980).

	Long-term[a]			*1979*		*1980*	
Location	*Mean Rainfall* (mm)	*Mean PET*[b] (mm)	*Sim.*[c] *MYI* (%)	*Rainfall* (mm)	*MYI* (%)	*Rainfall* (mm)	*MYI* (%)
Soledade	366	1614	30	195	50	302	26
Petrolina	577	2080	38	508	52	536	80

[a] Long-term data are from *Table 3.1.*

[b] PET - Potential evapotranspiration

[c] Sim. - Simulated (data from *Table 3.3*).

Rainfall distribution through the year in those municipalities is quite variable, which may help to explain why, in 1979, the computed yield for Soledade was greater than that in 1980, despite the fact that the annual rainfall was less than in 1980. What happened was that rainfall was better distributed throughout 1979. In 1980 rainfall was concentrated in the months of February, March and April, with heavy rainfall occurring on isolated days widely separated from one another during those months.

With respect to 1983 which was considered in Section 2 as a year of extreme drought, the model was applied for Petrolina, the only Municipality where daily data were available. The computed yield index was 71% which is much greater than the expected index (38%) that had been computed from the long series of years, although the annual precipitation (540 mm) was much less than the long-term annual average of 577 mm. This suggests that identifying extreme drought in NEB on the basis of total annual rainfall alone can be seriously misleading.

3.4.2. Climate impact assessment for the specified scenarios

The selection of climatic scenarios was based on agricultural years rather than calendar years, and considered every year available in the data series for each Municipality. The fact that agricultural years are more representative of agricultural activity in each locality was also taken into account, and it was assumed that the greater the number of years in the series, the more precise the average estimated yield would be. *Table 3.8* describes some of the statistical characteristics of annual rainfall, by agricultural years, in each of the municipalities.

Table 3.8. Mean quantity, distribution and variability of the total annual rainfall (mm) in each locality studied.

Location	*Mean*[a]	*Min*[b]	*P10*[c]	*Q1*[d]	*Med.*[d]	*Q3*[d]	*Max*[e]	*Range*[f]	*STD*[g]	*P90*[h]	*CV (%)*
Jaicós	684	303	420	526	652	832	1282	979	223	993	33
Icó	720	166	447	570	687	864	1259	1093	233	1076	32
Santa Luzia	537	96	198	368	531	670	1239	1143	246	834	46
Soledade	366	93	182	210	318	448	1035	942	185	641	51
Ouricuri	559	166	240	435	565	664	1234	1068	223	820	40
Petrolina	577	239	334	484	585	669	852	613	166	828	29

[a] Mean is total annual average for the corresponding Municipality;
[b] Min is minimum total annual that occurred in the Municipality in the series;
[c] P10 is annual total which occurs at 10% probability, that is, the probability of rainfall being no more than that amount is 10%. P90 is annual total which occurs at 90% probability, i.e. the probability of rainfall being that much or less is 90%;
[d] Q1 and Q3 are totals corresponding to the first and third quartiles, respectively; occurrence of annual totals equal or less than Q1 and Q3 are at 25% and 75% probability, respectively; Med. is the annual total at 50% probability (median);
[e] Max is maximum annual total which occurred in the series;
[f] Range is difference: Max − Min;
[g] STD is standard deviation of annual totals, for each series and for each municipality;
[h] CV is coefficient of variability.

The first three localities present a greater absolute variability from year to year in the occurrence of annual precipitation, as indicated by the standard deviation, although the relative variability may be smaller. At Jaicós and Icó the coefficients of variability, 33% and 32% respectively, are smaller than at Soledade and Ouricuri (51% and 40%), indicating lower relative variability. The variability within the same year may be lower for the first three Municipalities than for the others.

The 1-in-10 analysis (*Table 3.9*), was performed by taking the annual rainfall closest to the of 10% and 90% levels, i.e. the P10 and P90 values from *Table 3.8*, and calculating the maximum yield index (MYI) for the corresponding agricultural year.

Table 3.9. Maximum yield index (MYI) for the 1-in-10 scenarios.

	Wet[a]			*Dry*[a]		
Location	*Year*	*Rainfall* (mm)	*MYI* (%)	*Year*	*Rainfall* (mm)	*MYI* (%)
Jaicós	1976/77	931	83	1971/72	413	82
Icó	1940	1031	92	1932	444	70
Santa Luzia	1970/71	806	86	1952/53	188	5
Soledade	1972	639	75	1946	164	47
Ouricuri	1946/47	786	89	1952/53	238	13
Petrolina	1974/75	828	73	1969/70	334	30

[a] In this table a 'wet' year is that one with annual rainfall closest to the P90 values of *Table 3.8*, while a 'dry' year is that with annual rainfall closest to the P10 level.

As expected, the MYI values in *Table 3.9* are quite high for wet years, indicating that the yield should tend to approximate the potential yield for each locality in such years. For the 1-in-10 dry years, MYI values for four of the other Municipalities are distinctly low. The high MYI's obtained for these years at Jaicós and Icó reflect some anomalous features of these particular years in those localities, probably in the within-year rainfall distributions.

Extreme years were selected from among all the years in the analyzed series (*Tables 3.10* and *3.11*). *Table 3.10* shows values obtained for the yield index in a year of extreme drought, and for comparison, the long-term values based on the whole data series. One may note that even in the best case, that for Icó, the productivity level indicated was so low as to be considered catastrophic. The better performance indicated at Icó than elsewhere may be related to the fact that its calculation included consideration of the final one hundred days of the year 1918 (a year for which total rainfall was 1078 mm), since Icó has an agricultural year which coincides with the calendar year.

Table 3.10. Maximum yield index (MYI) for the extreme drought scenario compared with long-term values.

	Long-term			*Extreme drought*		
Location	*Mean Rainfall*	*Mean PET*	*Simulated MYI (%)*	*Year*	*Rainfall*	*MYI* (%)
Jaicós	684	1882	69	1914/15	303	22
Icó	720	2020	70	1919	166	43
Santa Luzia	537	1811	60	1918/19	96	21
Soledade	366	1614	30	1958	93	7
Ouricuri	559	1965	42	1929/30	166	8
Petrolina	577	2080	38	1975/76	239	14

In *Table 3.11* MYI data indicate that for very wet agricultural years, the yield would approach the potential yield, except at Petrolina where it would apparently only reach two thirds of potential. That may be related to rainfall variability within the year at Petrolina.

Table 3.11. Maximum yield index (MYI) for the extreme wet year scenario compared with long-term values.

	Long-term			*Extreme wet year*		
Location	*Mean Rain*	*Mean PET*	*Simulated MYI (%)*	*Year*	*Rainfall*	*MYI (%)*
Jaicós	684	1882	69	1923/24	1282	98
Icó	720	2020	70	1917	1259	97
Santa Luzia	537	1811	60	1963/64	1239	94
Soledade	366	1614	30	1924	1035	92
Ouricuri	559	1965	42	1934/35	1234	88
Petrolina	577	2080	38	1968/69	852	67

To summarize the foregoing, *Table 3.12* shows the percentage change in yield estimated in the several localities for extreme years, for 1-in-10 events, and for the back-to-back scenario proposed in Section 2. The figures for extreme drought indicate yields generally more than 50% below the long-term average, demonstrating the futility of trying to produce a cowpea crop in anomalously dry years. Results for Santa Luzia, Ouricuri and Petrolina, also indicated very low yields for the driest 10% of years.

Table 3.12. Relative impacts (%) of different scenarios on MYI values in the simulation of cowpea yield. The scenario MYI values are shown expressed as percentages of the long-term MYI's.

		Scenarios					
		Extreme		*1-in-10*		*Back-to-back*	
Location	*Base years*	*dry year*	*wet year*	*dry*	*wet*	*1979*	*1980*
Jaicós	100	31	142	119	120	–	–
Icó	100	61	138	100	131	–	–
Santa Luzia	100	35	156	8	143	–	–
Soledade	100	23	306	156	250	166	87
Ouricuri	100	19	209	31	212	–	–
Petrolina	100	36	176	79	192	137	210

3.5. Model Validation

As mentioned by Garagorry and Porto (1983), when the model was applied according to its original objectives, it was well-accepted among professionals and farmers. The results are being confirmed by feedback in response to inquiries made to farmers of the NEB Region.

Some comparison was also made between the model outputs and IBGE data. The values obtained from the simulation of yield index (%) were compared to the present yield (t/ha) provided by IBGE. Since current yield data are available only for Petrolina, and only from 1975 on, it was not possible to carry out validation tests for the other Municipalities.

A regression analysis was performed, where the dependent variable was observed yield, and the independent one was yield index. If the yield index was a good indicator, one would expect the determination coefficient and the correlation coefficient (r^2 and r) to be high. However, those values were very small. This could indicate that the yield index may not be a good indicator, but it could also be a reflection of inadequate sample size for analysis. Pending further research, these results should be considered as inconclusive.

3.6. Concluding Remarks

This study demonstrates that a simulation model can be utilized not only for its main original purpose of helping to select best planting times, but also for estimating the impacts of climatic variations on crop yields. In the latter case, the model's usefulness stems from the fact that the results indicate the probabilities of obtaining good crops. It can thus be useful as a component of measures to lessen the risks associated with climatic variations. Although there would still be a risk of crop loss, the model provides for the estimation of that risk. For example, in Jaicós (Piauí State), Icó (Ceará State) and Santa Luzia (Paraíba), the probability of obtaining good crops is 93%, 92% and 76% respectively when precipitation is 10% greater than average and potential evapotranspiration is 10% below average (*Table 3.2*). At Soledade (Paraíba), Ouricuri (Pernambuco) and Petrolina (Pernambuco), the probability of achieving acceptable crops under the same conditions is 54% at the most. In these cases, the chances of loss are great, even if the best planting season is chosen.

We may summarize the interaction between knowledge of climatic risk and the economics of agricultural production as follows. At present, planting decisions based on a limited knowledge of climatic risk place farmers at point A on on the supply diagram (*Figure 3.5*). However, a more precise knowledge of risk may cause them to alter their decision-making and to move them to B, implying an increase in product supply (A to B). Under these semi-arid conditions, even if the best planting seasons are known there are still substantial risks of loss. An irrigation policy could move the supply

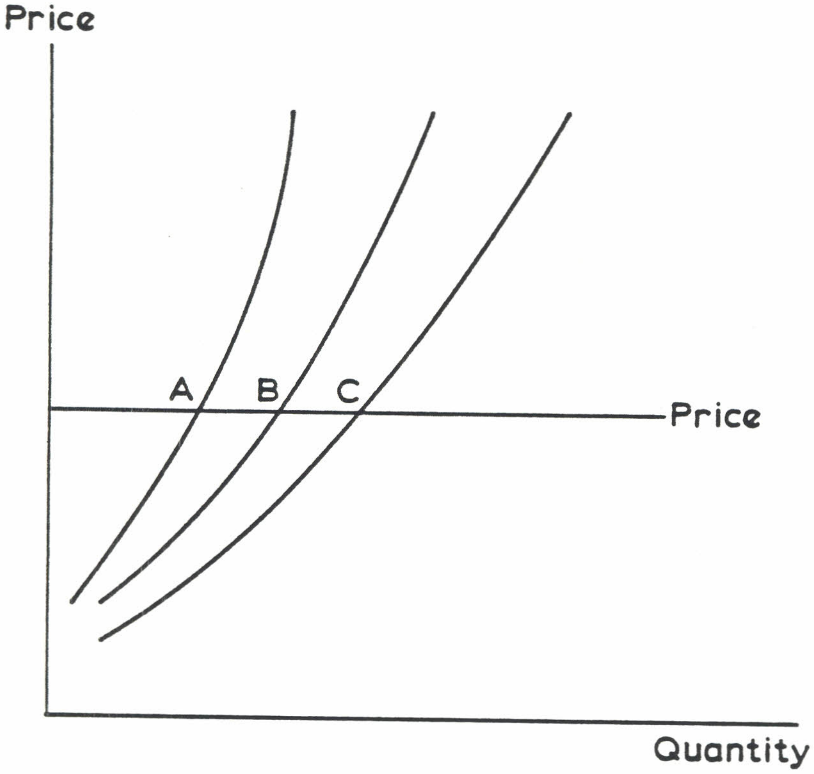

Figure 3.5. Supply curves of agricultural production. A = initial situation; B = situation with decisions based on knowledge of optimal planting times; C = situation after introduction of irrigation.

curve to C, which represents a situation where climatic risks due to moisture constraint are largely eliminated. The benefits derived from this policy are translated into a larger supply product.

Another implication arising from the analyses made with this model is that, to maintain the water-soil-plant balance so as to minimize damage caused by droughts, there must be not only optimum utilization of water, but also a guaranteed water supply. Both water conservation, and practices aimed at improving the soil's capacity to retain water, are needed. These techniques will reduce the damage caused by consecutive years of droughts, which have been shown to have very adverse effects on the population and the economy of northeast Brazil.

4. The Effects of Drought on Agricultural Production and Yields

4.1. Introduction

The droughts which occurred in northeast Brazil (NEB) during the 1979–1983 period brought serious consequences to the economy and population of that region. The extreme drought of 1983, which affected 88% of NEB, reduced the regional gross product by 15.8%. It was worse than in 1979 and 1980, when production growth rates were zero and –0.9%, respectively (MINTER, 1973). In 1983 2.5 million people received assistance in coping with the drought, but it has been estimated that the total number affected reached 12 million people (Section 1).

There is evidence that the industrial sector is less affected by drought, partly because some of its raw materials can be obtained from other regions (MINTER, 1973). The most severe impacts of droughts are on the agriculture sector, especially on subsistence crops. As noted in Section 1, subsistence crops are more affected than cattle, and small farmers are more affected than large landowners. Figueroa (1977) reports that for medium and large farm owners drought is mainly a problem of production, while for small farmers it involves family subsistence.

Table 4.1. Main occupation and other occupations of workers enlisted in emergency public works, by type of occupation, 1978.

Type of occupation	*Main occupations* %	*Other occupations* %
Landholder	20.1	0.8
Landless farmer	75.1	11.4
Herdsman	1.2	2.9
Tradesman	0.2	1.2
Urban worker	1.2	3.8
Other	1.8	2.6
Without occupation	0.4	77.3
Total	100.0	100.0

Source: Nabuco (1983).

Examination of the distribution of workers engaged in emergency public works (*Table 4.1*) reveals that in these projects landless farmers predominated (75.1%), followed by landowners. Together, they represented 95.2% of