A CROP PRODUCTION AND ENVIRONMENT MODEL FOR LONG-TERM CONSEQUENCES OF AGRICULTURAL PRODUCTION

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FOREWORD

The Food and Agriculture Program at IIASA focuses its research activities on understanding the nature and dimensions of the world's food problems, on exploring possible alternative policies that can help alleviate current problems and prevent future ones.

As a part of the research activities investigations of alternative paths of technological transformation in agriculture in the context of resource limitations and long term environmental consequences are being investigated. The purpose is to identify production plans strategies which are sustainable. The general approach and methodology has been developed at IIASA and is being applied in several case studies on the regional level in different countries with the help of collaborating insitutions.

An important element in this methodology is the development of a model that relates soil, climate and genetic properties of crops to yield input relationships. In addition the changes in soil characteristics that take place as a consequence of cultivation of crops, inputs applied and culturing practices followed have also to be quantified. The changes in soil affect the future productivity and thus provide a feedback mechanism to explore interactions between soil resources, cultivation technologies and environment.

A model developed by Nicolaas Konijn to explore these interactions: *A Crop Production and Environment Model for Long-Term Consequences of Agricultural Production*. is described by him in this paper.

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Food and Agriculture Program.

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1. Introduction

Most existing crop production models suffer from a lack of transferability. Too many changes are required to adapt a model to a different physical environment. This is often due to an inadequate selection of input characteristics that are supposed to describe the physical environment. The model described below attempts to overcome this problem, requiring only limited adaptations to be widely applicable. Most of the selected input characteristics, if not all, are usually available.

Such a model, sensitive to the input characteristics that describe the physical environment, offers at the same time the possibility of estimating the effect of a changing agricultural production environment on crop yields. Figure 1 visualizes the role of the Crop and Environment Model (C.E.M.) in relation to the changes in input characteristics because of agricultural production itself. There is a great variety of input characteristics that will determine the crop yield. Land classes are determined by a unique set of soil, site and climatic characteristics. Beside those characteristics there are the variable ones which are determined by farmer's decisions, which are mainly determined by the interpretation of the farmer of the economic situation. They comprise irrigation, fertilizer, and all kinds of other management characteristics. So for each land class there might be a considerable number of alternatives, each having its related yield, residue and environmental consequences.

Supposing that the decision model is able according to a certain criterion or certain criteria to choose among the generated alternatives, the chosen alternatives should then be entered into the updating procedure (resource adjustment module in Figure 1). Only the soil characteristics require updating in the model. Site characteristics such as slope characteristics are affected, but not to a measurable extent. Characteristics of the climate are supplied exogenously, and the effects of a growing crop and the changes in the soil on the climate are not considered. Other characteristics are influenced in the future in response to the present year's farmer-decision. This is modelled as part of a decision model which is described more fully in Reneau et al.(1981).

The crop production and environment model (C.E.M.) can also be used without the interference of a decision model. In that case the resource adjustment takes place immediately after the C.E.M. estimations, for no selection among alternatives is necessary. Instead, the production circumstances (e.g. type of rotation) are preset.

To be able to validate and apply the model as visualized in Figure 1, case studies on a regional level were selected. A regional level being areas of 10.000 to 100.000 km^2. They were intended to meet the requirements for both, the Crop and Environment Model and the Decision Model.

In the following sections we will describe the crop production module, the environment module and the procedure for updating the input characteristics that are affected by the modelled agricultural production.

More detailed information on the functioning of the model is available elsewhere: the required input characteristics are described in detail by Konijn (1983a), and the way the model functions with special reference to the UNIX System of the VAX 11/780 at IIASA is detailed in Konijn (1983b).

2. The Crop Production Module

In the crop production module we follow the structure of the Physical Crop Production Model of the Center for World Food Studies (1980). Moreover we employ many of the crop production/physical environment relationships on which that model is based. The majority of these relationships have been selected from the literature, where they have proved to be generally applicable.

The structure of the crop production model is shown in Figure 2. It has a hierarchical structure: production levels determined at a higher level can be progressively constrained at each of the lower levels. The model is of a mixed dynamic/static nature; estimations of photosynthetic dry matter production and the availability of water for plant growth are carried out per third of a month time period, while the effect of nutrients available for plant growth is evaluated on an annual basis.

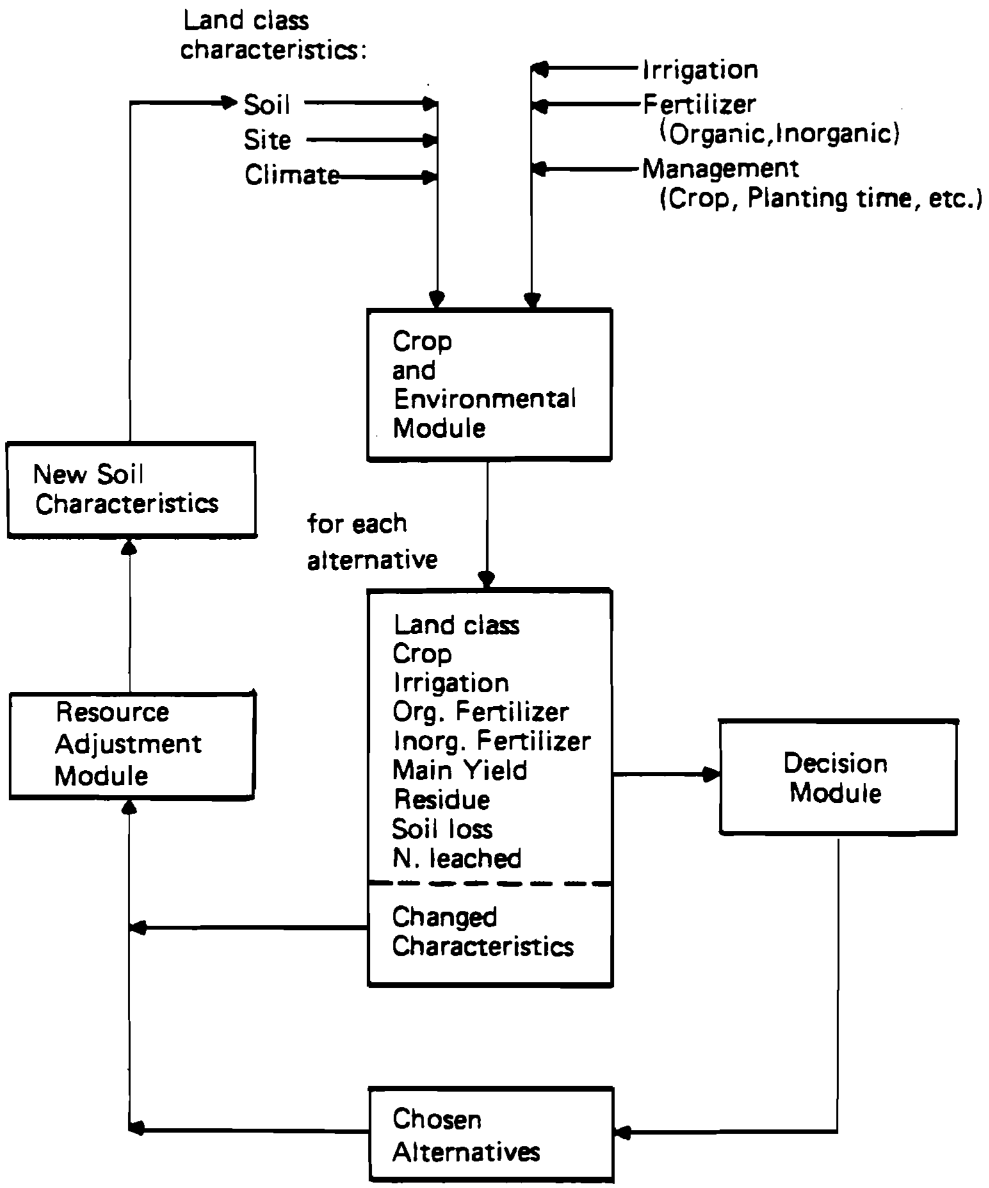

Figure 1. Relation between the various modules

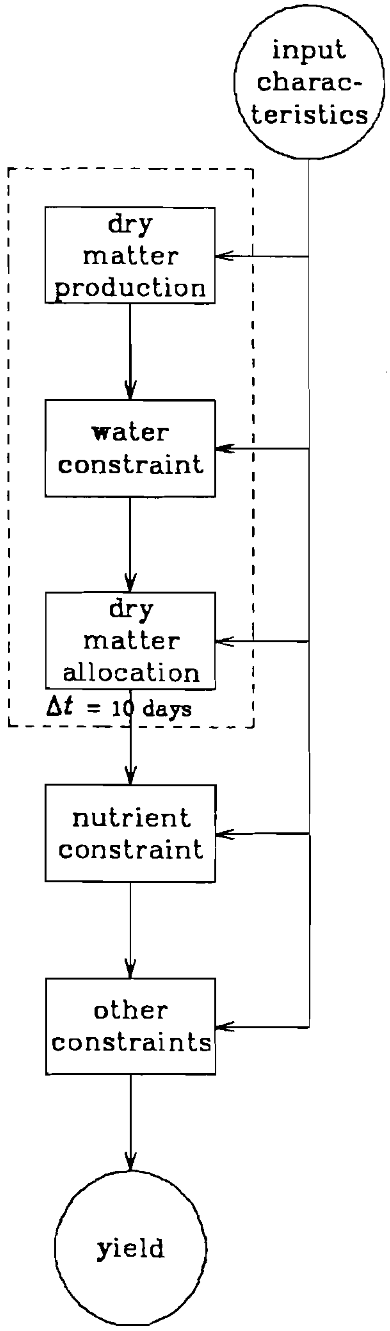

Figure 2. The Structure of the Crop Production Module

2.1. Dry Matter Production

Because of the pigments they contain plants are able to absorb visible light of wavelengths between 400 and 700 nanometers.[*] The accumulated energy is used in biochemical reactions during which carbon dioxide is absorbed by the plants through their stomata (photosynthesis). The products that stem from these reactions are necessary for plant life. Experiments have shown that the rate of photosynthesis can be expressed as a function of the absorbed radiation. The absorbed radiation forms a part of the global radiation that reaches the canopy, the global radiation being the sum of the direct solar radiation and the solar radiation that has been scattered in the earth's atmosphere (diffuse radiation). Global radiation is a frequently measured meteorological characteristic.

The following factors relate the global radiation to the absorbed radiation:

- The composition of the global radiation: cloudy days have relatively more diffuse radiation than clear days. Photosynthesis from diffuse radiation is relatively more efficient than from direct solar radiation, because diffuse light penetrates plant canopies more effectively.
- The inclination of the sun and the location of the place under consideration: these can be described by geometric equations. Information about the height of the sun is necessary, taking into account the annual course of the sun. These values are integrated over a daily time period, throughout the year.
- Canopy properties are also important. The leaf angle distribution can vary between horizontal and vertical, is crop specific and depends on the stage of crop growth.

The interception of light depends very much on the angle between light direction and leaf angle. The optical properties of leaves and the leaf arrangement in various layers also influence light absorption by plants.

De Wit (1965) related these aspects of radiation to the rate of photosynthesis in order to estimate photosynthetic dry matter production. He showed that the leaf angle distribution under normal conditions is negligible. Only for crops with an extremely high leaf area index, growing at low latitudes (tropical regions) is the effect of the leaf angle distribution significant. Such situations are rarely encountered and may be ignored.

At the end of the 1960's it was discovered that two main groups of plants with different photosynthetic pathways could be distinguished, one group being much more effective than the other in absorbing carbon dioxide (under normal carbon dioxide concentrations). This group of C-4 plants is characterized by the first detectable stable product formed when carbon dioxide is fixed: either malate or aspartate. The less effective plants belong to the C-3 group, which

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[*] 1 nanometer = 10^9 meter

have phospoglyceric acid as the first stable synthesized product after carbon dioxide fixation. Table 1a gives the daily total photosynthesis values for a C-3 crop with a spherical leaf distribution for the 15th of each month and at various latitudes, for a clear day as well as an overcast day. Table 1b shows the corresponding values for C-4 crops.

Photosynthesis, as we have said, also depends on the availability of carbon dioxide in the canopy. The consumption of carbon dioxide by plants will decrease its concentration in the canopy, a fact that has been observed by various investigators. In Evans (1963) for example, diurnal and annual cycles of carbon dioxide in canopies are reported. To maintain the rate of photosynthesis it is important that the exchange of CO_2 with the rest of the atmosphere is maintained at a sufficiently high level and this is a function of the wind speed. We assume that wind speeds exceeding 2 meters per second are sufficiently high to replenish the carbon dioxide in the crop canopy. In our case studies this value is usually surpassed. Should wind speed be restrictive, we have to see whether carbon dioxide produced by soil is able to replenish the CO_2 concentration in the canopy to a sufficiently high level.

Air temperature is not considered in the calculations of the CO_2 assimilation, since it has been shown that temperature over a wide range does not affect photosynthesis (De Wit, 1965, op.cit.).

To estimate dry matter production the values in Table 1 are used (from Goudriaan and Van Laar, 1978). Their table is an updated version of one produced by De Wit in 1965, incorporating additional information such as the above-mentioned distinction between C3 and C4 plant types.

Table 1 displays data on the daily gross dry matter assimilation for a closed canopy for several dates and for various latitudes. Dry matter production is given for a standard clear day and for a standard overcast day. This makes it possible to interpolate between these to suit specific circumstances, if adequate data exist. The values are expressed in kilograms of carbon dioxide per hectare ($kg\ CO_2 \cdot ha^{-1}$).

Before we start our calculations we have to replace Table 1 by a table showing ten-day values of gross daily dry matter production. Linear interpolation was adequate to produce a table of the following form:

$tab1_{j,k,\Delta t,m}$

$(j = 1,2;\ k = 1,8;\ \Delta t = 1,36;\ m = 1,2)$

where

j = type of plant (C3 or C4)
k = latitude, in grades from 0 ° till 80 °
Δt = 10 day period of the year, the first one being 1-10 January
m = overcast or clear day

Knowing the latitude of our case study area, xlat, we determine the dry matter production as follows:

Table 1a. Daily gross CO_2 assimilation of the closed canopy of a C-3 crop with a spherical leaf angle distribution (kgs CO_2/ha), for two standard sky conditions

North. lat.		15 jan.	15 feb.	15 mar.	15 apr.	15 may	15 jun.	15 jul.	15 aug.	15 sep.	15 oct.	15 nov.	15 dec.
0.	Cl	623.	642.	654.	648.	630.	616.	622.	641.	654.	648.	629.	616.
0.	Ov	293.	305.	312.	309.	297.	289.	292.	304.	312.	309.	297.	289.
10.	Cl	560.	600.	638.	664.	670.	669.	670.	669.	652.	616.	572.	549.
10.	Ov	259.	282.	304.	318.	320.	318.	319.	320.	311.	291.	266.	252.
20.	Cl	486.	545.	610.	668.	699.	711.	707.	684.	637.	570.	503.	469.
20.	Ov	217.	250.	286.	318.	334.	340.	338.	327.	301.	264.	227.	208.
30.	Cl	396.	475.	566.	657.	716.	742.	732.	686.	607.	510.	419.	375.
30.	Ov	169.	211.	260.	309.	341.	353.	349.	325.	282.	230.	181.	159.
40.	Cl	294.	389.	507.	633.	721.	763.	747.	676.	562.	433.	321.	270.
40.	Ov	117.	164.	225.	292.	339.	360.	352.	315.	254.	187.	130.	105.
50.	Cl	183.	288.	429.	593.	716.	776.	753.	652.	499.	339.	211.	158.
50.	Ov	63.	112.	181.	265.	329.	359.	348.	296.	217.	137.	76.	51.
60.	Cl	66.	175.	333.	536.	704.	790.	756.	615.	417.	230.	98.	38.
60.	Ov	15.	57.	130.	229.	312.	354.	338.	268.	170.	81.	25.	8.
70.	Cl	0.	45.	220.	467.	699.	846.	784.	572.	318.	109.	0.	0.
70.	Ov	0.	10.	72.	184.	293.	357.	331.	234.	116.	27.	0.	0.

Cl = Clear day
Ov = Overcast day
Source: Goudriaan and Van Laar (1978).

Table 1b. Daily gross CO_2 assimilation of the closed canopy of a C-4 crop with a spherical leaf angle distribution (kgs CO_2/ha), for two standard sky conditions

North. lat.		15 jan.	15 feb.	15 mar.	15 apr.	15 may	15 jun.	15 jul.	15 aug.	15 sep.	15 oct.	15 nov.	15 dec.
0.	Cl	894.	926.	946.	937.	906.	883.	892.	925.	947.	937.	904.	883.
0.	Ov	321.	336.	345.	341.	327.	316.	321.	335.	345.	341.	326.	316.
10.	Cl	796.	859.	920.	960.	967.	964.	966.	966.	941.	884.	815.	777.
10.	Ov	282.	309.	335.	351.	353.	350.	352.	353.	344.	320.	290.	274.
20.	Cl	680.	773.	873.	963.	1010.	1027.	1021.	988.	915.	812.	707.	654.
20.	Ov	234.	272.	314.	351.	369.	375.	373.	361.	332.	289.	245.	224.
30.	Cl	543.	663.	803.	942.	1032.	1070.	1056.	987.	865.	716.	576.	511.
30.	Ov	180.	227.	283.	340.	376.	390.	385.	358.	309.	248.	194.	168.
40.	Cl	389.	529.	707.	898.	1033.	1095.	1071.	964.	790.	595.	427.	354.
40.	Ov	122.	174.	242.	318.	372.	396.	387.	344.	275.	199.	137.	109.
50.	Cl	227.	377.	584.	829.	1014.	1104.	1069.	918.	688.	451.	266.	192.
50.	Ov	64.	116.	193.	286.	358.	393.	379.	320.	232.	144.	78.	52.
60.	Cl	71.	212.	437.	733.	980.	1107.	1057.	850.	558.	289.	107.	40.
60.	Ov	15.	58.	135.	244.	336.	383.	365.	287.	180.	84.	25.	8.
70.	Cl	0.	47.	268.	615.	948.	1151.	1066.	766.	403.	119.	0.	0.
70.	Ov	0.	10.	74.	193.	311.	381.	353.	247.	120.	28.	0.	0.

Cl = Clear day
Ov = Overcast day
Source: Goudriaan and Van Laar (1978)

Table 2. Daily total photosynthetic active radiation for a standard clear day

North. lat.	15 jan.	15 feb.	15 mar.	15 apr.	15 may	15 jun.	15 jul.	15 aug.	15 sep.	15 oct.	15 nov.	15 dec.
0.	334.	351.	362.	357.	340.	329.	333.	350.	362.	357.	340.	329.
10.	290.	321.	350.	368.	369.	366.	368.	370.	360.	333.	300.	282.
20.	239.	280.	326.	367.	387.	393.	391.	378.	346.	298.	251.	227.
30.	181.	230.	291.	353.	393.	409.	403.	373.	319.	253.	195.	168.
40.	121.	174.	246.	328.	386.	413.	402.	356.	282.	200.	135.	107.
50.	62.	115.	193.	291.	368.	406.	392.	328.	234.	142.	76.	50.
60.	15.	56.	133.	245.	342.	392.	372.	290.	178.	82.	24.	8.
70.	0.	9.	71.	191.	312.	384.	354.	245.	117.	26.	0.	0.

All values in $\mathrm{cal \cdot cm^{-2} \cdot day^{-1}}$

Source: Goudriaan and Van Laar (1978).

Table 3. Soil Texture and Soil Parameters

Soil texture	porosity %	k_0 $\mathrm{cm \cdot day^{-1}}$	γ
coarse sand	39.5	1120	0.1
fine sand	36.4	50	0.0288
loamy fine sand	43.9	26.5	0.0312
sandy loam	46.5	16.5	0.0264
silt loam	50.9	6.5	0.0185
loam	50.3	5.0	0.0180
clay loam	44.5	0.98	0.0058
light clay	45.3	3.5	0.0085
basin clay	54.0	0.22	0.0042

Source: Centre for World Food Studies (Personal Communication)

$$\mathrm{dm}_{j,\Delta t,m} = (\mathrm{tab}_{j,k1,\Delta t} - \mathrm{tab1}_{j,k1+10,\Delta t}) \cdot (\mathrm{xlat} - \mathrm{k1})/10 + \mathrm{tab1}_{j,k1+10,\Delta t} \qquad (1)$$

$(j = 1,2;\ \Delta t = 1,36;\ m = 1,2)$

with

dm = gross daily dry matter production, kg $CO_2 \cdot ha^{-1} day^{-1}$
k1 = latitude, so that $k1 \leq xlat$ and $k1+10 > xlat$
j, Δt, m = see above

For the estimation of the potential dry matter production, that is the dry matter production based on global radiation, an interpolation between the production on a clear day and on an overcast day has to be carried out. The radiation on an overcast day is assumed to be one fifth of the radiation of a standard clear day.

$$\mathrm{pdm}_{j,\Delta t} = (\mathrm{dm}_{j,\Delta t,m1} - \mathrm{dm}_{j,\Delta t,m2}) \cdot (\mathrm{globra}_{1,\Delta t} - 0.2 \cdot \mathrm{cleard}_{1,\Delta t}) + \mathrm{dm}_{j,\Delta t,m1} \qquad (2)$$

where

pdm = potential dry matter production, kg $CO_2 \cdot ha^{-2} \cdot day^{-1}$
globra = value for global radiation, cal $\cdot cm^{-2} \cdot day^{-1}$
cleard = standard radiation value for a clear day, cal $\cdot cm^{-2} \cdot day^{-1}$
m1 = overcast day
m2 = clear day
j, Δt = as before

For these calculations we need to know the radiation value for a standard clear day. Table 2 presents data on a standard clear day radiation for each month and latitude interpolation can be applied accordingly as for Table 1:

$$\mathrm{cleard}=(\mathrm{tab2}_{k1,\Delta t} - \mathrm{tab2}_{k1+10,\Delta t}) \cdot (\mathrm{xlat} - \mathrm{k1})/10 + \mathrm{tab2}_{k1+10,\Delta t} \qquad (3)$$

(symbols as Eq. (1) and (2)))

Tables 1 and 2 are for the northern hemisphere. For the southern hemisphere the year starts with July instead of January.

2.2. Water Constraint on Dry Matter Production

Few areas are never affected by drought. Precipitation patterns change from year to year and even within a year during the cropping season shortage of water may restrict yields. Prediction of precipitation and yield can only be based on statistical interpretation of collected data.

We will work under the assumption that plant transpiration is proportional to the CO_2 assimilation of plants. This means that if transpiration drops because of a decrease in atmospheric demand for water or because of restrictions in plant available water in the soil, the dry matter production will drop as well.

To determine the availability of water for plants the water balance can be expressed as follows:

$$S_{t+\Delta t,l,c} = S_{t,l,c} + P_{\Delta t,l} + I_{\Delta t,l,c} - E_{\Delta t,l,c} - R_{\Delta t,l,c} - D_{\Delta t,l,c} \qquad (4)$$

$(t = 1,36;\ l = 1,l;\ c = 1,c)$

where

S = soil moisture content of the root zone, cm
P = precipitation, cm
I = irrigation, cm
E = evapotranspiration, cm
R = runoff, cm
D = drainage, cm
l = land class, the number of land classes depending on the case study
c = crop
Δt = time period

The water balance determines the soil moisture content at the end of the time period Δt given the initial moisture content and quantities of the other variables for the time period concerned. Each of the components of the water balance is described below.

2.2.1. Soil Moisture Content (S)

The soil moisture content is an important element in the calculation of the water balance. It is related to soil moisture tension which expresses the energy status of the water in the soil. It tells us whether or not water is available for plants. If the tension reaches a certain critical value, Ψ_{cr}, the plant closes its stomata and transpiration will be reduced. This critical value varies with type of crop.

The following equation describes the relationship between moisture content and moisture tension.

$$\Psi = e^{(\gamma^{-1} \cdot \ln \frac{v_0}{v_\Psi})^{\frac{1}{2}}} \tag{5}$$

with

Ψ = soil moisture tension, cm H_2O
v_0 = maximum soil moisture content, which is equal to the soil porosity, volumetric %
v_Ψ = soil moisture content, vol. %
γ = soil specific parameter

The gamma (γ) is soil specific constant. It can be determined by regression analysis of the soil moisture tension and soil moisture content. Values for γ are given in Table 3, and observations in the Netherlands suggest that soil texture is a good indicator of soil moisture characteristics (P.M.Driessen, personal communication). To convert from soil moisture tension to moisture content we may need:

$$v_\Psi = v_0 \cdot e^{-\gamma \cdot \ln^2 \Psi} \tag{6}$$

symbols as before

It should be noted that the water balance applies to the rooting zone such that:

$$S = v_\Psi \cdot rd \tag{7}$$

where

S = soil moisture content, cm.

rd = rooting zone depth, cm.

Rooting development and rooting depth are crop specific, one reason why some crops are more drought resistant than others. In the model rooting depth depends on the stage of crop development.

2.2.2. Precipitation (P)

Standard precipitation data are required as one component of the water balance. The interception of precipitation by the crop is taken into account while estimating the runoff.

2.2.3. Irrigation (I)

Under certain climatic conditions irrigation water is required for optimal plant growth. The model responds to the following input variables:

- the amount of available water over the whole growing season
- the amount of water available at the time of application
- a soil water content threshold value below which irrigation is required
- the kind of irrigation system
- the efficiency of the irrigation

At present our interest lays only in the irrigation efficiency after the water has reached the field. Efficiency in the field is mainly determined by the type of irrigation and the soil type, assuming ideal management by the farmer.

2.2.4. Evapotranspiration (E)

Evaporation from a free water surface can be approximated by the Penman-formula (Penman, 1948):

$$E_{ws} = \frac{\frac{\Delta}{\gamma} \cdot \frac{R_n - G}{L} + (e_s - e_a) \cdot f(u)}{\frac{\Delta}{\gamma} + 1} \qquad (8)$$

where

E_{ws} = evaporation from a free water surface, cm $\cdot$day^{-1}

R_n = net radiation, cal $\cdot$cm^{-2} $\cdot$day^{-1}

G = soil heat flux, cal $\cdot$cm^{-2} $\cdot$day^{-1}

Δ = rate of change of the saturation vapor pressure with temperature, mbar $\cdot$°C^{-1}

γ = psychrometric coefficient, °C $\cdot$mbar^{-1}

e_s = saturation vapor pressure, mb

e_a = actual vapor pressure, mb

$f(u)$ = wind speed function, m $\cdot$sec^{-1}

L = latent heat of vaporization of liquid water, cal $\cdot$gm^{-1}

The soil heat flux is negligible over the 10-day model time steps. The saturation vapor pressure at air temperature (T) can be determined with the following equation (Goudriaan, 1977):

$$e_s = 6.11 \cdot e^{\frac{17.4\,T}{T+239}} \tag{9}$$

with

T = air temperature, centigrade

The slope of saturation vapor pressure (Δ) curve can be estimated by:

$$\Delta = \frac{25409}{(T + 239)^2} \cdot e^{\frac{17.4T}{T + 239}} \qquad 10)$$

(the symbols before)

The net radiation can be measured directly, but this is not often done. However, because of derived empirical relationships, related measurements can help us in determining the net radiation. Angström (1924) related the hours of sunshine to the solar radiation, while Prescott (1940) gave this relationship more practical applicability by replacing standard clear day radiation by extra-terrestrial radiation. Excluding reflection and longwave terms, this relationship can be expressed as:

$$R_n = R_a \cdot (1 - r) \cdot (a + b \cdot \frac{n}{N}) - lw \tag{11}$$

where

R_a = extra terrestrial radiation or angot-value, cal $\cdot cm^{-2} \cdot day^{-1}$
r = reflection of water surface
a,b = climate dependent constants
n = actual hours of sunshine, hr
N = max. possible hours of sunshine, hr.
lw = longwave radiation, cal $\cdot cm^{-2} \cdot day^{-1}$

The long wave radiation (lw) lost by the earth surface can be approximated by:

$$lw = \sigma \cdot (T + 273.2)^4 \cdot (c - d \cdot \sqrt{e_a}) \cdot (e + f \cdot \frac{n}{N}) \tag{12}$$

with

σ = Stefan-Boltzmann constant ($11.69 * 10^{-8} \cdot cal \cdot cm^{-2} \cdot {}^\circ C^{-4} \cdot day^{-1}$)
e_a = actual vapor pressure, mbar
c,d,e & f = climate dependent constants

This procedure for estimating net radiation requires measurements of vapor pressure and hours of sunshine. If the hours of sunshine are replaced by observations of global radiation, increased accuracy can be expected.

In situations with agricultural production at altitudes considerably different from sea level, a correction for the psychrometric coefficient will be necessary:

$$\gamma = \frac{c_p \cdot P_h}{L \cdot \varepsilon} \tag{13}$$

where

c_p = specific heat of air at constant pressure cal $\cdot gm^{-1} \cdot mbar^{-1}$
p_h = air pressure at altitude h, mbar
L = latent heat of vaporization, cal $\cdot gm^{-1}$
ε = ratio of molecular weight of water over molecular weight of air, i.e. mixed ratio

The atmospheric pressure at altitude h can be determined by the altimeter equation:

$$p_h = p_o \cdot e^{\frac{-gh}{RT}} \tag{14}$$

where

g = gravitational acceleration,m $\cdot sec^2$
p_o = barometric pressure at sea level, mbar
R = gas constant, J $\cdot mol^{-1} \cdot {}^\circ C^{-1}$
h = altitude, meters above sea level

To calculate the potential evapotranspiration (E_p) the reflection of a water surface (equation 11) should be replaced by the reflection for a crop canopy. Although the reflection may change from crop to crop, an adequate representative value is 0.25 (Monteith,1973).

Potential evapotranspiration can be converted to crop evapotranspiration by:

$$E = kc_{c,s} \cdot E_p \tag{15}$$

with

E = crop evapotranspiration
kc = crop coefficient
c = crop
s = stage of crop development

The crop coefficient (kc) depends mainly on the stage of crop development. Values for different types of crops at their different stages are taken from FAO (1977).

2.2.5. Runoff (R)

Not all the precipitation becomes runoff, because of the recharge capacity of the soil. The recharge capacity or retention is determined by:

- the interception of rainfall by crop cover
- the ponding on the soil surface because of limited infiltration and irregularities on the surface.
- amount of water intake by the soil.

The part of the infiltration in excess of the minimum infiltration (Table 4), the interception by the crop cover, and the ponding together form what is known as the initial abstraction.

The relationship between runoff (R) and precipitation (P) is illustrated if Figure 3 and may be expressed as follows (Soil Conservation Service, 1964):

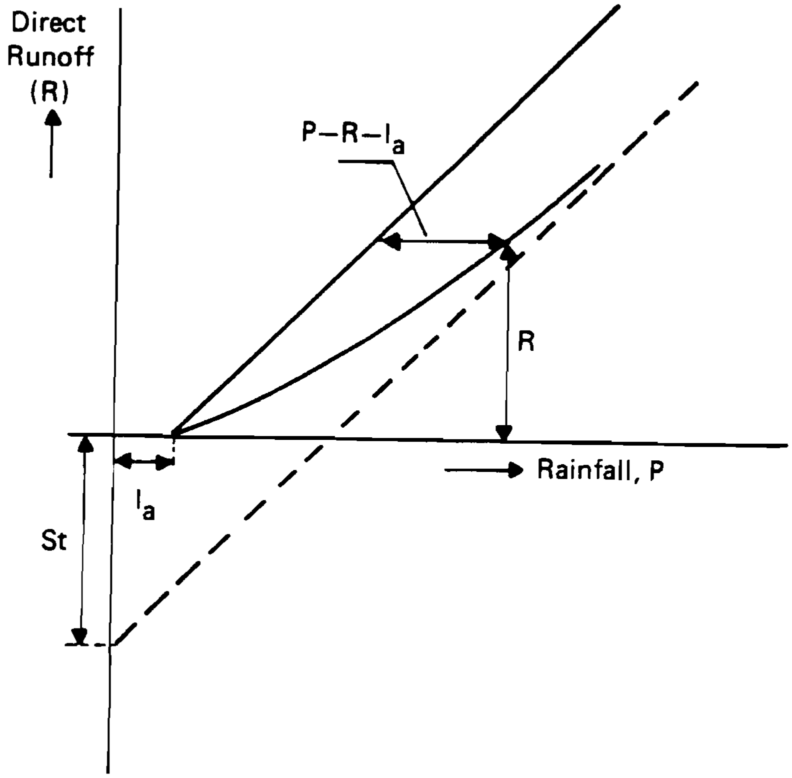

Figure 3. Rainfall/Runoff relationship

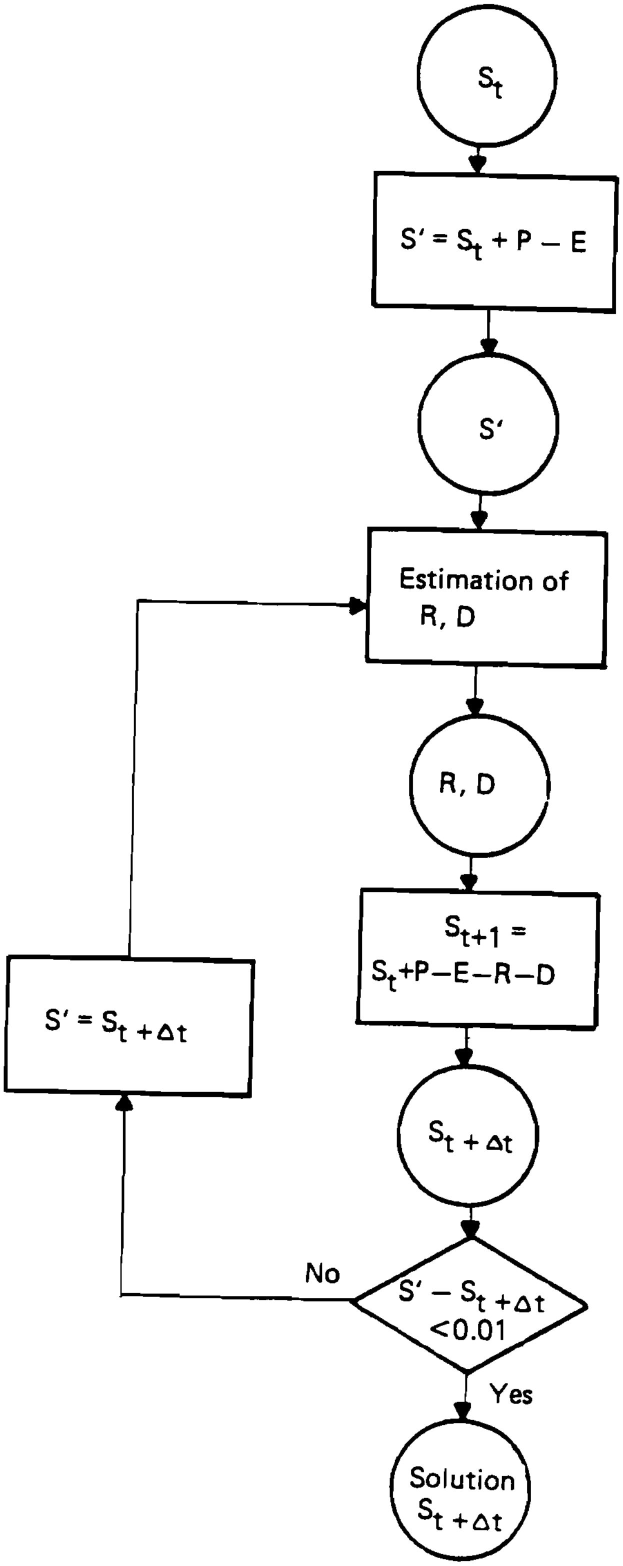

Figure 4. Schematic presentation of the water balance estimation

Table 4. Curve Number for Various Minimum Infiltration Cover-Combinations.

Cover			Minimum Infiltration cm/hr			
land use	treatment or practice	hydrologic condition	0.95	0.6	0.25	0.06
fallow	straight row	—	77	86	91	94
row crops*	straight row	poor	72	81	88	91
row crops*	straight row	good	67	78	85	89
row crops*	contoured	poor	70	79	84	88
row crops*	contoured	good	65	75	82	86
row crops*	contoured & terraced	poor	66	74	80	82
row crops*	contoured & terraced	good	62	71	78	81
small grain**	straight row	poor	65	76	84	88
small grain**	straight row	good	63	75	83	87
small grain**	contoured	poor	63	74	82	85
small grain**	contoured	good	61	73	81	84
small grain**	contoured & terraced	poor	61	72	79	82
small grain**	contoured & terraced	good	59	70	78	81
close	straight row	poor	66	77	85	89
seeded	straight row	good	58	72	81	85
legumes	contoured	poor	64	75	83	85
or	contoured	good	55	69	78	83
rotation	contoured & terraced	poor	63	73	80	83
meadow	contoured & terraced	good	51	67	76	80
pasture		poor	68	79	86	89
or		fair	49	69	79	84
range		good	39	61	74	80
pasture	contoured	poor	47	67	81	88
or	contoured	fair	25	59	75	83
range	contoured	good	6	35	70	79
meadow		good	30	58	71	78
woods		poor	45	66	77	83
		fair	36	60	73	79
		good	25	55	70	77

* maize, sorghum, soybeans, sugarbeets
** wheat, oats, barley, flax

Source: U.S. Soil Conservation Service (1972)

$$R = \frac{(P - I_a)^2}{P - I_a + St} \tag{16}$$

where

R = actual runoff, cm

P = precipitation, cm

St = recharge capacity, cm

I_a = initial abstraction

The maximum recharge capacity, St_{max}, will be reached if the soil is in a dry condition. This maximum retention can be estimated from the so called curve number (cn) for a dry soil condition.

$$St_{max} = \frac{1000}{cn-10} \tag{17}$$

The curve numbers have been experimentally determined and Table 4 shows their value for various surface conditions. For a given soil it is the minimum infiltration, in addition to its land use that co-determine the curve number. The kind of land use also influences the curve number; a "good" rotation is one with at least 2 years of meadow out of 4 years, and a "poor" one, has no meadow at all in the rotation (Table 4). Knowing the soil porosity and the actual soil moisture content, we are able to calculate the actual recharge capacity (St):

$$St = St_{max}\,(v_o - v_\Psi) \tag{18}$$

(symbols as before)

Finally we need to know the initial abstraction I_a. This value is normally close to 0.2 (Soil Conservation Service, 1964), but it may be useful to validate this by means of locally collected data.

2.2.6. Drainage (D)

If the soil moisture content reaches a level such where capillary forces are no longer able to withhold the water against the gravitational force, drainage will take place. This will happen if the moisture content is greater than field capacity. Profiles with a deep ground water level reach field capacity at a soil moisture tension of approximately $\frac{1}{3}$ bar. Thus whether drainage takes place or not can be described by:

$$S_t + P - R > \frac{v_{fc} \cdot rd}{100} \tag{19}$$

where

S = initial soil moisture content in root zone, cm

P = precipitation, cm

R = runoff, cm

v_{fc} = soil moisture content at field capacity, vol%
rd = root zone depth, cm

However, over the period concerned, evapotranspiration will also occur thus reducing the possible drainage, giving:

$$D = S + P - R - v_{fc} \cdot rd - 0.5 \cdot E \tag{20}$$

If $D \leq 0$ no drainage will take place.

2.2.7. Solving the Water Balance

The water balance is solved per land class (l) and per crop (c). Three different periods of crop production are recognized: a pre-crop period, the cropping period and the post-crop period. The first- and last-mentioned periods require slightly different methods of solving the water balance. However, basically in each period we solve the water balance per 10 day intervals. We first describe the water balance during the cropping season.

2.2.7.1. Water Balance during the Crop Season

Solving the water balance gives us the soil moisture content at the end of the time interval concerned. This value serves as the initial value for the next time interval.

One complicating factor is that we need to know the end moisture content beforehand in order to be able to estimate the value of the drainage and runoff terms in the balance. For the evapotranspiration we need to know $S_{t+\Delta t}$ only if the critical value, Ψ_{cr}, that will restrict water uptake by plants is surpassed.

If $\Psi < \Psi_{cr}$ we solve the water balance as is shown by the flow chart of Figure 4. Giving an initial soil moisture content, we make a first approximation of $S_{t+\Delta t}$, which is called S'. With this value we estimate the drainage and runoff. This enables us to improve the $S_{t+\Delta t}$ value. If the last value still differs considerably from S' we replace it and go through the calculations again.

If, during the time interval concerned, Ψ becomes greater than Ψ_{cr}, then we have to split our time interval (Δt) into two parts. Therefore we have to know the critical moisture content Ψ_{cr}. This value is crop dependent, some crops show wilting at lower soil moisture tensions than others. In the following equation we estimate the fraction of the total amount of available water at which stomatal closure will reduce evapotranspiration (F.A.O., 1979).

$$\begin{aligned} pt = p5 \cdot (3.05 - 0.577 \cdot Ep - 2.216 \cdot p5 + 0.0523 \cdot Ep^2 + 0.1766 \cdot Ep \cdot p5 \\ + 3.33 \cdot p5^2 - 0.0014 \cdot Ep^3 - 0.0289 \cdot Ep^2 \cdot p5 + 0.322 \cdot Ep \cdot p5^2 \\ - 0.3778 \cdot p5^3) \end{aligned} \tag{21}$$

where

pt = fraction of available water
p5 = fraction of available water at standard value
Ep = potential evapotranspiration, mm $\cdot \mathrm{day}^{-1}$

Table 5 shows the standard values for p5 of various crops. The critical soil moisture content can be estimated as follows:

$$v_{cr} = pt \cdot (v_{fc} - v_{pwp}) \tag{22}$$

and the critical soil moisture tension, from (5) is :

$$\Psi_{cr} = e^{(\gamma^{-1} \cdot \ln \frac{v_o}{v_{cr}})^{\frac{1}{2}}} \tag{23}$$

with

v_{fc} = soil moisture content at field capacity
v_{pwp} = soil moisture content at permanent wilting point
v_{cr} = critical soil moisture content
Ψ_{cr} = critical soil moisture tension

With Ψ_{cr} known we can calculate the part of time interval Δt required to reach that value:

$$S_{t+\delta,l,c} = S_{t,l,c} + P_{\delta,l,c} - E_{\delta,l,c} - R_{\delta,l,c} - D_{\delta,l,c} \tag{23}$$

$$S_{t+\Delta t,l,c} = S_{t+\delta,l,c} + P_{\Delta t-\delta,l,c} - E_{\Delta t-\delta,l,c} - D_{\Delta t-\delta,l,c} \tag{24}$$

where

Δt = the original time interval
δ = time interval at which the critical soil moisture is reached
(other symbols as in Eq. 4)

2.2.7.2. Water Balance during Pre- and Post-Crop Periods.

We follow the calculation procedure described above, however the evapotranspiration should be replaced by the evaporation when no crop is grown. The estimation of the evaporation has been described in section 2.2.4.

2.2.8. Dry Matter Production with Water as a Constraint

By solving the water balance we obtain values for evapotranspiration per time interval:

$E_{\delta,l,c}$, $E_{\Delta t-\delta,l,c}$ and/or $E_{\Delta t,l,c}$

Only if those values are equal to the potential evapotranspiration is potential dry matter production possible. When real evapotranspiration shows plants to be water stressed then dry matter production will be reduced. The reduction in production will be proportional to the reduction in evapotranspiration.

$$wdm_{l,c,\Delta t} = pdm_{j,\Delta t} \cdot \left[\frac{E_{\delta,l,c} + E_{\Delta t-\delta,l,c}}{Ep_{\Delta t,l,c}} \right] \quad \text{for} \quad 0 \leq \delta < \Delta t \tag{26}$$

where

wdm = dry matter production including water constraint, kg $\cdot ha^{-1}$
pdm = potential dry matter production, kg $\cdot ha^{-1}$
E = real evapotranspiration
$\delta, \Delta t$ = time interval
j = type of plant
l = land class
c = crop

2.3. From Dry Matter to Plant Material

The dry matter production is composed of a great variety of components that can be chemically distinguished. We have already expressed the photosynthetically produced assimilates as kg CO_2 per ha. In order to make a chemical distinction, the dry matter term is reexpressed as a quantity of carbon dioxide, and we consider plant material to be a product of the physiological functioning of the plant. This functioning includes the allocation of the dry matter between the various plant organs, respiration and conversion of the fixed carbon dioxide during plant growth.

2.3.1. Respiration and Conversion of Dry Matter.

In order to maintain a functioning metabolism during growth, plants must respire, a process involving the consumption of a proportion of the stored assimilates. The rate of respiration is dependent on temperature, being about 1.5% of the standing dry matter at 25 °C. The respiration rate approximately doubles with an increase in temperature of 10 °C ($Q_{10} \sim 2$).

During growth the fixed carbon dioxide is converted to chemical compounds such as carbohydrates, proteins and lignin. The efficiency of the conversion is independent of temperature and values for this efficiency are given in Table 6 (Penning de Vries, 1975). In this table the photosynthesis substrate has been expressed in grams of glucose ($C_6H_{12}O_6$), requiring the conversion from carbon dioxide to glucose. The production in plant material is described in the following way:

$$wpm_{l,c,\Delta t} = com_c \cdot (wdm_{l,c,\Delta t} - maint_c \cdot wdm_{l,c,t}) \qquad (27)$$

where

wpm = produced plant material kg $\cdot ha^{-1}$
com = efficiency of conversion from dry matter to plant material
wdm = dry matter production after water constraints, kg $\cdot ha^{-1}$
maint = respiration coefficient
t = $\sum \Delta t$

2.3.2. Allocation of Dry Matter over Plant Organs

The distribution of plant material between the various plant organs is dependent on the stage of crop development (Figure 5).

The distribution ratios are specified after the conversion into the various plant compounds has taken place. We may describe the allocation by:

Table 5. Standard Values for Fraction of Available Water for some Crops

Crops	p5
spinach	0.2
peppers	0.25
lettuce	0.3
clover	0.35
groundnut	0.4
sunflower	0.45
maize	0.5
wheat	0.55
sorghum	0.60
sugarcane	0.65
sisal	0.8

Source: FAO 1977. Crop water requirements. FAO irrigation and drainage paper No. 24.

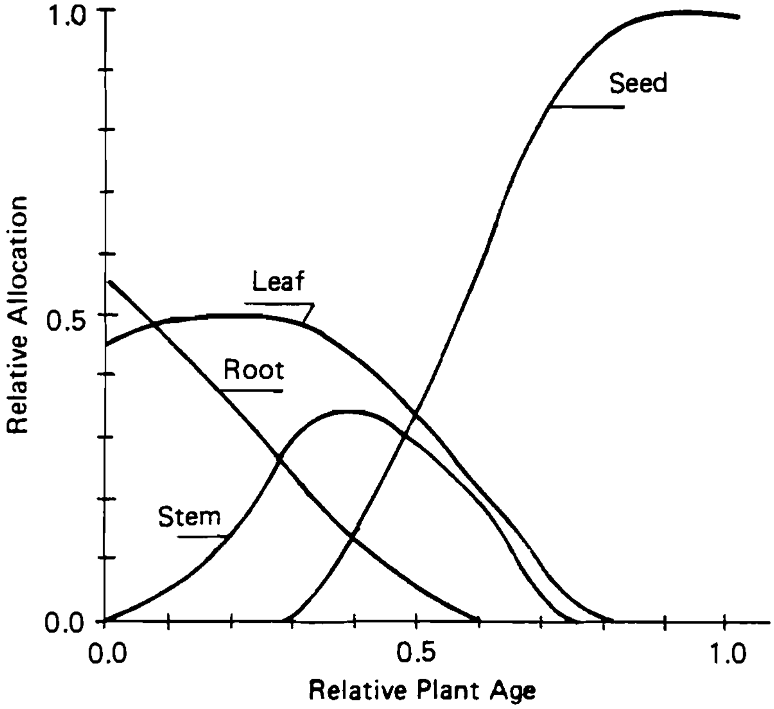

Figure 5. Relative partioning over plant organs

Table 6. Values for the Conversion of Glucose into the Main Chemical Fractions of Plant Material.

Chemical Fraction	gr product/gr CH_2O
Nitrogenous compounds (normal mix of amino acids, proteins and nucleic acids)	
from NO_3^-	0.404
from NH_3	0.616
Carbohydrates	0.826
Organic acids	1.104
Lignin	0.465
Lipids	0.330

Source: Penning de Vries (1975)

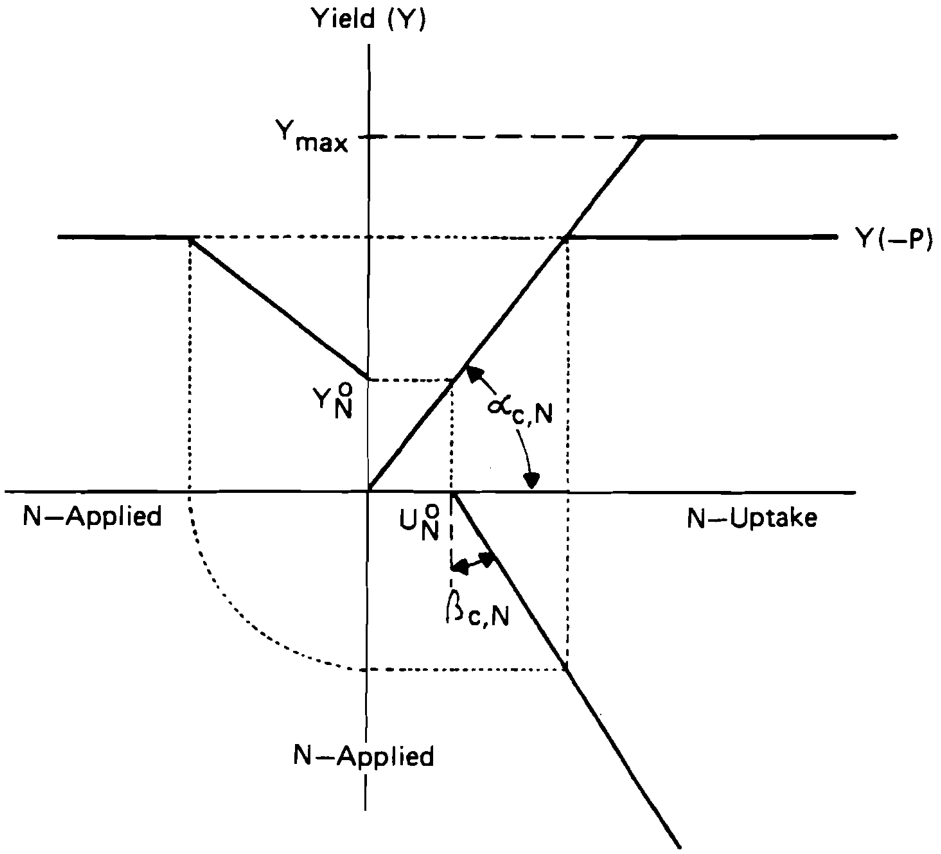

Figure 6. Graphical presentation of response to chemical fertilizers

$$wpm_{j,l,c,\Delta t} = wpm_{l,c,\Delta t} \cdot alloc_j \tag{28}$$

with

alloc= relative allocation factor
j = plant organ
(other symbols as before)

2.4. The Nutrient Constraint

While estimating the effect of water availability on the yield we assumed that no plant nutrients were limiting to growth. However, many nutrients are essential for plant growth and their depletion or absence may restrict plant production. The reason may be imbalanced soil nutrient availability or simply a nutrient deficiency.

In general nitrogen and phosphorus are the most widespread deficient nutrients. Because of the relatively large amount of these nutrients required, commercial fertilizers are needed to replenish the nutrients taken away when the marketable product is removed. The soil itself is usually not able to mineralize sufficient nutrients from organic matter or through weathering of soil minerals to replenish losses.

In some situations potassium may limit growth as well, but potassium requirements are more site- and crop-specific. We first describe the effect of nutrition on plant growth (2.4.1) and then we emphasize the role of organic matter, by describing how decay of organic matter takes place and how it supplies nutrients (2.4.2).

2.4.1. Soil Fertility and Response to Soil Fertilization

The effect of nutrients on crop yields is shown in Figure 6 (van Keulen, 1982). The top-right hand quadrant shows the relation between nutrient uptake and the marketable yield. The yield/nutrient uptake ratio (α) is approximately constant and is determined by the crop and the nutrient concerned.

If no fertilizers are applied the yield (Y^o) depends on the nutrient status of the soil; U_N^o is the amount of nutrient mineralized from the organic matter. The maximum yield can only be reached through the application of organic and/or inorganic fertilizers.

The bottom-right hand quadrant of Figure 6 shows the relationship between the nutrient uptake and the applied nutrient. This relation is determined by the efficiency of the fertilizer (β). This efficiency depends on the chemical properties of the fertilizer, the way it is applied, and the behavior of the fertilizer in the soil. The crop itself has a role as well, because the rate of growth of the roots and the root distribution through the soil codetermine how efficiently the nutrients are taken up.

In the top-left hand quadrant of Figure 6 we find a direct relation between the fertilizer applied and the yield. This is the conventional way of presenting fertilizer trial information.

We can express the response to fertilizers as follows:

$$Y_F = Y_F^o + \alpha_{c,F} \cdot \beta_{c,F} \cdot V_F \tag{29}$$

with

Y = marketable yield, kg $\cdot$ha^{-1}
Y^o = yield based on natural fertility, kg $\cdot$ha^{-1}
V = amount of fertilizer applied, kg $\cdot$ha^{-1}
α = nutrient uptake coefficient
β = fertilizer efficiency coefficient
c = crop variety
F = kind of fertilizer

One of the oldest concepts in soil fertilization states that no response to a fertilizer is possible if another nutrient limits the production. Although some contradictory evidence exists we will apply the concept here, being convinced that it describes reality well enough. Combining this with the characteristics already mentioned, namely plant composition, uptake of nutrients and the efficiency of fertilizers gives us a rather simple description of response to nutrients, expressed as a minimum law:

$$Y_F = \min \left[Y_F^0 + \alpha_{c,F} \cdot \beta_{c,F} \cdot V_F \right] \tag{30}$$

$$F = N, P, K$$

Knowledge about the fertilizer efficiency coefficient and soil analysis are crucial in the determination of the response to fertilizers. The kind of data required for their determination are described elsewhere (Konijn, 1983a)

2.4.2. Organic Matter Decay

Among the solid parts of the soil, organic matter undergoes the quickest transformations. The rates of the transformations are such that their effects are noticeable even within the cropping season. They operate concurrently with the mineralization and fixation of plant nutrients, of which nitrogen is by far the most important. But the role of organic matter is not restricted to the chemical fertility of the soil. Changes in organic matter content bring about changes in structural stability and affect the soil moisture characteristics of the soil. The latter will be dealt with when we describe the resource adjustment; here we restrict ourselves to the "weal and woe" of the organic matter as has been developed by P. Driessen (CWFS, Wageningen, personal communication)

Due to the heterogeneity of the organic matter, six fractions have been distinguished. They are assumed to be universal: proteins, sugars, cellulose, lignin, humic substances and inert material. Each of them is subject to decay because of their use as nutrient and energy source by the various soil organisms. The rate of change of decay is a function of the amount of material in the particular fraction:

$$\frac{dfr_j}{dt} = -k \cdot fr_j \tag{31}$$

with

fr = amount in fraction
k = coefficient of decay
j = the fraction

The coefficient of decay will however change with time. This is due to the change in heterogeneity (q) of each of the fractions.

$$\frac{dk_j}{dt} = -q \cdot k_j \tag{32}$$

Values for heterogeneity and decay rates are given in Table 7. The rate of decay is also affected by the soil environment: soil acidity, soil temperature and soil moisture content. Moreover, the quality of the organic matter, which is determined by the carbon/nitrogen ratio (C/N-quotient), plays a role. Each factor may cause a reduction in decay rate, the most limiting determines the actual rate of decay.

$$k(ac)_j = rc \cdot k_j \tag{33}$$

with

k(ac)= actual decay rate
rc = reduction factor
j = fraction

The transformations of organic matter are schematized in Figure 7. Each of the fractions follows the conversions illustrated and the rates of those conversions are controlled by the above-mentioned factors affecting decay rate. The dead plant material (primary material) undergoes a biochemical degradation. The primary material is only partly decomposed, an intermediate product is formed that will be used by microorganisms as a source of nitrogen and carbon. This leads to the formation of secondary products which is accompanied by losses in liquid and gaseous form. With each time step a part of these secondary products (intermediate product 2) forms the basis for condensation, that is, synthesis of various organic products that are grouped as tertiary products. Their formation is again accompanied by losses in liquid and gaseous form. Part of the tertiary products will undergo the fate of intermediate products 1.

These transformations are repeated from time interval to time interval and if there is no replenishment by means of fresh organic matter, it is obvious that a gradual loss of organic matter takes place over time. By adding up the primary, secondary and tertiary material after each time step we are able to follow the changes in organic matter content. However, not only the organic matter content changes over time; soil acidity and the mineralization of nitrogen will change as well.

The soil acidity is determined by the cation exchange capacity. It is described by an empirical relation:

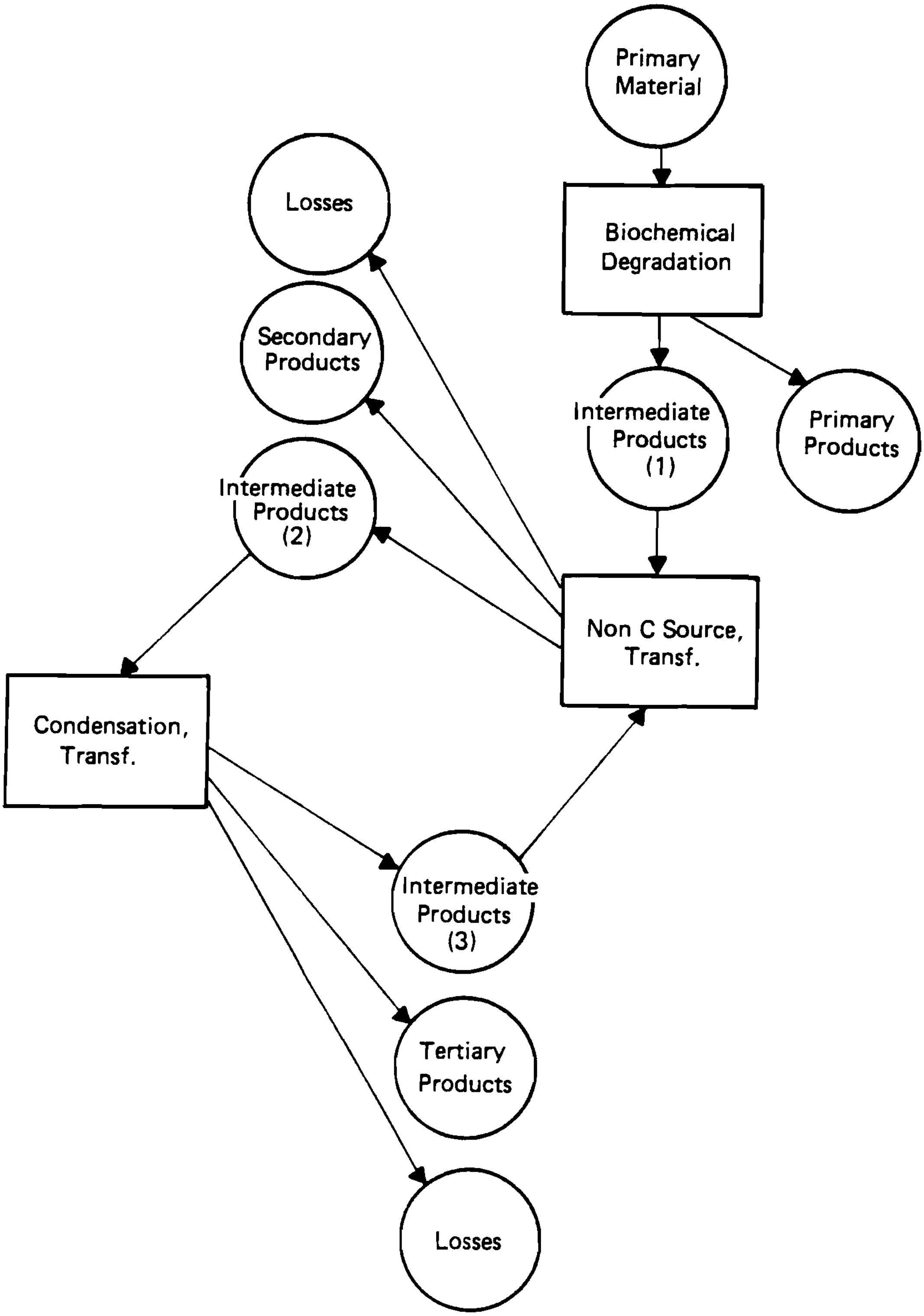

Figure 7. The decay of organic material

Table 7. Fractions of Organic Matter: their Decay Rates and Heterogeneity

Fraction	heterogeneity q	decay rate per day	 per 365 days
Proteins	0.0008	0.23	0.17
Sugars	0.0035	0.17	0.05
Cellulose	0.0071	0.05	0.0037
Lignin	0.0015	0.0023	0.0013
Humic substances	4.5×10^{-6}	1.2×10^{-4}	1.2×10^{-4}

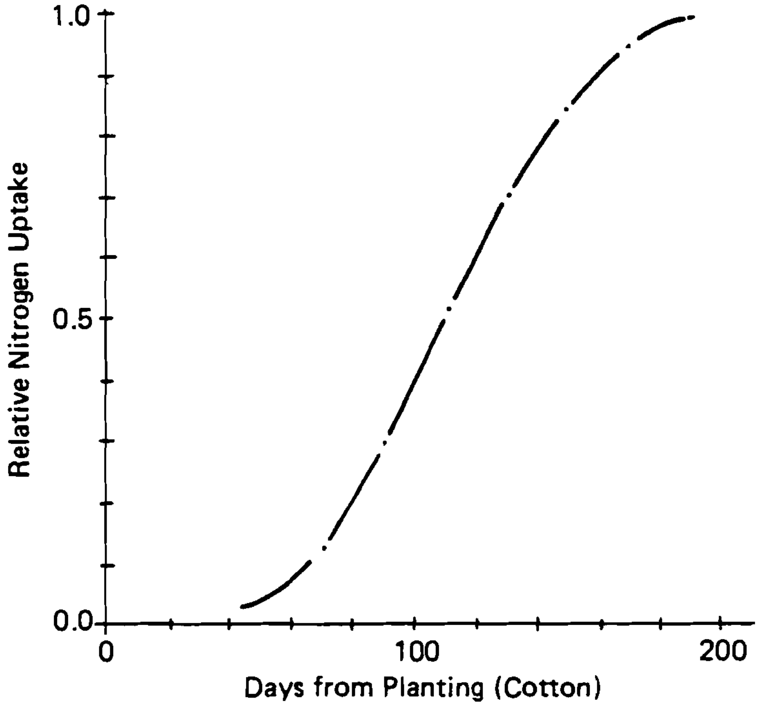

Figure 8. Relative nitrogen uptake during the growing season

$$\Delta pH_{\Delta t} = \frac{(cec_t - cec_{t+\Delta t}) \cdot (17.6 \cdot pH - 50)}{(280 \cdot depth + 17.6 \cdot cec_t)} \qquad (34)$$

where

ΔpH = change in soil acidity
cec = cation exchange capacity of organic matter meq. $\cdot ha^{-1}$
$depth$ = thickness of horizon with organic matter, cm
t = time
Δt = time step

During the transformations nitrogen is mineralized. Depending on the nitrogen requirement by the crop, the soil environment (pH, T, v) and the quality of the organic matter, all or a part of the nitrogen will go to the plant.

Depending on the crop, there are certain potential uptake pattern for nutrients, which normally follows a sigmoid pattern (Figure 8). This potential uptake may not be reached because of the factors mentioned above. Here again, the most limiting factor will determine the reduction on potential uptake that will take place:

$$U_{N,c} = \sum_{\Delta t} (U^{pot}_{N,c,\Delta t} \cdot rf_{\Delta t}) \qquad (35)$$

where

$U_{N,c}$ = uptake of N for crop c
U^{pot} = potential uptake
rf = reduction due to soil environment or organic matter quality
Δt = time period

For the other nutrients potassium and phosphorus we follow the same procedure, although the quantities involved are considerably smaller than for nitrogen.

3. The Environment Module

Although the environment module is described separately, its processes also take place during the growing season, it is logical that intermediate output from the crop production module should be used in determining the environmental consequences.

With regards to agricultural production we distinguish between two kinds of environmental effects.

- the on-site effects: they are mainly comprised of changes in soil properties
- the off-site effects including the occurrence of soil sediments in surface waters and nitrogen in ground water.

These are the result of various processes that act upon the land during agricultural production. The importance of the processes is site determined and, although fully recognizing the importance of the other processes, we will restrict ourselves for the moment to water erosion.

3.1. Water Erosion

We will use the Universal Soil Loss Equation (U.S.L.E.) which was developed by the U.S.D.A. (Wischmeier and Smith, 1978). Estimated soil loss, using the USLE, is given as:

$$A_{l,c,\Delta t} = R_{l,\Delta t} \cdot K_{l,\Delta t} \cdot L_{l,\Delta t}\, S_{l,\Delta t} \cdot C_{c,\Delta t} \cdot P_{l,c,\Delta t} \qquad (36)$$

where

A = soil loss
R = rainfall erosivity factor
K = soil erodibility factor
L = slope length factor
S = slope grade factor
C = crop and management factor
P = practice support factor
$l,c,\Delta t$= resp. land class, kind of crop and time period

For standard conditions all the factors except the rainfall erosivity and soil erodibility become equal unity. Information from a large number of field trials have led to the possibility of estimating these factors when deviating conditions occur.

Each of the terms of the USLE may briefly be described as follows:

- Rainfall Erosivity

  In principal erosivity should be determined through the analysis of rainfall data. Therefore the rainfall has to be registered continuously, for example as pluvigrammes. Empirically, the maximum 30 minutes intensity of each rainstorm multiplied by the total rainstorm energy gives the best fit with the soil loss under standard conditions for a certain kind of soil. The accumulated values for the erosivity per month should be determined to be able to make a good estimate for the cover and management factor (explained below).

- Soil Erodibility

  The following relation determines the erodibility (K) based on information about soil texture, soil organic matter, soil structure, and permeability (Wischmeier and Smith, 1978).

$$K_1 = \left[2.1 \cdot M^{1.14} \cdot 10^{-4} \cdot (12 - a1) + 3.25 \cdot (a2-2) + 2.5 \cdot (a3-3)\right] / \ 100 \qquad (37)$$

with

M = % silt · (100 - % clay)
$a1$ = percent organic matter
$a2$ = soil structure code used in soil classification
$a3$ = profile - permeability class

- Slope Length and Slope Grade

The slope length and slope grade factors are determined jointly in the following formula:

$$L \cdot S = \left[\frac{\lambda}{21.8}\right]^m \cdot (65.41 \cdot \sin^2\vartheta + 4.56 \cdot \sin\vartheta + 0.065) \quad (38)$$

where

λ = slope length in meters and
ϑ = slope angle in degrees
m = a slope dependent "constant"

- Cover and Management

  Like erosivity, the value for the cover and management factor changes over the year. During the year such events as land preparation and crop development bring about changes in plant cover. Therefore information for a complete year with all its agricultural activities is required (see Konijn, 1983a).

- Support Practice

  This factor requires information on such practices as terracing, contour plowing etc. For details, see Konijn (1983a).

Some of the above input characteristics are similar to those required for the crop production module; others, especially the site characteristics exclusive to the erosion estimation. There is also a technology input and finally, some input has been created as output from the crop production module. The result is the soil loss for various periods of the year (Δt) which, when accumulated, give the annual soil loss.

As we will see in Section 4, the soil loss is used as a basis for the estimation of changes in some soil properties (on-site effects). To evaluate the off-site effects we have to estimate which part of the soil loss will be transported into the surface waters. This will require a more geographical interpretation of the area under study. Catchment areas have to be recognized, and assumptions on the division of the catchment area into various kinds of land use are required. They allow us to make a rough estimate of the amount of sediment that can be expected in the surface water.

$$A_{a,\Delta t} = \sum_{l,c} O_{a,l,c} \cdot A_{a,l,c,\Delta t} \quad (39)$$

with

A = soil loss, metrictons $\cdot$year^{-1}
O = area of specific land class/crop combination
a = catchment area
l = land class
c = crop
Δt = time period

The sediment delivery ratio (sdr) is a function of the size of the catchment area

$$sdr_a = f(O_a) \tag{40}$$

Therefore the sediment in the surface water leaving the area is:

$$\dot{S}_{a,\Delta t} = sdr_a \cdot A_{a,\Delta t} \tag{41}$$

4. The Resource Adjustment Module

Some of the soil characteristics are subject to gradual changes over the year because of agricultural production. Of these characteristics some have to be updated at the end of the year. This is the consequence of the way we apply the hierarchical system (section 2). Estimations are not carried out per time step through all the hierarchical levels, but per hierarchical level for the whole year. A characteristic used at a higher level but affected by a characteristic that changes during crop production at a lower level can only be updated at the end of the year. Only those characteristics that are updated at the end of the year are described below.

4.1. Soil Organic Matter

As a result of decay during the year, loss in organic matter takes place throughout the whole topsoil horizon. A description of the decay of the organic matter is given in paragraph 2.4.2. In contrast, erosion does not affect the whole topsoil horizon, acting upon only the soil surface. Knowing the soil loss and the bulk density of the soil we are able to calculate the loss in topsoil thickness.

$$tsl_{l,c} = \frac{sl_{l,c} \cdot 10^{-2}}{bd_l} \tag{42}$$

with

tsl = topsoil loss, cm
sl = soil loss, metrictons$\cdot$ha^{-1}
bd = bulk density, gm$\cdot$cm^{-3}
l = land class
c = crop

Depending on the module, we need to know the organic matter expressed in different dimensions. For the total amount of organic matter per hectare we simply use the soil loss per hectare multiplied by the percentile content of organic matter. For other conversions we need to know the thickness of the topsoil horizon and the bulk density.

4.2. Soil Moisture Characteristic

The soil moisture characteristic concerns the relation between the soil moisture content (v) and soil moisture tension (Ψ) (see Section 2.2.1., equation 5).

This relation is affected by a change in organic matter content (Figure 9). This in turn affects the pore size distribution: a decrease in organic matter means a decrease in porosity and the value of v_o will change. The porosity can be expressed as a function of the specific soil density and the soil bulk density.

$$v_o = \frac{100 \cdot (sd - bd)}{sd} \tag{43}$$

where
sd = specific soil density, gm $\cdot$cm^{-3}
bd = soil bulk density, gm $\cdot$cm^{-3}

The change in soil density with organic matter content is described in the next section.

4.3. Soil Bulk Density

Both the specific density and bulk density are functions of the composition of the soil, that is its mineral and organic parts. Because of its low specific density, relatively small changes in organic matter content have a considerable effect on the soil bulk density.

$$sd = \frac{100}{\sum_i \frac{a_i}{sd_i}} \text{ and } bd = \frac{100}{\sum_i \frac{b_i}{bd_i}}$$

where a and b express the percentages for each of the soil components (i):

$$\sum_i a_i = 100 \text{ and } \sum_i b_i = 100$$

The pore distribution in the soil is assumed to be constant, which means that the soil constant γ will not be affected.

4.4. Nitrogen

Nitrogen in the various fractions, in the soil and taken up by the plant can be calculated as well. For the moment no interaction between the soil's organic matter and applied nitrogen is assumed to exist, and no carry over of fertilizer nitrogen from one year to the next is supposed to be possible. This means that we assume complete loss of nitrogen through such processes as leaching and denitrification.

This is clearly a provisional solution and will require a more realistic approach in the near future.

4.5. Phosphorus

Phosphorus applications are known for their inefficiency. It has been observed that to maintain yield at its maximum level regular annual applications are required. This is due to the fixing capacity of most of the soils. However although the efficiency within the cropping season is low, there is a clear residual effect of the applied phosphorus fertilizer. This means that the crop yield in the second year without phosphorus application will be higher than they would have been with no application in the first year.

Our concern here is the carry-over from year to year of the soil phosphorus, with or without fertilizer application.

Figure 10 shows the relationship between the soil analysis and yield. We consider a linear relationship to be a close approximation.

$$y = \varphi \cdot \alpha \cdot sa \qquad (45)$$

where

y = yield
φ = soil test coefficient
α = crop uptake coefficient
sa = soil analysis

In case no crop is grown, the rate of change of the residual effect of phosphorus fertilizers is approximately proportional to the amount applied.

$$\frac{d(sa)}{dt} = -b \cdot sa \qquad (46)$$

The soil analysis (sa) can be used for this purpose because we assume that the efficiency of the applied phosphorus fertilizer does not differ from the phosphorus already in the soil.

If a crop is grown a part of the available P is removed. For a linear uptake over the growing season then:

$$\frac{d(sa)}{dt} = -a \qquad (47)$$

which would give us the following analytical solution.

$$sa = \frac{a + b \cdot sa_o}{b} \cdot e^{-b(t - t_o)} - \frac{a}{b} \qquad (48)$$

where

sa = soil analysis at time t
sa_o = soil analysis at time t_o
t = time
a = crop specific constant
b = soil specific constant

If no crop is grown the residual effect becomes:

$$sa = sa_o \cdot e^{-b(t-t_o)} \qquad (49)$$

The values for φ and b should preferably be derived from local information.

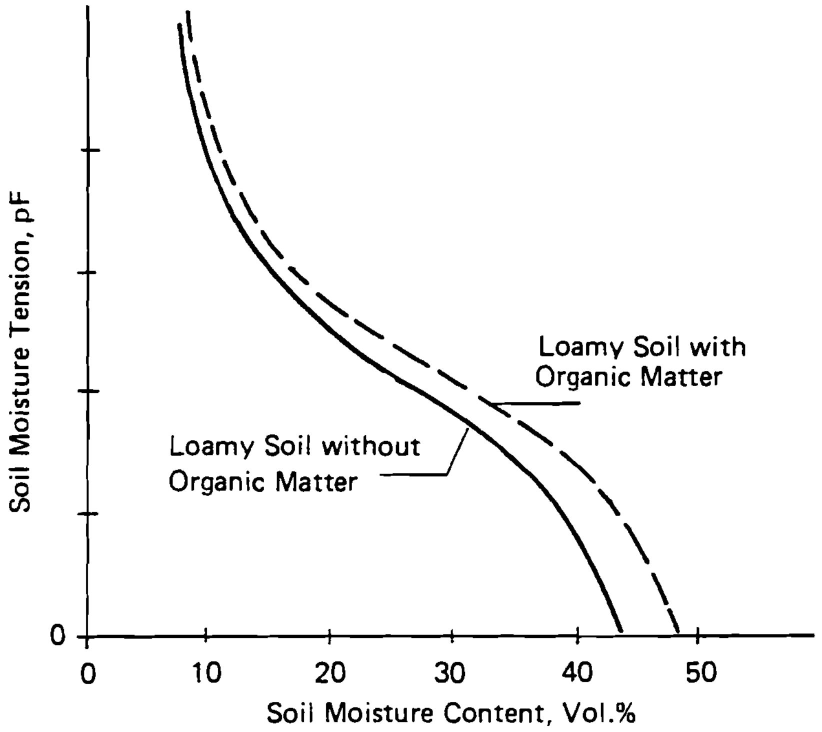

Figure 9: Soil moisture retention curve as determined by organic matter content

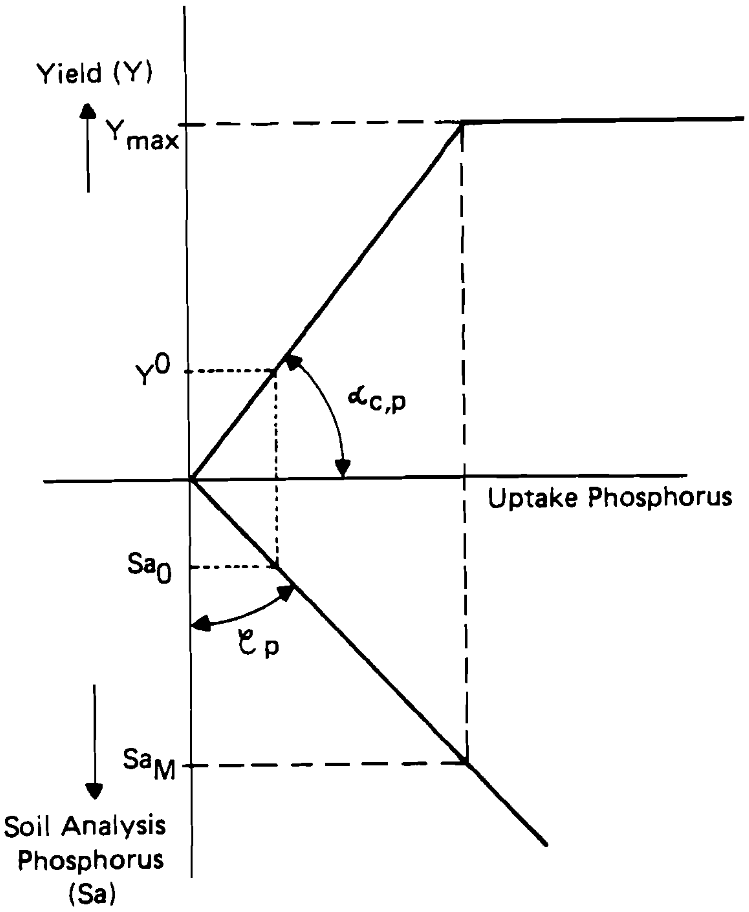

Figure 10: Response to fertilizers bazsed upon soil analysis

4.6. Potassium

Figure 11 can be applied for potassium as well. The most common soil analysis for available potassium is the estimation of exchangeable potassium together with the potassium in the soil solution, the latter being under humid conditions rather small. Soils that fix potassium strongly should be first brought to a potassium-level where our relation soil analysis/yield applies again.

The removal and application of potassium can be respectively subtracted and added to that which is in an exchangeable form. The new value will simply replace the old available potassium value.

$$K_{t+1}^{av} = K_t^{av} - K^{upt} + K^{appl}$$

Summary and Conclusions

The internal structure and the relationships used in the crop production module, environment module and the resource adjustment module have been described in some detail. The complete model is able to generate crop production values depending on a set of characteristics that describe the physical production environment. The role the model may play in connection with economic models has also been indicated.

Although the model in intended to be generally applicable, it is realized that certain parts still need improvement to fulfill this purpose completely. Moreover, certain yield determining processes are omitted, like the effect of weed and pest control. In the environment module we restricted ourselves to water erosion, so that wind erosion, salinization, sodification etc. are not yet considered. However, the open-ended characteristic of the hierarchical structured model should make it rather simple to add these other processes.

Examples of runs with the model and its validation will be presented in a separate paper.

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