MGOPT_CROP, a multiple goal linear programming model for optimisation of crop rotations, version 1.0

Quantitative Approaches in Systems Analysis

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Samenvatting

Dit rapport beschrijft versie 1.0 van het lineaire programmeringsmodel MGOPT_CROP, waarmee gewasrotaties worden geoptimaliseerd naar economische en milieukundige doelstellingen, volgens de techniek van interactieve meervoudige doelprogrammering. In MGOPT_CROP zijn per gewas een groot aantal produktietechnieken onderscheiden naar cultivar, teeltfrequentie, omgevingsfactoren en wijzen van bemesting en gewasbescherming. Hierbij wordt zoveel mogelijk gebruik gemaakt van verklarende relaties. Effecten van produktietechniek, gewasvolgorde en teeltfrequentie op economische en milieukundige doelstellingen zijn in MGOPT_CROP geformuleerd. Met het model wordt een optimale gewasrotatie berekend, afhankelijk van de te optimaliseren doelstelling en de beperkingen op overige doelstellingen. Doelstelling en beperkingen worden door de gebruiker gekozen. Daarmee is MGOPT_CROP een hulpmiddel bij de ontwikkeling en verkenning van geïntegreerde bedrijfssystemen. MGOPT_CROP heeft een open structuur: omdat productietechnieken of gewascombinaties niet a priori zijn gekoppeld, kunnen productietechnieken en doelstellingen worden toegevoegd, verwijderd of gewijzigd.

Summary

This report formally describer version 1.0 of MGOPT_CROP, an Interactive Multiple Goal Linear Programming (IMGLP) model for calculation of crop rotations. MGOPT_CROP distinguishes a number of production techniques for each crop according to cultivar, crop frequency, environmental factors and nutrient and pest management techniques, using explanatory knowledge where possible. No prefixed crop combinations are necessary because the interactions among crops are explicitly formulated. The relations in MGOPT_CROP include restrictions of crop sequence, crop frequency and production technique on economic and on environmental objectives. MGOPT_CROP calculates the crop rotation which is optimal for the selected objective and limitiations set on other goals. Objective and limitations are set by the user. Hence, MGOPT_CROP is a tool for development of integrated farming systems. MGOPT_CROP has an open structure: production techniques and objectives can be added, deleted or altered.

Preface

The work presented here was part of the projects 'Introduction of Integrated Production Systems in Arable Farming' (AB-DLO, project 795) and 'Development of methods for designing, validation and optimization of integrated cropping systems' (AB-DLO and LUW-TPE, project 796). I would like to thank Gerrie van de Ven (AB-DLO) for helping me more than once with SCICONIC peculiarities and 'problem infeasibilities', and Barbara Habekotté, Jaap Schröder, Frank de Ruijter (AB-DLO), Walter Rossing (LUW-TPE) and Frank Wijnands (PAGV) for discussions contributing to the structure of this model.

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1. Introduction

The concept of Integrated Farming Systems (IFS), developed in response to negative economic and ecological effects of maximum-yield oriented farming systems, has become the focus of Dutch agricultural policy (MLNV,1990; MLNV, 1991). IFS are designated here as farming systems that integrate and meet economic and ecological goals of agricultural land use, by applying all relevant methods and techniques. Experimental research on IFS for arable farming since 1979 (Wijnands & Vereijken, 1992) has resulted in guidelines for methodic development of prototype IFS and planned introduction of IFS on commercial farms (Vereijken, 1992). Based on these guidelines, experimental development of IFS production techniques has been started in various agricultural sectors (Vereijken & Van Beusichem,1992).

However, experimental research on IFS is expensive and timeconsuming, because systems must be compared at farm level. Therefore, only a limited number of systems can be compared at a limited number of locations, and compromises of conflicting goals are difficult to establish and to expand to other situations. Systems analysis of IFS based on Interactive Multiple Goal Linear Programming (IMGLP, de Wit et al., 1988) allows evaluation of the effects of many alternative production techniques on various goals simultaneously and indicates optimal production techniques for any desired compromise of distinguished goals. The results may set directions for complementary experimental research and provide insight in the consequences of different policy options.

Linear Programming (LP) models for arable farming have generally been developed for maximization of farm income, employing only a small number of production alternatives per crop. Recently, parameters for environmental effects of production techniques have been incorporated (e.g. Wossink, 1993). However, the environmental effects are not considered as separate goals but as restrictions on farm income only. Hence, one cannot know the potential contribution of production techniques to environmental goals. Moreover, the effects of frequencies and sequences of crops on crop yields, and the limitations of crop sequence on implementation of crop husbandry techniques are generally not accounted for in LP models of arable farming. This may result in optimization results which are infeasible on practical farms.

With the IMGLP model MGOPT_CROP, presented in this report, crop rotations are optimised with respect to economic and environmental goals, accounting for crop rotational restrictions and employing a database of many production techniques. The optimisation procedure is described in Chapter 2. In Chapter 3 the formal description of MGOPT_CROP is given. MGOPT_CROP was developed using the software packages MGG (EDS_Scicon, 1992) and SCICONIC (EDS-Scicon, 1993). A user guide for running MGOPT_CROP with these packages and a concise illustration of MGOPT_CROP results are presented in Chapter 4. Some concluding remarks are given in Chapter 5. Detailed applications of MGOPT_CROP are described by Jansma et al. (1994) and by Habekotté & Schans (1996).

2. Optimisation procedure

The procedure for calculation of crop rotations, optimal for multiple goals, is presented in figure 2.1. The crop rotation is composed of a number of crops with specified production techniques. A crop production technique is designated here as the set of husbandry actions from ploughing until harvest, including manipulation of yield-determining (e.g. growing season, cultivar productivity), yield-defining (e.g. mineral and water supply) and yield-reducing (pests, diseases and weeds) factors. For each crop many production techniques are conceivable, each characterised by a unique set of contributions to the various goals of agricultural land use (e.g. yield of valuable products and nitrate loss). A standardised formulation of production techniques for all crops has been developed to allow generic formulation of objective functions and constraints.

According to this formulation production techniques for each crop are characterised by 5 components (figure 2.1 A), covering the major environmental factors and husbandry methods affecting the goals of agricultural land use. For each component a number of alternatives is formulated (figure 2.1 B). The first component, designated e, concerns the environment of crop production, including soil type and groundwater table, which are not affected by crop husbandry, and soil structure and presence of multi-host soil-borne pests and diseases, which are affected by previous crops. The second component, r, defines the frequency of a crop in the rotation. The third component, v, defines the crop cultivar. It is not possible to define general cultivar characteristics for all crops; therefore, coefficients which are affected by cultivar must always be quantified depending on both crop species and cultivar. The fourth component, p, concerns pest management. Depending on the knowledge of the relations between control methods and yield loss, the number of alternatives may be different for each crop. The fifth component, n, concerns nutrient management. The first three levels of this component are reserved for exclusive use of fertilisers, whereas at levels 4-6 nutrient supply is based on animal manure.

Systematic combination of all alternatives results in a range of production techniques, covering a range from high to low contributions to the distinguished goals (figure 2.1 C). Each production technique is characterised by a unique set of inputs and outputs. A FORTRAN program for systematic generation of these inputs and outputs, named TCG_CROP, has been developed by Habekotté (1994) This program has been adapted for flower bulb coefficients by De Ruijter & Jansma (1994).

The optimisation model MGOPT_CROP (Chapter 3) creates an IMGLP-matrix for the formulated production techniques, consisting of objective functions and constraints. Solving this matrix for one of the defined objectives results in a crop rotation with selected production techniques, optimal for the considered objective. This crop rotation is applicable on a farm, as characterised by the farm area (designated AMX) and available labour per bimonthly period (discussed in section 3.10). The IMGLP optimisation procedure consists of several iterations. In the first round, each objective is optimised with minimum restrictions on the other objectives. This gives the best attainable value for each of the objectives and the associated worst values to be accepted for the other objectives, as well as the associated crop rotations. In subsequent rounds, each of the objectives is optimised again, while stepwise tightening the restrictions on the other objectives. Thus economic and ecological objectives are gradually integrated, until the most acceptable compromise is reached. This compromise is accomplished with the finally selected crop rotation, representing the optimal IFS (figure 2.1 D). The results also include the tradeoffs between objectives, indicating the 'price' of one objective in terms of another.

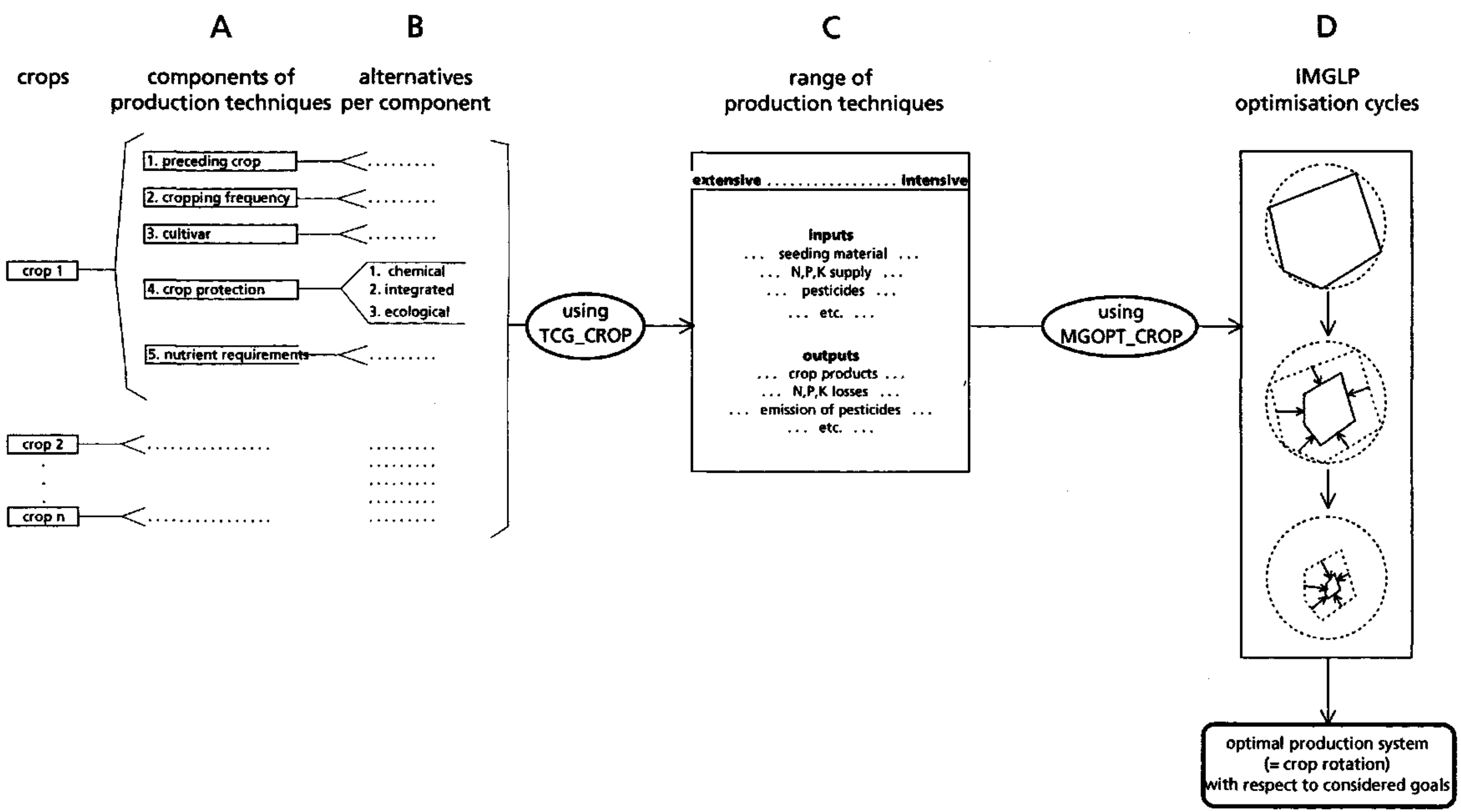

Figure 2.1. Procedure for Multiple Goal Optimisation of crop rotations.

3. Description of MGOPT_CROP

3.1. Overview

The matrix generated by MGOPT_CROP consists of rows and columns. The rows are linear mathematical equations, representing objective functions (section 3.2) and restrictions of crop production (section 3.3), crop frequency (section 3.4), crop sequence (section 3.5), operations between successive crops (section 3.6), supply of minerals (section 3.7), mineral balances (section 3.8), pesticide use (section 3.9), labour (section 3.10) and land hire (section 3.11). The columns are the variables in these equations: land used for crop production techniques, production factors (e.g. seed and planting material, fertilisers and pesticides), products (e.g. crop products and mineral losses), and intermediate variables required to fully formulate the problem. Each variable is characterised by technical coefficients quantifying its contribution to the equations. The equations must satisfy a 'right hand side' vector, which includes the system boundaries and the restrictions on the objective variables. The equations of MGOPT_CROP are presented in this report as illustrated in figure 3.1, using symbols and notation given in table 3.1. The name 'EXMP' after the Eq. number in figure 3.1 refers to the name used in the model formulation of MGOPT_CROP. CRITARR(i,n) is an example of the criterion arrays used in MGOPT_CROP. These arrays define conditions for the formation of specific matrix equations and subsets of variables for which the equations must be satisfied. For instance, the criterion array 'CRIT(g)' in Eq. 4 specifies that this equation is created for a crop species g, only if CRIT(g) equals 1.0. The value of CRIT(g) is set to 1.0, only if technical coefficients for that crop are specified in the file TCCROPS.DAT. For a second example, the criterion array CRPRE(z,e,i,g) used in Eq. 11 specifies which crops g can be grown previous to crop z in environment e with between-crop operation i. Only if the value of CRPRE equals 1.0, the variable XPR(z,e,i,g,x) is included in the equation. The values of criterion array elements are defined by the user.

Table 3.1. Symbols and notation in this report.

Symbol	meaning
$\sum$	summation
$\ni$	such that
$\forall$	for all
$\wedge$	logical 'and'
$\vee$	logical 'or'

Notation of summation over multiple indices:

standard	this report
$\sum_i \sum_j \sum_k \sum_l \mathrm{VAR}(i,j,k,l)$	$\sum_{i,j,k,l} \mathrm{VAR}(i,j,k,l)$

Eq. exmp ('EXMP')

$$\sum_{i,\dots,n} tc\_VARa * VARa(i,\dots n)$$
$$+\sum_{j,\dots m} tc\_VARb * VARb(j,\dots m)$$
$$\leq RHS\_exmp$$
$$n \ni (CRITARR(i,n) = 1.0)$$

variables		
VARa(i,...,n)	description of variable VARa	unit
VARb(j,...,m)	description of variable VARb	unit
coefficients		
tc_VARa	description of technical coefficient tc_VARa	unit
tc_VARb	description of technical coefficient tc_VARb	unit
RHS		
RHS_exmp	description of Right Hand Side parameter RHS_exmp	unit
Criterion arrays		
CRITARR(i,n)	description of criterion array	

Figure 3.1. Presentation of equations in this report.

In subsequent paragraphs different sections of MGOPT_CROP are presented. Acronyms of variables, coefficients, arrays and functions used in the text are explained with every equation. An overview of all variables is presented in 3.2.

Intensive use is made of indices to characterise variables, coefficients and arrays. These are explained in table 3.3. In some equations, different ranges of crop species or cropping frequencies were compared within the equation. In these cases 'alias indices' had to be introduced for crop species (alias z for index g) and for cropping frequency (alias x for index r). These alias indices are also indicated in table 3.3.

Table 3.2. Overview of all variables used in MGOPT_CROP

Variable	Description	unit
Objective		
FINTC	Financial result of crop rotation, based on allocated costs (including variable costs and costs for contract labour and machinery)	Dfl.
NLOSS	Total N lost from rotation	kg N
IPEST(F)	Input of pesticides specified by effect F	F-units
Land use		
L(G,E,R,V,P,N)	Land with production technique (G,E,R,V,P,N)	ha
LRTOT(G,R)	Semi-continuous variable representing total area of crop G in frequency R	ha
H(G,E,R,V,P,N)	Hired land with production technique (G,E,R,V,P,N)	ha
Crop sequence		
XBETW(G,E,I)	Crop g at environment e preceded by between-crop operation i	ha
XPR(Z,E,I,G,X)	Crop G preceding crop Z, with crop z at environment e and between-crops operation i	ha
XPTOT(Z,G,X)	Semi-continuous variable, area of crop g preceding total area of crop z, XPTOT in frequency x	ha
Crop frequency		
BINRO(Y)	Binary variable to selection precisely one combination of crop frequencies	-
Crop production		
PROD(G,V,Q)	Harvested products of crop g, cultivar v, quality class q	tonne
Nutrient management		
FERK	Fertiliser K on crop g at nutrient level n	kg K
FERKH	Fertiliser K used on hired land	kg K
FERN(G,N)	Fertiliser N on crop g at nutrient level n	kg N
FERNH	Fertiliser N used on hired land	kg N
FERP(G,N)	Fertiliser P_2O_5 on crop g at nutrient level n	kg P_2O_5
FERPH	Fertiliser P_2O_5 used on hired land	kg P_2O_5
FIXN(G,N)	N fixed by leguminous crops	kg N
FYCNI(G,E,N)	Input of farmyard compost	kg
MANU(S,G,N)	Animal manure of type s, on crop g, at nutrient level n	tonne
NTR(G,N)	N transfer from preceding crop	kg N
Labour		
ILAB(L,T)	Total bimonthly labour input	hour
LABFA(L,T)	Labour present on farm of type l in period t	hour
LABHI(L,T)	Hired labour of type l in period t	hour
Miscellaneous		
BINPV(B)	Binary variable to exclude area with unfumigated PCN*-susceptible potato cultivars without fumigation, when PCN-resistant cultivars are selected	-
KLOSS	Amount of K lost from rotation	kg K
NDIFF	Difference between N loss as calculated on crop and rotation bases	kg N
NH_3C(G,N)	N lost as ammonia volatilisation per crop	kg N
NLOSC(G,N)	Total N loss per crop g at nutrient level n	kg N
NLOSH	Total N lost on hired land per crop	kg N
NO_3C(G,N)	N lost as nitrate per crop	kg N
NREST(G,N)	N remaning after harvest	kg N
PLOSS	P_2O_5 lost from rotation	kg P_2O_5

* potato cyst nematode

Table 3.3. Indices used in MGOPT_CROP

e	**environment (soil type, damage by soilborne diseases)**
1	clay, no damage
2	clay, damage level 1
3	clay, damage level 2
4	sand, no damage
5	sand, damage level 1
6	sand, damage level 2
f	**pesticide characteristics**
1	total active ingredients
2	environmental hazard
3	health hazard
g, (alias z)	**crop**
1	ware potato
2	seed potato
3	starch potato
4	sugar beet
5	fodder beet
6	reserve
7	winter wheat
8	summer wheat
9	winter barley
10	summer barley
11	winter rye
12	maize
13	grass seed
14	fallow
15	onion
16	carrot
17	cabbage
18	chicory
19	pea
20	bean
21	faba bean
22	reserve
23	rye grass
24	clover
25	alfalfa
26	temporary grassland
27	tulip
28	narcissus
30	lily
31	iris
32	gladiolous
33	hyacinth
34	dahliah
35	reserve

Table 3.3 Continued

i	**between-crop operation**
1	soil fumigation + cellulose
2	inundation
3	inundation + straw
4	straw incorporation
5	green manure crop + GFT-compost
6	no operation
l	**labour class**
1	routine labour
2	expert labour
n	**nutrient management**
1	fertilisers only, maximum yield level
2	fertilisers only, reduced yield level 1
3	fertilisers only, reduced yield level 2
4	manure based, maximum yield level
5	manure based, reduced yield level 1
6	manure based, reduced yield level 2
p	**crop protection**
1	convential 1
2	convential 2
3	convential 3
4	ecological
5	convential 1 with soil fumigation
q	**quality class**
1	not specified
r (alias x)	**crop rotation**
1	1:2
2	1:3
3	1:4
4	1:5
5	1:6
6	1:7
7	1:8
s	**animal manure type**
1	dry chicken manure
2	cow slurry
3	pig slurry
t	**period of the year**
1	january-february
2	march-april
3	may-june
4	july-august
5	september-october
6	november-december
v	**cultivar**
1 - 8	variety 1 - 8, distinguished specifically for each crop
y	**valid combinations of crop frequencies**
1	1:2 , 1:4 , 1:8
2	1:2 , 1:6
3	1:3 , 1:6
4	1:4 , 1:6
5	1:5

3.2. Objectives

Three goals of agricultural land use are presently distinguished: economic efficacy, nitrogen loss ,and pesticide input. Economic efficacy can be calculated in many ways, varying from simple gross margin to detailed farm economic analysis. Here, the principal aim is a fair comparison of various production techniques. Some techniques rely strongly on chemical crop protection, employing rather cheap machinery but expensive chemicals, while others use mechanical and biological crop protection methods with more expensive machinery, but with less or no chemical input. Therefore, a gross margin equation, extended with allocated costs of machinery and contract labour, is formulated to calculate the financial result of the crop rotation, 'FINTC' (Eq. 1). This margin is required for remuneration of labour, investment costs other than the allocated machinery (e.g. drainage tubes) and profit.

Eq. 1 ('GVFIN')

$$
\begin{aligned}
& \sum_{g,v,q} PRPRO(g,v,q) * PROD(g,v,q) \\
- & \sum_{s,g,n} PMANU(s) * MANU(s,g,n) \\
- & \sum_{g,n} PFERN * FERN(g,n) \\
- & \sum_{g,n} PFERP * FERP(g,n) \\
- & \; PFERK * FERK \\
- & \sum_{g,e,r,v,p,n} COL * L(g,e,r,v,p,n) \\
- & \sum_{g,e,i} PBETW(i) * XBETW(g,e,i) \\
- & \sum_{l1,t} PLABH * LABHI(l1,t) \\
- & \sum_{g,e,r,v,p,n} COH * H(g,e,r,v,p,n) \\
- & \; PFERN * FERNH \\
- & \; PFERP * FERPH \\
- & \; PFERK * FERKH \\
- & \; FINTC \\
= & \; 0.0
\end{aligned}
$$

$$l1 \ni (l1 = 1)$$

$$
\begin{aligned}
COL = & \; CMA(g,e,p,n) + CCL(g,e,p,n) + COI(g,e,p,n) \\
& + COGR(e,n) - ECBON(g)
\end{aligned}
$$

$$COH = COL + PLAND(e)$$

Variables

PROD(g,v,q)	harvested product of crop g, cultivar v, quality class q	tonne
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FERN(g,n)	fertiliser N on crop g at nutrient level n	kg N
FERP(g,n)	fertiliser P_2O_5 on crop g at nutrient level n	kg P_2O_5
FERK	fertiliser K on crop g at nutrient level n	kg K
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha
LABHI(l1,t)	hired labour of type l1 in period t	hours
H(g,e,r,v,p,n)	hired land with production technique g,e,r,v,p,n	ha
FERNH	fertiliser N used on hired land	kg N
FERPH	fertiliser P_2O_5 used on hired land	kg P_2O_5
FERKH	fertiliser K used on hired land	kg K
FINTC	financial result of crop rotation, based on all allocated costs	Dfl

Coefficients

PRPRO(g,v,q)	Price of product of crop g, cultivar v and quality class q	$Dfl.tonne^{-1}$
PMANU(s)	Price of animal manure of type s	$Dfl.tonne^{-1}$
PFERN	Price of fertiliser N	$Dfl.kg^{-1}$
PFERP	Price of fertiliser P_2O_5	$Dfl.kg^{-1}$
PFERK	Price of fertiliser K	$Dfl.kg^{-1}$
CMA((g,e,p,n)	Costs of machinery for crop g,e,p,n	$Dfl.ha^{-1}$
CCL(g,e,p,n)	Costs of contract labour for crop g,e,p,n	$Dfl.ha^{-1}$
COI(g,e,p,n)	Costs of all non-specified inputs	$Dfl.ha^{-1}$
COGR(e,n)	Costs of green manure crop	$Dfl.ha^{-1}$
ECBON(g)	EC-bonus according to McSharry regulations	$Dfl.ha^{-1}$
PLAND(e)	Price of hired land	$Dfl.ha^{-1}$
PLABH	Price of hired labour	$Dfl.hour^{-1}$
PBETW(i)	Price of between-crop operation i	$Dfl.ha^{-1}$

FINTC is maximised (Eq. 2), with the restriction of a minimum financial result RFN (Eq. 3). The IMGLP iterations are carried out by varying the value of RFN.

Eq. 2 ('GFIN')

MAXIMISE (FINTC)

Variables

FINTC	financial result of crop rotation, based on all allocated costs	Dfl

Eq.3 ('GRFIN')

$$FINTC \geq RFN$$

Variables

FINTC	financial result of crop rotation, based on all allocated costs	Dfl

RHS:

RFN	minimum restriction for FINTC	Dfl

Equations similar to Eqs. 2 and 3 are formulated for minimisation of nitrogen loss 'NLOSS' and of total input of active ingredients of pesticides 'IPEST', and their restrictions. The value of NLOSS is calculated with equations discussed in sections 3.7 and 3.8. Total nitrogen loss is allotted to nitrate, ammonia and denitrification losses, (section 3.8). These variables can also be employed as objectives. Pesticide use is further restricted by the legal maximum level of the area treated with soil fumigants, i.e. 20 % and 16.67 % of the total area for sand and clay, respectively.

3.3. Crop production

Crop products in different quality classes, PROD(g,v,q), are produced with production techniques L(g,e,r,v,p,n), where the indices refer to the components listed in table 3.3. (Eq. 4).

Eq. 4 ('APROD')

$$
\begin{aligned}
& - \sum_{e,r,p,n} YLD(g,e,r,v,p,n,q) * L(g,e,r,v,p,n) \\
& + PROD(g,v,q) \\
& = 0.0 \\
& g \ni (CRIT(g) = 1.0) \\
& v \ni (CRIV(g,v) = 1.0) \\
& q \ni (CRIQ(g,v,q) = 1.0)
\end{aligned}
$$

Variables		
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
PROD(g,v,q)	harvested crop products of crop g, variety v, quality class q	tonne
Coefficients		
YLD(g,e,r,v,p,n,q)	crop yield of quality class q in specified production technique	$tonne.ha^{-1}$
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIV(g,v)	existence of data for cultivar v of crop g	
CRIQ(g,v,q)	existence of data for quality q of cultivar v of crop g	

In addition to these marketed products, other crop parts may be composted into FYCNI(g,e,n), which may be recycled in the crop rotation (Eq. 5)

Eq. 5 ('AFYC')

$$
\begin{aligned}
& \sum_{g,e,n} FYCNI(g,e,n) \\
& - \sum_{g,e,r,v,p,n} FYCNPR(g,e,r,v,p,n) * L(g,e,r,v,p,n) \\
& \leq 0.0
\end{aligned}
$$

Variables		
FYCNI(g,e,n)	input of farmyard compost	kg
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
Coefficients		
FYCNPR(g,e,r,v,p,n)	farmyard compost production rate	$kg.ha^{-1}$

The whole farm area AMX must be employed for crop production (Eq. 6). Land used permanently for other purposes, e.g. long-term nature elements, is excluded from this area.

Eq. 6 ('LAUSE')

$$\sum_{g,e,r,v,p,n} L(g,e,r,v,p,n) = AMX$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
RHS		
AMX	total cultivated area	ha

The value of AMX is to be defined by the user. The default value is 1 ha, permitting interpretation of the selected crop production techniques in terms of crop frequencies.

The selection of crop production techniques in the rotation is restricted because constraints for crop frequencies and sequences must be satisfied.

Frequencies and sequences of the crops affect the objectives through effects on soil-borne pests and diseases, soil structure and nitrogen availability. The major effect of high crop frequencies is increased yield reduction by crop-specific soil-borne pests and diseases, such as potato cyst nematodes on potato (section 3.4). The crop sequence influences the environment at the start of each crop and, hence, the yield potential of the crop due to effects of preceding crops on the population level of multi-host soil-borne pests and diseases and on soil structure (section 3.5). Transfer of nitrogen with crop residues and leguminous N-fixation is accounted for in the sections on crop mineral requirements and nutrient balances (sections 3.7 and 3.8).

In addition to farm land, land may be hired elsewhere, a common practice of flower bulb growers. Production techniques on hired land are designated H(g,e,r,v,p,n). The area of hired land is limited by labour availability only (discussed in section 3.11).

3.4. Crop frequency constraints

For all distinguished cropping frequencies seperate crop production techniques are formulated in the matrix. These techniques differ in yield level and derived coefficients, such as nutrient requirements. If a crop is selected in the rotation, then only one frequency is possible because multiple crop frequencies are nonsensical on a farm. Moreover, each production technique may be selected in the rotation only if its pre-defined frequency equals the realised frequency in the solution. To formulate these constraints a semi-continuous variable LRTOT(g,r) is introduced, which represents the total area of crop g in rotation r, including all selected alternatives for pest management, nutrient management, etc (Eq. 7). Its upper bound is set equal to its lower bound, and is calculated as: $AMX / RDU(g,r)$ (Eq. 8). Hence, LRTOT(g,r) is either zero or the fraction of the total farm area corresponding to the cropping frequency of rotation r. Eq. 7 imposes that if production techniques for crop g in rotation r are selected, then they have to be implemented on the appropriate fraction of the total cultivated area.

Eq. 7 ('ROSUM')

$$\sum_{e,v,p,n} L(g,e,r,v,p,n)$$

$$- LRTOT(g,r)$$

$$= 0.0$$

$$g \ni (CRIT(g) = 1.0)$$

$$r \ni (CRIR(g,r) = 1.0)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
LRTOT(g,r)	semi-continous variable representing total area of crop g in frequency r	ha
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIR(g,r)	existence of data for crop g in rotation r	

According to Eq. 8 at most one crop rotation and hence, at most one cropping frequency, is possible for each crop.

Eq. 8 ('ROONE')

$$\sum_r RDU(g,r) * LRTOT(g,r)$$

$$\leq AMX$$

$$g \ni (CRIT(g) = 1.0)$$

Variables

LRTOT(g,r)	semi-continous variable representing total area of crop g in frequency r	ha
Coefficients		
RDU(g,r)	rotation duration, i.e. inverse of cropping frequency, of crop g in frequency r	years
RHS		
AMX	total cultivated area	ha
Criterion arrays		
CRIT(g)	existence of data for crop g	

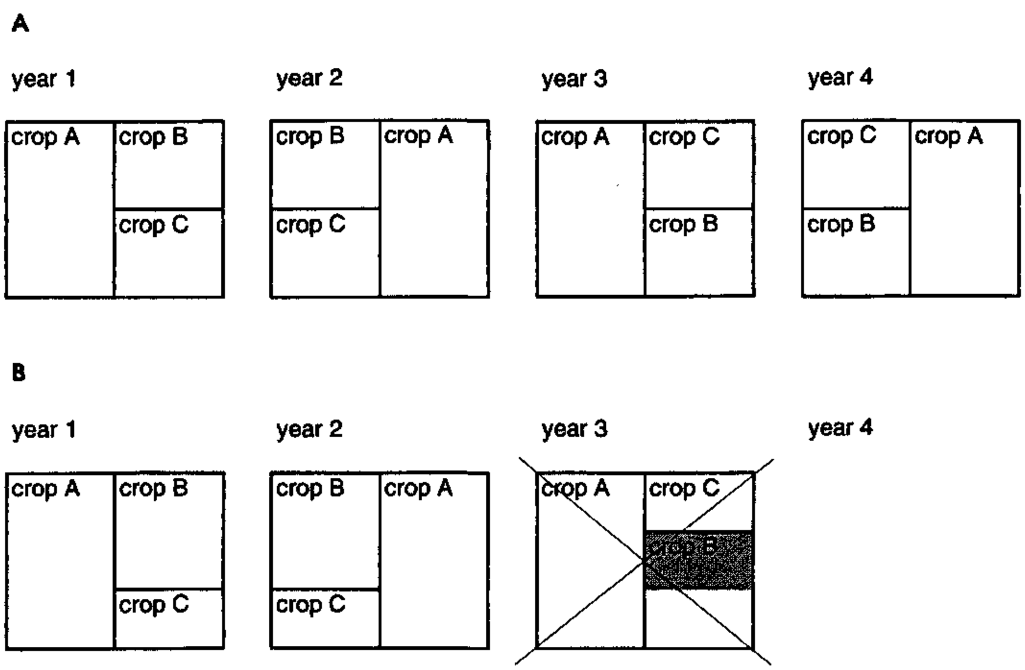

Figure 3.2. Example of feasible (A) and infeasible (B) combination of cropping frequencies in crop rotation.

With Eqs. 7 and 8, production techniques are selected on the appropriate area for each cropping frequency. However, only certain frequencies of different crops can be combined into a realistic crop rotation. For instance, it is possible to implement a crop rotation of 1:2 crop A, 1:4 crop B and 1:4 crop C (figure 3.2A), but a rotation of 1:2 crop A, 1:3 crop B and 1:6 crop C is impossible (figure 3.2B). In figure 3.2A each crop not only uses the approriate fraction of the total area, but this fraction also agrees with the inverse of the associated rotation duration. In figure 3.2B, the fraction of total area disagrees with the fraction of total rotation duration for crop B. In year 3 part of crop B is grown on the hatched area, resulting in a cropping frequency of 50 % on this area while the coefficients for crop B are quantified for a frequency of 33 %. This would lead to erroneous calculations.
These limitations are accounted for by Eqs. 9 and 10, employing an array of binary variables 'BINRO(y)'. With Eq. 9, exactly one array element is assigned the value one, the others are zero. In Eq. 10, the non-zero element of BINRO(y) is employed as a switch to select precisely one valid combination of cropping frequencies, defined by criterion array EXROT(y,r).

Eq. 9 ('EXRO1')

$$\sum_{y} \mathrm{BINRO}(y) = 1.0$$

Variables

BINRO(y)	binary variable to select precisely one combination of crop frequencies	-

Eq. 10 ('EXRO2')

$$\sum_{g,e,r1,v,p,n} L(g,e,r1,v,p,n)$$
$$- \mathrm{AMX} * \mathrm{BINRO}(y)$$
$$\geq 0.0$$
$$\forall\ y$$
$$r1 \ni (\mathrm{EXROT}(y,r1) = 1.0)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
BINRO(y)	Binary variable to select precisely one combination of crop frequencies	-
Coefficients		
AMX	total cultivated area	ha
Criterion arrays		
EXROT(y,r)	specification of feasible combinations of cropping frequencies in rotation	

3.5. Crop sequence constraints

The combination of crops into realistic rotations is limited further by effects of the preceding crop on yield of the current crop and associated coefficients. In MGOPT_CROP various levels for these effects are distinguished with component e, and for each level seperate production techniques are formulated. For instance, some production techniques for potato are defined on the assumption of yield reduction by Verticillium wilt. These techniques must be included, and are permitted in the solution only if the selected preceding crop promotes presence of this disease, i.e. pea or faba bean. Some effects of preceding crops can be eliminated by field operations between successive crops, e.g. the damage caused by Pratylenchus nematodes.

To model these constraints a variable 'XPR(z,e,i,g,x)' is defined as the area of crop g, which precedes crop z in environment e with between-crop operation i (section 3.6), and which occurs in frequency x, as illustrated in figure 3.3. Here, crop A (L(A,e,1,v,p,n)) is grown in a 1:2 rotation, and crop B and C are grown in a 1:4 rotation (L(B,e,3,v,p,n) and L(C,e,3,v,p,n), respectively). Crop A is preceding crop B and crop C, each on 25 % of the area (XPR(B,e,i,A,3) and XPR(C,e,i,A,3), respectively). Crop B and crop C are both preceding crop A (XPR(A,e,i,B,3) and XPR(A,e,i,C,3), respectively). Over 4 years, crops B and C have completed one cycle, while the cycle of crop A has been completed twice.

According to Eq. 11, the area of each crop g in environment e must be immediately preceded by the appropriate crops g2 (selected with criterion array CRPRE(z,e,i,g)), unless the effects are eliminated by valid between-crop operations (selected with criterion array CRBTW(g,e,i)).

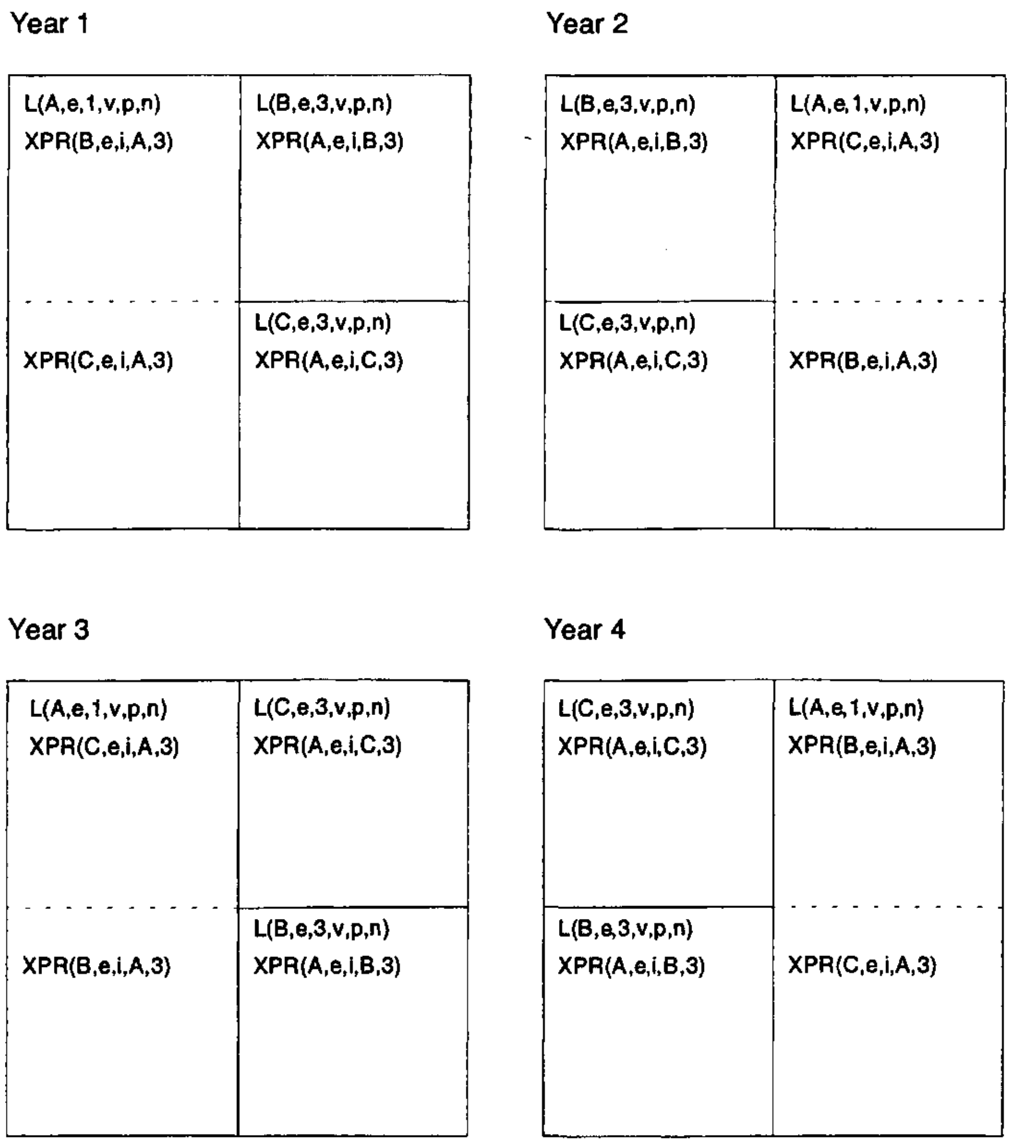

Figure 3.3. Illustration of crop areas and preceding crop areas.

Eq. 11 ('PREA')

$$\sum_{r,v,p,n} L(g,e,r,v,p,n)$$
$$- \sum_{i1} XBETW(g,e,i1)$$
$$- \sum_{z2,i2,g2,x2} XPR(z2,e,i2,g2,x2)$$
$$= 0.0$$
$$g \ni (CRIT(g) = 1.0)$$
$$e \ni (CRIE(g,e) = 1.0)$$
$$i1 \ni (CRBTW(g,e,i1) = 1.0)$$
$$z2 \ni (z2 = g)$$
$$i2 \ni (i2 \geq 4)$$
$$g2 \ni (CRPRE(z2,e,i2,g2) = 1.0)$$
$$x2 \ni (CRIR(z2,x2) = 1.0)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
XBETW(g,e,i)	crop g in environment e preceded by between-crop operation i	ha
XPR(z,e,i,g,x)	crop g preceding crop z in environment e and between-crop operation i	ha

Criterion arrays

CRIT(g)	existence of data for crop g
CRIE(g,e)	existence of data for crop g in environment e
CRBTW(g,e,i)	specification of between-crop operations for a disease-free environment
CRPRE(z,e,i,g)	specification of crops g which can be grown preceding crop z at level e with between-crop operation i
CRIR(z,x)	existence of crop z in rotation x

With the criterion array CRBTW(g,e,i) only those between-crop operations eliminating damage by soil-borne pests and diseases are selected. However, the area of preceding crops must also fit with all other between-crop operations i, valid before crop g at environment e. This is formulated with Eq. 12.

Eq. 12 ('PREB')

$$XBETW(g,e,i)$$
$$- \sum_{z1,g1,x1} XPR(z1,e,i,g1,x1)$$
$$= 0.0$$
$$g \ni (CRIT(g) = 1.0)$$
$$e \ni (CRIE(g,e) = 1.0)$$
$$i \ni (FXBTW(g,e,i) = 1.0)$$
$$z1 \ni (z1 = g)$$
$$g1 \ni (CRPRE(z1,e,i,g1) = 1.0)$$
$$x1 \ni (CRIR(z1,x1) = 1.0)$$

Variables

XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha
XPR(z,e,i,g,x)	crop g preceding crop z at environment e and between-crop operation i	ha

Criterion arrays

CRIT(g)	existence of data for crop g
CRIE(g,e)	existence of data for crop g in environment e
FXBTW(g,e,i)	existence of area with between-crop operation i before crop g,e
CRPRE(z,e,i,g)	specification of crops g which can be grown preceding crop z at level e with between-crop operation i
CRIR(z,x)	existence of crop z in rotation x

To avoid multiple allocation of crop area to preceding crop area, the total area of each crop must be preceding other crops (Eq. 13), while the total area of preceding crops must equal the total cultivated area (Eq. 14).

Eq. 13 ('PREC')

$$\sum_{e,r,v,p,n} L(g,e,r,v,p,n) - \sum_{z,e,i,g1,x1} XPR(z,e,i,g1,x1) = 0.0$$

$$g \ni (CRIT(g) = 1.0)$$
$$g1 \ni (g1 = g \wedge CRPRE(z,e,i,g1) = 1.0)$$
$$x1 \ni (CRIR(z,x1) = 1.0)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
XPR(z,e,i,g,x)	crop g preceding crop z at environment e and between-crop operation i	ha

Criterion arrays

CRIT(g)	existence of data for crop g
CRPRE(z,e,i,g)	specification of crop g which can be grown preceding crop z at level e with between-crops operation i
CRIR(z,x)	existence of crop z in rotation x

Eq. 14 ('PRED')

$$\sum_{z,e,i,g,x} XPR(z,e,i,g,x) = AMX$$

Variables

XPR(z,e,i,g,x)	crop g preceding crop z at environment e and between-crop operation i	ha

RHS

AMX	total cultivated area	ha

Similar to the restrictions concerning the appropriate area for cropping systems with rotation r (Eq. 7 and Eq. 8), Eq. 15 and Eq. 16 are formulated to calculate the area of preceding crops with rotation x at the approriate fraction of the total area.

Eq. 15 ('XPSUM')

$$\sum_{e,i} XPR(z,e,i,g,x)$$
$$- XPTOT(z,g,x)$$
$$= 0.0$$
$$z \ni (CRIT(z) = 1.0)$$
$$g \ni (CRIT(g) = 1.0 \wedge g \neq z)$$
$$x \ni (CRIR(z,x) = 1.0)$$

Variables

XPTOT(z,g,x)	semi-continous variable, crop g preceding crop z in frequency x	ha
XPR(z,e,i,g,x)	crop g preceding crop z at environment e and between-crop operation i	ha
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIR(z,x)	existence of crop z in rotation x	

Eq. 16 ('XPONE')

$$\sum_{x} RDU(z,x) * XPTOT(z,g,x)$$
$$\leq AMX$$
$$z \ni (CRIT(z) = 1.0)$$
$$g \ni (CRIT(g) = 1.0 \wedge g \neq z)$$

Variables

XPTOT(z,g,x)	semi-continous variable, crop g preceding crop z in frequency x	ha
Coefficients		
RDU(z,x)	rotation duration, i.e. inverse of cropping frequency, of crop z in frequency x	years
RHS		
AMX	total cultivated area	ha
Criterion arrays		
CRIT(g)	existence of data for crop g	

Except with two crops grown both in a 1:2 rotation, crop g is not permitted to precede crop z, when z is preceding g. Hence, the area of crop g preceding z must equal zero if crop z is preceding crop g. This is formulated in Eq. 17.

Eq. 17 ('XPTO2')

$$\sum_{x1} RDU(z,x1) * XPTOT(z,g,x1)$$
$$+ \sum_{z2,e,i,g2,x2} XPR(z2,e,i,g2,x2)$$
$$\leq AMX$$
$$z \ni (CRIT(z) = 1.0)$$
$$g \ni (CRIT(g) = 1.0)$$
$$x1 \ni (x1 \geq 2)$$
$$z2 \ni (z2 = g)$$
$$g2 \ni (g2 = z \wedge CRPRE(z2,e,i,g2) = 1.0)$$
$$x2 \ni (x2 \geq 2 \wedge CRIR(z2,x2) = 1.0)$$

Variables		
XPTOT(z,g,x)	semi-continuous variable, crop g preceding crop z in frequency x	ha
XPR(z,e,i,g,x)	crop g preceding crop z at environment e and between-crop operation i	ha
Coefficients		
RDU(z,x)	rotation duration, i.e. inverse of cropping frequency, of crop z in frequency x	years
RHS		
AMX	total cultivated area	ha
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRPRE(z,e,i,g)	specification of crops g which can be grown preceding crop z at level e with between-crop operation i	
CRIR(z,x)	existence of data for crop z in rotation x	

3.6. Actions between crops

In a crop rotation various actions between harvest of a crop and sowing of the following crop can be distinguished, which are either not specifically aimed at yield of the following crop, e.g. erosion control on sand, or which affect the yield of several crops in the rotation, e.g. soil fumigation. Presently 5 between-crop operations are defined (index i in table 3.3). The green manure crop sown with animal manure application in autumn on clay is considered an auxilliary measure for nutrient supply. It is discussed in section 3.7.

In MGOPT_CROP equations are formulated to account for between-crop operations (Eqs. 18 - 20). According to Eq. 18, an area XBETW(g,e,i) is defined for all crops. The selection of the type of between-crop operation is governed by Eq. 11 and Eq. 12, where between-crop operations determine the crop yield levels and possible crop sequences.

Eq. 18 ('LBETW')

$$\sum_{i} XBETW(g,e,i) - \sum_{r,v,p,n} L(g,e,r,v,p,n) = 0.0$$

$$g \ni (CRIT(g) = 1.0)$$

$$e \ni (CRIE(g,e) = 1.0)$$

Variables

XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha

Criterion arrays

CRIT(g)	existence of data for crop g
CRIE(g,e)	existence of data for crop g in environment e

In the case of damage due to multi-host soil-borne diseases on crop g, soil fumigation must precede crop g immediately to prevent this damage. However, the timing of soil fumigation is irrelevant for control of those soil-borne pests and diseases whose population levels are affected only by the frequency of specific crops. Presently these effects are quantified for potato cyst nematodes (PCN) on potato and for beet cyst nematodes (BCN) on sugar beet (Habekotté,1994). Damage due to these pests occurs in relation to the frequency of susceptible potato and beet cultivars, respectively, and not by other crops in the rotation. For MGOPT_CROP it is assumed that on fumigated land, susceptible potato and beet cultivars can be grown at damage-free yield levels (identified by variants 5 and 6 of index v for potato and variants 3 and 4 for beet). The fumigation can occur before any suitable crop in the rotation (Eq.19 and Eq. 20).

Eq. 19 ('FUMPO')

$$\sum_{g1,e,r,v1,p,n} L(g1,e,r,v1,p,n) - \sum_{g2,e,i2} XBETW(g2,e,i2) \leq 0.0$$

$$v1 \ni (v1 = 5 \lor v1 = 6)$$

$$g1 \ni (g1 \leq 3)$$

$$g2 \ni (g2 \geq 1)$$

$$i2 \ni (i2 = 1)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha

Eq. 20 ('FUMSB')

$$\sum_{g1,e,r,v1,p,n} L(g1,e,r,v1,p,n) - \sum_{g2,e,i2} XBETW(g2,e,i2) \leq 0.0$$

$$v1 \ni (v1 = 3 \vee v1 = 4)$$
$$g1 \ni (g1 = 4 \vee g1 = 5)$$
$$g2 \ni (g2 \geq 1)$$
$$i2 \ni (i2 = 1)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha

Without fumigation, PCN-susceptible and -resistant potato cultivars can not be combined in a crop rotation, because of their differential effects on the population level of PCN. It is assumed that the effects of susceptible crops on fumigated land and of resistant crops on population density of PCN are identical, allowing for valid combinations in the crop rotation. This is accounted for with Eq. 21 and Eq. 22, employing a binary variable BINPV(b).

Eq. 21 ('PWEX1')

$$- \sum_{g1,e,r,v1,p,n} L(g1,e,r,v1,p,n) + AMX * BINPV(b) \geq 0.0$$

$$\forall b$$
$$g1 \ni (g1 \leq 3)$$
$$v1 \ni (PWEXT(b,v1) = 1.0)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
BINPV(b)	binary variable to exclude unfumigated PCN-susceptible cultivars when PCN-resistant cultivars are selected	-
Coefficients		
AMX	total cultivated area	ha
Criterion arrays		
PWEXT(B,V)	specification of valid combinations of potato cultivars	

Eq. 22 ('BISUM')

$$\sum_{b} BINPV(b) = 1.0$$

Variables

BINPV(b)	binary variable to exclude unfumigated PCN-susceptible cultivars when PCN-resistant cultivars are selected	-

In MGOPT_CROP a maximum frequency for potato cultivars resistant to potato cyst nematodes is set at 0.25 (Eq. 23). With 6 crops of this cultivar before resistance breakthrough, this limitation allows for 25 years of breeding for new resistant cultivars. This guarantees the continuation of production techniques based on these cultivars.

Eq. 23 ('PCNRE')

$$\sum_{gl,e,r,vl,p,n} L(gl,e,r,vl,p,n)$$
$$\leq 0.25 * AMX$$
$$gl \ni (gl \leq 3)$$
$$vl \ni (vl = 3 \vee vl = 4)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
RHS		
AMX	total cultivated area	ha

3.7. Supply of minerals

Attainment of crop yield requires specific amounts of nutrients. Here, only the major minerals N, P, and K are considered. The amounts of N, P and K, required to attain the yield for each crop production technique, are input to MGOPT_CROP. They are calculated for arable crops with TCG_CROP (Habekotté, 1994) and for flower bulb crops with TCG_CROP_BULB (de Ruijter & Jansma, 1994).

The required N is supplied from various sources (Eq. 24). A permanent supply originates from nitrogen deposition (NDEP) and mineralization of soil organic matter before and during crop growth (NMINS and NMING(g), respectively). These rates are assumed constant and not influenced by the production techniques.

Eq. 24 ('NCROP')

$$\sum_{e,r,v,p} CRN * L(g,e,r,v,p,n)$$
$$- NTR(g,n)$$
$$- \sum_{s} NCMAN(s) * MANU(s,g,n)$$
$$- \sum_{e} FYCNI(g,e,n)$$
$$- FERN(g,n)$$
$$- FIXN(g,n)$$
$$= 0.0$$
$$g \ni (CRIT(g) = 1.0)$$
$$n \ni (CRIN(g,n) = 1.0)$$

$$CRN = MAX(0.0, \quad NREQ(g,e,r,v,p,n) - NMINS - 0.5 * NDEP - NMING(g))$$

Variables		
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n (ha)	ha
NTR(g,n)	N transfer from previous crop (kg N)	kg N
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n (tonne)	tonnes
FYCNI(g,e,n)	input of farmyard compost (kg)	kg
FERN(g,n)	fertiliser N on crop g at nutrient level n (kg N)	kg N
FIXN(g,n)	N fixed by leguminous crops (kg N)	kg N
Coefficients		
NREQ(g,e,r,v,p,n)	N requirement of production technique g,e,r,v,p,n	kg $N.ha^{-1}$
NMINS	available mineral N in spring	kg $N.ha^{-1}$
NDEP	N deposition	kg $N.ha^{-1}$
NMING(g)	N mineralised during growth period of crop g	kg $N.ha^{-1}$
NCMAN(s)	crop-available N content of animal manure	kg $N.tonne^{-1}$
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIN(g,n)	existence of data for crop g with nutrient management n	

Only if the N-requirement exceeds this permanent supply (computed as 'CRN'), additional N must be supplied from variable sources: mineralisation of organic residues transfered from a suitable previous crop (including green manure crops) ('NTR'), animal manure ('MANU'), farmyard compost ('FYCNI') or inorganic N-fertiliser ('FERN'). If the crop is a leguminous species, all additionally required N is assumed to be supplied by N-fixation ('FIXN').

The N supply from animal manure requires some further attention. N in animal manure consists of three fractions: N fixed in stable organic matter (Nr), N fixed in organic matter, which is mineralized during the first year after application (Ne), and mineral N (Nmin). The ratio of the fractions depends on the animal species. For reasons of technical feasibility, a minimum quantity of manure must be supplied per hectare. In MGOPT_CROP this is described with Eq. 25, where the minimum is set at 25 kg $Nmin.ha^{-1}$.

Eq. 25 ('MANE')

$$\sum_{s} \mathrm{NMMAN}(s) * \mathrm{MANU}(s,g,n)$$
$$- \sum_{e,r,v,p} (25.) * \mathrm{L}(g,e,r,v,p,n)$$
$$\geq 0.0$$
$$g \ni (\mathrm{CRIT}(g) = 1.0)$$
$$n \ni (n \geq 4 \wedge \mathrm{CRIN}(g,n) = 1.0)$$

Variables		
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
Coefficients		
NMMAN(s)	mineral N content of animal manure of type s	kg $N.tonne^{-1}$
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIN(g,n)	existence of data for crop g with nutrient management n	

On sand, it is assumed that manure is applied in spring, without a green manure crop. The amount of N available for crop growth then equals (Habekotté,1994):

0.45 * Ne + 0.7 * Nmin.

On clay, it is assumed that animal manure is applied in autumn, always in combination with a green manure crop to retain N. The maximum N uptake by a green manure crop is 80 kg ha^{-1}, all of it from the Nmin fraction (van Bon et al., 1994). Corrected for emission losses during application, the maximum amount of Nmin in manure is 80/0.9 kg N/ha, as formulated in Eq. 26. The amount of N in the green manure crop, which is carried over to the main crop, is specified in coefficient NCMAN(s) of Eq. 24.

Eq. 26 ('MANF')

$$- \sum_{e,r,v,p} (80./0.9) * L(g,e,r,v,p,n)$$

$$+ \sum_{s} (CLAY * NMMAN(s)) * MANU(s,g,n)$$

$$\leq 0.0$$

$$g \ni (CRIT(g) = 1.0)$$

$$n \ni (N \geq 4 \wedge CRIN(g,n) = 1.0)$$

Variables		
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
Coefficients		
CLAY	identification of soil type	-
NMMAN(s)	mineral N content of animal manure of type s	kg $N.tonne^{-1}$
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIN(g,n)	existence of data for crop g with nutrient management n	

Autumn application of animal manure on clay is possible only for specific crop successions (Habekotté & Schans, 1995).This is accounted for in Eq. 27.

Eq. 27 ('MANG')

$$\sum_{e1,r,v,p,n1} L(g,e1,r,v,p,n1)$$

$$- \sum_{z1,e1,i,g1,x} XPR(z1,e1,i,g1,x)$$

$$\leq 0.0$$

$$g \ni (FMANG(g) = 1.0)$$

$$e1 \ni (e1 \leq 3)$$

$$n1 \ni (n1 \geq 4)$$

$$z1 \ni (z1 = g)$$

$$g1 \ni (FMNG(z1,e1,i,g1) = 1.0)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
XPR(z,e,i,g,x)	crop g preceding crop z at environment e and between-crop operation i	ha

Criterion arrays

FMANG(g)	criterion for manure application in autumn on crop g
FMNG(z,e,i,g)	criterion for manure application in autumn after crop g

Nitrogen transfer from crop residues (NTR) can originate from preceding crops and from actions between subsequent crops (Eq. 28).

Eq. 28 ('RNTR')

$$\sum_{n} NTR(g,n)$$
$$- \sum_{z1,e,i,g1,x1} NFOLC(g1)*XPR(z1,e,i,g1,x1)$$
$$- \sum_{i1} 30.0*XBETW(g,e,i1)$$
$$= 0.0$$
$$g \ni (CRIT(g) = 1.0)$$
$$z1 \ni (z1 = g)$$
$$g1 \ni (CRPRE(z1,e,i,g1) = 1.0)$$
$$x1 \ni (CRIR(z1,x1) = 1.0)$$
$$i1 \ni (i1 = 5)$$

Variables

NTR(g,n)	N transfer from previous crop g	kg N
XPR(z,e,i,g,x)	crop g preceding crop z at environment e and between-crop operation i	ha
XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha

Coefficients

NFOLC(g)	N transfer rate from preceding crop	kg N.ha^{-1}

Criterion arrays

CRIT(g)	existence of data for crop g
CRIN(g,n)	existence of data for crop g with nutrient management n
CRPRE(z,e,i,g)	specification of crops g which an be grown preceding crop z at level e with between-crop operation i
CRIR(z,x)	existence of data for crop z in rotation x

Formulated more simply, the P and K requirements of a production technique and 'unavoidable losses of P and K', are supplied by animal manure, farmyard compost and inorganic fertilisers (Eqs. 29 and 30).

Eq. 29 ('PCROP')

$$\sum_{g,e,r,v,p,n} (PREQ(g,e,r,v,p,n)+PUNA)*L(g,e,r,v,p,n)$$
$$- \sum_{s,g,n} PCMAN(s)*MANU(s,g,n)$$
$$- \sum_{g,e,n} PCFYC*FYCNI(g,e,n)$$
$$- \sum_{g,n} FERP(g,n)$$
$$= 0.0$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FYCNI(g,e,n)	input of farmyard compost	kg
FERP(g,n)	fertiliser P_2O_5 on crop g at nutrient level n	kg P_2O_5

Coefficients

PREQ(g,e,r,v,p,n)	P_2O_5 requirement of production technique g,e,r,v,p,n	kg $P_2O_5.ha^{-1}$
PUNA	unavoidable losses of P_2O_5	kg $P_2O_5.ha^{-1}$
PCMAN(s)	crop available P_2O_5 in animal manure of type s	kg $P_2O_5.tonne^{-1}$
PCFYC	crop available P_2O_5 in farmyard compost	kg P_2O_5 $.kg^{-1}$ N

Eq. 30 ('KCROP')

$$\sum_{g,e,r,v,p,n} (KREQ(g,e,r,v,p,n) + KUNA) * L(g,e,r,v,p,n)$$
$$- \sum_{s,g,n} KCMAN(s) * MANU(s,g,n)$$
$$- \sum_{g,e,n} KCFYC * FYCNI(g,e,n)$$
$$- FERK$$
$$= 0.0$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FYCNI(g,e,n)	input of farmyard compost	kg
FERK	fertiliser K on crop g at nutrient level n	kg K

Coefficients

KREQ(g,e,r,v,p,n)	K requirement of production technique g,e,r,v,p,n	kg $K.ha^{-1}$
KUNA	unavoidable losses of K	kg $K.ha^{-1}$
KCMAN(s)	crop-available K in animal manure of type s	kg $K.tonne^{-1}$
KCFYC	crop-available K in farmyard compost	kg $K.kg^{-1}$ N

The amount of P_2O_5 applied per ha is subject to legal restrictions (Eq. 31, ref.).

Eq. 31 ('PLEG')

$$\sum_{s} PCMAN(s) * MANU(s,g,n)$$
$$+ FERP(g,n)$$
$$- \sum_{e,r,v,p} PMX * L(g,e,r,v,p,n)$$
$$\leq 0.0$$
$$g \ni (CRIT(g) = 1.0)$$
$$n \ni (CRIN(g,n) = 1.0)$$

Variables		
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FERP(g,n)	fertiliser P_2O_5 on crop g at nutrient level n	kg P_2O_5
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
Coefficients		
PCMAN(s)	rop-available P_2O_5 in animal manure of type s	kg P_2O_5.tonne^{-1}
PMX	legal maximum application rate of P2O5	kg P_2O_5.ha^{-1}
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIN(g,n)	existence of data for crop g with nutrient management n	

3.8. Mineral balances

Mineral balances, i.e. the difference between input and output per mineral, have been formulated to compute losses of minerals. N loss is computed on a crop basis and on a rotation basis, while P and K losses are computed on a rotation basis only.
The N balance is calculated separately for each nutrient management variant of each crop (Eq. 32) to prevent compensation of N loss among nutrient variants. The inputs of the balance are: total yearly mineralisation, total yearly deposition, N supplied with seed or planting material, N supplied from previous crop residues, N fixed by leguminosous crops, and N supplied with fertiliser and animal manure. The outputs are: mineral N content of the upper 60 cm soil, N removed with crop products and N in crop residues transferred to the following crop. The difference between output and input is the N loss.

Eq. 32 ('NBALC')

$$
\begin{aligned}
&\sum_{e,r,v,p} BCN * L(g,e,r,v,p,n) \\
&+ NTR(g,n) \\
&+ FIXN(g,n) \\
&+ FERN(g,n) \\
&+ \sum_{s} (NEMAN(s) + NMMAN(s)) * MANU(s,g,n) \\
&+ \sum_{e} FYCNI(g,e,n) \\
&- NLOSC(g,n) \\
&= 0.0 \\
&g \ni (CRIT(g) = 1.0) \\
&n \ni (CRIN(g,n) = 1.0)
\end{aligned}
$$

$$
\begin{aligned}
BCN = {} & NMINT + NDEP + NSEED(g) - NMINS - \\
& \sum_{q} NPROD(g) * YLD(g,e,r,v,p,n,q) - NFOLC(g) - \\
& FYCNPR(g,e,r,v,p,n)
\end{aligned}
$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
NTR(g,n)	N transfer from previous crop	kg N
FIXN(g,n)	N fixed by leguminous crops	kg N
FERN(g,n)	fertiliser N on crop g at nutrient level n	kg N
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FYCNI(g,e,n)	input of farmyard compost	kg
NLOSC(g,n)	total N loss per crop g at nutrient level n	kg N
Coefficients		
NMINT	total yearly N mineralisation	kg $N.ha^{-1}$
NDEP	N deposition	kg $N.ha^{-1}$
NSEED(g)	N content of seed/planting material	kg $N.ha^{-1}$
NMINS	available mineral N in spring	kg $N.ha^{-1}$
NPROD(g)	N content of harvested fresh product	kg $N.tonne^{-1}$
YLD(g,e,r,v,p,n,q)	crop yield of quality class q in specified production technique	$tonne.ha^{-1}$
NFOLC(g)	N transfer from preceding crop	kg $N.ha^{-1}$
FYCNPR(g,e,r,v,p,n)	farmyard compost production rate	$kg.ha^{-1}$
NEMAN(s)	organic N content of animal manure mineralsied in the first year	kg $N.tonne^{-1}$
NMMAN(s)	mineral N content of animal manure of type s	kg $N.tonne^{-1}$
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIN(g,n)	existence of data for crop g with nutrient management n	

A similar calculation is performed to compute N loss on a rotation basis (Eq. 33). Here, the terms are summed over all crops selected in the rotation, but terms accounting for transfer between crops have been removed. A check on the calculations is performed by comparing the sum of all N-losses per crop with the N-loss of the rotation: permitting rounding errors, the difference must approach zero (Eq. 34).

Eq. 33 ('NBROT')

$$
\begin{aligned}
& \sum_{g,e,r,v,p,n} BRN * L(g,e,r,v,p,n) \\
&+ \sum_{s,g,n} (NEMAN(s) + NMMAN(s)) * MANU(s,g,n) \\
&+ \sum_{g,n} FERN(g,n) \\
&+ \sum_{g,n} FIXN(g,n) \\
&+ \sum_{g,e,i1} 30.0 * XBETW(g,e,i1) \\
&+ \sum_{g,e,n} FYCNI(g,e,n) \\
&- \sum_{g,v,q} NPROD(g) * PROD(g,v,q) \\
&- NLOSS \\
&= 0.0 \\
& i1 \ni (i1 = 5)
\end{aligned}
$$

$$BRN = NMINT + NDEP + NSEED(g) - NMINS - FYCNPR(g,e,r,v,p,n)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FERN(g,n)	fertiliser N on crop g at nutrient level n	kg N
FIXN(g,n)	N fixed by leguminous crops	kg N
XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha
FYCNI(g,e,n)	input of farmyard compost	kg
PROD(g,v,q)	harvested crop products of crop g, variety v, quality class q	tonne
NLOSS	total N loss from rotation	kg N

Coefficients

NMINT	total yearly N mineralisation	kg N.ha^{-1}
NDEP	N deposition	kg N.ha^{-1}
NSEED(g)	N content of seed/planting material	kg N.ha^{-1}
NMINS	available mineral N in spring	kg N.ha^{-1}
FYCNPR(g,e,r,v,p,n)	farmyard compost production rate	kg.ha^{-1}
NEMAN(s)	organic N content of animal manure mineralised in the first year	kg N.tonne^{-1}
NMMAN(s)	mineral N content of animal manure of type s	kg N.tonne^{-1}
NPROD(g)	N content of harvested fresh product	kg N.tonne^{-1}

Eq. 34 ('NCHEK')

$$
\begin{aligned}
&-\sum_{g,n} \text{NLOSC}(g,n) \\
&+ \text{NLOSS} \\
&+ \text{NDIFF} \\
&= 0.0
\end{aligned}
$$

Variables

NLOSC(g,n)	total N loss per crop g at nutrient level n	kg N
NLOSS	total N loss from rotation	kg N
NDIFF	difference between N loss as calculated on crop and rotation bases	kg N

Similarly, P_2O_5 and K losses are calculated for the crop rotation (Eq. 35 and Eq. 36). Inputs to these balances are: contents of these minerals in seed and planting material, animal manure, fertilisers and farmyard compost. Ouputs are contents of these minerals in harvested products and in produced farmyard compost. The differences between input and output are the losses of P_2O_5 and K, including the unavoildable losses.

Eq. 35 ('PBROT')

$$\sum_{g,e,r,v,p,n} BRP * L(g,e,r,v,p,n)$$
$$+ \sum_{s,g,n} PCMAN(s) * MANU(s,g,n)$$
$$+ \sum_{g,n} FERP(g,n)$$
$$+ \sum_{g,e,n} PCFYC * FYCNI(g,e,n)$$
$$- PLOSS$$
$$= 0.0$$

$$BRP = PSEED(g) - \sum_{q} PPROD(g) * YLD(g,e,r,v,p,n,q) - PCFYC * FYCNPR(g,e,r,v,p,n)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FERP(g,n)	fertiliser P_2O_5 on crop g at nutrient level n	kg P_2O_5
FYCNI(g,e,n)	input of farmyard compost	kg
PLOSS	total P_2O_5 loss from rotation	kg P_2O_5

Coefficients

PSEED(g)	P_2O_5 content of seed/planting material	kg $P_2O_5.ha^{-1}$
PPROD(g)	P_2O_5 content of harvested fresh product	kg $P_2O_5.tonne^{-1}$
YLD(g,e,r,v,p,n,q)	crop yield of quality class q in specified production technique	$tonne.ha^{-1}$
PCFYC	crop-available P_2O_5 in farmyard compost, per kg N	kg $P_2O_5.kg^{-1}$ N
FYCNPR(g,e,r,v,p,n)	farmyard compost production rate	$kg.ha^{-1}$
PCMAN(s)	crop-avaialble P_2O_5 in animal manure of type s	kg $P_2O_5.tonne^{-1}$

Eq. 36 ('KBROT')

$$\sum_{g,e,r,v,p,n} BRK * L(g,e,r,v,p,n)$$
$$+ \sum_{s,g,n} KCMAN(s) * MANU(s,g,n)$$
$$+ FERK$$
$$+ \sum_{g,e,n} KCFYC * FYCNI(g,e,n)$$
$$- KLOSS$$
$$= 0.0$$

$$BRK = KSEED(g) - \sum_{q} KPROD(g) * YLD(g,e,r,v,p,n,q) - KCFYC * FYCNPR(g,e,r,v,p,n)$$

Variables		
L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
FERK	fertiliser K on crop g at nutrient level n	kg K
FYCNI(g,e,n)	input of farmyard compost	kg
KLOSS	total K loss from rotation	kg K
Coefficients		
KSEED(g)	K content of seed/planting material	kg $K.ha^{-1}$
KPROD(g)	K content of harvested fresh product	kg $K.tonne^{-1}$
YLD(g,e,r,v,p,n,q)	crop yield of quality class q in specified production technique	$tonne.ha^{-1}$
KCFYC	crop-available K in farmyard compost, per kg N	kg $K.kg^{-1}$ N
FYCNPR(g,e,r,v,p,n)	farmyard compost production rate	$kg.ha^{-1}$
KCMAN(s)	crop-avaialble K in animal manure of type s	kg $K.tonne^{-1}$

The N lost per crop can be separated into the fraction lost as ammonia and the fraction lost as nitrate, with Eq. 37 and Eq. 38.

Eq. 37 ('VNH3')

$$-\sum_{s} \mathrm{VRNH3}(s,n) * \mathrm{MANU}(s,g,n)$$
$$+ \mathrm{NH3C}(g,n)$$
$$= 0.0$$
$$g \ni (\mathrm{CRIT}(g) = 1.0)$$
$$n \ni (\mathrm{CRIN}(g,n) = 1.0)$$

Variables		
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
NH3C(g,n)	N lost via ammonia volatilisation per crop	kg N
Coeffcients		
VRNH3(s,n)	volatilisation rate of NH_3	kg $N.ha^{-1}$
Criterion arrays		
CRIT(g)	existence of data for crop g	
CRIN(g,n)	existence of data for crop g with nutrient management n	

Eq. 38 ('LNO3')

$$-(1.0 - \mathrm{RDEN}) * \mathrm{NLOSC}(g,n)$$
$$+(1.0 - \mathrm{RDEN}) * \mathrm{NH3C}(g,n)$$
$$+\mathrm{NO3C}(g,n)$$
$$= 0.0$$
$$g \ni (\mathrm{CRIT}(g) = 1.0)$$
$$n \ni (\mathrm{CRIN}(g,n) = 1.0)$$

Variables

NLOSC(g,n)	total N lost per crop	kg N
NH3C(g,n)	N lost via ammonia volatilisation per crop	kg N
NO3C(G,N)	N lost as nitrate per crop	kg N

Coeffcients

RDEN	denitrification rate	-

Criterion arrays

CRIT(g)	existence of data for crop g
CRIN(g,n)	existence of data for crop g with nutrient management n

Eq. 39 computes the rest N after harvest for each crop, using the linear regression of crop N requirement on rest N derived by Schröder et al. (1993).

Eq. 39 ('RESTN')

$$- \sum_{e,r,v,p} (NRSC(g) * (NREQ(g,e,r,v,p,n)) * L(g,e,r,v,p,n)$$
$$- \sum_{s} (0.05 * (NEMAN(s) + NMMAN(s))) * MANU(s,g,n)$$
$$+ NREST(g,n)$$
$$= 0.0$$
$$g \ni (CRIT(g) = 1.0)$$
$$n \ni (CRIN(g,n) = 1.0)$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
MANU(s,g,n)	animal manure of type s, on crop g, at nutrient level n	tonne
NREST(g,n)	rest N after harvest	kg N

Coefficients

NRSC(g)	crop specific parameter derived by Schröder et al.	-
NREQ(g,e,r,v,p,n)	N requirement of production technique g,e,r,v,p,n	kg $N.ha^{-1}$
NEMAN(s)	organic N content of animal manure mineralsied in the first year	kg $N.tonne^{-1}$
NMMAN(s)	mineral N content of animal manure of type s	kg $N.tonne^{-1}$

Criterion arrays

CRIT(g)	existence of data for crop g
CRIN(g,n)	existence of data for crop g with nutrient management n

3.9. Pesticides

Policies to reduce negative effects of pesticides on the environment focus on (1) introduction of production techniques with diminished pesticide dependence, (2) use of environmentally safe application methods, and (3) reduction of input of active ingredients per hectare (MNLV,1991). In MGOPT_CROP the first policy path is included through the formulation of such production techniques. The second path is included because each production technique is quantified for the best technical means. The third path is formulated with Eq. 40, calculating total amount of active ingredients, or other defined characteristics of pesticides.

Eq. 40 ('APEST')

$$
\begin{aligned}
& - \sum_{g,e,r,v,p,n} PES(g,e,p,f) * L(g,e,r,v,p,n) \\
& - \sum_{g,e,r,v,p,n} PES(g,e,p,f) * H(g,e,r,v,p,n) \\
& - \sum_{i} PSBTW(i,f) * XBETW(g,e,i) \\
& + IPEST(f) \\
& = 0.0 \\
& \forall f \\
& i \ni (i=1)
\end{aligned}
$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
H(g,e,r,v,p,n)	hired land with production technique g,e,r,v,p,n	ha
XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha
IPEST(f)	inputs of pesticides specified by effect f	f-units
Coefficients		
PES(g,e,p,f)	pesticide effect f per production technique	f-units.ha^{-1}
PSBTW(i,f)	pesticide effect f of between-crop operation i	f-units.ha^{-1}

3.10. Labour

In MGOPT_CROP two types of labour are distinguished: routine labour and expert labour. It is assumed that a fixed amount of labour is present on the farm. For instance, a 50 ha arable farm on clay with 1.5 workers has about 10 hours of labour available per ha per bimonthly period. Current farms are specialised family-based enterprises, and it is assumed that all labour present on the farm is capable of doing both routine and expert labour. If needed, additional labour can be hired for routine tasks.The need for additional labour is evaluated per bimonthly period. For expert tasks, no labour can be hired in MGOPT_CROP, assuming that farmers prefer to keep control of these tasks. The labour input of each labour type and for each bimonthly period is calculated based on the labour requirements of the seperate production techniques (Eq. 41).

Eq. 41 ('ALAB')

$$
\begin{aligned}
& - \sum_{g,e,r,v,p,n} LAB(g,e,p,n,l,t) * L(g,e,r,v,p,n) \\
& - \sum_{g,e,r,v,p,n} LAB(g,e,p,n,l,t) * H(g,e,r,v,p,n) \\
& - \sum_{g,e,i} LABBT(i,l,t) * XBETW(g,e,i) \\
& + ILAB(l,t) \\
& = 0.0 \\
& \forall l \\
& \forall t
\end{aligned}
$$

Variables

L(g,e,r,v,p,n)	land with production technique g,e,r,v,p,n	ha
H(g,e,r,v,p,n)	hired land with production technique g,e,r,v,p,n	ha
XBETW(g,e,i)	crop g at environment e preceded by between-crop operation i	ha
ILAB(l,t)	total bimonthly labour input	hours

Coefficients

LAB(g,e,p,n,l,t)	bimonthly labour requirement per production technique and labour type	$hours.ha^{-1}$
LABBT(i,l,t)	bimonthly labour requirement of between-crop operation i	$hours.ha^{-1}$

The total labour input per bimonthly period is supplied by labour present on the farm and by hired labour (Eq. 42). However, the input of expert labour is supplied by labour present on the farm only (Eq. 43).

Eq. 42 ('ALAB2')

$$- \sum_{l} ILAB(l,t) + \sum_{l1} LABFA(l1,t) + \sum_{l2} LABHI(l2,t) \geq 0.0$$

$$\forall t$$

$$l1 \ni (l1 = 2)$$

$$l2 \ni (l2 = 1)$$

Variables

ILAB(l,t)	total bimonthly labour input	hours
LABFA(l,t)	labour present on farm of type l in period t	hours
LABHI(l,t)	hired labour of type l in period t	hours

Eq. 43 ('ALAB3')

$$- ILAB(l,t) + LABFA(l,t) \geq 0.0$$

$$l \ni (l = 2)$$

$$\forall t$$

Variables

ILAB(l,t)	total bimonthly labour input	hours
LABFA(l,t)	labour present on farm of type l in period t	hours

3.11. Land hire

In addition to land present on the farm, land may be hired elsewhere, a common practice of flower bulb growers. This option is incorporated in MGOPT_CROP, to allow optimisation of farming systems with small farm size and, hence, excessive availability of expert labour. Effects of land hire on income, on pesticide effects, and on labour input are incorporated in Eq. 1, Eq. 40 and Eq. 41, respectively. In this section, the nutrient inputs and N loss on hired land are calculated. It is assumed that animal manure is not applied on hired land. The inputs of fertiliser N, P and K are computed with Eq. 44, Eq. 45 and Eq. 46, repsectively.

Eq. 44 ('NCROH')

$$\sum_{g,e,r,v,p,n} CRH * H(g,e,r,v,p,n)$$
$$- FERNH$$
$$= 0.0$$

$$CRH = MAX(0.0, NREQ(g,e,r,v,p,n) - NMINS - 0.5 * NDEP - NMING)$$

Variables		
H(g,e,r,v,p,n)	hired land with production technique g,e,r,v,p,n	ha
FERNH	fertiliser N used on hired land	kg N
Coefficients		
NREQ(g,e,r,v,p,n)	N requirement of production technique g,e,r,v,p,n	kg $N.ha^{-1}$
NMINS	available mineral N in spring	kg $N.ha^{-1}$
NDEP	N deposition	kg $N.ha^{-1}$
NMING(g)	N mineralised during growth period of crop g	kg $N.ha^{-1}$

Eq. 45 ('PCROH')

$$\sum_{g,e,r,v,p,n} (PREQ(g,e,r,v,p,n) + PUNA) * H(g,e,r,v,p,n)$$
$$- FERPH$$
$$= 0.0$$

Variables:		
H(g,e,r,v,p,n)	hired land with production technique g,e,r,v,p,n	ha
FERPH	fertiliser P_2O_5 used on hired land	kg P_2O_5
Coefficients:		
PREQ(g,e,r,v,p,n)	P_2O_5 requirement of production technique g,e,r,v,p,n	kg $P_2O_5.ha^{-1}$
PUNA	unavoidable losses of P_2O_5	kg $P_2O_5.ha^{-1}$

Eq. 46 ('KCROH')

$$\sum_{g,e,r,v,p,n} (KREQ(g,e,r,v,p,n) + KUNA) * H(g,e,r,v,p,n)$$
$$- FERKH$$
$$= 0.0$$

Variables		
H(g,e,r,v,p,n)	hired land with production technique g,e,r,v,p,n	ha
FERKH	fertiliser P_2O_5 used on hired land	kg K
Coefficients		
KREQ(g,e,r,v,p,n)	K requirement of production technique g,e,r,v,p,n	kg $K.ha^{-1}$
KUNA	unavoidable losses of K	kg $K.ha^{-1}$

The total N loss on hired land is calculated with Eq. 47.

Eq. 47 ('NBALH')

$$\sum_{g,e,r,v,p,n} BCH * H(g,e,r,v,p,n)$$
$$+ FERNH$$
$$- NLOSH$$
$$= 0.0$$

$$BCH = NMINT + NDEP + NSEED(g) - NMINS - \sum_{q} NPROD(g) * YLD(g,e,r,v,p,n,q)$$

Variables		
H(g,e,r,v,p,n)	hired land with production technique g,e,r,v,p,n	ha
FERNH	fertiliser N on hired land	kg N
NLOSH	total N lost on hired land	kg N
Coefficients		
NMINT	total yearly N mineralisation	kg $N.ha^{-1}$
NDEP	N deposition	kg $N.ha^{-1}$
NSEED(g)	N content of seed/planting material	kg $N.ha^{-1}$
NMINS	available mineral N in spring	kg $N.ha^{-1}$
NPROD(g)	N content of harvested fresh product	kg $N.tonne^{-1}$
YLD(g,e,r,v,p,n,q)	crop yield of quality class q in specified production technique	$tonne.ha^{-1}$

4. Concluding remarks

The model presented in this report enables the to construction of crop rotations optimal for specific economic and environmental goals and limitations, using input and output of crop production techniques for building elements. Because the interactions among crops are explicitly formulated in MGOPT_CROP, no prefixed crop combinations are necessary. The distinguished indices to characterise production techniques allow for a high degree of explanatory knowledge in the quantification of coefficients of the production techniques. For instance, interacting effects of cultivar resistance, pesticide input and nutrient supply on crop yield can be taken into account if this knowledge is available. MGOPT_CROP has an open structure: production techniques can be altered or added; prices, labour availability, etc. can be varied easily; and objectives can be changed and added. Hence, this model is suited for analysis of the contribution of production techniques to integration of goals.

A disadvantage of MGOPT_CROP is that the use of binary variables is responsible for long computation times. In a subsequent version, this problem should receive attention.

Under some conditions, erroneous results can be produced by MGOPT_CROP. A 1:4 production technique may be selected in the solution, with half the crop being grown after two years of other crops and the other half being grown after four years of different crops, thus combining a 1:3 rotation with a 1:5 rotation. Strictly speaking, it is not allowed to employ the coefficients for a 1:4 rotation in this situation. However, in practice the associated errors are negligible, especially when considering opposite effects of weather variation on yields of different crops. These erroneous results are possible only if a 1:4 production techniques is combined with 1:8 production techniques, or if a 1:3 production technique is combined with a 1:6 technique. The results do not occur all the time, but in a subsequent version the constraints governing the sequence of crops should be tightened.

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Appendix I

MGOPT_DATA: file containing general data for MGOPT_CROP

The model coefficients are specified in separate files, to allow application of MGOPT_CROP in different economic and environmental settings (e.g. price levels, farm size, labour availability, soil type) and to incorporate data for new crops or new knowledge for crops already specified, without changing the model formulation. The file MGOPT_DATA contains general data on prices, mineral contents of crop products and manure, environmental characteristics and right hand side values (Appendix 1). The file TCCROPS.DAT contains specific data (Technical Coefficients) for all defined crop production techniques (Appendix 2). The data in TCCROPS.DAT are read using a FORTRAN program READTC.FOR (Appendix 3). This program also creates the criterion arrays. At this stage, a number of criterion arrays are still generated by functions within the MGOPT_CROP program. These functions, listed in Appendix 4 should be incorporated in READTC.FOR for greater independence between model and data. Use of MGOPT_CROP with the SCICONIC packages and interpretation of output is explained in the SCICONIC manuals (EDS-Scicon, 1992, 1993).

```
*
*PTION!---OPTIONS---------------------------------------------------------------
*
*ITLE!--PROBLEM-TITLE-----------------------------------------------------------
TITLE OPTICROP - OPTImization of Crop ROtation - Program
*
*ABS !--TAB-COLUMNS-------------------------------------------------------------
*ERSION!--VERSION-NO--VERSION-NAME----------------------------------------------
VERSION  1          june_1995
*NITS!--BIG--SMALL--------------------------------------------------------------
UNITS SMALL=0.01
*AXIMA!!!--SUFFIX-MAXIMA--------------------------------------------------------
*
EXTERNAL VALUES
*
*
*          * Suffix G  - KGNAME
*
*GNAME-SEQ-!!!!!GGGGGGGGGGGGGGGGGG!-EX-
* lifted crops
KGNAME  1       WARE_POTATO
KGNAME  2       SEED_POTATO
KGNAME  3       STARCH_POTATO
KGNAME  4       SUGAR_BEET
KGNAME  5       FODDER_BEET
KGNAME  6       reserve_1
* cereal crops
```

```
KGNAME  7        WINTER_WHEAT
KGNAME  8        SUMMER_WHEAT
KGNAME  9        WINTER_BARLEY
KGNAME 10        SUMMER_BARLEY
KGNAME 11        WINTER_RYE
KGNAME 12        MAIZE
KGNAME 13        GRASS_SEED
KGNAME 14        FALLOW
* vegetable and leguminous crops
KGNAME 15        ONION
KGNAME 16        CARROT
KGNAME 17        CABBAGE
KGNAME 18        CHICORY
KGNAME 19        PEA
KGNAME 20        BEAN
KGNAME 21        FABA_BEAN
KGNAME 22        reserve_3
* green manure crops (green fallow)
KGNAME 23        RYE_GRASS
KGNAME 24        CLOVER
* perannual crops
KGNAME 25        ALFALFA
KGNAME 26        TEMP_GRASSLAND
* flower bulb crops
KGNAME 27        TULIP
KGNAME 28        NARCISSUS
KGNAME 29        CROCUS
KGNAME 30        LILY
KGNAME 31        IRIS
KGNAME 32        GLADIOLUS
KGNAME 33        HYACINTH
KGNAME 34        DAHLIAH
KGNAME 35        reserve_5
*
*          * Suffix E  - KENAME
*
* DIS0 - No soilborne diseases and pests
* DIS1 - multi-host soilborne diseases and pests; damage level 1
* DIS2 - multi-host soilborne diseases and pests; damage level 2
*ENAME-SEQ-!!!!!EEEEEEEEEEEEEE!-EX-
KENAME 1         CLAY_DIS0
KENAME 2         CLAY_DIS1
KENAME 3         CLAY_DIS2
KENAME 4         SAND_DIS0
KENAME 5         SAND_DIS1
KENAME 6         SAND_DIS2
*
*
*          * Suffix R  - KRNAME
*
```

```
*RNAME-SEQ-!!!!!RRRRRRRR!-EX-
KRNAME 1        R1
KRNAME 2        R2
KRNAME 3        R3
KRNAME 4        R4
KRNAME 5        R5
KRNAME 6        R6
KRNAME 7        R7

*
*          * Suffix V  - KVNAME
*
* VAR1 - susceptible for crop-specific soilborne diseases
*      - no soil fumigation
* VAR2 - resistant to crop-specific soilborne diseases
*      - no soil fumigation
* VAR3 - another resistant to crop-specific soilborne diseases
*      - no soil fumigation
* VAR4 - another cultivar
*
*VNAME-SEQ-!!!!!VVVVVVVV!-EX-
KVNAME 1        VAR1
KVNAME 2        VAR2
KVNAME 3        VAR3
KVNAME 4        VAR4
KVNAME 5        VAR5
KVNAME 6        VAR6
KVNAME 7        VAR7
KVNAME 8        VAR8
*
*          * Suffix P  - KPNAME
*
*PNAME-SEQ-!!!!!PPPPPPPP!-EX-
KPNAME 1        CONVEN_1
KPNAME 2        CONVEN_2
KPNAME 3        CONVEN_3
KPNAME 4        NO_PEST
KPNAME 5        CONV_1_F
*
*          * Suffix C  - KCNAME
*
*CNAME-SEQ-!!!!!CCCCCCCC!-EX-
KCNAME 1        TR0
KCNAME 2        TR30
*
*          * Suffix N  - KNNAME
*
*NNAME-SEQ-!!!!!NNNNNNNN!-EX-
KNNAME 1        N1
KNNAME 2        N2
```

```
KNNAME 3        N3
KNNAME 4        N4
KNNAME 5        N5
KNNAME 6        N6
*
*          * Suffix I  - KINAME
*
*INAME-SEQ-!!!!!IIIIIIII!-EX-
KINAME 1        I1
KINAME 2        I2
KINAME 3        I3
KINAME 4        I4
KINAME 5        I5
KINAME 6        I6
KINAME 7        I7
*
*          * Suffix S  - KSNAME
*
*SNAME-SEQ-!!!!!SSSSSSSS!-EX-
KSNAME 1        CHI-MAN
KSNAME 2        COW-SLU
KSNAME 3        PIG-SLU
*
*          * Suffix F  - KFNAME
*
*FNAME-SEQ-!!!!!FFFFFFFFFFFFFFFFFFFF!-EX-
KFNAME 1        Active_ingredients
*
*          * Suffix T  - KTNAME
*
*TNAME-SEQ-!!!!!TTTTTTTT!-EX-
KTNAME 1        BIM1
KTNAME 2        BIM2
KTNAME 3        BIM3
KTNAME 4        BIM4
KTNAME 5        BIM5
KTNAME 6        BIM6
*
*          * Suffix L  - KLNAME
*
*LNAME-SEQ-!!!!!LLLLLLLL!-EX-
KLNAME 1        ROUTINE
KLNAME 2        EXPERT
*
*          * Suffix B  - KBNAME
*
*BNAME-SEQ-!!!!!BBBBBBBB!-EX-
KBNAME 1        B1
KBNAME 2        B2
*
```

```
*          * Suffix Y  - KYNAME
*
*YNAME-SEQ-!!!!!YYYYYYYY!-EX-
KYNAME 1        Y1
KYNAME 2        Y2
KYNAME 3        Y3
KYNAME 4        Y4
KYNAME 5        Y5
*
*          * External value ECBON(G) (KWIN 92/93)
*
*CBON -SEQ---------+--------+--------+--------+--------+--------+--------+
ECBON    1       0.       0.       0.       0.       0.                473.
ECBON    2     473.     473.     473.     341.     473.     752.     851.
ECBON    3       0.       0.       0.       0.     473.     473.     473.
ECBON    4       0.       0.       0.       0.
*
*          * External value PLAND
*
*LAND --------+
PLAND    6000.0
*
*          * External value PLABH (GLD HOUR-1)
*
*LABH --------+
PLABH      15.0
*
* Price of nitrogen fertilizer  (gld.kg-1 N)
*          * External value PFERN
*
*FERN --------+
PFERN      1.02
*
* Price of phosphate fertilizer  (gld.kg-1 P2O5)
*          * External value PFERP
*
*FERP --------+
PFERP      0.82
*
* Price of potassium fertilizer  (gld.kg-1 K2O)
*          * External value PFERK
*
*FERK --------+
PFERK      0.54
*
* Price of animal manure of type S (gld ton-1)
*          * External value PMANU(S)
*
*MANU !!!!!--------+--------+--------+--------+
PMANU           5.00     2.00     2.00
```

```
*
* Total costs (middel+mach+trekker+loonw) of between-crop
*       measures (gld ha-1)
*          * External value PBETW(I)
*
*BETW !!!!!--------+--------+--------+--------+--------+--------+--------+
PBETW        1060.00  2184.00  2874.00   845.00   166.40       0.
*
*          * External value PSBTW(I,F)
*
*SBTW !IIIIIIII!!!!!--------+--------+--------+
PSBTW  I1              150.
*
* price of high quality crop products of crop G and variety V (gld ton-1)
* KWIN 92/92
*          * External value PPH(G,V)
*
*PH    !GGGGGGGGGGGGGGGGGGG-SEQ---------+--------+--------+--------+--------+
PPH    WARE_POTATO          1      210.00   210.00   210.00   210.00   210.00
PPH    WARE_POTATO          2      210.00   210.00   210.00
PPH    SEED_POTATO          1      460.00   460.00   460.00   460.00   460.00
PPH    SEED_POTATO          2      460.00   460.00   460.00
PPH    SUGAR_BEET           1      116.00   116.00   116.00   116.00   116.00
PPH    SUGAR_BEET           2      116.00   116.00   116.00
PPH    WINTER_WHEAT         1      290.00   290.00   290.00   290.00   290.00
PPH    WINTER_WHEAT         2      290.00   290.00   290.00
PPH    SUMMER_WHEAT         1      380.00   380.00   380.00   380.00   380.00
PPH    SUMMER_WHEAT         2      380.00   380.00   380.00
PPH    SUMMER_BARLEY        1      350.00   350.00   350.00   350.00   350.00
PPH    SUMMER_BARLEY        2      350.00   350.00   350.00
PPH    MAIZE                1      220.00   220.00   220.00   220.00   220.00
PPH    MAIZE                2      220.00   220.00   220.00
PPH    ONION                1      160.00   160.00   160.00   160.00   160.00
PPH    ONION                2      160.00   160.00   160.00
PPH    PEA                  1      320.00   320.00   320.00   320.00   320.00
PPH    PEA                  2      320.00   320.00   320.00
PPH    FABA_BEAN            1      290.00   290.00   290.00   290.00   290.00
PPH    FABA_BEAN            2      290.00   290.00   290.00
PPH    GRASS_SEED           1     2100.00  2100.00  2100.00  2100.00  2100.00
PPH    GRASS_SEED           2     2100.00  2100.00  2100.00
* source : IKC-BLOEMBOLLEN, (crocus is estimated value)
PPH    TULIP                1     4000.00  4000.00  4000.00  4000.00  4000.00
PPH    TULIP                2     4000.00  4000.00  4000.00
PPH    NARCISSUS            1     1000.00  1000.00  1000.00  1000.00  1000.00
PPH    NARCISSUS            2     1000.00  1000.00  1000.00
PPH    LILY                 1     5500.00  5500.00  5500.00  5500.00  5500.00
PPH    LILY                 2     5500.00  5500.00  5500.00
PPH    HYACINTH             1     6000.00  6000.00  6000.00  6000.00  6000.00
PPH    HYACINTH             1     6000.00  6000.00  6000.00
PPH    CROCUS               1      700.00   700.00   700.00   700.00   700.00
```

```
PPH     CROCUS                 2       700.00   700.00   700.00
*
* Price of low quality crop products of crop G and variety V
*          * External value PPL(G,V)
*
*PL     !GGGGGGGGGGGGGGGGGGGG-SEQ---------+--------+--------+--------+--------+
PPL     WARE_POTATO            1        50.00    50.00    50.00    50.00
PPL     SEED_POTATO            1        50.00    50.00    50.00    50.00
PPL     SUGAR_BEET             1        50.00    50.00    50.00    50.00
PPL     WINTER_WHEAT           1        50.00    50.00    50.00    50.00
PPL     SUMMER_BARLEY          1        50.00    50.00    50.00    50.00
PPL     MAIZE                  1        50.00    50.00    50.00    50.00
PPL     ONION                  1        50.00    50.00    50.00    50.00
PPL     PEA                    1        50.00    50.00    50.00    50.00
PPL     FÁBA_BEAN              1        50.00    50.00    50.00    50.00
PPL     GRASS_SEED             1        50.00    50.00    50.00    50.00
*
*          * External value NSEED(G) (kg N ha-1) (Habekotte,1994,
*                                                 tab VI.2.10)
*
*SEED -SEQ--------+--------+--------+--------+--------+--------+--------+
NSEED  1          7.0      7.0      7.0      0.0                        4.0
NSEED  2                            4.0               0.0      0.0
NSEED  3          0.0      0.0                        5.0               5.0
*SEED  4                                                       38.9     95.7
*SEED  5                   27.4                       53.2
*
*          * External value PSEED(G)
*
*SEED -SEQ--------+--------+--------+--------+--------+--------+--------+
PSEED  1          2.5      2.5      2.5      0.0                        1.7
PSEED  2                            2.1               0.0      0.0
PSEED  3          0.0      0.0                        1.5               1.6
*SEED  4                                                       5.8      13.7
*SEED  5                   3.4                        8.1
*
*          * External value KSEED(G)
*
*SEED -SEQ--------+--------+--------+--------+--------+--------+--------+
KSEED  1          10.6     10.6     10.6     0.0                        1.0
KSEED  2                            1.6               0.0      0.0
KSEED  3          0.0      0.0                        2.1               1.9
*SEED  4                                                       41.7     87.2
*SEED  5                   39.8                       40.2
*
*          * External value NPROD(G) (kg t-1,vers, Habekotte, 1994,
*                                     tabel VI.2.1)
*            !!! NB !!
*            !!! NPROD/NHI for G=7-11,13 vanwege afvoer bijprodukt !!!
*            !!! NHI = 0.77 (Habekotte, tabel vi.2.3)
```

```
*            !!! NHI = 0.36 voor grass seed uitgaande van
*                                  6 ton stro afvoer (Habekotte,31-1-95)
*
*PROD -SEQ--------+--------+--------+--------+--------+--------+--------+
NPROD  1         3.3      3.3      3.7      1.5      1.5               26.0
NPROD  2                          21.4               4.6      50.0
NPROD  3         2.0      1.5                       34.0               40.0
NPROD  4                                                       3.9      3.8
NPROD  5                  4.2                        4.1
*
*          * External value PPROD(G)
*            !!! NB !!
*            !!! PPROD/PHI for G=7-11,13 vanwege afvoer bijprodukt !!!
*            !!! (gecorrigeerde HABEKOTTE TABEL vi.2.2)
*
*PROD -SEQ--------+--------+--------+--------+--------+--------+--------+
PPROD  1         1.2      1.2      0.9      1.0                         9.6
PPROD  2                           9.0               1.7      21.6
PPROD  3         0.9      0.7                       10.0               13.0
PPROD  4                                                       0.6      0.5
PPROD  5                  0.5                        0.6
*
*          * External value KPROD(G)
*            !!! NB !!
*            !!! KPROD/KHI for G=7-11,13 vanwege afvoer bijprodukt !!!
*            !!! (gecorrigeerde HABEKOTTE TABEL vi.2.2)
*
*PROD -SEQ--------+--------+--------+--------+--------+--------+--------+
KPROD  1         5.0      5.0      5.2      2.3                        11.1
KPROD  2                          18.6               6.0     104.5
KPROD  3         2.4      4.5                       14.0               15.0
KPROD  4                                                       4.2      3.5
KPROD  5                  6.1                        3.1
*
*          * External value NRSC(G)
*
*RSC  -SEQ--------+--------+--------+--------+--------+--------+--------+
NRSC   1        0.21     0.21     0.21     0.13     0.13     0.13     0.13
NRSC   2        0.13     0.13     0.13     0.13     0.21     0.13     0.00
NRSC   3        0.21     0.13     0.13     0.13     0.13     0.13     0.13
NRSC   4                                                     0.21     0.21
NRSC   5                 0.21                       0.21
*
*          * External value NDEP (kg N ha-1 yr-1)
*
*DEP  --------+
NDEP        50.
*
*
*          * External value RDEN
```

```
*
*DEN  --------+
RDEN         0.1
*
*          * External value NMINS (Nmin in spring, kg ha-1)
*
*MINS --------+
NMINS       40.
*
*          * External value NMINT (total yearly Nmineraliz., kg ha-1)
*            (1okt-1mrt: 40 kg + 1mrt-31jul: 50 kg + 1aug-31sep: 20 kg)
*MINT --------+
NMINT      110.
*
*          * External value NMING(G) (Nmineraliz. during crop growth)
*
*MING -SEQ--------+--------+--------+--------+--------+--------+--------+
NMING  1         50.      50.      50.      50.      50.      50.      50.
NMING  2         50.      50.      50.      50.      50.      50.      50.
NMING  3         50.      50.      50.      50.      50.      50.      50.
NMING  4         50.      50.      50.      50.      50.      25.      25.
NMING  5         25.      50.      50.      50.      25.      50.      50.
*
*                            * Unavoildable losses of P and K (kg ha-1)
*UNA  --------+
PUNA        20.
*
*UNA  --------+
KUNA        25.
*
*          * External value RFN
*
*FN   --------+
RFN      -9999.
*
*          * External value RFM
*
*FM   --------+
RFM      -9999.
*
*          * External value RNT (kg N)
*
*NT   --------+
RNT       9999.
*
*          * External value RNR
*
*NR   --------+
RNR       9999.
*
```

```
*          * External value RFU
*            RFU = 0.166667 voor klei, 0.2 voor zand !
*
*FU    --------+
*FU         0.2
RFU    0.166667
*
*          * External value RP1 (kg active ingredients)
*
*P1    --------+
RP1       9999.
*
*
*          * External value AMX (ha)
*
*MX    --------+
AMX         1.0
*
*          * External value LABMX(L,T)
*
*ABMX !LLLLLLLL!!!!!--------+--------+--------+--------+--------+--------+
* voor akkerbouw (AMX= 1ha):
*ABMX  ROUTINE           999.     999.     999.     999.     999.     999.
LABMX  ROUTINE             0.       0.       0.       0.       0.       0.
LABMX  EXPERT             11.      11.      11.      11.      11.      11.
* voor bloembollen (1 VAK = 350 uur; AMX=10 ha)
*ABMX  ROUTINE             0.       0.       0.       0.       0.       0.
*LABMX  EXPERT            700.     700.     700.     700.     700.     700.
* voor bloembollen (1 VAK = 350 uur; AMX= 25ha):
*ABMX  ROUTINE             0.       0.       0.       0.       0.       0.
*ABMX  EXPERT           1400.    1400.    1400.    1400.    1400.    1400.
*
*          * External value NFOLC(G)
*
*FOLC -SEQ---------+--------+--------+--------+--------+--------+--------+
NFOLC  1         0.0      0.0      0.0     30.0     30.0      0.0      0.0
NFOLC  2         0.0      0.0      0.0      0.0      0.0     30.0     30.0
NFOLC  3         0.0      0.0      0.0      0.0     30.0     30.0     30.0
NFOLC  4         0.0      0.0     30.0     30.0      0.0      0.0      0.0
NFOLC  5         0.0      0.0      0.0      0.0      0.0      0.0      0.0
*
*
* N-fracties in dierlijke mest (kg ton-1)
*        droge kip    runderdrijf  varkdrijf
* Nmin      10.9          2.2         3.3
* Ne         9.0          1.1         2.2
* Nr         4.4          1.1         1.1
*
*
*          * External value NMMAN(S) (Nmin) content of manure,
```

```
*                                      kg ton-1)
*
*MMAN !!!!!--------+--------+-------+--------+
NMMAN          10.9      2.2      3.3
*
*          * External value NEMAN(S) (Ne) content of manure,
*                                      kg ton-1)
*
*EMAN !!!!!--------+--------+-------+--------+
NEMAN           9.0      1.1      2.2
*
*          * External value NOMAN(S) (Nr content of manure, kg ton-1)
*                                  N organic matter, not mineralisable
*
*OMAN !!!!!--------+--------+-------+--------+
NOMAN           4.4      1.1      1.1
*          * External value NCMAN(S)
*            CLAY (fall apll.) : 0.29*Ne + 0.122*0.9*Nmin
*            SAND (spring appl): 0.48*Ne + 0.85 *0.9*Nmin
*cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
*C:PREVIOUS CALCULATION:
*C
*C      N.B. on clay: always green manure crop with animal manure
*C                    avaialble to crop =
*C                      NGRMAN * L(g,e,r,v,p,n)
*C                    + (0.29*NEMAN) * MANU
*C                    + (NMMAN*MANU-80.*L(g,e,r,v,p,n))*0.122*0.9
*C                    ===
*C                      (NGRMAN-80.*0.122*0.9) * L(g,e,r,v,p,n)
*C                    + (0.29*NEMAN+0.122*0.9*NMMAN) * MANU
*cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
*
*cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
*C new calculation on clay:
*C - obligatory green manure crop in fall with manure appl.
*  - green manure crop takes up all Nmin applied with manure, to a
*    maximum of 80 kg N/ha
*  - 0.25 of Nmin is transferred to main crop next season
*C
*  - hence: crop available N in animal manure equals:
*    0.29*Ne + 0.25* Nmin
*
* ! CLAY !!!!!!!
*CMAN !!!!!--------+--------+--------+--------+
NCMAN          5.335    0.869    1.463
*
* ! SAND !!!!!!!
*CMAN !!!!!--------+--------+--------+--------+
*NCMAN         12.659    2.211    3.581
*
```

```
*          * External value PCMAN(S)
*
*CMAN !!!!!--------+--------+--------+--------+
PCMAN          28.3      1.8      3.9
*
*          * External value KCMAN(S)
*
*CMAN !!!!!--------+--------+--------+--------+
KCMAN          22.2      5.5      6.8
*
*          * External value VRNH3(S,N)
*          * 0.1 * Nmin (direct inwerken !)
*
*RNH3 !SSSSSSSS!!!!!--------+--------+--------+--------+--------+--------+
*VRNH3  CHI-MAN             0.       0.       0.      1.1      1.1      1.1
*VRNH3  COW-SLU             0.       0.       0.     0.22     0.22     0.22
*VRNH3  PIG-SLU             0.       0.       0.  -  0.33     0.33     0.33
*
*          * External value NGRMAN
*
*GRMAN--------+
*NGRMAN     30.
*
*          * External value PCFYC
*
*CFYC --------+
*
*          * External value KCFYC
*
*CFYC --------+
*
*          * Legal maximum applicatio rate of P2O5 (kg .ha-1)
*MX    --------+
PMX      125.0
*
*          * External value COGR(E,N)
*
*OGR  !EEEEEEEEEEEEEEE-SEQ--------+--------+--------+--------+--------+
COGR        CLAY_DIS0   1        0.       0.       0.    166.4    166.4
COGR        CLAY_DIS0   2     166.4
COGR        CLAY_DIS1   1        0.       0.       0.    166.4    166.4
COGR        CLAY_DIS1   2     166.4
COGR        CLAY_DIS2   1        0.       0.       0.    166.4    166.4
COGR        CLAY_DIS2   2     166.4
*
*          * External value COMAP(N)
*
*OMAP !!!!!--------+--------+--------+--------+--------+--------+
COMAP            0.       0.       0.     178.     178.     178.
*
```

```
*          * External value LABGR(L,T)
*
*ABGR !LLLLLLLL!!!!!--------+--------+--------+--------+--------+--------+
LABGR  ROUTINE                                          1.1
*
*          * External value LABBT(I,L,T)
*
*ABBT !IIIIIIII!LLLLLLLL-SEQ---------+--------+--------+--------+--------+
LABBT  I2        ROUTINE    1                                  6.5      3.5
LABBT  I3        ROUTINE    1                                  6.5      3.5
LABBT  I4        EXPERT     1                                  1.6
LABBT  I5        ROUTINE    1                                  3.3
*
*LAY  --------+
CLAY       1.0
ENDATA
```

Appendix II

TCCROPS.DAT (excerpt): file containing specific data for production techniques

```
'WARE_POTATO'  1
  2  6  6  2  6    0.
  1  1  1  1  1   34.10    2.00   40.89  249.19  170.44 2260.00    0.00 2150.85    0.40    5.10    4.90    4.00   18.20    0.70   21.60
  1  1  1  1  2   32.40    2.00   38.85  195.65  161.92 2260.00    0.00 2150.85    0.40    5.10    4.90    4.00   18.20    0.70   21.60
  1  1  1  1  3   30.69    2.00   36.80  171.04  153.40 2260.00    0.00 2150.85    0.40    5.10    4.90    4.00   18.20    0.70   21.60
  1  3  2  1  4   48.76    4.00   63.73  388.39  265.65 2230.40  188.00 2150.85    0.40    4.70    4.90    4.00   18.20    0.70   21.60
  1  3  2  1  5   46.33    4.00   60.55  304.95  252.37 2230.40  188.00 2150.85    0.40    4.70    4.90    4.00   18.20    0.70   21.60
  1  3  2  1  6   43.89    4.00   57.36  266.58  239.09 2230.40  188.00 2150.85    0.40    4.70    4.90    4.00   18.20    0.70   21.60
 'WINTER_WHEAT'  7
  2  6  2  2  3    1.
  1  1  1  1  1    7.98    2.00   68.51  299.51   40.36 1404.40    0.00  832.25    1.20    0.00    4.30    5.20    3.10    2.80    4.28
  1  1  1  1  2    7.58    2.00   65.08  265.76   38.34 1404.40    0.00  832.25    1.20    0.00    4.30    5.20    3.10    2.80    4.28
  1  1  1  1  3    7.18    2.00   61.66  241.29   36.32 1404.40    0.00  832.25    1.20    0.00    4.30    5.20    3.10    2.80    4.28
  1  1  1  2  1    7.34    2.00   63.03  275.55   37.13 1453.60    0.00  633.50    1.20    1.20    3.40    5.20    3.10    2.80    1.35
  1  1  1  2  2    6.97    2.00   59.88  244.49   35.27 1453.60    0.00  633.50    1.20    1.20    3.40    5.20    3.10    2.80    1.35
  1  1  1  2  3    6.61    2.00   56.72  221.98   33.42 1453.60    0.00  633.50    1.20    1.20    3.40    5.20    3.10    2.80    1.35
```

Appendix III

READTC.FOR: subroutine for reading of TCCROPS.DAT and for specification of criterion arrays

```
      SUBROUTINE READTC

C (Subroutine for) reading of data from external datafile TCCROPS.DAT

      INCLUDE 'MGCOMS'

      CHARACTER*20 CRPNAM
      INTEGER GG1, II

C I used as alias for E to create criterion table CET, lumping disease
C levels per soil type
      CET(1,1)  = 1.0
      CET(1,2)  = 1.0
      CET(1,3)  = 1.0
      CET(2,1)  = 1.0
      CET(2,2)  = 1.0
      CET(2,3)  = 1.0
      CET(3,1)  = 1.0
      CET(3,2)  = 1.0
      CET(3,3)  = 1.0
      CET(4,4)  = 1.0
      CET(4,5)  = 1.0
      CET(4,6)  = 1.0
      CET(5,4)  = 1.0
      CET(5,5)  = 1.0
      CET(5,6)  = 1.0
      CET(6,4)  = 1.0
      CET(6,5)  = 1.0
      CET(6,6)  = 1.0

C criterion array to specify crops with identical
C rotational effects
      CRRID(1,1) = 1.0
      CRRID(1,2) = 1.0
      CRRID(1,3) = 1.0
      CRRID(2,1) = 1.0
      CRRID(2,2) = 1.0
      CRRID(2,3) = 1.0
      CRRID(3,1) = 1.0
      CRRID(3,2) = 1.0
```

```
      CRRID(3,3)  = 1.0
      CRRID(4,4)  = 1.0
      CRRID(4,5)  = 1.0
      CRRID(5,4)  = 1.0
      CRRID(5,5)  = 1.0
      CRRID(7,7)  = 1.0
      CRRID(7,8)  = 1.0
      CRRID(8,7)  = 1.0
      CRRID(8,8)  = 1.0
      CRRID(10,10)  = 1.0
      CRRID(12,12)  = 1.0
      CRRID(13,13)  = 1.0
      CRRID(14,14)  = 1.0
      CRRID(15,15)  = 1.0
      CRRID(16,16)  = 1.0
      CRRID(19,19)  = 1.0
      CRRID(21,21)  = 1.0
      CRRID(27,27)  = 1.0
      CRRID(28,28)  = 1.0
      CRRID(29,29)  = 1.0
      CRRID(30,30)  = 1.0
      CRRID(31,31)  = 1.0
      CRRID(33,33)  = 1.0
      CRRID(34,34)  = 1.0

C specification of operations between crops that provide a disease-free
C environment (E=1 or E=4)
      CRBTW(1,1,1)  = 1.0
      CRBTW(2,1,1)  = 1.0
      CRBTW(4,1,1)  = 1.0
      CRBTW(5,1,1)  = 1.0
      CRBTW(19,1,1)  = 1.0
      CRBTW(1,4,1)  = 1.0
      CRBTW(2,4,1)  = 1.0
      CRBTW(3,4,1)  = 1.0
      CRBTW(4,4,1)  = 1.0
      CRBTW(5,4,1)  = 1.0
      CRBTW(19,4,1)  = 1.0
      CRBTW(27,4,1)  = 1.0
      CRBTW(28,4,1)  = 1.0
      CRBTW(30,4,1)  = 1.0
      CRBTW(33,4,1)  = 1.0
      CRBTW(28,4,2)  = 1.0
      CRBTW(30,4,3)  = 1.0

C specification of rotation duration allowed for technically feasible
C combinations of crop frequencies
      EXROT(1,1)   = 1.0
      EXROT(1,3)   = 1.0
      EXROT(1,7)   = 1.0
```

```
      EXROT(2,1)   = 1.0
      EXROT(2,5)   = 1.0
      EXROT(3,2)   = 1.0
      EXROT(3,5)   = 1.0
      EXROT(4,3)   = 1.0
      EXROT(4,5)   = 1.0
      EXROT(5,4)   = 1.0

C specification of valid combinations of potato varieties
C (pcn-susceptible or pcn-resistant)
      PWEXT(1,1) = 1.0
      PWEXT(1,2) = 1.0
      PWEXT(2,3) = 1.0
      PWEXT(2,4) = 1.0
      PWEXT(2,5) = 1.0
      PWEXT(2,6) = 1.0

      CALL FOPEN (20,'TCCROPS.DAT','OLD','NVT')
C      CALL FOPEN (25,'TEST.DAT','NEW','DEL')
C      CALL FOPEN (55,'TABTST.DAT','NEW','DEL')

C initial settings:
C kriterium voor opname van gewasvariabelen (L..) is FALSE voor
C alle gewassen

      DO 5 G = 1,MAXG
        CRIT(G) = 0.
        CRCR1(G) = 0.
5     CONTINUE

C main program

10    READ (20,*) CRPNAM,GG1
      WRITE (*,'(1X,A20,I4)') CRPNAM,GG1
      IF (CRPNAM .EQ. 'END_CROPDATA') THEN
        GO TO 50
      ELSE IF (GG1 .GT. MAXG .OR. CRPNAM .NE. KGNAME(GG1)) THEN
        CALL ERROR ('READTC','Crop name or code number in
     &  TCG_CROP different from MGOPT_CROP')
      ELSE
        G = GG1
        CRIT(G) = 1.0
      END IF

      READ (20,*) NE(G),NR(G),NV(G),NP(G),NN(G),CRCR1(G)
      JJ = NE(G)*NR(G)*NV(G)*NP(G)*NN(G)
      DO 20 II=1,JJ
        READ(20,*) E,R,V,P,N,YHQ(G,E,R,V,P,N),RDU(G,R),
     &    PREQ(G,E,R,V,P,N),NREQ(G,E,R,V,P,N),KREQ(G,E,R,V,P,N),
     &    CMA(G,E,P,N),CCL(G,E,P,N),COI(G,E,P,N),
```

```
     &     LAB(G,E,P,N,2,1),LAB(G,E,P,N,2,2),LAB(G,E,P,N,2,3),
     &     LAB(G,E,P,N,2,4),LAB(G,E,P,N,2,5),LAB(G,E,P,N,2,6),
     &     PES(G,E,P,1)
C    &     ,FYCNPR(G,E,R,V,P,N)
        CRIE(G,E) = 1.0
        CRIR(G,R) = 1.0
        CRIV(G,V) = 1.0
        CRIP(G,P) = 1.0
        CRIN(G,N) = 1.0
20    CONTINUE
      GO TO 10

50    CONTINUE

       DO 300 Z=1,MAXZ
         DO 290 E=1,MAXE
           DO 280 I=1,MAXI
             DO 270 G=1,MAXG
               CRPRE(Z,E,I,G) = FCRPRE(Z,E,I,G)
270          CONTINUE
280        CONTINUE
290      CONTINUE
300    CONTINUE

      DO 400 G=1,MAXG
        DO 390 R=1,MAXR
          ABIL(G,R) = 1.0
390     CONTINUE
400   CONTINUE

      DO 500 Z=1,MAXZ
        DO 490 G=1,MAXG
          DO 480 X=1,MAXX
            ABIX(Z,G,X) =1.0
480       CONTINUE
490     CONTINUE
500   CONTINUE

      DO 600 Y=1,MAXY
        ABIR(Y) = 1.0
        IF (Y.EQ.4) ABIR(Y)=0.0
600   CONTINUE

      DO 700 B=1,MAXB
        ABIV(B) = 1.0
700   CONTINUE

      CLOSE (UNIT=20)

      RETURN
```

```
      END

      FUNCTION FCRPRE(ZA,EA,IA,GA)
      INTEGER ZA,EA,IA,GA
      FCRPRE = 0.0

C specification of crops G which can be grown before crop Z(E) with
C intermediate operation I
C CRPRE(Z,E,I,G): crop G can be grown before crop Z(e) with XBETW(z,i)

C mogelijkheid van tussenteeltmaatregelen voor niet-bolgewassen
C nog verder uitwerken !! Nu staat alles op I=5 (groenbemester)

C possible crops preceding ware, seed and starch potato
      IF ((ZA.GE.1 .AND. ZA.LE.3) .AND. (EA.EQ.1) .AND.
     &    (IA.EQ.1 .OR. IA.EQ.6) .AND. ((GA.GE.7 .AND. GA.LE.18)
     &    .OR. (GA.GE.22 .AND. GA.LE.35))) THEN
        FCRPRE = 1.0
      END IF
C          ! fumigation no effect on Vert. dahliae;
      IF ((ZA.GE.1 .AND. ZA.LE.3) .AND. (EA.EQ.2) .AND.
     &    (IA.EQ.1 .OR. IA.EQ.6) .AND. (GA.EQ.19
     &    .OR. GA.EQ.20 .OR. GA.EQ.21)) THEN
        FCRPRE = 1.0
      END IF
C          ! fumigation not possible after beet
      IF ((ZA.GE.1 .AND. ZA.LE.3) .AND. (EA.EQ.2) .AND.
     &    (IA.EQ.6) .AND. (GA.EQ.4 .OR. GA.EQ.5)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.GE.1 .AND. ZA.LE.3) .AND. (EA.EQ.4) .AND.
     &    (IA.EQ.1 .OR. IA.EQ.5) .AND. ((GA.GE.7 .AND. GA.LE.18)
     &    .OR. (GA.GE.22 .AND. GA.LE.35))) THEN
        FCRPRE = 1.0
      END IF
C          ! fumigation no effect on Vert. dahliae;
      IF ((ZA.GE.1 .AND. ZA.LE.3) .AND. (EA.EQ.5) .AND.
     &    (IA.EQ.1 .OR. IA.EQ.5) .AND. (GA.EQ.19
     &    .OR. GA.EQ.20 .OR. GA.EQ.21)) THEN
        FCRPRE = 1.0
      END IF
C          ! fumigation not possible after beet
      IF ((ZA.GE.1 .AND. ZA.LE.3) .AND. (EA.EQ.5) .AND.
     &    (IA.EQ.6) .AND. (GA.EQ.4 .OR. GA.EQ.5)) THEN
        FCRPRE = 1.0
      END IF
C
C possible crops preceding sugar and fodder beet
      IF ((ZA.EQ.4 .OR. ZA.EQ.5) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND.
     &    (IA.EQ.1) .AND. (GA.LE.3 .OR. (GA.GE.7 .AND. GA.LE.35))) THEN
```

```
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.4 .OR. ZA.EQ.5) .AND. (EA.EQ.1) .AND.
     &    (IA.EQ.6) .AND. (GA.GE.7 .AND. GA.LE.35)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.4 .OR. ZA.EQ.5) .AND. (EA.EQ.2) .AND.
     &    (IA.EQ.6) .AND. (GA.LE.3)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.4 .OR. ZA.EQ.5) .AND. (EA.EQ.4) .AND.
     &    (IA.EQ.5 .OR. IA.EQ.6) .AND. (GA.GE.7 .AND. GA.LE.35)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.4 .OR. ZA.EQ.5) .AND. (EA.EQ.5) .AND.
     &    (IA.EQ.5) .AND . (GA.LE.3)) THEN
        FCRPRE = 1.0
      END IF
C
C possible crops preceding winter wheat
      IF ((ZA.EQ.7) .AND. (EA.EQ.1) .AND. (IA.EQ.6) .AND.
     &    (GA.LE.5 .OR. GA.GE.12)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.7) .AND. (EA.EQ.2) .AND. (IA.EQ.6) .AND.
     &    (GA.GE.8 .AND. GA.LE.11)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.7) .AND. (EA.EQ.4) .AND. (IA.EQ.6) .AND.
     &    (GA.LE.5 .OR. (GA.GE.12 .AND. GA.LE.29) .OR.
     &    GA.GE.31)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.7) .AND. (EA.EQ.4) .AND. (IA.EQ.6) .AND.
     &    (GA.EQ.30)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.7) .AND. (EA.EQ.5) .AND. (IA.EQ.6) .AND.
     &    (GA.GE.8 .AND. GA.LE.11)) THEN
        FCRPRE = 1.0
      END IF
C
C NOG NIET nader bepaald:
C possible crops preceding summer barley
      IF ((ZA.EQ.10) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND.
     &    (IA.EQ.6)
     &    .AND. (GA.NE.4.AND. GA.NE.5 .AND. GA.NE.10)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.10) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND.
```

```
     &    (IA.EQ.6)
     &    .AND. (GA.NE.10)) THEN
        FCRPRE = 1.0
      END IF
C
C NOG NIET nader bepaald:
C possible crops preceding maize
      IF ((ZA.EQ.12) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND.
     &    (IA.EQ.6)
     &    .AND. (GA.NE.4.AND. GA.NE.5 .AND. GA.NE.12)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.12) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND. (IA.EQ.6)
     &    .AND. (GA.NE.12)) THEN
        FCRPRE = 1.0
      END IF
C
C NOG NIET nader bepaald:
C possible crops preceding grass_seed
      IF ((ZA.EQ.13) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND.
     &    (IA.EQ.6) .AND. (GA.NE.13)) THEN
        FCRPRE = 1.0
      END IF
C
C NOG NIET nader bepaald:
C possible crops preceding fallow
      IF ((ZA.EQ.14) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND.
     &    (IA.EQ.5 .OR. IA.EQ.6)
     &    .AND. (GA.NE.4.AND. GA.NE.5 .AND. GA.NE.14)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.14) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND. (IA.EQ.6)
     &    .AND. (GA.NE.14)) THEN
        FCRPRE = 1.0
      END IF
C
C NOG NIET nader bepaald:
C possible crops preceding onion
      IF ((ZA.EQ.15) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND.
     &    (IA.EQ.5 .OR. IA.EQ.6)
     &    .AND. (GA.NE.4.AND. GA.NE.5 .AND. GA.NE.15)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.15) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND. (IA.EQ.6)
     &    .AND. (GA.NE.15)) THEN
        FCRPRE = 1.0
      END IF
C
C possible crops preceding dry pea
      IF ((ZA.EQ.19) .AND. (EA.EQ.1 .OR. EA.EQ.4) .AND. (IA.EQ.1)
```

```
     &    .AND. (GA.NE.4 .AND. GA.NE.5 .AND. GA.NE.19)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.19) .AND. (EA.EQ.1) .AND. (IA.EQ.6) .AND.
     &    (GA.LE.6 .OR. (GA.GE.14 .AND. GA.LE.18) .OR.
     &    GA.GE.20)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.19) .AND. (EA.EQ.2) .AND. (IA.EQ.6) .AND.
     &    (GA.GE.7 .AND. GA.LE.13)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.19) .AND. (EA.EQ.4) .AND. (IA.EQ.5) .AND.
     &    (GA.LE.3 .OR. (GA.GE.14 .AND. GA.LE.18) .OR.
     &    GA.GE.20)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.19) .AND. (EA.EQ.5) .AND. (IA.EQ.5) .AND.
     &    (GA.GE.8 .AND. GA.LE.12)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.19) .AND. (EA.EQ.4) .AND. (IA.EQ.6) .AND.
     &    (GA.EQ.4 .OR. GA.EQ.5 .OR. GA.EQ.7 .OR.
     &    GA.GE.20)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.19) .AND. (EA.EQ.5) .AND. (IA.EQ.6) .AND.
     &    (GA.EQ.7)) THEN
        FCRPRE = 1.0
      END IF
C
C possible crops preceding faba bean
      IF ((ZA.EQ.20 .OR. ZA.EQ.21) .AND. (EA.EQ.1) .AND. (IA.EQ.6)
     &    .AND. (GA.GE.4 .AND. GA.NE.20 .AND. GA.NE.21)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.20 .OR. ZA.EQ.21) .AND. (EA.EQ.2) .AND. (IA.EQ.6)
     &    .AND. (GA.LE.3)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.20 .OR. ZA.EQ.21) .AND. (EA.EQ.4) .AND. (IA.EQ.5)
     &    .AND. (GA.GE.8 .AND. GA.NE.20 .AND. GA.NE.21)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.20 .OR. ZA.EQ.21) .AND. (EA.EQ.5) .AND. (IA.EQ.5)
     &    .AND. (GA.LE.3)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.20 .OR. ZA.EQ.21) .AND. (EA.EQ.4) .AND. (IA.EQ.6)
     &    .AND. (GA.EQ.4 .OR. GA.EQ.5 .OR. GA.EQ.7)) THEN
```

```
        FCRPRE = 1.0
      END IF
C
C possible crops preceding tulip
      IF ((ZA.EQ.27) .AND. (EA.EQ.1) .AND. (IA.EQ.6) .AND.
     &    (GA.LE.26)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.4) .AND. (IA.EQ.1) .AND.
     &    (GA.LE.3 .OR. (GA.GE.7 .AND. GA.LE.26) .OR. GA.EQ.28
     &    .OR. GA.EQ.33)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.4) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
     &    (GA.LE.5 .OR. (GA.GE.14 .AND. GA.LE.26))) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.4) .AND. (IA.EQ.5 .OR. IA.EQ.6) .AND.
     &    (GA.GE.7 .AND. GA.LE.13)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.5) .AND. (IA.EQ.4) .AND.
     &    (GA.EQ.28 .OR. GA.EQ.30)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.5) .AND. (IA.EQ.5) .AND.
     &    (GA.EQ.28)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.5) .AND. (IA.EQ.6) .AND.
     &    (GA.EQ.30)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.6) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
     &    (GA.EQ.33)) THEN
        FCRPRE = 1.0
      END IF
C
C possible crops preceding narcissus
      IF ((ZA.EQ.28) .AND. (EA.EQ.1) .AND. (IA.EQ.6) .AND.
     &    (GA.LE.26)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.28) .AND. (EA.EQ.4) .AND. (IA.EQ.2) .AND.
     &    (GA.EQ.27 .OR. GA.EQ.33)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.28) .AND. (EA.EQ.4) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
     &    (GA.LE.5 .OR. (GA.GE.14 .AND. GA.LE.26))) THEN
        FCRPRE = 1.0
```

```
      END IF
      IF ((ZA.EQ.28) .AND. (EA.EQ.4) .AND. (IA.EQ.5 .OR. IA.EQ.6) .AND.
     &    (GA.GE.7 .AND. GA.LE.13)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.28) .AND. (EA.EQ.5) .AND. (IA.EQ.4) .AND.
     &    (GA.EQ.27 .OR. GA.EQ.33)) THEN
        FCRPRE = 1.0
      END IF
C
C possible crops preceding lily
      IF ((ZA.EQ.30) .AND. (EA.EQ.4) .AND. (IA.EQ.1) .AND.
     &    (GA.LE.3 .OR. (GA.GE.7 .AND. GA.LE.28) .OR. GA.EQ.33)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.30) .AND. (EA.EQ.4) .AND. (IA.EQ.3) .AND.
     &    (GA.EQ.27 .OR. GA.EQ.33)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.30) .AND. (EA.EQ.4) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
     &    (GA.LE.5 .OR. (GA.GE.14 .AND. GA.LE.26) .OR. GA.EQ.28)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.30) .AND. (EA.EQ.4) .AND. (IA.EQ.6) .AND.
     &    (GA.GE.7 .AND. GA.LE.13)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.30) .AND. (EA.EQ.5) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
     &    (GA.EQ.27 .OR. GA.EQ.33)) THEN
        FCRPRE = 1.0
      END IF
C
C possible crops preceding hyacinth
      IF ((ZA.EQ.33) .AND. (EA.EQ.4) .AND. (IA.EQ.1) .AND.
     &    (GA.LE.3 .OR. (GA.GE.7 .AND. GA.LE.28))) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.4) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
     &    (GA.LE.5 .OR. (GA.GE.14 .AND. GA.LE.26))) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.27) .AND. (EA.EQ.4) .AND. (IA.EQ.5 .OR. IA.EQ.6) .AND.
     &    (GA.GE.7 .AND. GA.LE.13)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.33) .AND. (EA.EQ.5) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
     &    (GA.EQ.28)) THEN
        FCRPRE = 1.0
      END IF
      IF ((ZA.EQ.33) .AND. (EA.EQ.6) .AND. (IA.EQ.4 .OR. IA.EQ.5) .AND.
```

```
     &    (GA.EQ.27)) THEN
            FCRPRE = 1.0
         END IF

         END


         SUBROUTINE FOPEN (IUNIT,FILE,STATUS,PRIV)

*        Opens a sequential, formatted file
*        after doing an inquiry about the existence.

*        IUNIT  - unit number used to open file                          I
*        FILE   - name of the file to be opened                          I
*        STATUS - status of the file                                     I
*                 = 'old' --> existing file is opened
*                 = 'new' --> new file is created (see PRIV)
*        PRIV   - privilege ; in case status='new' and file exists:      I
*                 = 'del' --> old file is overwritten
*                 = 'nod' --> old file saved, program stopped
*                 = 'unk' --> interactive choice in case file exists
*
*        Examples:
*        CALL FOPENG (20,'a.dat','old',' ')
*           opens existing formatted sequential file
*        CALL FOPENG (20,'a.dat','new','unk')
*           creates new, formatted, sequential file ; in case a file a.dat
*           already exists the routine asks permission to overwrite
*        CALL FOPENG (20,'a.dat','new','del')
*           creates new, formatted, sequential file ; a possibly existing
*           file a.dat is deleted
*
*        Subroutines and/or functions called:
*        - from library TTUTIL: ERROR, ILEN, UPPERC

*        Author: Daniel van Kraalingen, Kees Rappoldt
*        Date  : April 1992
*        TTUTIL Version 3.11

*        formal parameters
         INTEGER IUNIT
         CHARACTER*(*) FILE, STATUS, PRIV

**       local variables + function called
         INTEGER IO, ILFIL, ILEN, INOPEN
         CHARACTER LSTAT*3, LPRIV*3, CHOICE*1, DUMMY*1, STAT(2)*3
         LOGICAL THERE, OPENT
         SAVE

*        length of filename, existence
```

```
      ILFIL = ILEN (FILE)
      INQUIRE (FILE=FILE(1:ILFIL),EXIST=THERE)
      IF (THERE) THEN
         INQUIRE (FILE=FILE(1:ILFIL),OPENED=OPENT)
      ELSE
         OPENT = .FALSE.
      END IF
      IF (OPENT) THEN
         WRITE (*,'(2A,/,A)')
     $     ' Cannot open file ',FILE(1:ILFIL),
     $     ' File is already open'
         CALL ERROR ('FOPEN',' ')
      END IF

*     unit number free ?
      INQUIRE (UNIT=IUNIT,OPENED=OPENT)
      IF (OPENT) THEN
         WRITE (*,'(2A,/,A,I3,A)')
     $     ' Cannot open file ',FILE(1:ILFIL),
     $     ' Unit number',IUNIT,' already in use'
         CALL ERROR ('FOPEN',' ')
      END IF

*     status and privilege
      LSTAT = STATUS
      CALL UPPERC (LSTAT)
      LPRIV = PRIV
      CALL UPPERC (LPRIV)

*     check privilege
      IF ((LPRIV.EQ.'DEL' .OR. LPRIV.EQ.'NOD' .OR. LPRIV.EQ.'UNK') .AND.
     $  LSTAT.EQ.'OLD') WRITE (*,'(A)')
     $  ' WARNING from FOPEN: DEL, NOD or UNK used with status OLD'

      IF ((LSTAT.EQ.'OLD' .AND. THERE) .OR.
     $     (LSTAT.EQ.'NEW' .AND. .NOT.THERE)) THEN
*        simple file open
         INOPEN  = 1
         STAT(1) = LSTAT

      ELSE IF (LSTAT.EQ.'NEW' .AND. THERE) THEN
*        default procedure: open(old), delete, open(new)
         INOPEN  = 2
         STAT(2) = 'OLD'
         STAT(1) = 'NEW'

*        execution depends on privilege
         IF (LPRIV.EQ.'UNK') THEN
*           interactive choice
            CHOICE = ' '
```

```
10          IF (CHOICE.NE.'Y' .AND. CHOICE.NE.'N') THEN
               WRITE (*,'(3A,/,A,$)')
     $          ' File ',FILE(1:ILFIL),' already exists',
     $          ' Overwrite (Y/N): '
               READ (*,'(A)') CHOICE
               CALL UPPERC (CHOICE)
            GOTO 10
            END IF

            IF (CHOICE.EQ.'N') THEN
               WRITE (*,'(A,/,A)')
     $          ' File not overwritten, program stopped',
     $          ' press <RETURN>'
               READ (*,'(A)') DUMMY
               STOP
            END IF

         ELSE IF (LPRIV.EQ.'NOD') THEN
            WRITE (*,'(3A)')
     $       ' Existing file ',FILE(1:ILFIL),' is not deleted'
            CALL ERROR ('FOPEN','program stopped')

         ELSE IF (LPRIV.NE.'DEL') THEN
            CALL ERROR ('FOPEN','Unknown privilege')
         END IF

      ELSE IF (LSTAT.EQ.'OLD' .AND. .NOT.THERE) THEN
         WRITE (*,'(3A)') ' File ',FILE(1:ILFIL),' does not exist'
         CALL ERROR ('FOPEN','program stopped')
      ELSE
         CALL ERROR ('FOPEN','Unknown file status')
      END IF
*     no errors, privilege OK, open file
      DO 20 IO=INOPEN,1,-1
         OPEN (IUNIT,FILE=FILE(1:ILFIL),STATUS=STAT(IO),RECL=500)
         IF (IO.EQ.2) CLOSE (IUNIT,STATUS='DELETE')
20    CONTINUE

      RETURN
      END
```

Appendix IV

Functions used in MGOPT_CROP

Functions to define criterion arrays, temporarily defined in MGOPT_CROP.
N.B. These functions should be incorporated in READTC.FOR for greater independence between model and data !

```
FUNCTIONS
C
C-----------------------------------------------------------------------
C       criterion for exclusion of crop production techniques for
C       which no data have been read from data file TCCROPS.DAT

      FUNCTION FCRIL()

        FCRIL = CRIT(G)
        IF (CRIE(G,E) .NE. 1.0) FCRIL = 0.
        IF (CRIR(G,R) .NE. 1.0) FCRIL = 0.
        IF (CRIV(G,V) .NE. 1.0) FCRIL = 0.
        IF (CRIP(G,P) .NE. 1.0) FCRIL = 0.
        IF (CRIN(G,N) .NE. 1.0) FCRIL = 0.
C maximum frequency of potato on CLAY as of 1994 = 0.33 !
        IF (G.LE.3 .AND. R.EQ.1) FCRIL=0.

C exclude VAR-levels 7 and 8 for all potato crops
        IF (G.LE.3 .AND. (V.EQ.7 .OR. V.EQ.8)) FCRIL=0.

C varieties 1,4,5,7 of potato not in combination with PES-level 2
        IF (G.LE.3 .AND. (V.EQ.1 .OR. V.EQ.4 .OR. V.EQ.5 .OR. V.EQ.7)
     &       .AND. P.EQ.2) FCRIL = 0.

C variety 1 of maize not in combination with PES-level 2
        IF (G.EQ.12 .AND. V.EQ.1 .AND. P.EQ.2) FCRIL = 0.

C tijdelijk voor bloembollen
C        IF (E.LT.4) FCRIL = 0.
      RETURN
      END
C-----------------------------------------------------------------------
C        Criterion for exclusion of farmyard compost variable
      FUNCTION FGEN()
        FGEN = CRIT(G)
        IF (CRIN(G,N) .NE. 1.0) FGEN = 0.
      RETURN
      END
C-----------------------------------------------------------------------
C        Criterion for exclusion of manure variables
```

```
      FUNCTION FCRIM()
        FCRIM = CRIT(G)
        IF (CRIN(G,N) .NE. 1.0) FCRIM = 0.
        IF (N.LE.3) FCRIM=0.
        IF (NMMAN(S) .EQ. 0.0)  FCRIM = 0.
      RETURN
      END
C-----------------------------------------------------------------------
      FUNCTION FMANG()
        FMANG = 0.
        IF (G.LE.5 .OR. G.EQ.10 .OR.
     &       G.EQ.12 .OR. G.EQ.13 .OR. G.EQ.15) FMANG = 1.0
        IF (CRIT(G).EQ.0.0) FMANG=0.
      RETURN
      END
C-----------------------------------------------------------------------
      FUNCTION FMNG()
        FMNG = 0.
        IF ((G1.EQ.2 .OR. G1.EQ.7 .OR. G1.EQ.10) .AND.
     &      (CRPRE(Z1,E1,I,G1).EQ.1.0)) FMNG=1.
        IF (CRIT(G1).EQ.0.) FMNG=0.
      RETURN
      END
C-----------------------------------------------------------------------
      FUNCTION FNAM()
        FNAM = CRIT(G)
        IF (CRIN(G,N) .NE. 1.0) FNAM = 0.
        IF (N.LE.3) FNAM=0.
        IF (CLAY.EQ.0.) FNAM=0.
      RETURN
      END
C-----------------------------------------------------------------------
C       criterion for exclusion of binary variable BINCF
      FUNCTION FCF()
        FCF = 1.
        IF (CRIT(Z) .EQ. 0.) FCF = 0.
        IF (CRIR(Z,R) .EQ. 0.) FCF = 0.
        IF (NR(Z) .EQ. 1) FCF = 0.
      RETURN
      END
C-----------------------------------------------------------------------
C       criterion for exclusion of area with preceding crops
      FUNCTION FCXPR()
        FCXPR = CRIT(Z)
        IF (CRIE(Z,E) .EQ. 0.0) FCXPR = 0.
        IF (CRIT(G) .EQ. 0.0) FCXPR = 0.
        IF (CRPRE(Z,E,I,G) .EQ. 0.0) FCXPR = 0.
        IF (CRIR(Z,X) .EQ. 0.0) FCXPR = 0.
      RETURN
      END
```

```
C-----------------------------------------------------------------------
C        criterion for exclusion of LRTOT
      FUNCTION FCBIL()
        FCBIL = CRIT(G)
        IF (CRIR(G,R) .EQ. 0.0) FCBIL = 0.
C
C add specific exclusion combinations for GLOBAL optimization
C
      RETURN
      END
C-----------------------------------------------------------------------
C        criterion for exclusion of XPR and XPTOT
      FUNCTION FCBIX()
        FCBIX = CRIT(Z)
        IF (CRIT(G) .EQ. 0.0) FCBIX = 0.
        IF (CRIR(Z,X) .EQ. 0.0) FCBIX = 0.
        IF (CRIR(G,X) .EQ. 0.0) FCBIX = 0.
        IF (Z.EQ.G) FCBIX = 0.
C
C add specific exclusion combinations for GLOBAL optimization
C
      RETURN
      END
C-----------------------------------------------------------------------
C          criterion for exclusion of area with intermediate
C          crop operations
      FUNCTION FXBTW()
       FXBTW = 0.0

C clay
       IF ((G.NE.7 .AND. G.NE.9 .AND. G.NE.11 .AND. G.NE.13)
     &     .AND. (E.LE.3) .AND. (CRIE(G,E).EQ.1.0)
     &     .AND. (I.EQ.1 .OR. I.EQ.6)) FXBTW = 1.0
       IF ((G.GE.7) .AND. (E.LE.3) .AND. (CRIE(G,E).EQ.1.0)
     &     .AND. (I.EQ.6)) FXBTW = 1.0

C sand
       IF ((G.NE.7 .AND. G.NE.9 .AND. G.NE.11 .AND. G.NE.13 .AND.
     &      G.NE.27 .AND. G.NE.28 .AND. G.NE.30 .AND. G.NE.33) .AND.
     &     (E.EQ.4 .OR. E.EQ.5) .AND. (CRIE(G,E).EQ.1.0) .AND.
     &     (I.EQ.1)) FXBTW = 1.0
       IF ((G.EQ.27 .OR. G.EQ.28 .OR. G.EQ.30 .OR. G.EQ.33)
     &     .AND. (E.EQ.4) .AND. (CRIE(G,E).EQ.1.0)
     &     .AND. (I.EQ.1)) FXBTW = 1.0
       IF ((G.EQ.28) .AND. (E.EQ.4) .AND. (CRIE(G,E).EQ.1.0)
     &     .AND. (I.EQ.2)) FXBTW = 1.0
       IF ((G.EQ.30) .AND. (E.EQ.4) .AND. (CRIE(G,E).EQ.1.0)
     &     .AND. (I.EQ.3)) FXBTW = 1.0
       IF ((G.GE.27 .AND. G.LE.35) .AND. (E.EQ.4 .OR. E.EQ.5
     &     .OR. E.EQ.6) .AND. (CRIE(G,E).EQ.1.0)
```

```
     &      .AND. (I.EQ.4 .OR. I.EQ.5 .OR. I.EQ.6)) FXBTW = 1.0
        IF ((G.LE.27 .AND. G.NE.7 .AND. G.NE.13) .AND.
     &      (E.EQ.4 .OR. E.EQ.5 .OR. E.EQ.6) .AND.
     &      (CRIE(G,E).EQ.1.0)
     &      .AND. (I.EQ.5 .OR. I.EQ.6)) FXBTW = 1.0
        IF ((G.EQ.7 .OR. G.EQ.13) .AND.
     &      (E.EQ.4 .OR. E.EQ.5 .OR. E.EQ.6) .AND.
     &      (CRIE(G,E).EQ.1.0)
     &      .AND. (I.EQ.6)) FXBTW = 1.0

      RETURN
      END
C-----------------------------------------------------------------------
C     criterion for exclusion of hired land
C
      FUNCTION FCRIH()
        FCRIH = 0.
      RETURN
      END
C
C     FCRIH for BULB farm analysis
C
C      FUNCTION FCRIH()
C        FCRIH = CRIT(G)
C        IF (CRIE(G,E) .NE. 1.0) FCRIH = 0.
C        IF (CRIR(G,R) .NE. 1.0) FCRIH = 0.
C        IF (CRIV(G,V) .NE. 1.0) FCRIH = 0.
C        IF (CRIP(G,P) .NE. 1.0) FCRIH = 0.
C        IF (CRIN(G,N) .NE. 1.0) FCRIH = 0.
C        IF (E .GE. 2) FCRIH = 0.
CC alleen 1:8 teelt
C        IF (R .NE. 7) FCRIH = 0.
C      RETURN
C      END
```