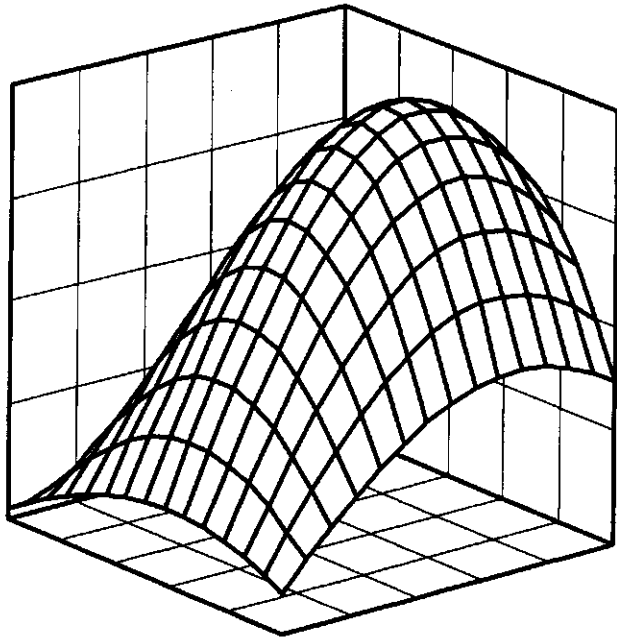# Rotation models for ecological farming

Quantitative Approaches in Systems Analysis

The Quantitative Approaches in Systems Analysis series provides a platform for publication and documentation of simulation models, optimization programmes, Geographic Information Systems (GIS), expert systems, data bases, and utilities for the quantitative analysis of agricultural and environmental systems. The series enables staff members, students and visitors of AB-DLO and PE to publish, beyond the constraints of refereed journal articles, updates of models, extensive data sets used for validation and background material to journal articles. The QASA series thus primarily serves to support peer reviewed articles published elsewhere. The inclusion of listings of programmes in an appendix is encouraged.

All manuscript are reviewed by an editorial board comprising one AB-DLO and one PE staff member. The editorial board may consult external reviewers. The review process includes assessing the following: relevance of the topic to the series, overall scientific soundness, clear structure and presentation, and completeness of the presented material(s). The editorial board evaluates manuscripts on language and lay-out matters in a general sense. However, the sole responsibility for the contents of the reports, the use of correct language and lay-out rests with the authors. Manuscripts or suggestions should be submitted to the editorial board. Reports of the series are available on request.

Quantitative Approaches in Systems Analysis are issued by the DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO) and The C.T. de Wit Graduate School for Production Ecology (PE).
AB-DLO, with locations in Wageningen and Haren, carries out research into plant physiology, soil science and agro-ecology with the aim of improving the quality of soils and agricultural produce and of furthering sustainable production systems.
The 'Production Ecology' Graduate School explores options for crop production systems associated with sustainable land use and natural resource management; its activities comprise research on crop production and protection, soil management, and cropping and farming systems.

Rotation models for ecological farming

CAMASE/PE workshop report

M.C. Plentinger & F.W.T. Penning de Vries (Eds.)

Table of Contents

Preface

One objective of the CAMASE project (CAMASE: a Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment) is to stimulate the development of models for cropping systems: crop rotations, crop sequences (including crop-grassland rotations), relay and intercropping.
The C.T. De Wit Graduate School for Production Ecology (PE) aims at productive, sustainable and safe agricultural production systems.
CAMASE and PE organized together the workshop "Rotation models for ecological farming" from 15-20 April, 1996, in Wageningen, The Netherlands.

Acknowledgements

Summary

CAMASE (a Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment) and PE (C.T. De Wit Graduate School for Production Ecology) organised together the workshop "Rotation models for ecological farming".
During this workshop, ecologists and modellers met to seek mutually acceptable starting points for the use of dynamic simulation models in crop rotations. On one hand, ecologists pointed out specific questions in their discipline, related to crop rotations. Modellers presented the current status of their models in the field of ecological farming systems, especially crop rotations. Strong issues and strong processes in models were stressed, while other demanding issues were placed on a priority list for further research and attention. Issues from this list may be assigned to model developing groups for further investigation. Ecologists reviewed the possibilities for the use of dynamic simulation models in monitoring their field experiments.

This document describes the models, their evaluation and applications.

1 Introduction

In ecological farming systems, crop rotations are vital to make efficient use of natural resources. The right choice in successive crops and cropping measures, use of optimal rotation frequencies may lead to more sustainable land use, minimal pollution, while pests and diseases are kept at a tolerable level. In crop rotations, crop growth takes place in a situation set by former crops. This will consequently influence the environment for following crops and their tillage systems. Especially biological, physical and chemical soil properties are influenced. However, the growth of one crop has different implications than the growth of another crop.

Several dynamic models simulate processes in each of the fields described above. The level at which and the way how these processes are simulated differ for almost each model. Some models extensively account for the decomposition of crop residues, while others thoroughly explore the soil water balance or crop growth. Not all sub-processes are equally important for solving all questions in crop rotations, although some might be crucial for the optimisation of specific crop rotations.

During the CAMASE (a Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment) / PE (C.T. De Wit Graduate School for Production Ecology) workshop, ecologists and modellers met to seek mutually acceptable starting points for the use of dynamic simulation models in crop rotations. On one hand, ecologists pointed out specific questions in their discipline, related to crop rotations. Modellers presented the current status of their models in the field of ecological farming systems, especially crop rotations. Strong issues and strong processes in models were stressed, while other demanding issues were placed on a priority list for further research and attention. Issues from this list may be assigned to model developing groups for further investigation. Ecologists reviewed the possibilities for the use of dynamic simulation models in monitoring their field experiments. Ecologists as well as modellers were invited to make available and bring with them full datasets to run and evaluate their models.

I Themes for the workshop

2   Designing a multifunctional crop rotation and laying it out in an agro-ecologically appropriate way

P.H. Vereijken
Research Institute for Agrobiology and Soil Fertility (AB-DLO), The Netherlands

2.1   Introduction

A EU-wide network of research teams has been set up (AIR-concerted action) to develop and standardise the methodology of prototyping Integrated and Ecological Arable Farming Systems (I/EAFS).

Building on initial experience with an experimental farm at Nagele (Vereijken, 1992) and the input of the research leaders from the network, prototyping of I/EAFS has been elaborated in a methodical way of 5 formal steps (Vereijken, 1994, 1995) (Outline 1). The outcome of these 5 steps is expressed in parts of an identity card for the prototype to facilitate the co-operation within the team and the exchange with the other teams in the network.

Outline 1 Methodical way of designing, testing, improving and disseminating prototypes of Integrated and Ecological (Arable) Farming Systems (I/EAFS)

1.	*Hierarchy of objectives:* making a hierarchy in 6 general objectives, subdivided into 20 specific objectives as a base for a prototype in which the strategic shortcomings of current farming systems are replenished (Part 1 of the identity card of a prototype).
2.	*Parameters and methods:* transforming the major (10) specific objectives into multi-objective parameters to quantify them, establishing the multi-objective methods needed to achieve the quantified objectives (Part 2 of the identity card).
3.	*Design of theoretical prototype and methods:* designing a theoretical prototype by linking parameters to methods (Part 3 of the identity card), designing methods in this context until they are ready for initial testing (Multifunctional Crop Rotation as major method and Part 4 of the identity card).
4.	*Layout of prototype to test and improve:* laying the prototype out on an experimental farm or on pilot farms in an agro-ecologically appropriate way (Part 5 of the identity card), testing and improving the prototype in general and the method in particular until (after repeated laying out) the objectives, as quantified in the set of parameters, have been achieved (Part 6 of the identity card).
5.	*Dissemination:* disseminating the prototype by pilot groups (< 15 farmers), regional networks (15-50 farmers) and eventually by national networks (regional networks interlinked) with gradual shift in supervision from researchers to extensionists.

In all theoretical prototypes of the I/EAFS-Network, the Multifunctional Crop Rotation (MCR) plays a central role as a major method to achieve desired results in the multi-objective parameters of soil fertility and environment, as well as in the Quality Production Indices (QPIs product^{-1}) and the major parameters of economic and energy efficiency. Consequently, MCR should be designed primarily to provide for a well-balanced 'team' of crops requiring a minimum of inputs that are polluting and/or based on fossil energy (nutrients, pesticides, machinery, fuel) to maintain soil fertility and crop vitality as a basis for quality production.

Besides, MCR should be laid out in an agro-ecologically appropriate way to ensure its efficacy and to compensate for its insufficient control of semi-soilborne and airborne harmful species.

In this paper, design and agro-ecological layout of MCR will be highlighted, each with 3 examples of EAFS prototypes from the EU-network.

2.2　Designing a Multifunctional Crop Rotation (MCR)

The basic task of I/EAFS designers, to replace physico-chemical methods by biological methods and techniques, requires an appropriate concept:

I/EAFS is an agro-ecological whole consisting of a 'team' of steadily interacting and rotating crops, plus their accompanying (beneficial or harmful) flora and fauna.

The designer's task can thus be specified as to design a rotation with a maximum of positive interactions and a minimum of negative interactions between the crops. These interactions strongly influence physical, chemical and biological fertility of the soil and consequently vitality and quality production of the crops.

This leads to the following brief definition:

MCR is a basic and comprehensive farming method to preserve soil fertility in biological, physical and chemical terms and to sustain quality production with a minimum of inputs (pesticides, machine and hand labour, fertilisers and support energy).

This definition could even be simplified to:

MCR is a farming method with such alternation of crops (in time and space) that their vitality and quality production can be ensured with a minimum of remaining measures or inputs.

The research teams of the I/EAFS network have adopted a standard procedure to design MCRs (outline 2).

The result of this designing procedure of 2 steps should be that short-term interests of marketing and profit are optimally blended with long-term interests of preserving soil fertility with minimum need for external inputs.

The designing procedure is illustrated by 3 examples of MCRs for EAFS (Tables 1.1-1.3).

Outline 2 Procedure of designing a Multifunctional Crop Rotation (MCR) for I/EAFS

1.	*Identifying and characterising potential crops for your region or farm (format A):*

- making a list of crops (set-aside included) in diminishing order of marketability and profit-ability (≥ 6 crops for IAFS and ≥ 8 crops for EAFS);
- characterising the crops in their potential role in the MCR in biological, physical and chemical terms, as listed in format 1 or adapted to your region.

2. *Drawing up an MCR based on (1) and simultaneously fulfilling a multi-functional set of demands (format B):*

- filling the first rotation block with crop no. 1;
- filling subsequent blocks while preserving biological soil fertility by limiting the share per crop species to ≤ 0.25 in IAFS and ≤ 0.167 in EAFS and the share per crop group to ≤ 0.50 in IAFS and ≤ 0.33 in EAFS;
- filling subsequent blocks, while preserving physical soil fertility by consistently scheduling a crop with a high rating of soil cover (erosion-susceptible soils) or effect on soil structure (compaction susceptible soils) after a crop with a low rating, overall the MCR resulting in a soil cover ≥ -1 in IAFS and = 0 in EAFS and a soil structure ≥ -1 in IAFS and ≥ 0 in EAFS;
- filling subsequent blocks while conserving chemical soil fertility by consistently scheduling a crop with a high rating of N transfer before a crop with a high rating of N need and a crop with a low N transfer before a crop with a low N need, overall the MCR resulting in an N need ≤ 2 in IAFS and ≤ 1 in EAFS;
- filling single blocks by 2 or 3 crops with corresponding characteristics, if needed for reasons of limited labour capacity or market demand;
- ensuring crop successions are feasible in terms of harvest time, crop residues and volunteers from preceding crops.

2.2.1 Mid-Belgium prototype (Table 1.1)

This MCR has been designed for a hilly area with clay soils, dominated by cereals and grass for dairy cows or beef cows. Grass can be permanent or rotational. The shares of single and related crops species can meet the demands (≤ 0.167 and ≤ 0.33). The demand of soil cover (= 0) is not met, contrary to the demands to soil structure (≥ 0) and N need (≤ 1).

2.2.2 Southeast and Midwest Ireland prototype (Table 1.2)

This MCR has been designed for wet areas with peaty sand, dominated by cereals and grass for beef cows and sheep. Grass can be permanent or rotational. The shares of single and related crops species cannot meet the demands (≤ 0.167 and ≤ 0.33), so the MCR has insufficient prevention of pests and diseases. Notwithstanding a high share of perennial crops, soil cover cannot meet the demand (= 0). The demands to soil structure (≥ 0) and N need are met.

2.2.3 Flevoland prototype (Table 1.3)

This MCR has been designed for a sandy clay area dominated by lifted crops. The shares of single crop species and related crop species are within the demand (≤ 0.167 and ≤ 0.33). How

ever, demands to soil cover (= 0) and soil structure (≥ 0) are not met. On the other hand, N need fulfils the demand (≤ 1).

2.3   Agro-ecological layout of MCR

MCR can only come to an optimal functioning if it is laid out in an agro-ecologically appropriate way. The research teams of the I/EAFS network have adopted a set of criteria for an agro-ecological layout (outline 3).

Outline 3 Criteria for an agro-ecological layout of I/EAFS.

1.	Field adjacency = 1
	All fields of a farming system should be adjacent to each other, to obtain an agro-ecological whole as a prerequisite for an agro-ecological identity.
2.	Field size ≥ 1 ha
	To obtain a prototype farming system with sufficient agro-ecological identity, the fields as sub-units have to be of a minimum size.
3.	Field length/width ≤ 4
	Round or square fields contribute optimally to the agro-ecological identity of a farming system. Therefore, a maximum is to be set to the length/width ratio of fields, to limit the loss in identity.
4.	Crop rotation blocks ≥ 4 (IAFS) or ≥ 6 (EAFS)
	The shorter the crop rotation, the greater the biotic stress on the crops and the need for external inputs to control that stress. Therefore, crop rotation is required based on 4 (IAFS) or 6 (EAFS) rotation blocks, at least (temporal dimension of crop rotation).
5.	*Adjacency of subsequent blocks = 0*
	Harmful semi-soilborne species are to be prevented from following their host crop by a crop rotation without any adjacency of subsequent blocks to ensure crops are not just moved to an adjacent field from year to year.
6.	*Share of cereals ≤ 0.5 (IAFS) or ≤ 0.3 (EAFS)*
	The larger the share of cereals in rotation, the greater the biotic stress and the need for external inputs for this, crop group the largest in European arable farming. Therefore, the crop rotation should have a maximum of 0.5 (IAFS) or 0.3 (EAFS) of cereals.
7.	*Ecological Infrastructure ≥ 5 % of I/EAFS area*
	To bridge the gap between 2 growing seasons, airborne and semi-soilborne beneficials need an appropriate ecological infrastructure of at least 5 % of the farm area.

The agro-ecological layout according to these criteria is illustrated by 3 examples of the same EAFS illustrating MCR (Figs. 1.1-1.3).

Table 1.1 Multifunctional Crop Rotation of EAFS prototype in mid-Belgium (B 1)

A. Selection of crops by pilot farm 1 (crops in order of profitability)

crop no.	biological species	group[1]	physical (ratings) cover[2]	rooting[3]	compaction[4]	structure[3+4]	chemical (N ratings) offtake[5]	transfer[6]
1	grassclover	grass/leg.	0	3	-2	1	2	2
2	potato	solan.	-4	1	-2	-1	3	2
3	maize	maize	-4	2	-2	0	3	2
4	winter wheat	cer.	-2	3	-1	2	3	1
5	triticale	cer.	-2	3	-1	2	3	1
6	oats	oats	-2	3	-1	2	2	1
7	rye	cer.	-2	3	-1	2	2	1
8	spelt	cer.	-2	3	-1	2	2	1
9								
10								
mean of crop selection			-2.3	2.6	-1.4	1.3	2.4	1.5

B. Multifunctional Crop Rotation of pilot farm 1

block no.	crop no.	biological species	group[1]	physical (ratings) cover[2]	structure[3+4]	chemical (N ratings) offtake[5]	transfer[6]	need[7]
I	1	grassclover	grass/leg.	0	1	2	2	0
II	1	grassclover	grass/leg.	0	1	1	2	-1
III	1	grassclover	grass/leg.	0	1	1	2	-1
IV	2	potato	solan.	-4	-1	3	2	1
V	4	winter wheat	cer.	-2	2	2	1	0
VI	3	maize	maize	-4	0	3	2	2
VII	5/6	triticale/oats	cer./oats	-2	2	2	1	0
VIII	5/6	triticale/oats	cer./oats	-2	2	2	1	1
mean of crop rotation		share species[-1] ≤ 0.167	share group[-1] ≤ 0.25	-1.8	1.0	2.0	1.6	0.3

1. Genetically and phytopathologically related groups, such as cereals, legumes, crucifers and chenopodes, composites, umbellifers, liliaceae. All subsequent blocks of perennial crops are counted as 1 block.

2. No cover in autumn and winter = -4, no cover in autumn or winter = -2, all others = 0 (green manure crops included).

3. Cereals, grasses and lucerne = 3, root, bulb and tuber crops = 1, all others = 2 (green manure crops included).

4. Compaction by mowing in summer = -1 and autumn = -2, lifting in summer = -2 and in autumn = -4.

5. N offtake by harvested crop product from soil reserves: legumes = 0. All other crops: 25-50 kg ha^{-1} = 1, 50-100 kg ha^{-1} = 2, 100-150 kg ha^{-1} = 3, 150-200 kg ha^{-1} = 4, etc..

6. N transfer is the expected net contribution of N to subsequent crop, based on N residues in the soil after harvest, N mineralisation from crop residues and N losses by leaching and denitrification. In this rating, the effect of green manure crops should be included. N transfer < 50 kg ha^{-1} = 1, 50-100 kg ha^{-1} = 2, 100-150 kg ha^{-1} = 3.

7. N need (block x) = N offtake (block x) minus N transfer (block x-1). N need is net N input to be provided by manure or N fertiliser.

Table 1.2 Multifunctional Crop Rotation of EAFS prototype in Southeast and Midwest Ireland (IRL 1)

A. Selection of crops by pilot farm 8 (crops in order of profitability)

crop no.	biological species	group[1]	cover[2]	physical (ratings) rooting[3]	compaction[4]	structure[3+4]	chemical (N ratings) offtake[5]	transfer[6]
1	wheat	cer.	-2	3	-1	2	3	1
2	bean	leg.	-2	2	-1	1	0	2
3	grassclover	grass/leg.	0	3	-1	2	2	2
4								
5								
6								
7								
8								
9								
10								
mean of crop selection			-1.3	2.7	-1	1.7	1.7	1.7

B. Multifunctional Crop Rotation of pilot farm 8

block no.	crop no.	biological species	group[1]	physical (ratings) cover[2]	structure[3+4]	chemical (N ratings) offtake[5]	transfer[6]	need[7]
I	1	wheat	cer.	-2	2	3	1	1
II	2	bean	leg.	-2	1	0	2	-1
III	3	grassclover	grass/leg.	0	2	2	2	0
IV	3	grassclover	grass/leg.	0	2	2	2	0
V	1	wheat	cer.	-2	2	3	1	1
VI	3	grassclover	grass/leg.	0	2	2	2	1
VII	3	grassclover	grass/leg.	0	2	2	2	0
VIII	3	grassclover	grass/leg.	0	2	2	2	0
mean of crop rotation	share species[-1] ≤ 0.40	share group[-1] ≤ 0.52	-0.8	1.9	2.4	2.8	0.3

1. Genetically and phytopathologically related groups, such as cereals, legumes, crucifers and chenopodes, composites, umbellifers, liliaceae. All subsequent blocks of perennial crops are counted as 1 block.

2. No cover in autumn **and** winter = -4, no cover in autumn **or** winter = -2, all others = 0 (green manure crops included).

3. Cereals, grasses and lucerne = 3, root, bulb and tuber crops = 1, all others = 2 (green manure crops included).

4. Compaction by mowing in summer = -1 and autumn = -2, lifting in summer = -2 and in autumn = -4.

5. N offtake by harvested crop product from soil reserves: legumes = 0. All other crops:
   25-50 kg ha^{-1} = 1, 50-100 kg ha^{-1} = 2, 100-150 kg ha^{-1} = 3, 150-200 kg ha^{-1} = 4, etc..

6. N transfer is the expected net contribution of N to subsequent crop, based on N residues in the soil after harvest, N mineralisation from crop residues and N losses by leaching and denitrification. In this rating, the effect of green manure crops should be included. N transfer < 50 kg ha^{-1} = 1, 50-100 kg ha^{-1} = 2, 100-150 kg ha^{-1} = 3.

7. N need (block x) = N offtake (block x) minus N transfer (block x-1). N need is net N input to be provided by manure or N fertiliser.

Table 1.3 Multifunctional Crop Rotation of EAFS prototype of Flevoland (NL 2)

A. Selection of crops by pilot farm 6 (crops in order of profitability)

crop no.	biological		physical (ratings)				chemical (N ratings)	
	species	group[1]	cover[2]	rooting[3]	compaction[4]	structure[3+4]	offtake[5]	transfer[6]
1	carrot	umbel.	-2	1	-4	-3	3	1
2	potato	solan.	-2	1	-2	-1	3	2
3	onion	lil.	-4	1	-2	-1	2	1
4	celeriac	umbel.	-2	1	-4	-3	2	1
5	sugar beet	chen.	-2	1	-4	-3	2	1
6	pea, bean	leg.	-2	2	-1	1	0	2
7	wheat	cer.	-2	3	-1	2	3	1
8	oats	oats	-2	3	-1	2	2	1
9	barley	cer.	-2	3	-1	2	2	2
10	grassclover	leg.	0	3	-1	2	2	2
mean of crop selection			-2.0	1.9	-2.1	-0.2	2.1	1.4

B. Multifunctional Crop Rotation of pilot farm 6

block no.	crop no.	biological		physical (ratings)		chemical (N ratings)		
		species	group[1]	cover[2]	structure[3+4]	offtake[5]	transfer[6]	need[7]
I	1/5	carrot/sugar beet	umbel./chen.	-2/-2	-3/-3	3/3	1/1	2
II	6	pea, bean	leg.	-2	1	0	2	-1
III	2	potato	solan.	-2	-1	3	2	1
IV	10	grassclover	grass/leg.	0	2	2	2	0
V	3/4	onion/celeriac	lil./umbel.	-4/-2	-1/-3	2/2	1/1	0
VI	7	wheat	cer.	-2	2	3	1	2
VII								
VIII								

mean of crop rotation	share species[-1]	share group[-1]					
	≤ 0.167	≤ 0.25	-1.8	-0.2	2.2	1.5	0.7

1. Genetically and phytopathologically related groups, such as cereals, legumes, crucifers and chenopodes, composites, umbellifers, liliaceae. All subsequent blocks of perennial crops are counted as 1 block.

2. No cover in autumn and winter = -4, no cover in autumn or winter = -2, all others = 0 (green manure crops included).

3. Cereals, grasses and lucerne = 3, root, bulb and tuber crops = 1, all others = 2 (green manure crops included).

4. Compaction by mowing in summer = -1 and autumn = -2, lifting in summer = -2 and in autumn = -4.

5. N offtake by harvested crop product from soil reserves: legumes ≈ 0. All other crops: 25-50 kg ha^{-1} = 1, 50-100 kg ha^{-1} = 2, 100-150 kg ha^{-1} = 3, 150-200 kg ha^{-1} = 4, etc..

6. N transfer is the expected net contribution of N to subsequent crop, based on N residues in the soil after harvest, N mineralisation from crop residues and N losses by leaching and denitrification. In this rating, the effect of green manure crops should be included. N transfer < 50 kg ha^{-1} = 1, 50-100 kg ha^{-1} = 2, 100-150 kg ha^{-1} = 3.

7. N need (block x) = N offtake (block x) minus N transfer (block x-1). N need is net N input to be provided by manure or N fertiliser.

2.3.1 Mid-Belgium prototype (Fig. 1.1)

This layout holds major risks for semi-soilborne pests and diseases for two reasons. First of all mean field length/width is far beyond the criterion (≤ 4), so fields have a marginal character and crops move across too short distances. Secondly, 4 out of 8 subsequent blocks are adjacent. For example, this layout may imply that in 1994 clover in block I hardly survived the seedling stage because of heavy infestation by Sitona beetles from the adjacent blocks II and III. The criterion for share of cereals (≤ 0.3) cannot be met by most of the group of 8 pilot farms. Besides, none of the pilot farms has a sufficient share of ecological infrastructure (≥ 0.05).

2.3.2 Southeast and Midwest Ireland prototype (Fig. 1.2)

This layout has not all rotational fields adjacent, though is considered as an agro-ecological whole because fields with permanent grass are in between. However, 3 out of 8 subsequent blocks are adjacent. Over the group, some farms cannot meet the criterion for ecological infrastructure.

2.3.3 Flevoland prototype (Fig. 1.3)

This layout can meet all agro-ecological criteria. However, over the group some pilot farms cannot meet the criterion for subsequent blocks adjacency and ecological infrastructure.

Considering the examples of I/EAFS layouts, the main obstacle to achieve an agro-ecologically valid layout is insufficient field adjacency. As a result, the prototypes cannot be laid out as an agro-ecological whole, which is a prerequisite for an agro-ecological identity.

There are various options for revising the layout of your prototype variants, depending on what value you attach to the criterion of field adjacency. The most consistent is to select only those pilot farms in which all fields are adjacent (permanent grassland included). Another consistent solution is to lay out the prototype only on the part of the farm with adjacent fields, so as to exclude non-adjacent fields. A compromise would be to include 1 or 2 non-adjacent fields if they can be connected to the other fields by the ecological infrastructure. In any case, teams with ongoing projects or projects in preparation are strongly recommended to lay out their prototypes as an agro-ecological whole, for several reasons.

Only if the farming system is an agro-ecological whole:
• can the prototype achieve sufficient agro-ecological identity in the midst of a turbulent and distorting environment, dominated by monocultures and short rotations with a chronic imbalance between beneficial and harmful flora and fauna and chronic use of pesticides to compensate for this imbalance;
• can the prototype achieve desired results in multi-objective parameters, which directly depend on an agro-ecological identity, such as Ecological Infrastructure requiring sufficient spatial continuity (for flora, fauna and recreation), and Exposure of Environment to Pesticides and Quality Production, both requiring sufficient support from beneficial flora and fauna;

- can the prototype achieve desired results in multi-objective parameters, which indirectly depend on an agro-ecological whole, insofar as that whole supports a management which is effective and efficient in timing and input of labour and energy. In principle, all parameters are involved, including Net Surplus and Energy Efficiency.

2.4   Discussion

Prototyping I/EAFS including designing and laying out MCRs is still in its infancy. As a result, the methodology needs to be strongly improved before it can be called reliable and appropriate for general use. To improve the methodology, crop rotations and layouts should be evaluated in their regional context, considering their major functions, notably quality production and maintenance of soil fertility with minimum inputs. The great constraints to do this on-farm are the huge costs and the many years it takes. Could simulation models provide for a solution, for example by replacing empirical research on specific parameters, or the entire on-farm research in specific regions?

2.5   References

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Vereijken, P., 1995. Designing and testing prototypes. Progress report 2 of the research network on Integrated and Ecological Arable Farming Systems for EU and associated countries. AB-DLO, Wageningen, The Netherlands, 90 pp.

14

University at
Louvain La Neuve

Brussels

●1 ●3 ●4 ⊞ 5

●2   ● 6

                    ●7

←100 km→
● pilot farm   ●8
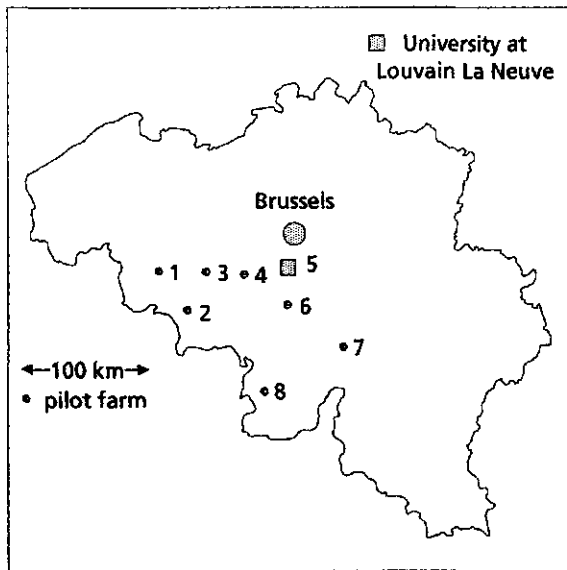
Mid-Belgium

8 EAFS-pilot farms

farm^{-1}	(lowest - highest)
production area	27 - 79 ha
field adjacency	0.5 - 1
mean field size	1.2 - 2.9 ha
mean field length/width	? - ?
crop rotation blocks	6 - 12
adj. of subsequent blocks	? - 1
share of cereals	0.3 - 0.6
share of ecol. infrastructure	0.02 - 0.04

I   II   III   VII VIII   VI

grass-clover   triticale/   maize
                  oats
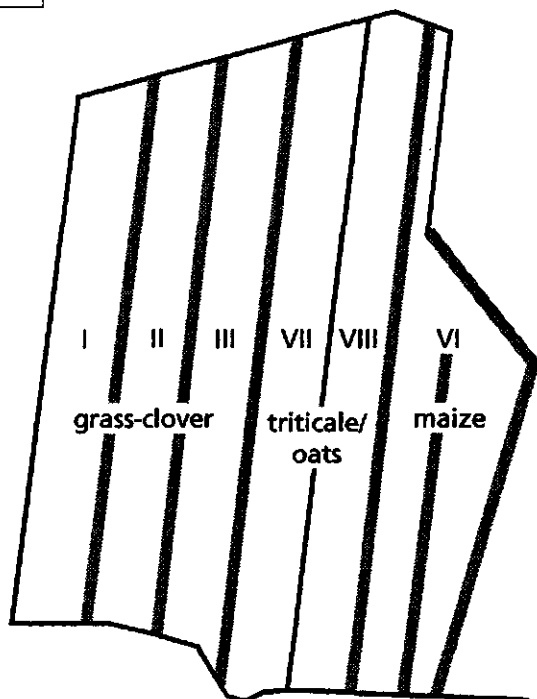
pilot farm 1:

☐ EAFS (32 ha)
I-VIII Crop rotation blocks 1994
━ Ecological Infrastructure

◄———200 m———►

(permanent grass)

V   IV

wheat   potato
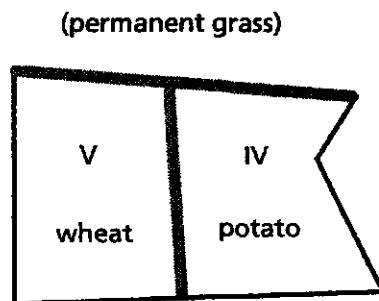
Figure 1.1   Layout of EAFS pilot project mid-Belgium (B 1)

←100 km→
• pilot farm

▣ Johnstown Castle
Research Centre
at Wexford
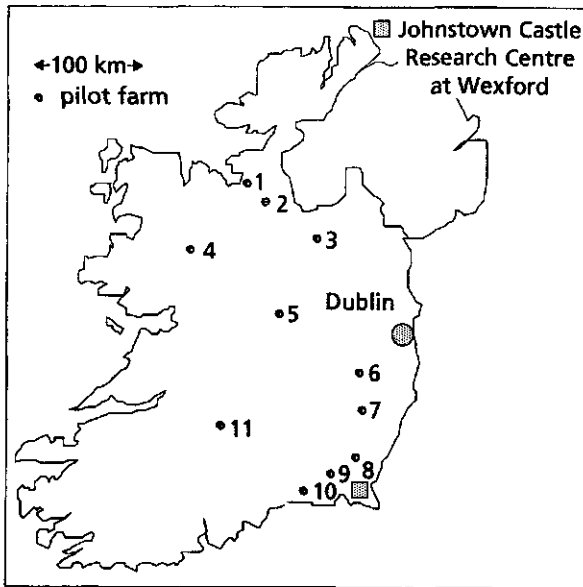
Southeast and Midwest Ireland

10 EAFS-pilot farms

farm^{-1}	(lowest - highest)
production area	8 - 93 ha
field adjacency	1 - 1
mean field size	1.7 - 5.2 ha
mean field length/width	1.3 - 3.1
crop rotation blocks	6 - 10
adj. of subsequent blocks	? - ?
share of cereals	0 - 0.2
share of ecol. infrastructure	0.03 - 0.09

pilot farm 1:

☐ EAFS (87 ha)
I-VIII Crop rotation blocks 1994
▬ Ecological Infrastructure
←——500 m——→
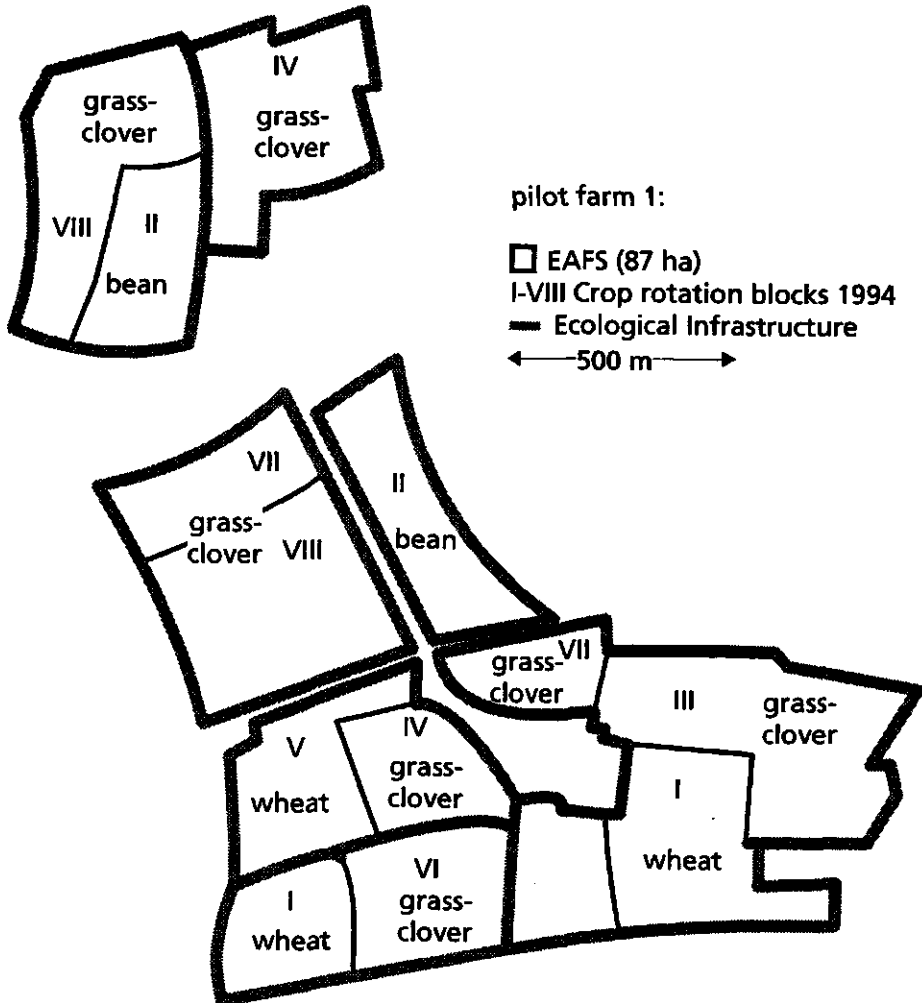
Figure 1.2   Layout of EAFS pilot project Southeast and Midwest (IRL 1)
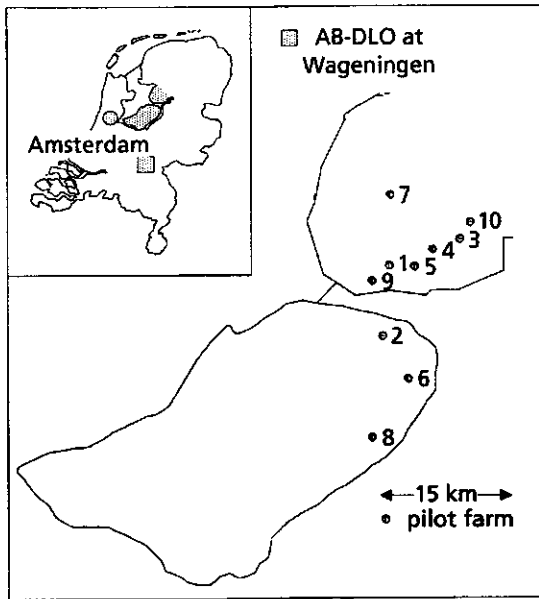
Flevoland

10 EAFS-pilot farms:

farm^{-1}	(lowest - highest)
production area	23 - 44 ha
field adjacency	1 - 1
mean field size	4 - 7 ha
mean field length/width	1 - 3
crop rotation blocks	6 - 6
adj. of subsequent blocks	0 - 0.33
share of cereals	0.16 - 0.33
share of ecol. infrastructure	0.04 - 0.06

pilot farm 6:

☐ EAFS (36 ha)
I-VI Crop rotation blocks 1994
▬ Ecological Infrastructure

◀——300 m——▶
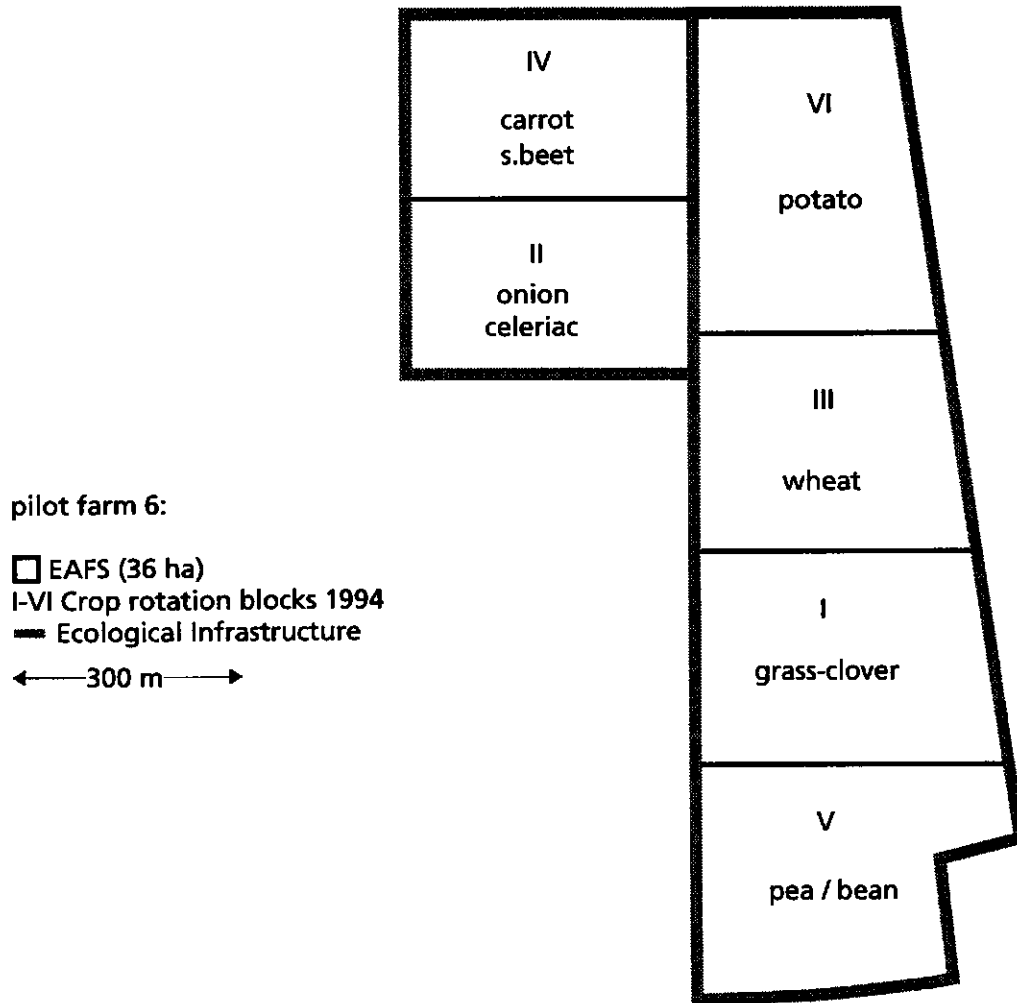
Figure 1.3   Layout of EAFS pilot project Flevoland (NL 2)

3   The modeller's perspective

F.W.T. Penning de Vries
Research Institute for Agrobiology and Soil Fertility (AB-DLO), The Netherlands

3.1   Introduction

Building models is a way to integrate knowledge and to make it accessible for various purposes. Both process and product are important (Penning de Vries & Rabbinge, 1995) because they:

• help to define and categorise the state of knowledge of the subject;
• help to set priorities for research, by helping to locate gaps in knowledge and to link scientists across disciplines, levels of aggregation and from fundamental and applied sciences;
• provide a means for disseminating knowledge;
• provide a tool to make integrated knowledge operational for policy making and for resource management.

Modelling in crop science has long been concentrated on crop phenology and growth, soil water and soil nutrient dynamics, and their relations to weather. Models are used extensively for all four purposes mentioned, including understanding the behaviour of the crops in specific environments, and optimisation of planting dates, fertiliser application and crop choice. More than one hundred of such models are characterised in the CAMASE-Register (Plentinger & Penning de Vries, eds., 1996). Some modelling studies also considered explicitly the cropping systems context (e.g. Aggarwal, 1993; Timsina et al., 1993 a, b). Demand is now increasing to use models for studies at even broader scales in time and space, and for more complex issues (Dent, 1993; Stroosnijder & Van Rheenen, 1993).

One such a demand is to involve models in the research of cropping systems: to quantify nutrient carry over between crops and losses to the environment, to optimise crop choice, to establish the impact of weed population dynamics, etc. Even more than in crop science, cropping and farming systems research needs models because experimentation has important though limited opportunities: it takes several years, few if any repetitions are possible and cost soon become prohibitive. Descriptive models, quantifying observed growth and nutrients fluxes in equations, do a good job in reproducing the original data, but have little power of extrapolation to years with different weather pattern, other soil types. Dynamic and explanatory simulation models, with much stronger capacities to generalise, could not really be used in this field until recently, because there was too little knowledge of the key soil and crop processes, computers may have been too slow to handle the complex models, and too few observations were available to get any feeling for the (in)accuracy of the model. In recent years several attempts were made by different simulation groups in the world to involve mechanistic models in understanding the behaviour of crop sequences and crop rotations. This CAMASE/PE meeting was called to bring together many of the modelers involved and the models to simulate crop rotations.

At the same time, we want to be careful not to develop rotation models as a goal in itself, but to listen carefully to scientists who actively investigate cropping systems and who design improved systems and improved system management. We aimed the meeting at actual and potential contributions of crop rotation modelling to research on ecological crop rotations, since much attention is given nowadays in the Netherlands to research on ecological farming (i.e. farming with use of little or no artificial fertiliser and a minimum of chemical inputs for crop protection; note that ecological farming thus defined is new in The Netherlands, but common practice in Australia!). While there are clearly questions that cannot not yet be answered with dynamic models (e.g. on crop quality, comparison of mechanistic and chemical removal of weeds, development soil structure, accounting for soil heterogeneity), models may provide answers to questions the ecologists had not thought of (adjusting results of a year with extreme weather, judging the effects of slow developments in soil organic matter, quantifying short-term effects of high rainfall on NO_3-leaching; pre-testing designs and experiments).

With crop rotation models, we may be roughly in a stage between 'preliminary' and 'comprehensive' modelling (Penning de Vries & Rabbinge, 1995). Main benefits of such models are in research, and moderately in prediction. With a concerted effort, we can reach in the next 5-10 years dynamic, deterministic summary models, whose value is in application in particular. With complex models as some of those on crop rotations, however, the distinction in three development stages for the entire model may not be fully adequate, but applicable to each of its submodels instead. Some of the models presented at this meeting clearly had parts that were well developed, tested and simplified ('summary models'), while other components are still in an early stage. Overviews are presented in the last chapters.

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II   Crop rotation models

4 APSIM, and its use in cropping systems analysis

H. Meinke, P.S. Carberry, B.A. Keating, D.M. Freebairn, J. Turpin & J. Dimes
DPI/CSIRO, Agricultural Production Systems Research Unit, Australia

4.1 Abstract

This paper gives an outline of the current systems simulation capabilities within the Agricultural Production Systems Research Unit (APSRU). Against a background of high rainfall variability, high potential for soil erosion, increasing salinity, increasing awareness regarding off-farm effects of agriculture and considerable fertility decline in some regions, the development, functionality and use of the Agricultural Production Systems Simulator (APSIM) are described. Emphasis is on the presentation of past and current uses of this systems modelling capability.

4.2 Introduction

Cropping in Australia poses many challenges. With European settlement of Australia about 200 years ago, farmers of the "new" continent were exposed to an environment that differed fundamentally from their experience. They had no means of assessing the land's suitability to cropping other than by trial and error. Their hard-won experiences, often featured in Australian contemporary art and folklore, were passed on and led to today's manifestation of diverse, regional cropping systems.

Analysing and improving these systems requires sound understanding of physical, chemical and physiological processes and tools to evaluate their interactions. Effects of management strategies need to be assessed and quantified in terms of productivity and their impact on the resource base. Additionally, the high rainfall variability throughout Australia often means that even one lifetime of cropping experience can be insufficient to sample the underlying variability adequately (Meinke & Hammer, 1995). Cropping systems models are one obvious choice of possible tools to address such issues. They have many potential applications ranging from environmental issues and policy matters to farm optimization and variety adaptation (e.g. Littleboy et al., 1992; Netherlands Scientific Council for Government Policy, 1992; Penning de Vries et al., 1993; Goldsworthy & Penning de Vries, 1994; Hammer et al., 1996a).

Care needs to be taken, however, that the methodology used is appropriate for the task. Modelling should not be seen as the panacea for all agricultural problems but rather as a convenient way of aggregating environmental interactions thus providing higher level data upon which decisions can be based. The technology integrates our knowledge of agricultural systems, allows generation of mostly probabilistic information useful to systems managers (e.g. What if? When? How often?) and highlights gaps in current understanding of the system. It is a means of making agricultural research more relevant to practice and thus adds value to existing knowledge and our research efforts. By simulating the production system, the state of the

system at any point in time is known, and alternative management options and their long-term impact on sustainability and productivity can be evaluated.

Models can be used to answer questions at various levels of aggregation. Irrespective of scale, processes of equal importance should be represented at the same level of resolution throughout a model. This is often constrained by scientists' specifically-focused expertise and hence limited knowledge of processes that, although not directly part of their field of research, need to be included in the model. Particularly when moving from single crops to cropping systems models, this becomes increasingly difficult as more and more disciplines are expected to contribute to the model. Additionally, only few agricultural scientists have had any formal training in software development that enables them to structure and write computer code efficiently and with the necessary precision and flexibility. The same rigour that is applied to vetting the science underlying the model needs to be applied to its implementation and to its maintenance (McCown et al., 1996). These issues have been addressed and are reflected in the design structure and the development of the Agricultural Production Systems sIMulator (APSIM).

4.3　　　Methods

APSIM provides a versatile and flexible infrastructure for model development, testing and application (McCown et al., 1996). Its main features are summarized in Table 1.

Table 1　Summary information for the Agricultural Production Systems SIMulator (APSIM)

Name of model	The Agricultural Production Systems SIMulator (APSIM)
Developed by	Agricultural Production Systems Research Unit (APSRU)
Reference	McCown, R.L., G.L. Hammer, J.N.G. Hargreaves, D.P. Holzworth & D.M. Freebairn, 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural systems research. Agricultural Systems 50: 255-271.
Principle aim	The simulation of agricultural production systems at the point/paddock scale.
Target use / user groups	Other researchers Regional planners & policy makers Agricultural advisors (extension officers, agribusiness advisors) Farmers
Type of model	A daily time-step model based on physiological, physical and chemical knowledge of system processes.

Brief description	APSIM is a flexible software environment for simulating systems rather than a model of a particular cropping system. Within APSIM there is a library of modules, each describing specific processes, that can be combined in meaningful ways to represent agricultural systems. Modules can be either biological (e.g. crop, pasture, surface residue), environmental (e.g. water balance, N balance, soil erosion), managerial (e.g. tillage, irrigation, fertilization) or economic (e.g. event log) and they communicate with each other via the APSIM "engine". The "engine" passes information between modules according to a standard protocol which allows modules to be plugged in or pulled out of the "engine" depending on the specifications for the simulation task. In this way, the simulation capacity of APSIM is limited only by the availability of modules to simulate aspects of the system of interest.
General or region specific	General
Data requirements	Climate (mostly daily data of temperature, solar radiation and rainfall) Site characterisation Crop model parameters Soil water balance parameters Soil nitrogen fertility parameters Surface residue parameters Soil erodability parameters
Model assumptions	System performance can be simulated through the linked simulation of individual processes.
Model testing/validation	APSIM has adopted many of the existing models that simulate crop, pasture, or soil processes in Australia and elsewhere. The accuracy of APSIM therefore derives from the validation accuracy of each original module plus the degree to which such validations are affected by the module combination linked into APSIM for a particular application. Testing of APSIM is an on-going task within APSRU.
Known good points	Ability to simulate agricultural systems (crop rotations, inter-species competition).
Known limitations	Few skilled operators/trainers
Commercial details	APSIM is regarded as the intellectual property of APSRU and strict control is maintained over its distribution. As a rule, APSIM is not made available to others outside APSRU, except by negotiation. Generally, negotiation for the use of APSIM involves either close collaboration with APSRU, e.g. through collaborative projects, exchange of modules or datasets, or by some funding arrangement.
Contact for further information	APSRU Management Committee, APSRU, P.O.Box 102, Toowoomba, Q. 4350, Australia. Phone: +61.76.314 394 Fax: +61.76.332 678 E-mail: lisettea@apsrusg.sth.dpi.qld.gov.au

APSIM results from a convergence of two previous efforts to achieve the combination of well performing crop models, the ability to simulate configurations of crops, sequences and management practices and software that is designed and tested. The first, PERFECT (Littleboy et al.,

1992) was mainly designed to assess effects of erosion on productivity in the Australian sub-tropics and for climatic risk analysis (Hammer et al., 1987). The second, AUSIM (McCown & Williams, 1989) developed a crop model template that ensures flexibility and efficiency when developing modules that interact to simulate systems and helps with the implementation of high programming standards.

The efforts of the PERFECT and AUSIM teams were combined to produce APSIM, which goes beyond its predecessors in its functionality and structure. APSIM's central engine, written by professional software developers, facilitates communication between modules, based on a plug-in, pull-out principle. This allows scientists to concentrate on developing individual modules in their area of expertise without being divorced from development activities in other areas. It also enhances communication among those scientists and supports model development activities through a range of tools such as graphic routines to analyse output or changing variable names throughout the module at the press of a button. It allows a fast and thorough evaluation of alternative modelling approaches (Meinke & Stapper, 1995).

Simulation of cropping systems requires representation of relevant management actions realistically taken in response to conditions. This is accomplished by the Manager module. This key feature of APSIM allows the user to mimic an unlimited number of management operations as they occur. Actions such as crop choice, planting, application of fertilizer, tillage or irrigation can be controlled using rules. The language for expressing rules is 'If?.condition(s) satisfied then ?action(s)'. This form allows great flexibility and enables ready construction of complex rules. The 'System Log' records interventions of the Manager.

Within APSIM each major soil or crop process is represented by a separate module. Thus, soil dynamics (i.e. water, nitrogen and carbon fluxes, residue decomposition, surface condition and erosion) provide the common basis for analysis of cropping systems. The core concept has changed from that of a crop responding to resource supplies in existing crop models to that of a soil responding to weather, management and crops. All modules are independent and communication between modules is handled by a central 'engine' which uses a unique message passing system. A standard interface design enables easy removal, replacement or exchange of modules without disrupting operation of the system. The shell allows rapid evaluation and further development of new modules. This structure facilitates the collaborative effort required in the development of a systems simulation model, where different processes are understood and developed by different people, and where alternative representations of a single process are sometimes needed. The WINDOWS based platform allows easy integration of existing models or modules. A sophisticated communication protocol and a modular structure assist users to combine desired modules at the click of a button. This configuration of modules can then be used to simulate the impact of land use on resources for a range of management scenarios associated with crop sequence, fertilization, and tillage. The necessary management rules for these scenarios can easily be constructed without recompiling. Information thus generated enables analysis of economic and resource risks in the variable climatic and marketing environments faced by most agricultural production systems in Australia.

Although APSIM is being developed as part of a systems and operational research approach to problems in production systems of north-eastern Australia, it is a suitable tool for similar applications elsewhere. Its main objectives are to combine crop and pasture models to simulate various production systems using soil and crop processes at levels that are balanced and appropriate to proposed applications.

Modules are grouped into crop, crop management, soil water, soil nutrient, surface management, economic and climatic modules. At present, crop modules are operational in APSIM for wheat, barley, sorghum, sunflower, maize, sugar cane, cotton, peanuts, chickpea and pastures. They are mostly based on existing models with varying degree of adaptation. Modules for soybean, mungbean and cowpea are under development. Adaptation of existing modules continues, because each of the modules reflects the purpose and environment for which it was originally developed.

APSIM can be used at different levels of aggregation, that is, crop, cropping system, farm and region. Added complexity is only sought if it clearly improves predictive capability across spatial and temporal scales. Often models are too complex, with complexity often poorly balanced, for the level of application (Goudriaan et al., 1994; Meinke, 1996). APSIM facilitates a better match between specific applications and the appropriate level of complexity.

4.4   Applications of APSIM - some examples

In the following section, we present abstracts of some selected past and current projects that relate to the topic of this workshop. Table 2 summarizes APSRU's project activities in the area of systems analysis and improvement.

Table 2   List of APSIM projects in the area of systems analysis and improvement

Analysis of cropping strategies (e.g. opportunity versus fixed fallows)

Assessment of drainage losses below alternative cropping strategies

Impact of fertiliser and residue management on soil fertility decline

Nitrate leaching from high input sugarcane production systems

Production and economics of cereal-legume rotations

Analysis of intercropping systems

Agroclimatic analyses - potential for existing or new cropping enterprises

Analysis of planting opportunities and crop choice ("Plant now or later")

Assessing the value of nitrate deep in the profile and adjusting N fertilisation regimes

Economics of investing in supplementary irrigation for sugar cane farms

Assessment of the value of a climate forecast in crop production

Impact of windbreaks on crop productivity

Fate of endosulphan in cotton production systems

Assessment of the impact of soil structural degradation under cropping

Design of sustainable systems of effluent irrigation of eucalypt forests

Trees and native pastures in northern Australia

Productivity of grazed pasture-crop rotations

Erosion from Leucaena / Maize alley cropping systems in the Philippines

Evaluation of farming systems in the semi-arid tropics of India and Africa (in collaboration with ICRISAT)

4.4.1 Modelling water, nitrogen and crop yield for a long-term fallow management experiment

Two models, CENTURY (monthly time step) and APSIM (daily time step), that differ markedly in how they represent the crop-soil system have been used to simulate soil processes and crop production in a long-term (25 years) experiment in Queensland (Probert et al., 1995). The experiment was designed to examine effects of tillage, stubble management and nitrogen fertilizer on the productivity of a winter cereal - summer fallow cropping system (Marley & Littler, 1989; Thompson, 1990). Both models predicted, in agreement with the observed data, that for this continuous cereal cropping system there has been a decline in soil organic matter for all treatments and a reduction through time in the capacity of the soil to mineralise and accumulate nitrate during the fallows. Although models differed in detail, they reproduced the observations well enough to indicate their suitability for providing useful insights into the behaviour of cropping systems where the focus is on depletion of soil fertility.

4.4.2 Intercropping

APSIM was specified for two mixed-crop systems: a maize-cowpea intercrop system and a crop-undersown pasture system (Carberry et al., 1996a). In the former case, APSIM was able to simulate the growth, development and yield of both maize and cowpea grown under a range of soil water and fertility conditions. Measured data were collated from experiments and from the literature where crops were arranged as sole crops, intercrops and where the relative time of sowing of each crop also changed. In the latter case, a mixture of pasture legume under a maize crop was simulated; growth of the mixture was predicted under conditions where the maize and pasture competed for light, water, and nitrogen during the cropping season. Predicted grain yield of maize and biomass yield of pasture legume were similar to observed yields for both intercrop and sole crop and pasture treatments.

In a further study (Carberry et al., 1996b), APSIM was able to reproduce the measured yields from sorghum, maize and verano grown either as sole crops, as intercrops or in rotations of several years. Likewise, a simulation analysis of several cropping options for Katherine, NT, resulted in the preferred outcome reflecting current farming practices in the region. This is superior in terms of both gross margin returns and long-term soil fertility status.

4.4.3 Pasture ley - cropping rotations

Two experiments used a field bio-assay approach to investigate the nitrogen benefit from pasture leys of Stylosanthes hamata to subsequent maize crops (Jones et al., 1996). Nitrogen uptake and yields of maize crops were higher after the verano leys than after grass ley, the effect persisting into the second crop. The main features of the experimental results, through both the ley and cropping phases, could be simulated adequately using APSIM, despite the fact that currently the model does not have a capability to grow perennial leys. The model provides opportunity to explore the fate of nitrogen in the system, thereby giving insights into system performance that cannot be addressed from experimental data.

4.4.4 Cropping rotations, fallow management and solute movement

Profile distributions of nitrate and chloride measured on a black earth in Queensland indicated that over 20 years of continuous winter cropping, nitrate losses by leaching represented up to 30% of applied fertilizer and were greatest where annual summer fallows were zero tilled (Turpin et al., 1996). APSIM was used to simulate the observed chloride movement patterns and investigate the influence of alternative cropping rotations with both conventionally tilled and zero tilled fallows. Simulation results demonstrated that within the period 1969 to 1992, there were only three periods of rapid leaching.

SWIM Version 2 (Ross et al., 1992) is a soil water and nutrient balance model based on a numerical solution of the Richards' and Convection-Dispersion equations. It has recently been incorporated into the APSIM framework to combine the benefits of both and to provide an alternative to the currently available cascading soil water balance module (Huth et al., 1996). APSIM-SWIM can now be used to calculate all flows of water and nutrients into, through and out of soils under a wide range of conditions. Further work examines how APSIM-SWIM can be used to devise management strategies that might limit nitrate leaching under sugar cane crops (Keating et al., 1996b; Verburg et al., 1996).

4.4.5 Drought assessment

Climatic variability is a natural part of farming in Australia and current Government policy sees drought more as a normal part of the production environment, than an unpredictable disaster requiring relief (Keating et al., 1996a). Despite this philosophy, the notion remains that drought policy should provide assistance to producers in those calamitous circumstances where government action is required as a measure of last resort. Government support to farmers suffering in the 1994 drought was provided because the circumstances were viewed as calamitous, although this view was not shared by all commentators. This study examines approaches and criteria for assessing the severity of a prolonged drought.

4.4.6 Participatory research with farmers and their advisors

Information generated by simulation models is perceived as having low credibility by farmers and their advisors. There has been little evidence that such information, when presented through traditional extension methods and decision support products, has benefited farmers. Therefore, important questions for industry, being asked to fund the further development of simulation models, are (i) can models really be used to benefit management of farming systems? and (ii) how can this proposed benefit be implemented? McCown (1995) and Foale et al. (1996) report on a participatory research approach which is attempting to address these questions. As farmers themselves are often experimenting with rotations and crop management, it has been feasible to join them in exploring farming systems issues on farm. With collaborating farmers and consultants, soil water and nutrient data are collected prior to planting from paddocks which differ in their cropping history. These data coupled with APSIM and the long-term climatic record are used to suggest production strategies that better meet grower objectives.

Showing that APSIM can reproduce on-farm results is important in order to provide credibility in model predictions.

4.4.7 Effect of cropping frequency on deep drainage

Keating et al. (1995) have used APSIM configured with wheat and sorghum modules to examine the impacts of cropping strategies on the deep drainage term in the water balance in the Liverpool Plains. This work highlights the tradeoffs between production risk and deep drainage risk for long-fallow wheat / sorghum systems compared to opportunity cropping systems.

4.4.8 Seasonal climate forecasting and tactical management

Recent advances in long-range rainfall and frost forecasting allow a pre-season evaluation of likely growing conditions in Eastern Australia (Stone et al., 1996). In this region of high climatic variability (Nicholls & Wong, 1991), a skilful seasonal forecast provides an opportunity for farm managers to better tailor crop management decisions to the season (Hammer et al., 1996b). Meinke et al. (1996) have shown in a case study for peanuts how such a probabilistic climatic forecasting system can be combined with a dynamic simulation model to forward estimate production levels and risk. However, implications of a seasonal forecast system go beyond single crop issues. Their impact on key cropping systems decisions, such as crop choice and cropping sequence, needs to be assessed. Other issues, such as the residual value of applied nitrogen to the following crop require agronomic and economic quantification. In close collaboration with farmers, the seasonal forecast techniques and modelling capabilities is used to gain improved insight in the longer-term consequences of possible decision options.

4.4.9 Tactical crop choice

Generally the choice of crop type is not difficult for farmers if planting rains occur in the 'main' season. This choice becomes problematic when rains are early or late, and there is uncertainty as to when the next opportunity will occur, a common problem in semi-arid tropics (Muchow et al., 1994; Meinke et al., 1996). As a case study, the outcomes of three scenarios (a) late wheat, with a fallow to the next winter wheat; (b) delay planting and wait for a early summer planting opportunity for sorghum or (c) late wheat with the possibility of a late summer crop (an opportunistic "double crop") were compared. After analysis of crop yield distributions and consideration of commodity prices, advice to farmers was to avoid late wheat if possible as future planting opportunities and rising levels of soil water storage for the coming summer crop indicated better financial returns. Results were disseminated using mass media (radio, farm journal), and officers' summary notes to district extension officers (Dimes et al., 1993). Timely analysis of such issues has been effective in facilitating dialogue between scientists and land managers, and we believe lead to better informed decisions. While all output is probabilistic, the analysis of climatic data through the cropping system model has been instructive to scientists and farmers alike.

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5   The CropSyst Model: A brief description

C.O. Stockle
Washington State University, Biological Systems Engineering Department, United States

M. Donatelli
Istituto Sperimentale Agronomico - Sezione di Modena, Italy

5.1   Introduction

CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface, and with a link to GIS software and a weather generator (Stockle, 1996). Link to economic and risk analysis models is under development. The model's objective is to serve as an analytical tool to study the effect of cropping systems management on crop productivity and the environment. For this purpose, CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. These are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilisation, pesticide applications, soil and irrigation water salinity, tillage operations, and residue management.

The model code is written in Pascal (DOS version) and C++ (Windows and Windows 95 versions). An advanced user-friendly interface allows users to easily manipulate input files, verify input parameters for range errors and cross compatibility, create simulations, execute single and batch run simulations, customise outputs, produce text and graphical reports, link to spreadsheet programmes, and even select a preferred language for the interface text. Simulations can be customised to invoke only those modules of interest for a particular application (e.g., erosion and nitrogen simulation can be disabled if not desired), producing more efficient runs and simplifying model parameterisation. The model is fully documented (Stockle & Nelson, 1994; Stockle & Nelson, 1996), and the manual is also available as a help utility from the CropSyst interface. CropSyst executable programme, manual, and tutorials can be retrieved directly over the Internet (http://www.cahe.wsu.edu/~bsyse/faculty/stockle/cropsyst/cropsyst. html).

5.2   Brief model description

The model is intended for crop growth simulation over a unit field area (m²). Growth is described at the level of whole plant and organs. Integration is performed with daily time steps using the Euler's method. A complete description of the model is given in the user's manual (Stockle & Nelson, 1994), which is currently being updated (Stockle & Nelson, 1996). The nitrogen and water submodels in CropSyst, and a general description of growth simulation have been presented elsewhere (Stockle et al., 1994). A new approach to determine crop nitrogen

demand has been recently developed (Stockle & Debaeke, 1996). A finite difference solution of Richards equation to simulate water transport (as an alternative to existing cascading approach), and crop response to salinity has been also recently added (Ferrer-Alegre, 1995). A general description of the model follows.

The water budget in the model includes precipitation, irrigation, runoff, interception, water infiltration, water redistribution in the soil profile, crop transpiration, and evaporation. Users may select different methods to calculate water redistribution in the soil profile and reference evapotranspiration. Water redistribution in the soil is handled by a simple cascading approach or by a finite difference approach to determine soil water fluxes. The latter allows accounting for upward flow (and chemical transport) from a water table, whose depth from the soil surface needs to be specified over time. CropSyst offers three options to calculate grass reference ET. In decreasing order of required weather data input, these options are: the Penman- Monteith model, the Priestley-Taylor model, and a simpler implementation of the Priestley-Taylor model which only requires air temperature. Crop ET is determined from a crop coefficient at full canopy and ground coverage determined by canopy leaf area index.

The nitrogen budget in CropSyst includes N transformations, ammonium sorption, symbiotic N fixation, crop N demand and crop N uptake. Nitrogen transformations of net mineralisation, nitrification and denitrification are simulated. The water and nitrogen budgets interact to produce a simulation of N transport within the soil. Chemical budgets (pesticides, salinity), including pesticide decay and absorption, are also kept and interact with the water balance. All balances within the model are checked at each time step and errors are reported in case of departures within set threshold values.

Crop development is simulated based on thermal time required to reach specific growth stages. The accumulation of thermal time may be accelerated by water stress. Thermal time may be also modulated by photoperiod and vernalisation requirements whenever pertinent. Daily crop growth is expressed as biomass increase per unit ground area. The model accounts for four limiting factors to crop growth: water, nitrogen, light, and temperature. Given the common pathway for carbon and vapor exchange of leaves, there is a conservative relationship between crop transpiration and biomass production. Following Tanner & Sinclair (1983), daily biomass accumulation is calculated as:

$$B_T = K_{BT} \, T \, / \, VPD \qquad\qquad \text{[Eq. 1]}$$

where B_T is the transpiration-dependent biomass production (kg m^{-2} day^{-1}), T is actual transpiration (kg m^{-2} day^{-1}), and VPD is the mean daily vapor pressure deficit of the air (kPa). The Tanner-Sinclair relationship has the advantage of capturing the effect of site atmospheric humidity on transpiration-use efficiency. However, this relationship becomes unstable at low VPD; indeed it would predict infinite growth at near zero VPD. To overcome this problem, a second estimate of biomass production is calculated following Monteith (1977):

$$B_L = e \, I_{PAR} \qquad\qquad \text{[Eq. 2]}$$

where B_L is the light-dependent biomass production (kg m^{-2} day^{-1}), e is the light-use efficiency (kg MJ^{-1}) and I_{PAR} is the daily amount of crop-intercepted photosynthetically active radiation (MJ^{-1} m^{-2} day^{-1}). Each simulation day, the minimum of BT and BL is taken as the biomass production for the day.

Although the parameter e (Eq. 2) includes the effect of the temperature regime prevailing during its experimental determination, temperature limitations during early growth are not captured and a single value is determined for the vegetative period or, more usually, for the entire growing season. However, more detailed measurements will show a decrease of e during early growth due to low temperature. Not accounting for this temperature effect may result in overprediction of biomass production during early growth, particularly in the case of winter crops. A temperature limitation factor is included in CropSyst to correct the value of e during this period, which is assumed to increase linearly from zero to one as air temperature fluctuates from the base temperature for development to an optimum temperature for early growth.

To account for nitrogen effects on biomass production, the minimum of B_T and B_L is used as base to determine the nitrogen-dependent biomass production (B_N):

$$B_N = Min \{B_T, B_L\} [1 - (N_{pcrit} - N_p) / (N_{pcrit} - N_{pmin})]$$ [Eq. 3]

where B_N is in kg m^{-2} day^{-1}, Np is plant nitrogen concentration (kg kg^{-1}), N_{pcrit} is the critical plant N concentration (kg kg^{-1}) below which growth is limited, and N_{pmin} is the minimum plant nitrogen concentration (kg kg^{-1}) at which growth stops. The values of N_{pcrit} and N_{pmin} (and also of maximum plant nitrogen concentration, needed to establish crop nitrogen demand) fluctuate as a function of accumulated biomass, following the concept of growth dilution. More detail on this is given by Stockle & Debaeke (1996).

The increase of leaf area during the vegetative period, expressed as leaf area per unit soil area (leaf area index, LAI), is calculated as a function of biomass accumulation, specific leaf area, and a partitioning coefficient. Leaf area duration, specified in terms of thermal time and modulated by water stress, determines canopy senescence. Root growth is synchronized with canopy growth, and root density by soil layer is a function of root depth penetration. The prediction of yield is based on the determination of a harvest index (grain yield/aboveground biomass). Although an approach based on the prediction of yield components could be used, the harvest index seems more conservative and reliable for a generic crop simulator. The harvest index is determined using as base the unstressed harvest index, a required crop input parameter, modified according to crop stress (water and nitrogen) intensity and sensitivity during flowering and grain filling.

5.3 Model inputs

Four input data files are required to run CropSyst: Location, Soil, Crop, and Management files. Separation of files allows for an easier link of CropSyst simulations with GIS software. A Simulation Control file combines the input files as desired to produce specific simulation runs. In addition, the Control file determines the start and ending day for the simulation, define the crop rotations to be simulated, and set the values of all parameters requiring initialisation. Definitions, usage, and range of variation of all parameters required by CropSyst are given in the User's Manual (Stockle & Nelson, 1994, 1996), and they are also available in the Help facility of the model interface.

The Location file includes information such as latitude, weather file code name and directories, rainfall intensity parameters (for erosion prediction), freezing climate parameters (for locations

where soil might freeze), and local parameters to generate daily solar radiation and vapour pressure deficit values.

The Soil file includes surface soil Cation Exchange Capacity and pH, required for ammonia volatilization, parameters for the curve number approach (runoff calculation), surface soil texture (for erosion calculation), and five parameters specified by soil layer: Layer thickness, Field Capacity, Permanent Wilting Point, Bulk Density, and Bypass Coefficient. The latter is an empirical parameter to add dispersion to solute transport, particularly when using the cascading approach for soil water redistribution.

The Management file includes automatic and scheduled management events. Automatic events (irrigation and nitrogen fertilisation) are generally specified to provide optimum management for maximum growth, although irrigation can also be set for deficit irrigation. Management events can be scheduled using actual date, relative date (relative to year of planting), or using synchronisation with phenological events (e.g., number of days after flowering). Scheduled events include irrigation (application date, amount, chemical or salinity content), nitrogen fertilisation (application date, amount, source- organic and inorganic-, and application mode- broadcast, incorporated, injected), tillage operations (primary and secondary tillage operations, which are basically related to residue fate), and residue management (grazing, burning, chopping, etc.).

The Crop file allows users to select parameters to represent different crops and crop cultivars using a common set of parameters. This file is structured in the following sections: Phenology (thermal time requirements to reach specific growth stages, modulated by photoperiod and vernalisation requirements if needed), Morphology (Maximum LAI, root depth, specific leaf area and other parameters defining canopy and root characteristics), Growth (transpiration-use efficiency normalised by VPD, light-use efficiency, stress response parameters, etc.), Residue (decomposition and shading parameters for crop residues), Nitrogen Parameters (defining crop N demand and root uptake), Harvest Index (unstressed harvest index and stress sensitivity parameters), and Salinity Tolerance.

5.4 Validation performed

CropSyst has been applied to simulate several crops (corn, wheat, barley, soybean, sorghum, and lupins) and regions (Western US, Southern France, Northern and Southern Italy, Northern Syria, Northern Spain, and Western Australia), generally with good results and also with a few problems (e.g. Donatelli et al., 1996a), particularly for applications to conditions not simulated by the model (for example, water balance of cracking vertisols). The quality and/or level of detail of the available data is often a constraint for more thorough model evaluation. For more information on CropSyst validation the reader is referred to Stockle et al. (1994), Pala et al. (1996), Stockle et al. (1996), Stockle & Debaeke (1996), Donatelli et al. (1996a), Donatelli et al. (1996b), and Ferrer-Alegre (1995). A few examples are given here.

Table 1 summarises validation work performed using data from US locations (Stockle et al., 1994) and from Tel Hadya (headquarters of ICARDA) in Northern Syria (Pala et al., 1996). Statistical analyses have indicated a satisfactory performance of CropSyst in these evaluations. Although not shown here, good agreement with observed seasonal evolution of ET, LAI, and

biomass was found for Northern Syria data, which is fundamental to provide a good base for adequate simulation of biomass and yield at harvest time.

Table 1   Summary of statistical results for comparisons of simulated and observed yields (from Pala et al.,1996, and Stockle et al., 1994)

Crop	Location	1)	2)	n	Obs. Mean (kg/ha)	Sim. Mean (kg/ha)	RMSE (kg/ha)	RMSE /Obs. Mean	d 3)
Wheat	Northern Syria	G	W/N	16	2180	2410	550	0.25	0.92
Wheat	Northern Syria	B	W/N	16	7310	7090	870	0.12	0.96
Wheat	Northern Syria	G	W/N	16	1750	2080	560	0.32	0.90
Wheat	Northern Syria	B	W/N	16	7190	7140	1030	0.14	0.92
Corn	Davis, CA ; Ft Collins, CO	G	W	28	9831	9026	724	0.081	0.95
	Davis, CA ; Ft Collins, CO	B	W	28	16460	16808	1246	0.076	0.954
Wheat	Logan, UT	G	W	18	4100	4261	443	0.108	0.979
	Logan, UT	B	W	18	8033	8460	1121	0.14	0.961
Wheat	Logan, UT	G	W/N	30	4946	4963	383	0.077	0.975
	Logan, UT	B	W/N	30	10293	10339	786	0.076	0.996

1) B = Biomass, G = Grain Yield

2) W = Water treatments were imposed, N = Nitrogen treatments were imposed

3) d = Willmott Index of Agreement (Willmott, 1982), ranging from 0 to 1, 1 being perfect agreement

Recent validation work was performed using data collected by the Institut National de la Recherche Agronomique (INRA) at Auzeville (near Toulouse), France (Stockle et al., 1996). These data are from long-term cropping system experiments conducted from 1983 to 1992 to evaluate crop rotations at three input levels. Input level I was not irrigated and received a minimum amount of fertilisation; level II received limited irrigation, restricted to the most sensitive growth phases, and a moderate amount of fertilisation; and level III received full irrigation and a large amount of fertilisation. The objective was to evaluate the ability of CropSyst to predict ET, biomass, and yield of maize, sorghum, and soybean in response to weather (three dry years: 1986, 1989, and 1990) and soil water availability. In addition, simulations were performed using four combinations of two ET and two infiltration/redistribution submodels. The ET submodels corresponded to the Penman-Monteith (P-M) and Priestley-Taylor (P-T) equations, the latter applied with a VPD-dependent P-T coefficient. Infiltration/redistribution submodels corresponded to the cascading [C] method and the finite difference (FD) method. CropSyst was found able to simulate well the observed ET, biomass, and grain yield for the three crops, three years, and three irrigation input levels as given by Wilmott index of agreement consistently over 0.95. Results in Table 2, which include only crop yield simulations, show that the best simulations tended to be associated with the use of the P-M ET and the FD water transport submodels. However, results using the simpler methods are not too different, which is encouraging for applications where data input or computer CPU time constraints may be an issue.

The capability of CropSyst to simulate different cropping systems using 6 years of data collected from rotation experiments at two locations, representative of the two largest plain areas of Italy, was tested by Donatelli et al. (1996a). Simulations were performed by initialising state variables at the beginning of 6-year rotations without further reinitialisation, thus constituting a severe test of the model's medium-term predictive capabilities. Data available did not allow for detailed corroboration of model components and limited further analysis for correction of situations where model performance was poor.

Model estimates of yield of maize, soybean, and barley at Modena, and sorghum and sunflower at Foggia, appeared reasonably accurate. CropSyst was not able to simulate soybean growth when the crop was sown as a second crop after durum wheat at Foggia. However, poor simulation of winter cereal yields proved to be the most critical limitation of the model, particularly at Foggia, and the variability observed in durum wheat yields at this location in different rotations could not be explained satisfactorily. The model was able to simulate correctly water use by crops in different years, but the rewetting of soil profile during the second part of the year was often overestimated for surface soil layers and underestimated for deeper soil layers, presumably as the consequence of a seasonal preferential water flow due to soil cracking. As an example, Figure 1 shows simulated and measured soil water content fluctuations for the two-years rotation sunflower-durum wheat at Foggia.
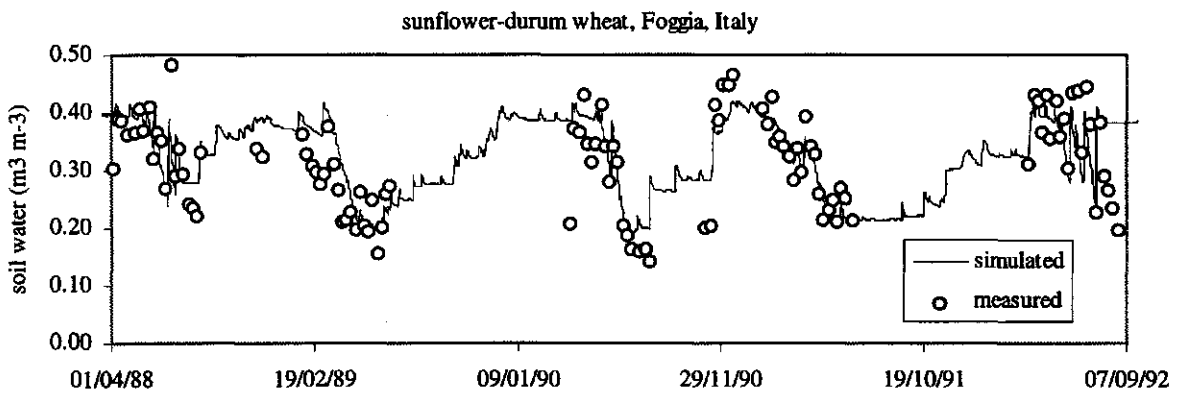
Figure 1   Simulated and measured soil water content for the rotation sunflower-durum wheat at Foggia, Italy. Average values of the soil layer 0.05 - 0.5 m depth.

Work under progress is applying CropSyst to study the economic risk of selected crop rotations in the Palouse region of the Pacific Northwest, USA. This is a dryland region characterised by steep gradients of precipitation fluctuating from 200 to 500 mm, with weather conditions ranging from excellent to marginal for small grain production. Crop rotations evaluated include Winter Wheat/Spring Barley/Spring Peas, Winter Wheat/Spring Peas, Winter Wheat/ Spring Barley/Fallow, Winter Wheat/Fallow, and continuous Spring Barley. Thirty-year average yield of the different crops within typical rotations have been compared with long-term farm-level yield averages. Both the simulated average and the coefficient of variation for the three crops compared well with observed values. Comparisons for winter wheat and spring barley are shown across the rainfall gradient (Figure 2).

Table 2   Summary of statistical results for comparisons of simulated and observed grain yield at Auzeville, France using different ET and water transport submodels (PM = Penman-Monteith ET submodel; PT = Priestley-Taylor submodel; C = cascading infiltration; FD = finite difference infiltration)

		PM/FD	PM/C	PT/FD	PT/C
Sorghum					
	Number of data points	8	8	8	8
	Observed average (Oavg) (kg/ha)	7601	7601	7601	7601
	Predicted average (kg/ha)	8060	7852	8822	8679
	RMSE (kg/ha)	935	860	1531	1339
	RMSE / Oavg	0.123	0.113	0.201	0.176
	Wilmott index of agreement	0.963	0.968	0.911	0.931
Soybean					
	Number of data points	9	9	9	9
	Observed average (Oavg) (kg/ha)	2828	2828	2828	2828
	Predicted average (kg/ha)	2738	2819	2984	3093
	RMSE (kg/ha)	356	398	395	473
	RMSE / Oavg	0.126	0.141	0.140	0.167
	Wilmott index of agreement	0.975	0.965	0.972	0.955
Maize					
	Number of data points	9	9	9	9
	Observed average (Oavg) (kg/ha)	8026	8026	8026	8026
	Predicted average (kg/ha)	7494	7503	8029	8064
	RMSE (kg/ha)	1858	2043	2001	2108
	RMSE / Oavg	0.231	0.255	0.249	0.263
	Wilmott index of agreement	0.958	0.946	0.952	0.943

Table 3   Statistical indices to evaluate simulation results at Modena and Foggia, Italy. Key: n, number of observations; $\bar{O}$, average measured yield; $\bar{P}$, average simulated yield; RMSE, root mean square error[†]; EF, modelling efficiency[†]; CRM, residual mass coefficient[†]; slope, intercept and $r2$ of the regression predicted vs. measured yield

	n	$\bar{O}$ (t ha⁻¹)	$\bar{P}$ (t ha⁻¹)	RMSE (%)	EF	CRM	Slope	Int.	r^2
Modena									
barley	48	6.01	5.91	7.42	0.59	0.0163	0.53	2.74	0.62
maize	39	9.35	9.44	4.84	0.64	-0.0103	0.81	1.90	0.68
soybean	50	2.90	2.85	13.73	0.85	0.0164	1.06	-0.21	0.89
Foggia									
durum wheat	70	2.58	2.50	15.59	-0.38	0.0303	0.06	2.34	0.01
sorghum	29	6.53	6.67	19.93	0.57	-0.0217	0.90	0.79	0.67
soybean(sum. sow.)	30	1.99	1.78	18.84	-0.62	0.1074	0.00	1.76	0.00
sunflower	20	3.23	3.24	20.66	0.63	-0.0020	0.69	0.99	0.63

† see Loague & Green, 1991

5.5 Plans for development

CropSyst improvement is an ongoing and challenging process. In general, the introduction of new management capabilities or new simulation modules is not very likely in the near future, but rather improvement of process simulation will be given priority. The capability of accounting for tillage effects on both infiltration and evaporation will be implemented in the model, and the evaporation process will be re-evaluated to more accurately simulate evaporation under fallow conditions.
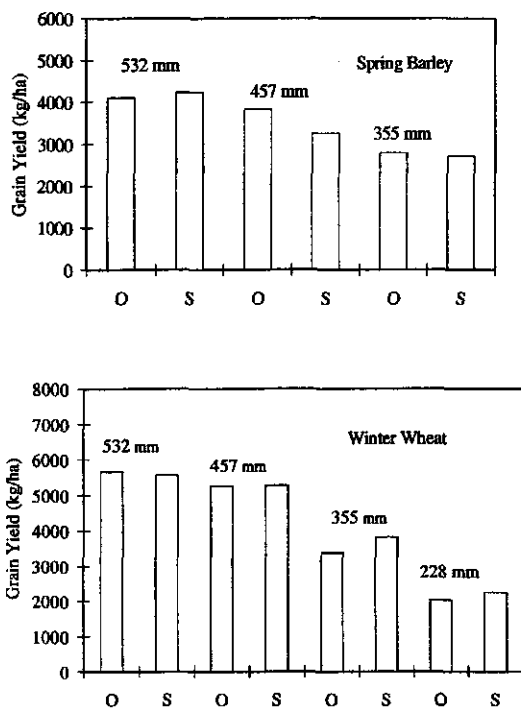
Figure 2   Simulated and observed long-term yields for winter wheat and spring barley in typical rotations at the Palouse region of the Pacific Northwest, USA (S = Simulated, O = Observed)

Validation with data sets from all over the world is of great interest to ensure robustness of the model. Test of the model with new crops such as potato (in progress), sugar beet, alfalfa, canola, and others will be attempted as proper data sets become available. Co-operation with agronomists and agricultural scientists around the world is desirable for further progress.

5.6 Acknowledgements

5.7 References

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6 The soil-plant-atmosphere model DAISY

H. Svendsen & N.E. Nielsen
The Royal Veterinary & Agricultural University, Dept. Agricultural Sciences, Denmark

6.1 Objective

The objective of the DAISY model is to simulate how climate, soil type, soil fertility and various agricultural management strategies and practices affect crop production, nutrient (nitrogen) and water use efficiencies and losses at the field scale.

6.2 DAISY

The one-dimensional and deterministic soil-plant-atmosphere model DAISY (Hansen et al., 1990, 1991) comprises a number of main modules, viz. a hydrological model including a sub-model for water dynamics, a soil temperature model, a soil nitrogen model including a sub-model for soil organic matter dynamics, a crop model including a submodel for nitrogen uptake and a management module allowing different agricultural practices and strategies for soil tillage, irrigation, fertilization and crop management.

The soil part of the DAISY model has a one-dimensional vertical structure and the soil profile is divided into homogeneous layers according to the physical, chemical and biological character-istics. Model calculations in soil are performed on the basis of user-defined node points. The DAISY model in its present form is adapted to the wet temperate climate of North-Western Europe.

The hydrological processes considered in the model include snow accumulation and melting, interception of precipitation by the crop canopy, evaporation from crop and surfaces, infiltra-tion, water uptake by plant roots, transpiration, and vertical movement of water in the soil profile. Snow melting is assumed to be influenced by incident radiation, and soil and air tem-peratures. Interception is determined either by precipitation or by the crop canopy. Descrip-tion of evapotranspiration is based on a climatic determined potential evapotranspiration and the availability of water. Modelling of water uptake by plant roots is based on a quasi steady state solution of the differential equation for radial water flow to the root surfaces, and the plant root density in the soil profile. The vertical movement of water in the soil profile is modelled by means of a numerical solution of the Richards' equation.

Soil temperature is modelled by solving the heat flow equation taking into account heat trans-fer by conduction and convection, and changes in heat content by freezing and melting processes. The freezing process induces water flow in the soil as ice formation is assumed to take place in the large soil pores extracting water from small soil pores resulting in water flows towards the freezing zone.

The DAISY modelling of soil organic matter turnover includes the three measurable main pools of soil organic matter: Added organic matter (AOM), soil microbial biomass (SMB) and native soil organic matter (SOM) as well as soil mineral N and soil respiration (CO_2 - C) (Figure 1).
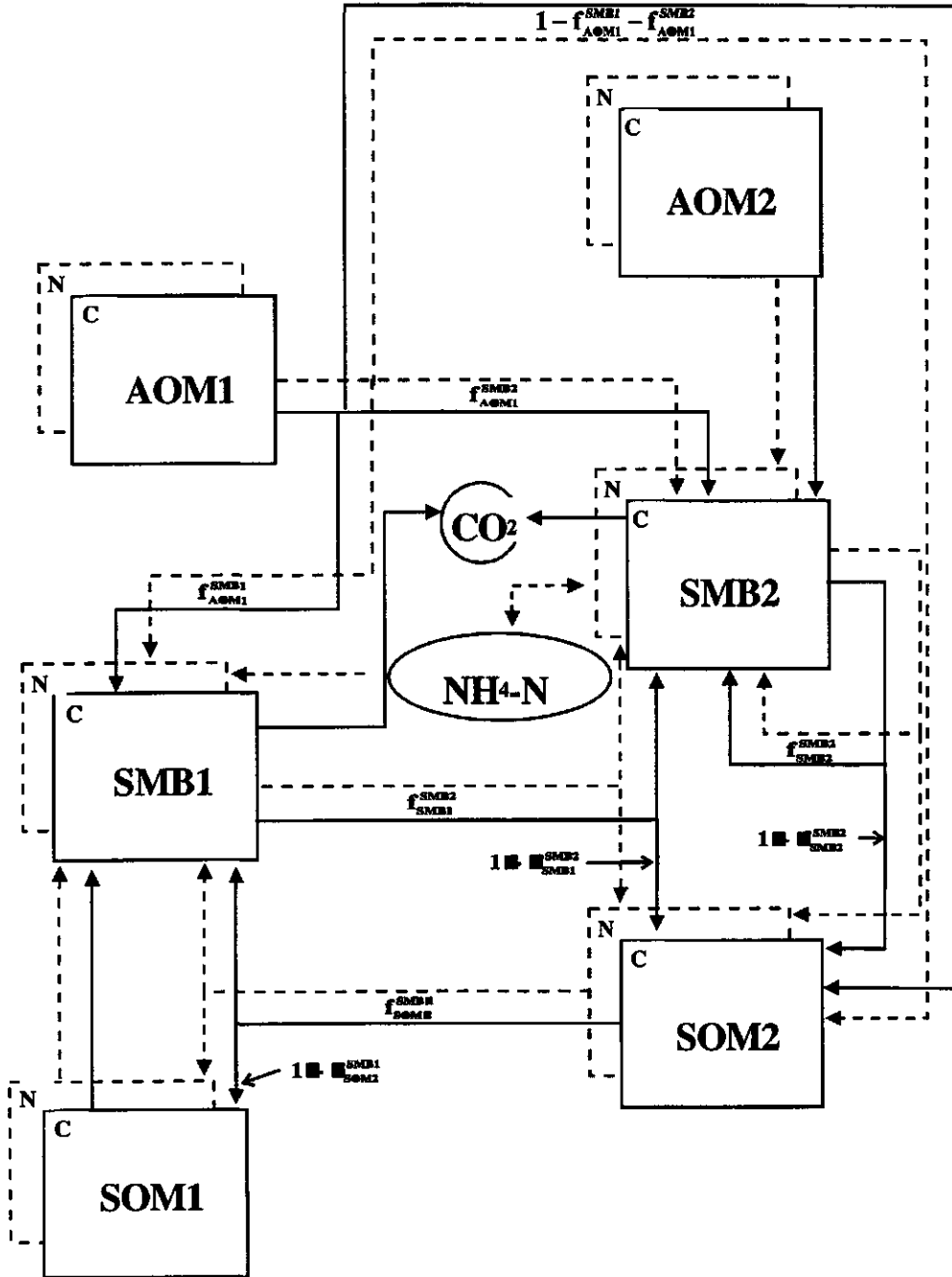
Figure 1   Pools and subplots of organic matter and related partitioning in DAISY
       AOM: Added organic matter, SMB: Soil microbial biomass, SOM: Soil organic matter

The pools: AOM, SMB and SOM are considered to be a continuum having a range of turnover rates. As seen from figure 1, it is assumed that those continua can be simulated if each pool is subdivided into two subplots: AOM1, AOM2, SMB1, SMB2, SOM1 and SOM2, one with a slow turnover rate (e.g. SOM1) and one with a high turnover rate (e.g. SOM2). It is assumed that

the turnover of each pool follows 1st order kinetics. Thus each subpool is characterised by its size, C/N-ratio, turnover rate coefficient and partitioning coefficient of C-flow between pools.

Furthermore in the case of SOM1, SOM2 and SMB1 the turnover rate coefficients are assumed to be influenced by soil temperature, soil water content and clay content of the soil whereas the turnover rate coefficients of AOM1, AOM2 and SMB2 are influenced by soil temperature and soil water content only.

The SMB1 + SMB2 utilises organic matter as substrate. Each of these subplots is characterised by a substrate utilization efficiency, a maintenance respiration coefficient, and an apparent death rate coefficient. The maintenance respiration and the death rate are assumed to be influenced by soil temperature and soil water content, and in the case of SMB1 by the clay content of the soil, too. Carbon is lost as carbon dioxide due to the respiration processes, whereas excesses of N in the soil microbial biomass is released to the soil solution as urea. The overall result of all the organic matter turnover may be net mineralisation and thereby release of ammonium or net immobilisation by which ammonium or nitrate is immobilised.

Nitrification is simulated by applying Michaelis-Menten kinetics assuming the rate coefficient to be influenced by soil temperature and soil water content.

Denitrification is simulated by defining a potential denitrification rate assumed to be related to the carbon dioxide evolution rate in the soil. The potential denitrification rate is reduced according to the oxygen status of the soil expressed as a function of soil water content. Hence the actual denitrification is simulated either as a function of the reduced potential denitrification rate or as a function of the rate by which soil nitrate is available for denitrification.

Soil mineral nitrogen submodel of DAISY includes also N uptake by plant roots and vertical N movement in the soil profile. The nitrogen uptake model is based on the concept of a potential nitrogen demand simulated by the crop model, and the plant availability of soil nitrogen, i.e. the rate by which nitrogen can be made available at the root surfaces. The transport of nitrogen from the bulk soil to the root surfaces is based on the assumptions that each root exploit an average effective volume of soil which is a cylinder around each root. The radius of this cylinder corresponds to the average half distance between the roots. The nitrogen transfer to the root surface takes place by mass flow and diffusion. It is assumed that the concentration-distance profile develops in time in a stepwise manner, and at each time step approximates to a steady state profile. In the present model it is assumed that nitrogen uptake equals the nitrogen flux towards the root surface. If the uptake is limited by the availability of nitrogen the concentration at root surface is assumed equal to zero and hence the root acts as a zero sink. In this case total uptake of nitrogen is calculated by integrating the flux over the entire root system. In the case of ample nitrogen supply the total nitrogen uptake is determined by the potential nitrogen demand. Then total uptake is distributed over the entire root zone by assuming a common concentration to exist along the root surfaces of the entire root system. Soil layers in which the concentration is less than the common concentration are assumed not to contribute to the nitrogen uptake. The calculations are performed for both ammonium and nitrate. It is assumed that ammonium is taken up by the plant roots in preference to nitrate. The mobility of the ammonium in soil is considered less than that of nitrate due to adsorption of ammonium to soil colloids which is described by an adsorption-desorption isotherm. The vertical movement of nitrogen is modelled by means of a numerical solution of the convection-dispersion equation for ammonium as well for nitrate. The source sink term in the

convection dispersion equation integrates the transformation processes in the case of ammonium as well as in the case of nitrate.

The crop growth model is based on the concept of production levels classified by the occurrence of growth-limiting factors. At production level 1, *potential production*, the growth rate of the crop only depends on the plant genotype, current state of the crop, radiation and temperature. Thus the crop has ample supply of water and nutrients. At production level 2, the availability of water limits crop production, the growth rate of the crops are limited for at least part of the growing season due to shortage of water. At production level 3, nitrogen availability in the soil limits crop production, the growth rate of the crops also may be limited due to shortage of water. Hence DAISY may account for moderate deficiencies of water and/or nitrogen only.

A crop is considered to consist of two or three parts viz. shoot, root and in some cases also storage organs. The shoot is characterised by dry matter and nitrogen content, leaf area index of photosynthetically active leaves, and total leaf area index. The root system is characterised by dry matter and nitrogen content, rooting depth and root density. Storage organs are characterised by dry matter and nitrogen content. The crop model is based on the thermal unit concept which imply that crop development from emergence to harvest can be described as a function of the temperature sum. Plant emergence and leaf area index at the early stage of crop canopy development are simulated solely as functions of temperature sum while leaf area index at later stages of crop canopy development is simulated as a function of both temperature sum and accumulated amounts of shoot dry matter. Simulation of crop dry matter production is based on calculation of daily gross canopy photosynthesis, partitioning of assimilates between crop parts, and respiration of each crop part, respectively. The calculation of gross canopy photosynthesis is based on the assumptions that gross leaf photosynthesis can be described by a single light response curve and that the light distribution within the crop canopy can be described by Beer's law. The assimilate partitioning between considered crop parts is simulated as a function of temperature sum. It is noted that internal pools of assimilate are not taken into account in the model. This approximation is assumed to be fairly good as the time step for the crop model is one day. Respiration is assumed to include growth respiration as well as a temperature-dependent maintenance respiration.

6.3   Driving variables and initialisation

Required meteorological variables to run the model are daily values of global radiation, air temperature and precipitation. If a fluctuating groundwater table constitutes the lower boundary condition for the simulation of soil water dynamics then groundwater table data also acts as a driving variable.

The model requires a number of parameters and initial values in order to define and characterise the considered soil-plant-atmosphere system (Hansen et al., 1990, 1991).

In general, crop parameters only has to be assessed once. The task of including a new crop in DAISY is normally equivalent to assessing a new set of parameters. At present crop parameters for spring barley, winter wheat, winter barley, spring rape, winter rape, fodder beet, potato and grass have been developed.

6.4   Model validations

Validation of the model is performed in numerous cases for various crops, soil types and climatic conditions. These validations are reported in the papers listed in the list of publications.

6.5   Outlook

Under the Danish Environmental Research Programme 1992-1996, Danish Centre for Root Zone Processes, numerous subprojects concerning short-term carbon and nitrogen transformation and the effect of abiotic factors and soil texture are being performed together with a subproject concerning macropore flow. The results from these projects will be used for further validation of the DAISY model and when necessary also to modify and improve the DAISY model. A main focus of our future activity will be studies on:

- strategies for nursery of soil microbial biomass in relation to plant nutrition and crop production,
- how to simulate biological nitrogen fixation in cropping systems,
- macropore flows of water and solutes having considerable environmental impacts.

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7   Simulation of crop rotations using the DSSAT 3 crop models

W.T. Bowen, P.K. Thornton & P.W. Wilkens
International Fertilizer Development Center (IFDC), United States

G. Hoogenboom
The University of Georgia, Dept. of Biological and Agricultural Engineering, United States

7.1   Introduction and objectives

Agricultural science today is expected to help achieve sustainable growth in food production while being asked to conduct research with dwindling resources. However this is done, much greater emphasis will need to be placed on the efficient organisation of research and the knowledge that it generates. One approach to improving efficiency is through the integration of research activities with the construction and application of dynamic simulation models.

In demonstrating the value of an integrated experimental and modelling effort, teams of researchers in various parts of the world have produced comprehensive models capable of providing quantitative estimates of crop production under a wide range of soil, weather, and management conditions. Constructed primarily for predicting crop yield during a single growing season, these models usually describe plant growth on a daily basis at the process level (carbon assimilation, partitioning, phenology, and water and nitrogen uptake). Attention to this level of detail has resulted in crop growth models that realistically simulate the sensitivity of growth and development to changes in solar radiation, temperature, photoperiod, and water and N availability. These models have helped to improve our understanding of crop, soil, weather, and management interactions, albeit during the course of a single growing season.

As questions continue to be raised about the sustainability of cropping systems, scientists must acquire a better understanding of how crop production is affected beyond one growing season by changes in the soil resource with time, and how these changes are related to weather, management, and the carry-over effects of crops grown in sequence. Long-term experiments and monitoring are of course needed, but so is a modelling approach that seeks to integrate this understanding into a logical and useful structure.

Two basic approaches are discernible: models that are able to mimic the sensitivity of plant growth and development during a single season, without the capability of simulating crops grown in sequence, and other models capable of simulating long term cropping sequences but with less sensitive and robust plant growth components. The objective of the DSSAT rotation models is really to see if more reliable tools for simulating the long-term consequences of crop management might not be obtained from linking more sensitive plant growth simulators with more realistic simulators of how the soil resource changes with time.

Consequently, the crop growth models distributed with the DSSAT version 3 software have been linked to enable them to simulate crops grown in a rotation or a continuous sequence.

Cropping sequences can be simulated for any number of years using either measured or generated weather. This sequencing capability is a new feature of the DSSAT, which also includes an analysis programme for studying long-term trends in simulated output using a combination of graphical and statistical tools.

7.2   The DSSAT crop models

The DSSAT contains five separate models for simulating the growth of 11 different crops:
- CERES-Generic, for maize, wheat, barley, millet, sorghum;
- CERES-Rice, for upland and flooded rice;
- CROPGRO, for soybean, peanut, dry bean;
- SUBSTOR-Potato; and
- CROPSIM-Cassava.

Although these models have been developed by different groups of researchers and institutions, there has been a co-ordinated effort to standardise input and output data formats (Jones et al., 1994) and to implement the same soil water and nitrogen balance in each model (Hoogenboom et al., 1994). Each model contains similar subroutines for reading and writing data and for simulating soil-related processes, using the same variable names. The models currently remain separate entities because crop growth and development processes continue to be described differently in each model. Standardised inputs are summarised in Table 1 and described in detail in Tsuji et al. (1993).

Table 1   Principal data inputs required to run the DSSAT version 3 models

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Daily weather
    maximum temperature, minimum temperature, rainfall, solar radiation
Site
    latitude, runoff and drainage, soil color/albedo
Soil property (by layer)
    sand, silt and clay content
    bulk density (moist)
    organic carbon content
    pH (water)
    optional: lower limit, drained upper limit, saturated water content, rooting preference index,
    total N
Soil initial condition (by layer)
    soil water content
    soil nitrate and ammonium content
Genotype data
    emergence, anthesis, maturity dates
    yield components under non-limiting conditions
Management
    planting date, plant population, row spacing
    irrigation scheduling (amount, date)
    fertiliser scheduling (amount, date, type, method)

The DSSAT crop models were originally developed for simulating the growth of annual crops during a single season. Their common structure, however, has facilitated the use of these same

models for the long-term simulation of cropping sequences with minimal modification to the code. To get the models to run in sequence, new subroutines were added to each model that permit the passing of relevant variables from one model to the next in a temporary file. When the cropping sequence option is specified, this temporary file is written to at the end of one model run and read from at the beginning of the next model run. A separate model driver programme was also developed to control the order in which the crop models are run. The driver programme reads the order of the cropping sequence from an experimental details file at the beginning of the simulation, then continues running the models for the number of years specified. A schematic diagram of the how cropping sequences are simulated is shown in Figure 1.
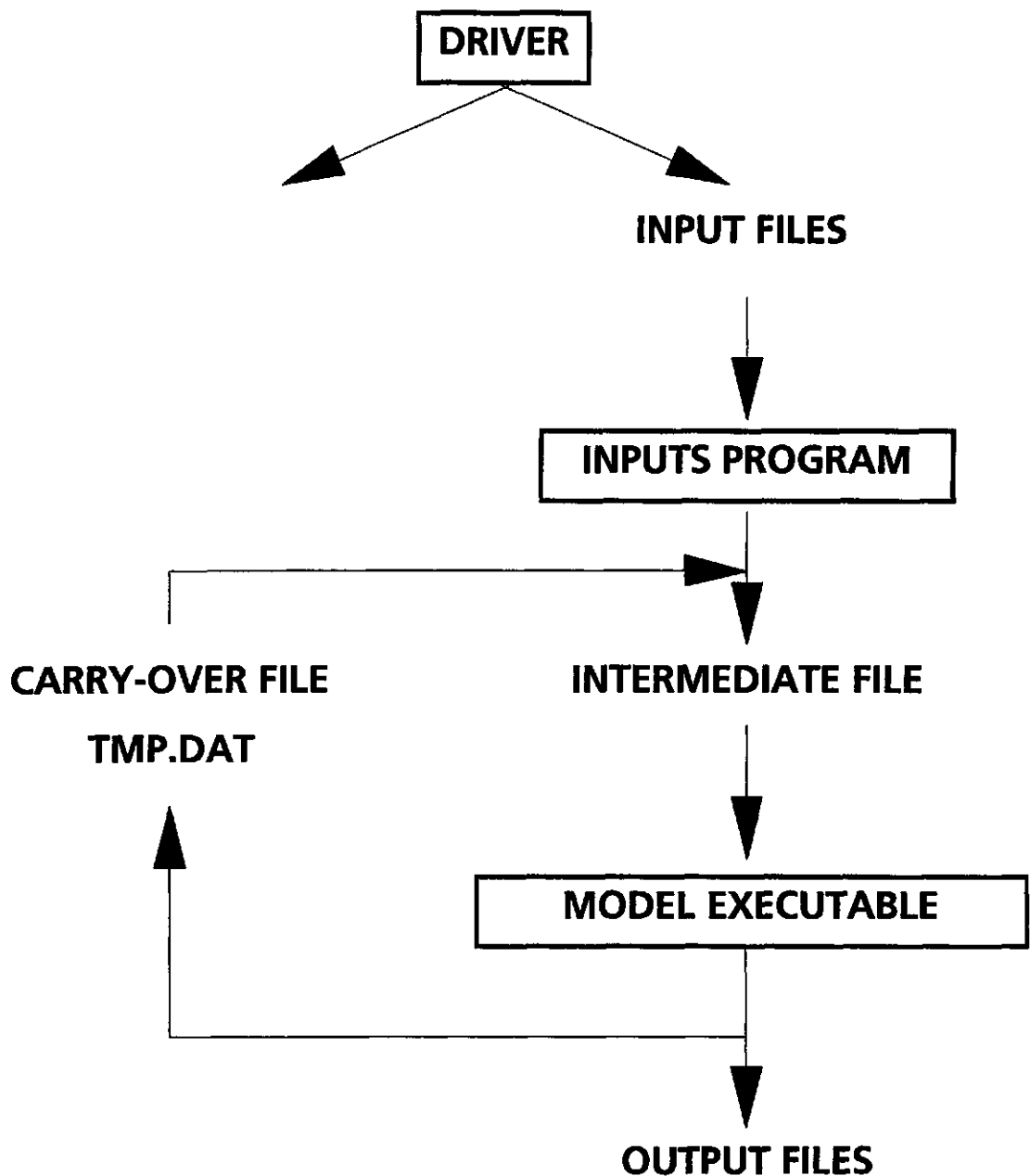
Figure 1   Crop sequencing in DSSAT-3

Since the simulation of a cropping sequence requires the continuous simulation of soil processes on a daily basis, including the days when no crop is growing (fallow periods), most of the variables passed in the temporary file are those needed for the continuous simulation of soil water, carbon, and nitrogen processes (Table 2). An illustration of the way the models are linked to continuously simulate soil process is provided in Figure 2.

Table 2 Principal variables passed in the temporary file used to link DSSAT version 3 models

YRSIM	Date at the end of the previous model run
NREP	Model run number
STOVRL	Aboveground plant residue (kg dry matter ha^{-1})
APTNPL	Amount of N in the aboveground plant residue (kg N ha^{-1})
RTWTL	Root weight in the soil profile (kg dry matter ha^{-1})
RTWTNL	Amount of N in the roots (kg N ha^{-1})
DEPMAX	Maximum soil depth where soil water content changes (mm)
NLAYR	Number of soil layers
ESW(L)	Extractable soil water content for soil layer L (mm)
SUMES1	Accumulative soil evaporation in state 1 (mm)
SUMES2	Accumulative soil evaporation in state 2 (mm)
TLL	Total soil water in the soil profile at the lower limit (cm)
PESW	Potentially extractable soil water in the profile, equal to total soil water minus total water at the lower limit (cm)
TSW	Total soil water in the profile (cm)
CUMDEP	Cumulative depth of the soil profile (cm)
TSAT	Total soil water in profile at filed saturation (cm)
SWDEF	Soil water deficit (cm)
ATHETA	Available water in irrigation management soil zone (%)
DMINR	Humic fraction decay rate (day^{-1})
FPOOL (L,J)	Fresh organic matter in layer L kg/O.M./ha. Pool comprises carbohydrates (J=1); cellulose (J=2); lignin (J=3)
WFY(L)	Yesterday's water factor for nitrification in layer L
TFY(L)	Yesterday's temperature factor, nitrification in layer L
PHN(L)	Zero to unity factor describing the effect of soil pH or nitrification rate in soil layer L
FOM(L)	Fresh organic matter (residue) in soil layer L (kg ha^{-1})
FON(L)	N in fresh organic matter in soil layer L (kg N ha^{-1})
HUM(L)	Stable humic fraction material in soil layer L (kg ha^{-1})
NHUM(L)	N associated with the stable humic fraction material in soil layer L (kg N ha^{-1})
TMA(K)	5 Day moving average soil surface temperature for day K (°C)
ATOT	Accumulator used to calculate moving average soil surface temperatures
RSEED	Random number seeds for weather generation
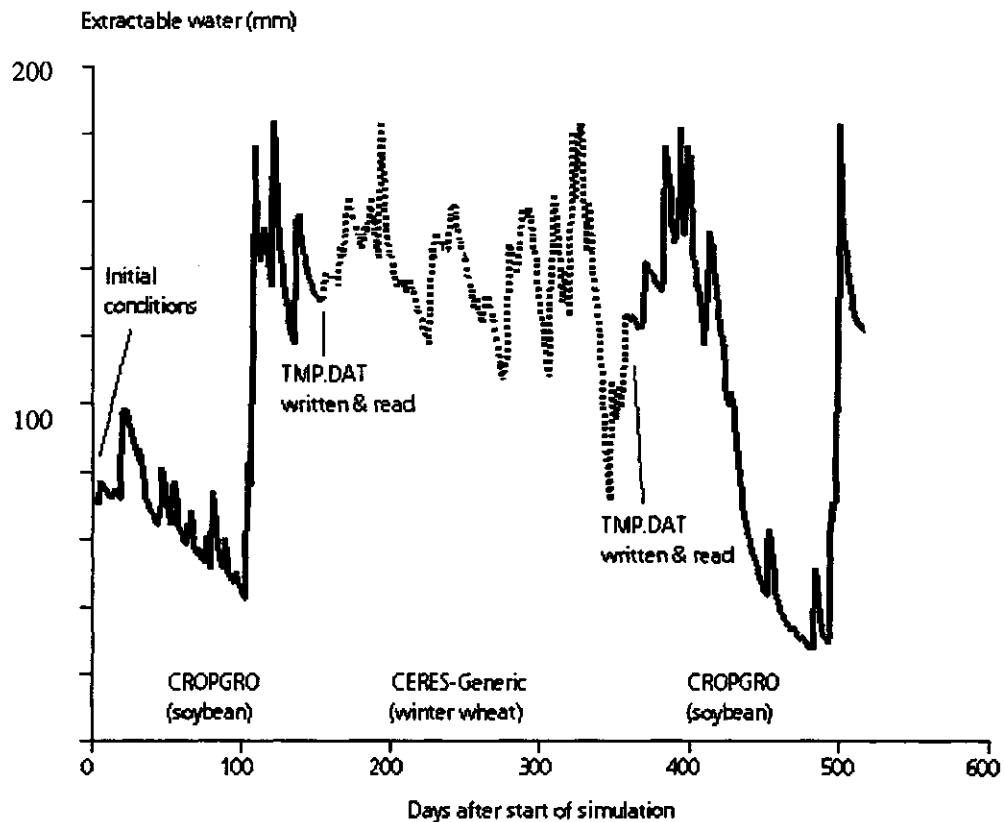
Figure 2   DSSAT-3 Crop sequencing: soil water carry-over

This example shows how extractable water varied on a daily basis for the first three crops of a simulated soybean-winter wheat rotation. Note that by linking the models in this way, it is possible to obtain a seamless long-term simulation while preserving the internal structure of each model. Initial conditions, such as volumetric soil water content, organic C, and inorganic N in each layer of the soil profile, still need to be specified for the first model in a sequence, but subsequent models start with the simulated values calculated for the last day of the previous model run.

7.3   Analysis of cropping sequence simulations

When simulating a cropping sequence, a user will not necessarily be interested in examining daily differences in soil water, inorganic N, biomass accumulation, or any other output generated on a daily basis, though such an analysis is possible. Usually of more interest will be the determination of any trends in end-of-season output such as yield, soil organic C levels, or

amount of N lost by leaching. The tendency for such variables to change with time in a consistent direction will define the trend, and it is this trend that can be used to estimate the potential sustainability of a defined cropping sequence and management system. For example, a 30-year simulation might show yields decreasing with time, thus indicating the defined system is not likely to be sustainable.

To facilitate the analysis of long-term trends, a software programme was developed to read simulated output, provide summary statistics, and present the data in both tabular and graphical forms (Thornton et al., 1994; Thornton et al., 1995). This programme also performs an analysis of net monetary returns or gross margins on the simulated output using product prices and production costs set by the user. Since future costs and prices are not known with certainty, the user can also choose to specify their variability.

The analysis programme is particularly useful when a cropping sequence is simulated using more than one series of synthetic weather. Unless a cropping sequence is being simulated to compare results against observed data, in which case there exists a unique series of measured weather, there is no way of knowing the exact weather pattern during the course of a simulated sequence. To account for expected variability in weather, the DSSAT-3 sequencing option also allows the user to specify the number of synthetic weather patterns to use for each year of the defined sequence. For example, a user could run a cropping sequence for 50 years, and specify 20 different synthetic weather patterns for each year of the sequence, which are generated by a statistical weather generator coded into each crop model (Hoogenboom et al., 1994). The analysis programme then provides statistics on the simulated output assuming there were 20 replications for each year of the sequence.

An example of possible trends in maize yields for a maize-fallow rotation with no N fertiliser applied is shown for a 60-year sequence in Figure 3a. This example was simulated using different sequences of generated weather for a site in central Brazil.

Figure 3b shows the corresponding probability of the maize enterprise failing to generate any positive income for the same time period, using constant costs and prices. Such figures (these are from Thornton et al., 1995) can be readily generated using the sequence analysis programme. Two relevant questions are, do the crop models do a good job of long-term simulations, and if not, what can be done about this situation?

7.4   Model validation and future developments

The soil resource is a critical component of productive cropping systems. If not managed properly, its capacity to supply water and nutrients can become limited, thus decreasing yield potential. A decrease in yield potential, however, may not be discernible for many years, particularly if weather variability is masking the effect of a gradual decline in soil productivity. Such a decline may be due to any number of reasons, including the loss of soil by erosion, a decrease in soil organic matter or the supply of an essential nutrient, or the build up of a toxic element.
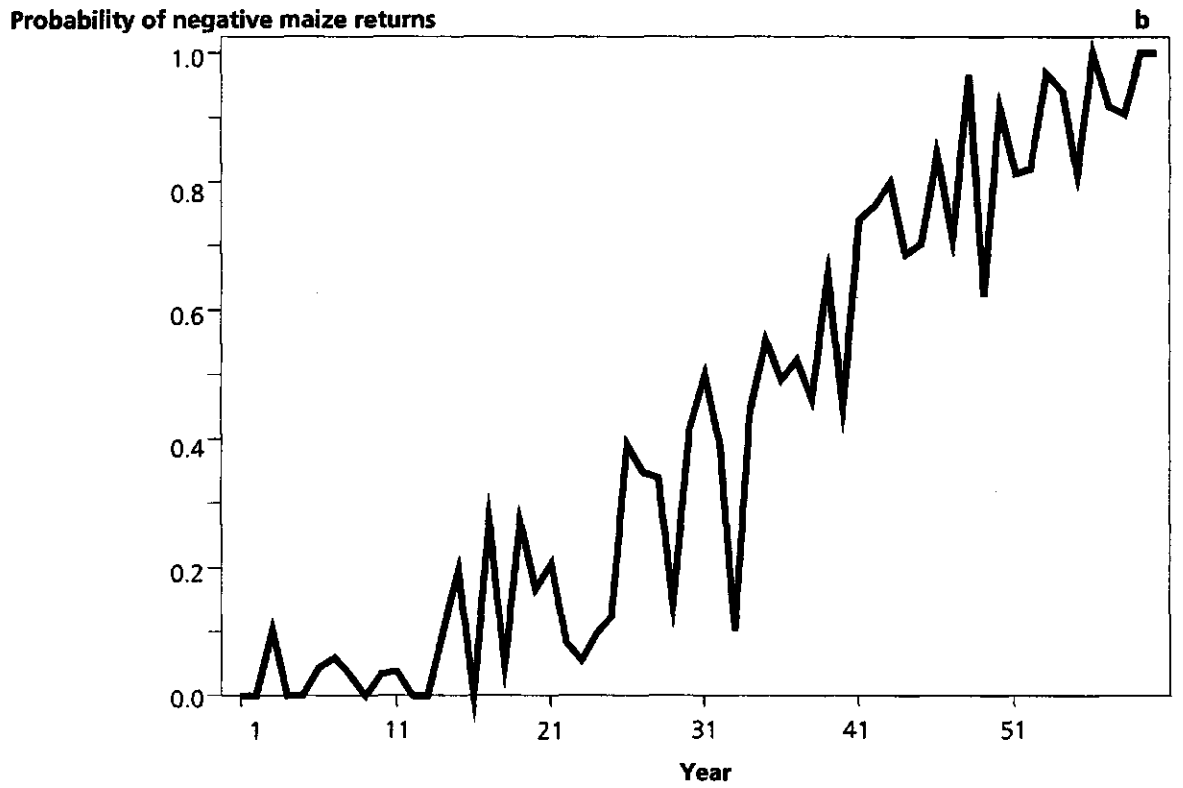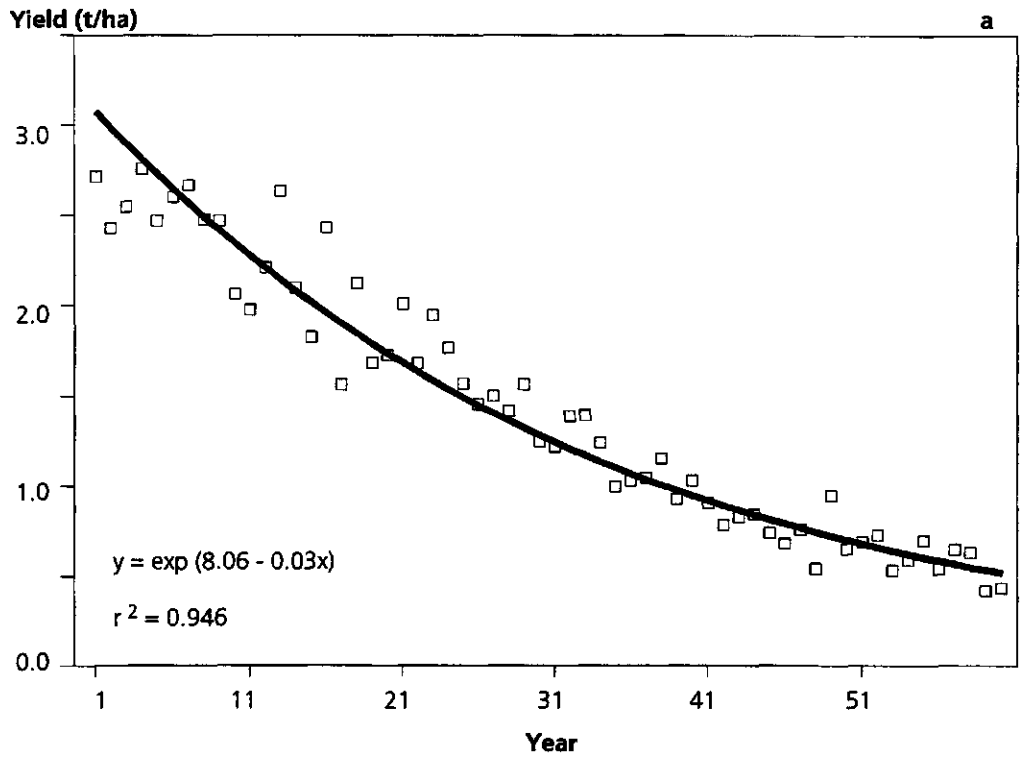
Figure 3 Continuous maize grown at a site in Central Brazil
a Mean maize yields
b Probability of negative maize gross margins

It is in the examination of long-term trends due to changes in soil productivity that simulation models offer particular value, but only if the models have been shown to provide realistic estimates of the effects of both management and time on important soil processes. Whereas field experiments often need to be conducted for many years before trends become measurable, sound models offer a screening tool which can provide a rapid first approximation of the effect of alternative management systems on long-term productivity; the effect of weather can be isolated from the effect of soil management by running the simulation for a number of years using replicated weather sequences. The more promising management options can then be evaluated through selective field experimentation.

Although the DSSAT models have been linked to simulate cropping sequences, their reliability in simulating long-term soil processes has yet to be demonstrated. This is mainly because the sequencing capability was added only recently, but also because there is a scarcity of complete data sets from long-term experiments for conducting appropriate tests of model assumptions. At some point, however, the DSSAT models must undergo more rigorous testing, and they need to be improved upon by adding new components such as tillage effects to expand the number of plausible scenarios they can be used to examine.

Very limited testing has been carried out to date. We are doing some testing of the models for crop sequences from experiments carried out in Alabama and Georgia; nothing is written up on this as yet. Some very general testing was reported by Bowen et al. (1993) for continuous maize production at a site in central Brazil, although this testing was not rigorous. Timsina et al. (1995) report testing of the CERES-Wheat and CERES-Rice model run in sequence over two growing seasons at sites in Bangladesh, and they compared model outputs with measurements obtained from the field.

Since the DSSAT models were originally developed to simulate soil processes (water, C, and N dynamics) during a single season, it is understandable that many of the components known to affect only long-term soil processes were not included. The more notable components presently lacking, but which probably need to be added, include soil erosion, tillage, and processes that affect the development of soil acidity or salinity with time. The simulation of other nutrient cycles also needs to be added, as has been done recently with a test version of the models that simulates P dynamics.

There is a need to address not only the inclusion of new components, but also to evaluate present assumptions in the models regarding soil processes. For example, the models assume that soil organic C is comprised of only one pool, with a constant C:N ratio of 10:1 (Godwin & Jones, 1992). This assumption may provide valid estimates of C and N dynamics during one growing cycle, but it may be completely invalid when used to estimate the size of C and N pools following a 20-year sequence of crops.

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8   The EPIC-based models for simulating cropping systems

Ph. Debaeke & M. Cabelguenne
INRA, Station d'Agronomie, France

8.1   Model objectives

EPIC for *Erosion Productivity Impact Calculator* was initially developed by the USDA-ARS (Temple, TX) to determine the relationship between soil erosion and soil productivity in an attempt to evaluate soil and water conservation strategies in the United States (Williams et al., 1984). Then, in 1988, the model was completed to investigate more specifically the relationships between crop production and environment (sustainability of cropping systems, water quality, irrigation requirements, global change).

In France, the model was first used in 1984 to simulate the relationships between crop rotations and soil fertility (water and nitrogen budgets). Then, in 1989, the model development was oriented towards the management of limited water resources in cropping systems (tactical choices, irrigation strategies, water management at crop rotation level).

8.2   Brief model description

8.2.1   Process modelling

EPIC is composed of physically based components for simulating wind and water erosion, plant growth, and related processes (e.g. water and nutrients dynamics). Since erosion can be a relatively slow process, EPIC was designed to simulate long-term series (> 100 years). The model is composed of 9 major components for weather, hydrology, erosion and sedimentation, nitrogen and phosphorous cycling, crop growth, tillage operations, soil temperature, economics, and crop management control. Since soil productivity is expressed in terms of crop yield, crop growth is one of the most important processes simulated by EPIC (Williams et al., 1989).

The *weather* characterised by daily inputs of precipitation, maximum and minimum air temperature, global radiation, wind speed, and relative humidity is the driving force of the model. Weather can either be inputted and/or generated stochastically.

The *hydrology* model simulates the volume of surface runoff water and peak discharge rate given daily rainfall amounts. Other hydrology components include evapotranspiration (4 optional methods), percolation, and lateral subsurface flow. The water balance components are the most important dynamic variables of the model. They determine the transport processes essential for plant growth and nitrate leaching. The water transport of the model is calculated

with a linear storage routing technique. The water storage held against gravity coincides with the field capacity of the soil. The water surplus increasing field capacity can be percolated. If the soil is divided in different layers (max. 10), the percolation process takes place as a cascade. The percolated water from one layer is added to the following layer. Percolation velocity is proportional to the available water (linear storage). The used algorithm is calculated successively for all soil layers. It is quicker than the often used transport equation and uses easily available parameters.

Sheet and rill *erosion/sedimentation* caused by runoff (from rainfall and irrigation) and wind erosion are estimated by different methods (see Williams et al., 1984).

The *N processes* that are simulated include runoff of nitrate, organic N transport by sediment, nitrate leaching, upward nitrate movement by soil water evaporation, denitrification, immobilisation, mineralisation, crop uptake, rainfall contribution, and symbiotic fixation by legumes. The N submodel is a modification of PAPRAN (Seligman & Van Keulen, 1981). The model considers 2 sources of mineralised N: fresh organic N associated with crop residues and microbial biomass and organic N associated with the soil humus pool. N immobilisation is closely linked with residue decomposition and plant uptake from the successive soil layers. EPIC describes the dynamic processes as fluxes between different pools and beyond the borders of the ecosystem by phenomenological equations. These equations do not describe physical, microbiological, and physiological processes but compute values available from experiments. The *P processes* that are simulated include runoff of soluble P, sediment transport of mineral and organic P, immobilisation, mineralisation, sorption-desorption, and crop uptake. Nutrients can be applied as mineral fertilisers, in irrigation water, or as animal manures.

Soil temperature is simulated to serve the nutrient cycling and root growth components of EPIC. It is predicted at the center of each soil layer as a function of the previous day's soil temperature and the current air temperature, crop residue, soil water content, bulk density, and snow cover.

The EPIC *tillage* model simulated ridge height, surface roughness, nutrient and crop residue mixing, change in bulk density, and conversion of residue from standing to flat.

EPIC simulates all crops with one single *crop growth* model using crop-specific parameters. Both annual and perennial plants (alfalfa, grasses) can be simulated in rotations. The plant growth processes include:
- Crop interception of solar radiation.
- Conversion of intercepted light into biomass.
- Division of biomass into roots, above-ground biomass, and economic yield (harvest index procedure for grain, fiber or tuber production).
- Root growth in depth.
- Water use.
- Nutrient uptake.

Potential plant growth is simulated daily and constrained by the minimum of 5 stress factors (water, nitrogen, phosphorous, temperature, and aeration). Root growth is constrained by soil strength and soil temperature. Crop-specific parameters are available for more than 25 different crops. Most of the validation tests have been performed on maize, wheat, sunflower, soybean, and sorghum. The model can also simulate crops grown in complex rotations (full-season

crops, doublecropping or catch crops) and in mixtures (with the ALMANAC version: undersow-ing, intercropping). As many as 3 crops may be grown during one calendar year.

The *crop management control* component provides options for automatic irrigation and N fertilisation according to a limited number of decision rules (annual amount, stress level, time between applications, upper and lower application limits ...). EPIC simulates a variety of crop management practices, including different crop cultivars, plant population, dates of planting and harvest, NP fertilisation, sprinkler irrigation, artificial drainage systems, tillage, runoff control with furrow dikes and other methods, liming and pest control. Crops may be harvested for grain or fodder, and they can be grazed or burned. Grain loss and stubble amount at harvest can be manipulated.

The *economics* component of EPIC uses a crop budget to calculate crop production costs. Income is determined from simulated annual crop yields.

8.2.2 Software structure

EPIC is composed of a main programme (210 K) written in FORTRAN (compiled with Microsoft Fortran 5.1) which reads data, initialises variables, and calls subprogrammes (about 85) to do the daily simulation and to summarise and output data. Nine peripheric files are used in simulations and are opened to users: basic user-supplied data set, weather data, crop parameters, tillage parameters, pesticide parameters, experimental parameters and economic data, graphics control, multi-runs, output variables.

Easily manipulated user interfaces (UTIL, Universal Text Integration Language) and graphical output utilities have been developed to aid in building data sets (general variables, soil and management files), to check the input values, to give access to the user manual on line, and to help interpreting the results (summary files, selection of output files including outputs for spreadsheets, output increment, output variables).

The model can be run with a wide variety of mainframes and PC's. With current computers, the calculation time is no more a limiting factor (for instance, about 1.5 s per simulated year with a PC 486 -100 Mhz).

A simulation data base is available for the United States including 134 climatic locations, parameters for 22 crops, input data for 50 types of farm equipment, and soils data for 737 soils, in order to facilitate national evaluations. In Europe, no such concerted effort has been done to build a similar data base for EPIC simulation but numerous data sets have been elaborated for EEC contracts (Polen recently).

8.3 Successive versions

The EPIC model has been modified, expanded, and tested extensively since 1982. Additional processes have been added by the US team:
* Interspecific plant competition for intercropping and weed-crop interaction (ALMANAC model).

- Salt addition in irrigation water and movement in the soil.
- Application, decomposition, and movement of agricultural pesticides in solution and attached to sediment: modification of GLEAMS model (Leonard et al., 1987).
- Linkage to ROTO model (Arnold, 1990), a continuous water and sediment routing model, to simulate movement of water and sediment from many fields through streams and reservoirs.
- Refinement of nitrogen dynamics: introduction of nitrification/ammonification and ammonia volatilisation.

In France, we developed the EPIC-Phase (real-time) version of the model for water management and tactical choices including a phased crop response to water and nitrogen stresses and interactive user interfaces for real-time management (Cabelguenne et al., 1994). As EPIC was more a soil-oriented model, the crop growth model was not sensitive enough to simulate dryland conditions and low-input management. The EPIC-Phase model is more dedicated to climatic risk analysis. A specific version of the model was developed by CETIOM and INRA for sunflower management (HEOL), with an effort to introduce crop loss by *Phomopsis helianthi* and a data base for simulating various combinations of soil, climate, genotypes, and management. Today, a collection of models derived from the EPIC concept are available.

8.4 Major input requirements and output variables for evaluation (summary)

8.4.1 For model running

Daily weather data
See above.

Soil data (layer by layer)
Soil texture, moisture at field capacity and wilting point, percentage of gravels, bulk density, initial mineral and organic nitrogen, carbon percentage, initial soil moisture.

Crop management
Sowing date, growing degree, days for maturity, dates and amounts of nitrogen fertilisation, dates and amounts of irrigation, tillage operations (for erosion), dates and amounts of pesticide applications (active compounds), crop and weed densities (for ALMANAC).

Crop parameters
A standard file is suggested for each crop, resulting from previous validation studies, but time-course of leaf area index and harvest index (EPIC), sensitivity of harvest index to water stress and phase duration (EPIC-Phase) are genotypic parameters that should be calibrated by each user.

The input parameters are easy to determine or are readily available; the model was designed to run on minimum data sets when some inputs were missing. Internal modules help to calculate available soil water as a function of physical soil properties (range of 'pedotransfer functions'). A function computes S curves given 2 (x,y) points for adjusting leaf area index, density

effect on maximal LAI, frost sensitivity ... A statistical module (WXPARM) creates the standard data file for weather generation (including probability of rain occurrence and distribution of climatic variables) using daily records over 25-50 years. Almost any combination of inputting and generating weather variables is possible. The same weather sequence may be repeated for any number of simulations at the same site or a new weather sequence may be generated for each simulation. So EPIC provides some flexibility in input requirements.

8.4.2 For model evaluation

State variables (daily, every 5-10 days, monthly): leaf area index, above-ground biomass, water use, volumetric water profile, N uptake, soil mineral N profile.
Final output variables (at harvest): biomass, grain yield, water use, N uptake.

8.5 Model evaluation

Numerous attempts to evaluate the EPIC model have been made in the United States and Europe (especially France and Italy). Evaluation on crop yield and biomass gave reasonable results in conditions of non-limiting water. Better performance was observed with the improved EPIC-Phase model (Quinones, 1989; Debaeke et al., 1996) for wheat, maize, and sunflower in water-limited environments. Few studies had insight into LAI, water dynamics, N uptake throughout the crop cycle, probably because the major interest was for long-term yield predictions. Good results were obtained with water and N percolation in lysimeters, because of the comprehensive description of major hydrological processes (Engelke & Fabrewitz, 1991; Debaeke et al., 1996). Nutrient dynamics (especially residue decomposition) and pesticide evolution were not evaluated in a sufficient range of weather, soil, and crop management conditions. The intercropping model gave rather good results for weed-oats mixtures (Debaeke et al., 1993).

8.6 Suggested further development

- Predictive quality of the model should be evaluated; the different type of errors (parameters, model structure, input data) should be separated in spite of the model complexity.
- Additional processes could be introduced: as decision rules in a way to build crop management schemes, effect of heat stress on harvest index, dilution curve for nutrients.
- Interfaces with supplemental information sources (soil and weather databases, field measurements, other agronomic and economic models, GIS) to improve the interest for decision-making.
- Definition of the role of the model in a decision-making scheme: functional link with management models at field or farm level or generation of data for such models.
- Include risk analysis (weather, technical efficiency, soil variability ...) in a deterministic and local (quadrat, plot) prediction.

8.7 Simulation studies

Although EPIC was designed primarily to assess the effect of erosion on soil productivity, it has several other potential uses. EPIC is capable of assisting with decisions involving drainage, irrigation, water yield, erosion control (wind and water), weather, fertilisation, pest control, planting dates, crop varieties, tillage, and crop residue management. Different uses for decision-making were done with the EPIC family's models.

8.7.1 Evaluation of agronomic strategies

The inherent ability of the model to simulate multiple management options under contrasting climatic conditions (with or without weather and management generation) over long periods was used here.

Recent applications:
- Long-term effects of soil and water conservation strategies on soil and crop productivity (USDA applications).
- Simulation of nitrate leaching as related to soil type, climate, crop management, and crop rotation (Cosserat, 1991; Williams & Kissel, 1991).
- Optimal strategy for water use under limited resource availability: wheat (Debaeke, 1995) and maize (Cabelguenne et al., 1995).
- Potential for a new crop or genotype in a cropping system (ex. soybean, Blanchet et al., 1988).
- Risks of water pollution through pesticides.
- Effects of a elevation of CO_2 on crop production (Stockle et al., 1992).
- Connection with linear programming models for economical purposes (POLEN): the model plays as a generator of production functions.

8.7.2 Diagnosis of limiting factors for crop production

The model was used for its ability to produce a "stress index" per phase in an attempt to diagnose limiting factors a posteriori.

The simulation of potential growth conditions, the discrepancy between "simulated" and "measured" values permit to quantify the occurrence of non simulated limiting factors (pests and diseases for instance). In addition, the simulation of alternative climatic series is a way to discuss the generality of a single experimental result.

Application: hierarchy of limiting factors in long-term experiments, especially water stress (Texier et al., 1990; Debaeke, 1995a).

8.7.3   Tactical choices in crop management

The model was used:

- To simulate soil-crop variables that are commonly useful for decision-making and difficult to measure routinely.
- To integrate continuously revised data from field observations.
- To predict short-term evolutions of selected variables.

Applications:

- Soil water deficit on the root depth to schedule irrigation (Cabelguenne & Debaeke, 1996).
- Above-ground dry matter of winter wheat at the beginning of stem elongation to predict potential ear number per m^2.
- Nitrogen plant content: when referred to biomass (dilution curve) could reveal N-deficiency or excess.
- Leaf area index: key-indicator for irrigation management in sunflower crop (Texier et al., 1990).
- Prediction of crop loss as a result of weed infestation; definition of integrated damage thresholds for weed control (Debaeke, 1995b).

In conclusion, major interests of EPIC family's models for cropping systems studies (research and decision-making) were:

- A rather comprehensive simulation of soil-climate-plant-crop management interactions for a range of soils, climates, and majors crops.
- A pluri-annual simulation.
- An option (though limited) to include "decision rules" for irrigation and N-fertilisation management.
- A weather generation.
- The estimation of variables difficult to measure routinely.
- An access to intermediate soil and crop variables.
- The possibility to include short-term weather forecasting.

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9 NDICEA: Modelling nitrogen dynamics in crop rotations in ecological agriculture

A.S.J. Habets & G.J.M. Oomen
Wageningen Agricultural University, Department of Ecological Agriculture, The Netherlands

9.1 Introduction

In ecological agriculture no artificial N fertilisers are used. The availability of nitrogen to the crop and at a certain moment is determined by farmer's decisions taken long before that moment: many processes and factors determine how much nitrogen is released and which part can actually be taken up or is lost. Although many of these are largely understood, in a real cropping history it turned out to be difficult to distinguish the influence of crops and crop residues, manuring, tillage and soil properties on release, uptake and loss of nitrogen. We were not able to explain the yields on experimental fields of the Department of Ecological Agriculture in a consistent way. Experiences gained in a specific year and on a specific place could not simply be used to explain results under other conditions. A review of literature, some time ago, did not bring an instrument to analyse crop rotations, but it furnished several fragments that could be used. We started to integrate most important factors into a calculating model. We tried to keep it simple, but it has gradually become more complex.

9.2 Objectives of the model

The model reconstructs the release and availability of nitrogen, the leaching of nitrogen, the fluctuations of soil suction, and accumulation/depletion of organic matter in crop rotations. Our initial, first, objective was to construct an instrument to analyse the nitrogen dynamics in a cropping history retrospectively, based on weather data, soil properties, historic yields and farming practices.

Our current, second, objective is to find out how it can be used as a tool in re-designing farm organisation and manuring strategy. We assume that the model can be used for that purpose if calculated release and loss of nitrogen correspond with an observed crop performance. It should at least function as an eye-opener or hypothesis generator.

Our future, third, objective is to use the model as a tool in short-term soil fertility management, especially to avoid situations that speed up the development of pests and diseases.

In this paper we present the result of our effort to construct such a retrospective model. It is more extensively explained and discussed in reports by Habets & Oomen (1993, 1994).

9.3 Brief description of contents, processes and level of detail

9.3.1 Approach

The empirical description of the whole process of organic matter dynamics in a crop rotation by Kortleven (1963) is the starting point for our calculations. The partial influences of the underlying processes on the release, loss and uptake of nitrogen are estimated, based on literature and practical experience. We have preferred to reach for the whole process and to accept some temporary inaccuracies in our estimations. The improvement of the chosen approach is a continuing story, until now without undermining the initial assumptions.

9.3.2 Processes considered in the model

- The *accumulation and mineralisation* of organic matter and nitrogen, based on the influence of the initial composition of every application, temperature, soil moisture, pH and soil texture and soil tillage operations.
- The *uptake of nitrogen* from top and subsoil based on historical total or expected uptake, rooting pattern, calculated availability of nitrogen and calculated pF in top- and subsoil.
- The *leaching of nitrogen* based on nitrate content of soil water, precipitation, evapotranspiration, rooting depth, soil texture and soil structure and water table (pF curve, capillary rise, bypass flow).

9.3.3 Level of detail

A simple two-layer-model of soil was chosen. In the top layer tillage, application and mineralisation of organic matter take place. The second layer is important for storage of water and nutrients. It reaches to where crops can take up water and nutrients. The timestep in the model is one week and the maximal length of a crop rotation is twelve years. To get an idea of the long-term effects the rotation can be repeated starting with the final results of a preceding rotation.

9.3.4 Overview of the calculations

9.3.4.1 Water balance

The actual evapotranspiration is calculated using:

$$ET_{act} = ET_{pot} * f_{crop} * f_{pF}$$ [Eq. 1]

ET_{act} = actual evapotranspiration
ET_{pot} = potential evapotranspiration
f_{crop} = correction factor for crop development stage
f_{pF} = correction factor for soil pF

The potential evapotranspiration calculated according to Penman's formula is taken from the nearest weather station and the crop factor is taken from Hooghart (1987).

A reduction factor for soil pF is based on the pF of the second layer: the evapotranspiration is reduced as soon as the pF of the second layer exceeds 2.7. The crops take water from both layers, 75% of the maximal amount ($ET_{pot}*f_{crop}$) from the top layer as long its pF < 2.7. Extraction of water from the top layer decreases linearly between pF 2.7 and 4.2 from 100% to 0% of 0.75 * $ET_{pot}*f_{crop}$ (Van Huet, 1983). That of the second layer from 100% to 0% of ($ET_{pot}*f_{crop}$ - the extraction from the top layer).

Precipitation is added to the top layer. After each time step the moisture content and pF are calculated for both layers using (Driessen, 1988):

$$\psi = e^{\sqrt{1/GAM*\ln(SMO/\theta)}}$$

[Eq. 2]

ψ	= matric suction (cm)
θ	= soil moisture content (m^3/m^3)
SMO	= saturated soil moisture content (m^3/m^3)
GAM	= texture specific constant

Water above field capacity present at the end of a time step is moved to the deeper layer. Water moved from the second layer is considered lost.

For every layer capillary rise is calculated. First potential capillary rise is calculated as follows:

CRpot = EXP((CRc-GWT)/CRx)

with	CRpot	= Capillary Rise based on Soil type and GWT [mm/day]
	CRc	= Distance to GWT where CR = 1 mm [cm]
	CRx	= Distance over which CR decreases a factor e [cm]
	GWT	= Ground Water Table [cm]

The coefficients CRc and CRx were determined from tables of CR at different distances to GWT at different pF (Driessen, The QLE-primer, 1988). A fixed pF of 2.4 was chosen because below this pF capillary rise is not important for plant growth and higher pF do not give much more increase of CR. Actual CR is then assumed to depend linearly on soil pF with a maximum of 5 mm/day:

CR = MAX(MIN((pF-pFGWT)/0.4,1),0) * MIN(CRpot,5)

with	pF	= Log(Fi) of a layer [-]
	Fi	= Soil matric suction [cm]
	pFGWT	= Log(Distance to GWT) of a layer

9.3.4.2 Decomposition of organic matter

The formula of Janssen (1984) is based on empirical data of Kortleven (1963).
To get an impression of the mineralisation within the year we have chosen a time step of 7 days and have added correction factors for temperature and soil moisture content.

$$C_t = C_0 * e^{4.7*[(a+fT*f\theta*ftext*fpH*t)^{0.6}-a^{-0.6}]}$$

[Eq. 3]

C_0	= amount of added organic carbon [kg]
C_t	= remaining amount of organic carbon at time t [kg]
a	= apparent initial age [years]
fT	= temperature correction factor [-]
fθ	= moisture correction factor [-]
ftext	= texture correction factor [-]
fpH	= pH correction factor [-]

Temperature correction factor

We assume that mineralisation is mainly a biological process and decreases to nil at 0°C. Therefore, we correct for temperature by use of a modified Arrhenius approach (Eq. 7). Using the soil temperature data at 10 cm depth obtained from the weather station we matched the Arrhenius approach, to the decomposition on an annual basis in a bare (continuously moist) soil according to Kortleven, by changing the reference temperature and adding an extra constant.

$$fT = e^{-9000*(\frac{1}{T}-\frac{1}{282})}-0.349$$

[Eq. 4]

fT	= temperature correction factor [-]
T	= temperature [K]

Moisture correction factor

The moisture correction factor for the mineralisation rate according to Rijtema (1980) is equal to 1 up to pF 2.7 and then decreases linearly to 0 at pF 4.2.

Cultivation effect

Quantification of the effect of cultivation on mineralisation is difficult because it seems to depend on so many complex factors like texture, saturation of the capacity to protect organic matter and soil condition during and after the cultivation, influenced by the weather, depth and type of cultivation. In the model effects of ploughing and seed bed preparation are included by taking a fixed fraction of the initial organic matter (450 kg in case of clay soils and 45 in case sandy soils) and adding it again with a lower apparent initial age (2.45 versus 24) each time the soil is cultivated. The tentative fixed amount is based on experiments with and without tillage in clay soils (Titulaer & Boone, 1984; Bakermans & De Wit, 1970). The effect of freezing and drought can be included in a similar way.

9.3.4.3 Calculation of N mineralisation

Janssen's formula describes the rate of net dissimilation of the organic matter. As mineralisation proceeds the remaining carbon will contain less carbon in original organic matter and more in the form of decomposition and conversion products and biomass.

The relation between the net dissimilation of carbon DC and of nitrogen DN (Eq. 5) shows that depending on initial C/N of the substrate (C_0/N_0) and C/N and A/D (assimilation/dissimilation) of the microorganisms (CN_{micro} and AD_{micro}), initially net mineralisation or immobilisation of nitrogen can occur.

$$D_N = [\frac{1}{CN_{micro}} - (AD_{micro} + 1) * (\frac{1}{CN_{micro}} - \frac{1}{C_0 / N_0}) * (\frac{C}{C_0})^{AD_{micro}}] * D_C \qquad \text{[Eq. 5]}$$

9.3.4.4 Nitrogen balance

A nitrogen balance for the mineral nitrogen was made using the calculated mineralisation (initial organic matter, crop residues, manure), addition of fertiliser and deposition as inputs. Plant uptake from the soil and losses are outputs.

Potential crop N uptake is calculated from historical or expected/intended yield, dry matter and N distribution over roots, residues and harvested part, crop evapotranspiration and crop development stage. Nitrogen uptake from top and second layer is based on equal proportionality for both layers to water uptake and mineral nitrogen concentration.

$$NUPT_1 = MINIMUM(\frac{NUPT_{pot}}{1 + \frac{UPT_2}{UPT_1} * \frac{N_2}{N_1} * \frac{M_1}{M_2}}, N_{avail,1}) \qquad \text{[Eq. 6]}$$

From the second layer:

$$NUPT_2 = MINIMUM(NUPT_{pot} - NUPT_1, N_{avail,2}) \qquad \text{[Eq. 7]}$$

$NUPT_{1(2)}$ = N uptake from layer 1(2) [kg ha^{-1}]
$NUPT_{pot}$ = potential N uptake [kg ha^{-1}]
$UPT_{1(2)}$ = water uptake layer 1(2) [mm]
$N_{1(2)}$ = mineral N stock layer 1(2) [kg ha^{-1}]
$M_{1(2)}$ = total water amount layer 1(2) [mm]
$N_{avail,1(2)}$ = available mineral nitrogen layer 1(2) [kg ha^{-1}]

9.3.4.5 Nitrogen fixation

Nitrogen fixation is not a mineral input to the soil. The nitrogen uptake from the soil is calculated as the nitrogen in the crop minus the nitrogen fixed. The fixation by legumes is found by trial and error in the following way: the legumes fix so much nitrogen that at the end of their growing season 10 kg N is left in the top soil.

9.3.4.6 Losses by leaching

Losses by leaching are proportionate to the water outflow and the mineral nitrogen concentration in the layer. The N concentration is calculated after each time step by mixing the residual and added water. Water transport is not homogeneous through the soil, a larger part of the water will follow larger pores and cracks, while mineral nitrogen is also present in smaller pores. Therefore, a leaching factor and a bypass flow factor are introduced for every layer. This phenomenon is still under research and literature values are difficult to find. Denitrification is not included in the model cannot be included as far as it is not proportional to the water outflow.

9.4 Required input

For a rough reconstruction most input data can be derived from farm administration and taken from the nearest weather station. Soil parameters have to be estimated. All time-dependent information has to be given per week.

The *cropping system:* yield, time of the main tillage operations, of planting, of reaching full cover, of starting ripening, of harvest and of manuring. Further data have to be given for the nitrogen fixation and amount and type of manure.

The *weather:* with the average temperature at 10 cm depth, precipitation, nitrogen deposition and potential evapotranspiration.

The *soil:* organic matter content of the topsoil at the beginning of the rotation, texture in topsoil and subsoil, rooting depth, water table and the fraction of the rainfall that is assumed to be drained via bypass flow.
For a more exact reconstruction of the nitrogen dynamics the input can be improved by measuring composition of manure and distribution of dry matter and nitrogen over harvested part, straw, stubble and roots.

The water balance can be improved by measuring the water retention curve.

9.5 Validation performed

The model was applied on 11-year data from a rotation on clay on 6 experimental fields of the Department of Ecological Agriculture of Wageningen (Habets & Oomen, 1995) The results did not lead to a rejection of the calculating procedure:

- Neither the model nor the measurements indicated a change of the mean organic matter content of the 6 fields. Therefore the total release of nitrogen during the 11 years equalled the total input of organic N.
- According to the model the crops could nearly always find the nitrogen they actually found.
- The measured mineral nitrogen (0-25 cm) in 1992 corresponded well with model results in 6 of 7 fields.

Furthermore, the model was used to analyse the nitrogen dynamics in several crop rotations. The available data did not allow a validation in strict sense. But in all cases the results helped to reach a better understanding of which processes were relevant (Bokhorst, 1996; Ponzio, 1996; Pluimers & Van der Marel, 1994).

9.6 Plans for development

Recently, the model has been provided with a menu, which makes it easier to handle. NDICEA will be more extensively tested on arable farms. We want to develop an acceptable procedure to match model with reality, if not all coefficients are well known. The model will also be used for scenario studies, at least as eye-opener. The possibilities to use it as a tool in short-term management will be studied.

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10 ROTASK 1.0

R.E.E. Jongschaap
Research Institute for Agrobiology and Soil Fertility (AB-DLO), Dept. of Agrosystems Research, The Netherlands

10.1 Objective

ROTASK 1.0 is meant to quantitatively evaluate rotation cropping strategies on farms for European tillage systems, regarding diverse management practices for the growth and tillage of various crops. Dry matter production, soil organic matter dynamics, and nitrogen flows are simulated, taking into account the development of pests and diseases. Based on simulation results, rotation cropping schemes can be valued, adjusted or adapted.

10.2 Description

10.2.1 ROTASK 1.0 basis

ROTASK 1.0 is a dynamic simulation model with a continuously running water, carbon and nitrogen cycle as main structure (Jongschaap, 1996). Crop growth modules can be attached separately, resulting in nutrient and water absorbance from the concurrent pools. ROTASK 1.0 simulates water and nutrient balances and crop growth of a single field during a crop rotation. Crop growth and management practices influence these balances in a mechanistic sense. In fallow periods (e.g. in between crop growth) the soil system is only affected by weather (temperatures, precipitation), tillage practices (ploughing, organic matter applications), soil organic matter dynamics and water fluxes.

10.2.2 Crop growth and rotation effects

Crop growth
Associated crop growth models include models for potato (based on Kooman, 1995), wheat (based on Luyten, 1995), grass (based on Stol & Schapendonk, unpublished) and sugar beet (based on Bouman et al., 1996). These crop growth models are LINTUL-models (for Light INTerception and UtiLization), with exception of the sugar beet model which is a SUCROS-type model. ROTASK 1.0 can handle all crop growth models with simulation steps of one day.

In LINTUL-models, the direct conversion of intercepted incoming radiation into dry matter is done with the use of one single parameter for Light Use Efficiency (LUE; kg dry matter J^{-1}). Dry matter is partitioned to plant organs like leaves, stems, roots and storage organs.

Crop growth is reduced by water and nitrogen stress. Water stress is experienced if required transpiration rates are not available in the root zone or if root densities are too low to realize demanded water uptake. Nitrogen stress is experienced if nitrogen concentrations in the crop

(or in special organs) get below optimal nitrogen concentrations. Mechanistic relations between water or nitrogen demand and growth reduction factors determine actual crop growth rates.

Rotation effects

The influence of previous crops on the growth of succeeding crops has various components. One component is to what extent nutrients are absorbed by previous crop growth. This aspect is dealt with separately as the nutrient balance is simulated dynamically.

Another rotation effect is the build-up of soil-borne pests specific to a crop species during continuous cropping. Such an effect can diminish crop growth significantly by increasing pressure of pests and diseases as a result of degradation of the growth environment. Effects can be observed for years, as is indicated in Table 1. For potatoes and sugar beet, a nematode effect is included as well. If no measures are taken against it, the nematode yield reduction factor will also be taken into account.

If, e.g., potatoes are grown in the first and third year of a rotation (1:2 rotation frequency), and measures are taken against nematodes, light use efficiency is reduced by 15% (correction factor 0.85).

Table 1   Rotation frequency of several crops with correction factor on light use efficiency as reciprocal of self-tolerance and responsible factor for yield degradation (Source: Habekotté, 1994)

1	2	3	4	5	6	7	8	Year
1 :	1	2	3	4	5	6	7	Rotation frequency
Crop								Main factors
Grass	0.85	0.95	0.99	1.00	1.00	1.00	1.00	unknown
Maize	0.87	0.87	0.92	0.95	0.97	1.00	1.00	*Pythium spp.*
Pea	0.62	0.70	0.77	0.85	0.92	1.00	1.00	*various*
Potato	0.75	0.85*	0.85	0.87	0.91	0.96	1.00	*Verticillium dahliae*
								Streptomyces spp.
								Rhizoctonia solani
(nematodes:	0.40	0.68	0.82	0.95	0.99	1.00	1.00	*Globera spp.)*
Wheat	0.85	0.95	0.99	1.00	1.00	1.00	1.00	unknown
Sugar beet	0.72	0.83	0.94	1.00	1.00	1.00	1.00	unknown
(nematodes:	0.52	0.63	0.74	0.90	0.95	1.00	1.00	unknown)

* example given in text

The third rotation component that affects actual crop growth is not self-tolerance, but tolerance for previous crop growth other than the same crop. To obtain reliable correction factors for this effect, complex and long-term experiments have to be analysed thoroughly. Some effects are given in Table 2. Correction factor 1 is used in places where question marks appear (no effect determined yet). These effects are valid for crops following the previous crop. Long-term effects for succeeding years are not yet included.

Table 2   Environment and rotation effects for several crops in ROTASK 1.0, expressed in correction factors on light use efficiency (Source: Habekotté, 1994)

Crop	Previous crop					
	Grass	Maize	Pea	Potato	Sugar beet	Wheat
Grass	*	?	?	0.980	0.980	0.850
Maize	?	*	?	?	?	?
Pea	?	?	*	?	?	?
Potato	?	?	0.930	*	0.910	?
Sugar beet	?	?	?	0.975	*	?
Wheat	0.850	?	?	0.980	0.980	*

*) See table 1 for self-tolerance effects

The growth correction factors for self-tolerance and rotation effects are directly applied to the light use efficiency parameter (LUE). Each interaction factor could be represented by a sub-model and attached to ROTASK 1.0 to predict its influence on crop growth. However, growth correction for interaction and self-tolerance effects is dealt with statically here.

10.3   Inputs data files

To execute ROTASK 1.0, various data files are necessary. In the following paragraphs it is indicated what kind of data is needed in each file.

10.3.1   Timer file

Start year and start day of simulation (-); number of days to simulate (-); time step (delt).

10.3.2   Weather file

For every simulation day daily data are required on: total global irradiation (kJ m^{-2} d^{-1}); early morning vapour pressure (kPa); average wind speed at 2 m height (m s^{-1}); minimum and maximum air temperature (degrees Celsius) and precipitation (mm d^{-1}).

10.3.3   Soil file

The soil file requires data on single soil variables, variables per soil horizon and information on mechanistic relations between environment and soil characteristics. Variables most likely to change in new soil descriptions are printed in italics.

Single soil variables

Soil type or *moisture characteristics* (pF characteristics); evaporation extinction coefficient (m^{-1}); *number of soil layers* (-); nitrogen concentration in precipitation (kg N cm^{-3} H$_2$O); *inorganic nitrogen in profile* (kg ha^{-1}); *plant residues in profile at start of simulation* (kg ha^{-1}); fraction carbon in decomposable, resistant and structural plant material pool (-); initial stable carbon fraction in shallow and deeper horizons (-); C/N quotient for decomposable, structural and resistant plant material pool (-); C/N quotient for labile organic matter pool (-); relative

decomposition rates for plant material pools, labile and stable organic matter pools (d⁻¹); de-composition efficiency factors per plant material pool (-).

Soil variables per soil horizon

Soil type; *carbon* (weight %); *nitrogen* (weight %); *bulk density* (g cm⁻³).

Mechanistic relations

Soil moisture depletion table for water availability (-); soil moisture reduction table for de-composition rates (-); assignment table for organic applications to decomposable, resistant and structural plant material pool (-).

10.3.4   Management file

The four columns in the management file MANAGE.DAT compose the management tasks that will be performed during simulation. The description of three lines in this data file are given in Table 3. All actions applied to the field are specified in MANAGE.DAT. The lower part of this data file consists of technical specifications for the management tasks that can be performed.

Table 3   Columns in file MANAGE.DAT to specify management tasks in ROTASK 1.0

YEAR	DATE	MCODE	MSPEC	Meaning
1996.	120.	100	25.	25 cm deep ploughing at day 120 in 1996
1996.	130.	210	15.	15 cm deep planting of potato at day 130 in 1996
1996.	135.	410	125.	125 kg KNO₃ ha⁻¹ fertilisation at day 135 in 1996

The first and second column indicate year and date of the management task to be performed. Date is given as Julian day number (DOY; Day Of Year). The third column (MCODE) refers to the management codes for the management tasks to be executed in the given year at the specified date. Table 4 resumes the possible management tasks in the model. The fourth column (MSPEC) enables the user to specify management tasks given in the third column (MCODE).

Ploughing, planting and sowing

For ploughing the ploughing depth (cm) has to be specified. Ploughing means complete mixing of water, carbon and nitrogen pools. For planting or sowing, one has to indicate planting or sowing depth (cm). Sowing or planting depth is important to calculate rooting depth, root densities and concurrent transpiration rates (mm ha⁻¹ d⁻¹).

Emergence

Emergence date can be given either as input (fixed) or calculated in the crop growth model.

Table 4   Codes in ROTASK 1.0 management file MANAGE.DAT

CODE	Meaning	Available types		Specification	Units
100	Ploughing	-		ploughing depth	cm
200	Planting or	210	Potato	planting depth	cm
	sowing	220	Wheat	sowing depth	
		230	Grass	sowing depth	
		240	Sugar beet	sowing depth	
300	Emergence	300		code (0,1,2,3)	-
400	Inorganic N	410	KNO$_3$	rate	kg ha^{-1} d^{-1}
500	Organic N	(Examples in table 5)		rate	kg ha^{-1} d^{-1}
600	Harvest	(See below)		code (0,1,2,3)	-
700	Soil fumigation	700		-	-
800	Irrigation	800		rate	mm ha^{-1} d^{-1}

Inorganic and organic applications

Use management codes (MCODE) for fertilisation type and management specifications (MSPEC) for fertilisation rates to apply inorganic and organic fertiliser to the system. Codes running in the 400 range are inorganic nitrogen applications (e.g. 410 for KNO$_3$ fertilisation), while codes running in the 500 range are intended for organic nitrogen applications.

Table 5   Some example for manure codes (animal excrements), technical coefficients and nitrogen contents (kg ton^{-1}) used as organic applications in ROTASK 1.0 (Source: Habekotté, 1994)

Code	Animal excretion	Carbon fraction (kg ton^{-1})	C/N quotient (-)	Total N (kg ton^{-1})	N-NH$_3$ (kg ton^{-1})	N-organic (kg ton^{-1})
Slurry						
510	Cattle slurry	40.0	9.10	4.40	2.20	2.20
511	Pig slurry	90.0	13.90	6.50	3.25	3.25
Farm yard manure						
520	Cattle manure	62.0	11.20	5.50	1.10	4.40
Liquid manure (urine)						
530	Cattle liquid manure	-	-	4.00	4.00	0.00
531	Calve liquid manure	-	-	5.00	3.00	0.00

In addition, specific organic applications can be defined as well. The application type has to be specified by technical coefficients in the section below the management dates and tasks. The self-defined code is given in the third column (MCODE). This code must be unique. The self-defined code must be added to the list with organic fertilisers. Values for technical coefficients must be specified in the succeeding columns as is demonstrated in Table 5. Application rate (kg ha^{-1}) can be given in the fourth column (MSPEC) at the top of the file.

Harvest

At harvest it is possible to indicate the destination of crop residues. As default all above-ground dry matter and yield will be removed from the field. Living roots, however, will die

and treated like organic application in the soil horizons in which they occur. Other possibilities include the removal of storage organs only, or leave all produced biomass in the field.

Irrigation
Irrigation (mm ha^{-1} d^{-1}) is added to precipitation rates. Up to a sum of 10 mm ha^{-1} d^{-1} infiltrates directly, while 15% of higher intensities is notified as run off.

10.4 Calibration and validation

A 50-year (!) rotation experiment at *De Lovinkhoeve* in The Netherlands will serve as calibration experiment for various crop growth and rotation modules.

No validation experiments have been performed until now.

10.5 Further developments

More calibration and validation tests will be conducted.
- A reference manual will be published (Jongschaap, 1996) with results of parameterisation and validation tests performed in The Netherlands.
- More crop growth models (carrot, onion, leguminosae) will be written in the right format or ROTASK 1.0 to extend rotation scenarios.
- Possibilities are examined to use ROTASK 1.0 in ecological farming trials executed by the DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO), for choices in rotation schedules and fertilisation strategies.

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11   Simulation of nitrogen turnover in crop rotations: Application of the SUNDIAL model

J.U. Smith, N.J. Bradbury, M.J. Glendining & P.E. Smith
IACR Rothamsted, Soil Science Department, United Kingdom

11.1   Introduction

Much of the research to improve knowledge about factors controlling nitrate leaching has concentrated on developing principles on a single crop or in a single year. In practice farmers operate within more complex systems involving rotations of crops and planning timescales of several years. The results of systems studies as well as simpler experiments have been used to develop process-based models of nitrogen (N) turnover in the soil/crop system. One such model, SUNDIAL (Bradbury et al., 1993; Smith et al., 1996a) is a dynamic model with a weekly description of the effects on N turnover of different weather patterns, methods and timing of cultivation and soil and crop types. SUNDIAL is designed to be used in a "carry-forward" mode with one years run providing the inputs for the next. This allows it to be used to investigate more complex systems involving rotations of crops and planning timescales of several years.

A decision support system (DSS) is currently being constructed around SUNDIAL that will allow farmers or policy makers to explore how arable rotations respond to practical strategies for reducing nitrate leaching. SUNDIAL calculates the quantity of N lost each week by leaching as nitrate, denitrification and ammonia loss and can simulate the effects of:

- Changes in sowing and harvest dates.
- Amount and timing of fertilizer applications.
- Straw incorporation.
- Set-aside.
- Use of cover crops.
- Organic manures.
- Different cropping sequences.

An automated systematic method or *scenario generator* derives all rotations of crops allowed within an imposed set of farming rules. Rules are initially defined by constraints on cropping and management practices for example, due to disease or EC regulations. New rules may be entered in response to changes in farming systems and regulations. The N dynamics of all permutations are automatically simulated and optimum management strategies selected and presented.

11.2   Model description

11.2.1   Objectives of model

SUNDIAL is a functional model originally developed to help scientists interpret N measurements in field experiments. It is now becoming one of a new generation of management tools, designed to provide dynamic simulations of all the major processes of N turnover in the soil/crop system, whilst requiring only minimal input data that would be readily available to a farmer or advisor. Decision support systems are being constructed that use SUNDIAL to provide fertiliser recommendations, explore practical strategies for reducing nitrate leaching in rotations, and simulate nitrate leaching in catchments. The systems will be compatible with each other, and with other decision support systems that provide advice on use of herbicides and fungicides.

11.2.2   Processes

SUNDIAL is a dynamic model, incorporating descriptions of all the major processes of N turnover in the soil/crop system on a weekly basis (Fig. 1).
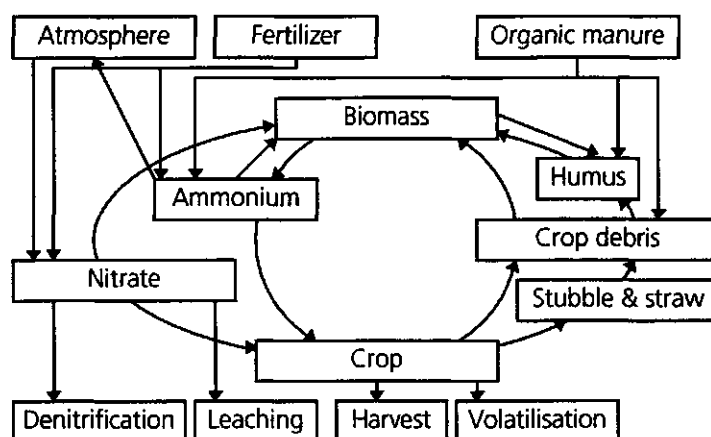
Figure 1   Structure of the SUNDIAL model showing the nitrogen pools and their interactions

Unlike many other N models, N dynamics in SUNDIAL are driven by the carbon (C) cycle. Nitrogen may be added to the soil/crop system as inorganic fertiliser, organic manure or by atmospheric deposition. Nitrate and ammonium are taken up by the crop in proportion to the expected yield of the crop and the cumulative temperature since sowing. Nitrogen and C are then returned to the soil, not only at harvest as stubble and straw, but also throughout the growing season as root exudates, dead leaves and fragments of roots. Decomposition of the crop debris is represented by partitioning the C and N into biomass and humus according to the soil type. The C:N ratios of these organic matter pools are assumed to remain constant. If the C:N ratio rises, due to a higher C:N composition of the crop debris, N is immobilised first from ammonium and then from nitrate in the soil. If the C:N ratio falls, N is mineralised to ammonium. Ammonium may then be nitrified to nitrate, and nitrate may be lost by denitrifi-

cation or leaching. A more detailed description of the model structure is given by Bradbury et al. (1993).

11.2.3   Input requirements

Each of the processes described above is represented in the model by an empirical expression, driven by *input variables* and *fixed parameters*. *Input variables* describe the details of the specific management scenario to be simulated. *Fixed parameters* are specific to the soil, organic waste or crop type, and only change when the model is developed for a new soil, organic waste or crop type. The requirement for input variables is minimal. Management scenarios are described using only simple measurements that are typically available to the farmer or advisor. Input variables provide five types of data: soil, weather, crops, fertilisers and organic manures. If additional information is also available, this may be entered to improve the parameters used in the model. The input requirements of SUNDIAL are summarised in table 1.

Table 1   SUNDIAL input data

Data type	Required input variables	Useful additional data
Soil	- Type: sand, loam, clay or texture class (Hall et al., 1977) - Depth (cm) - Previous crop type - Previous crop yield (t ha^{-1}) - Period under grass in the previous 10 years	- Total C (kg C ha^{-1}) - Mineral N on specified date to a specified depth (kg N ha^{-1} cm^{-1}) - Minimum amount of mineral N in soil (kg N ha^{-1} 5 cm^{-1}) - Available water at field capacity ((mm water) (150 cm soil)$^{-1}$)
Weather	- Total rainfall (mm week^{-1}) - Total evapotranspiration over grass (mm week^{-1}) - Average air temperature (°C week^{-1})	- Soil temperature on specified date to specified depth (°C) - Soil water content on specified date to specified depth (mm)
Crops and fertilisers	- Type - Sowing date (week) - Harvest date (week) - Yield - Number of fertiliser applications For each - Application date (week) - Amount (kg N ha^{-1}) - Type(% NO$_3^-$; % urea; % non-urea NH$_4^+$)	- N in crop at harvest (kg N ha^{-1}) - N in crop on specified date (kg N ha^{-1}) - N in straw or haulms (kg N ha^{-1})
Organic manures	- Type - Application date (week) - Amount (t manure ha^{-1})	- Dry matter content (t ha^{-1}) - Water content (t ha^{-1}) - Total N in manure (kg N ha^{-1}) - N available in first year (kg N ha^{-1}) - Total C in manure (kg C ha^{-1})

11.2.4   Simulating rotations

A *scenario generator*, attached to the SUNDIAL model, may be used to derive all rotations of crops allowed within an imposed set of farming rules. The user enters the number of years included in the rotation, sets the proportion of land allocated to a particular crop, specifies constraints imposed on the cropping and management practices and enters criteria of good management practice. Examples of constraints are given in table 2. Criteria of good management practice might include reducing nitrate leaching to below the EC limit whilst maintaining maximum crop yield.

Table 2   Examples of imposed constraints on cropping and management practices in an arable rotation due to pests and disease

Crop	Constraint	Reason
Brassica crops (e.g. oilseed rape, mustard)	At least a 4 year break between brassica crops	Avoid build up of persistent soil diseases
Sugar beet, other beets and brassica crops	At least a 4 year break between beet or brassica crops	Control of beet cyst nematode (*Heterodera schachtii*)
Peas and beans	At least a 4 year break between pea and bean crops	Avoid build up of soil-borne fungi and nematodes
Linseed	At least a 4 year break between linseed crops	Control of *Alternaria* spp.

The system then calculates all possible combinations of crops that result in the requested cropping ratio, and removes any rotations not allowed within the entered constraints. SUNDIAL is run to simulate the N dynamics of all remaining permutations. All rotations that meet the criteria for optimum management are saved and the N dynamics associated with each rotation are presented. This system allows the user to explore the influence on the N cycle of the whole rotation, and is designed to be of use to farmers and policy makers alike.

11.3   Model evaluation

Methods used to evaluate the performance of SUNDIAL are discussed in detail elsewhere (Addiscott et al., 1996; Smith et al., 1996c; Smith et al., 1996d). Each quantitative method used provides information on a distinct aspect of the accuracy of the simulation. The method selected to assess the goodness-of-fit between simulated and measured values depends on the type of measurements available.

The model was originally developed and parameterised for winter wheat using data from field experiments at Rothamsted, Woburn and Saxmundham, UK (Bradbury et al., 1993). Initial testing used ^{15}N data from different plots at the same sites and partitioned the observed errors between those due to error in the experimental data and those due to lack of fit between the model and measurement (after the method described by Whitmore, 1991). The root mean square of the difference between the modelled and the measured values of labelled N in soils

was c. 7.5 kg labelled N/ha. Such an evaluation against labelled-N measurements provides a strict test of the performance of the model, but because the model was developed and tested at the same sites, it gives no indication of model transferability between sites. The small errors observed in the simulations were attributed to variable uptake of N by the crop. Model developments are underway to incorporate a description of variable N uptake.

The sensitivity of the model to all fitted parameters was analysed with respect to labelled N remaining in the soil after 4 years and the cumulative recovery of residual labelled N by the crop in succeeding years. The results of the analysis suggest a reasonable sensitivity to the parameters tested (Bradbury et al., 1993). A quantitative comparison to measured data is currently underway.

SUNDIAL has been extended to include all major arable crops grown in the UK (Smith & Leech, 1995). Evaluations of model performance indicate comparable accuracy in simulations of nitrogen turnover under winter wheat, oilseed rape, potatoes, beans and sugar beet. The model is currently being tested against a wider range of independent data (Smith et al., 1996b).

11.4   Future developments

SUNDIAL is also currently being built into a DSS for fertiliser recommendation and for catchment nitrate policy support. Future work is currently focused on achieving these goals. The most important tasks are to:

- Incorporate compatibility with farm recording packages and datalogging weather stations.
- Devise methods of estimating local weather and expected yield.
- Develop a facility to express the fertiliser recommendation as growth stages of the crop.
- Develop the model for perennial crops, crops managed in rows, intercropping and unharvested crops.
- Include a more sophisticated description of the soil.
- Describe the effects of cultivation, compaction, drainage and irrigation.
- Develop a manure submodel driven by data on animal management, manure storage and spreading practice.
- Develop a ley-arable submodel.
- Attach a database of mean national, regional and sub-regional data on crop management.

11.5   Acknowledgements

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12   The modified WAVE model

H.W.G. Booltink, P. Droogers & J. Verhagen
Wageningen Agricultural University, Department of Soil Science and Geology, The Netherlands

12.1   Background and origin

Expansion of human activities causes dispersion of pollutants in the subsurface environment. Today, acid rain, hazardous chemical wastes, fertilizers, pesticides, sewage sludge are among the serious threats to soil and groundwater quality. For the development of adequate and durable measures, the systems analysis approach offers many interesting features. A system approach, encompassing the development and validation of simulation models, can give decision makers and scientists better insight in the complexity and the interaction of different processes affecting the fate of chemicals in the dynamic soil-crop environment. Mathematical modelling is an important part of many current environmental studies and it is believed that there is still a lot of scope for model development as long as new insights in processes will emerge and computing facilities improve.

The WAVE model (Water and Agrochemicals in soil, crop and Vadose Environment), is an example of such a mathematical tool. The model describes the transport and transformation of matter and energy in the soil, crop and vadose environment (Vadose: non-saturated soil) The model is mainly process-based, since physical, chemical and biological laws were considered when developing the model. The model is deterministic, which means that one set of input data always yields the same model output values. The model is numerical, since finite difference techniques were used for the solution of the differential equations describing matter and energy transport in the soil-crop continuum. The model is holistic, which means that an attempt was made to integrate the different subprocesses (and hence submodels) ruling the transfer and fate of different state variables in the complex soil-crop environment. The model is one-dimensional, because it is assumed that governing transport processes of matter and energy in the soil sub-system occur essentially in the vertical direction. The model is an explanatory model because it helps to understand the different processes and process interactions governing e.g. pollutants in the soil. However, results from these explanatory studies can always be used in extrapolation or prediction studies for decision making.

12.2   Model description

The Wave Model is a software package developed by the Institute for Land and Water Management of the K.U. Leuven, Belgium. The present version of the model integrates earlier models and packages developed by the institute or developed and published by other scientific institutes. The model is a revised version of the SWATNIT-model (Vereecken et al., 1990, 1991), which integrates the SWATRER-model (Feddes et al., 1978; Belmans et al., 1983; Dierckx et al., 1986), a nitrogen model based on SOILN-model (Bergström et al., 1991), a heat and solute transport model based on the LEACHN-model (Wagenet & Hutson, 1989) and the universal crop growth model SUCROS (Van Keulen et al., 1982; Spitters et al., 1988).

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The WAVE model is structured in a modular way, enabling the user to use only those modules required to analyse the problem. This also allows the extension of the present model with other modules without the need to adapt the model structure or existing input files of the model. It offers the possibility to exchange modules when new concepts and insights of certain processes become available. Figure 1 presents the different modules and the arrows indicate the 'uses-relationships' between them. For example, the solution flow equation needs to be proceeded by the solution of the water flow equation. Hence the solute model 'uses' the water flow module, which is indicated by the direction of the arrow.
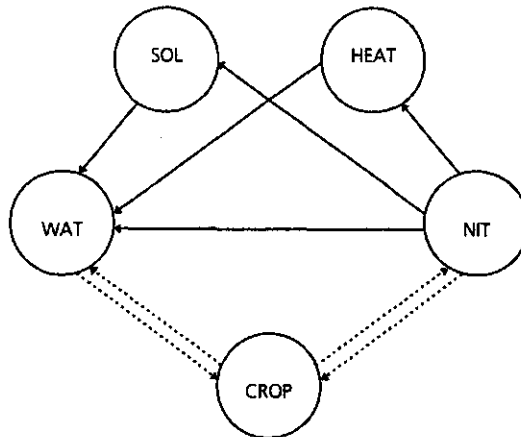
Figure 1   Schematic presentation of the modules in WAVE (release 2.0). Full line arrows represent obligatory 'uses relations', dashed arrows are optional relations

In the vertical direction, the model considers the existence of heterogeneity in the form of soil layers within a soil profile (Figure 2).The soil layers are subdivided into compartments. Halfway each compartment a node is defined, for which state variables are calculated. All soil compartments have the same thickness, which the user can specify.
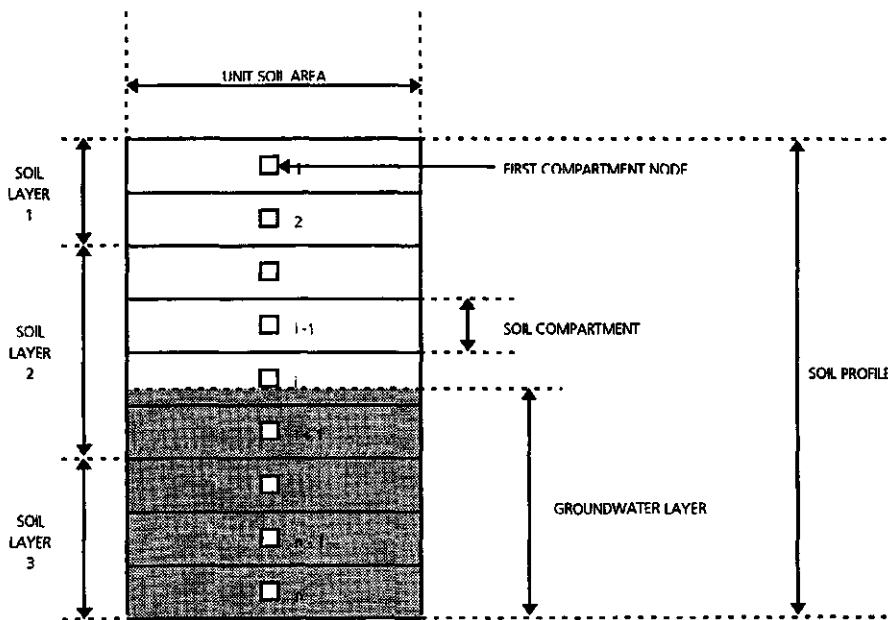
Figure 2   Concept of the vertical space scale of WAVE

The WAVE-model uses a time step smaller than a day to calculate the different state variables. The time step is variable and is chosen as to limit mass balance errors induced by solving the water flow equation. For crop growth a daily time step is used.

State variables are integrated after each day to yield daily output. The simulation period should not exceed 366 days.

12.3   Modifications

12.3.1   Water uptake

In the original WAVE model water is preferentially extracted near the soil surface. The plant roots start taking up at the first compartment and work their way down until the water demand is fulfilled or when the maximum rooting depth is reached.

We abandoned this approach and adapted the method as was originally used by SWATRER, in which water uptake is integrated over the rooting zone. The unclear crop-specific preferential uptake at the surface is thus avoided.

12.3.2   Nitrogen uptake

Nitrogen uptake was driven by the N concentration in the leaves assuming a constant N distribution over the leaves, stem, roots and storage organ. Via this relation the nitrogen demand could then be quantified; no distinction between crops was made.

The N leaf driven module was abandoned and replaced by a biomass driven model. The N distribution was taken out because not enough information is available to dynamically model N distribution over the individual plant parts.
The biomass driven model was after Greenwood et al. (1990). Figures 3 and 4 show the relation used between N concentration and plant mass for C3 and C4 plants respectively.

The equation for C3 crops is:

$$N_c = 5.7W^{-0.5}$$

and for C4 crop

$$N_c = 4.1W^{-0.5}$$

is used.

Biomass production is calculated daily; this increase in biomass results in a new N concentration which is checked against the desired N concentration (Greenwood). From the difference a N demand is calculated. The N uptake processes were not changed: the division in convective and diffuse N uptake was maintained. Reduction as a result of N deficit is defined as the ratio of N demand over N uptake.
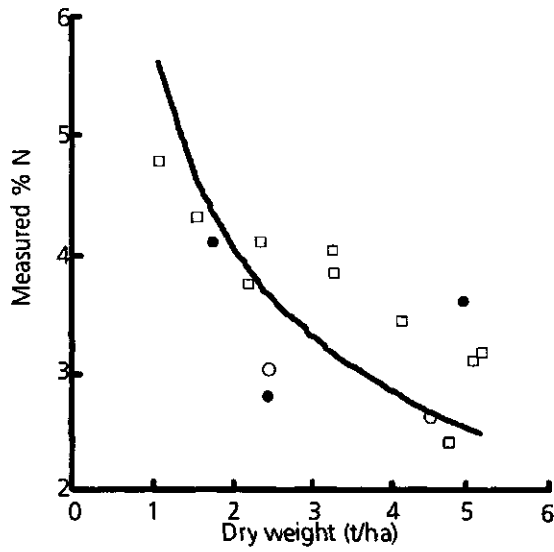
Figure 3 Measured % N and dry weights of some C3-crops
□ Represents rape, ● summer cabbage, and O French beans
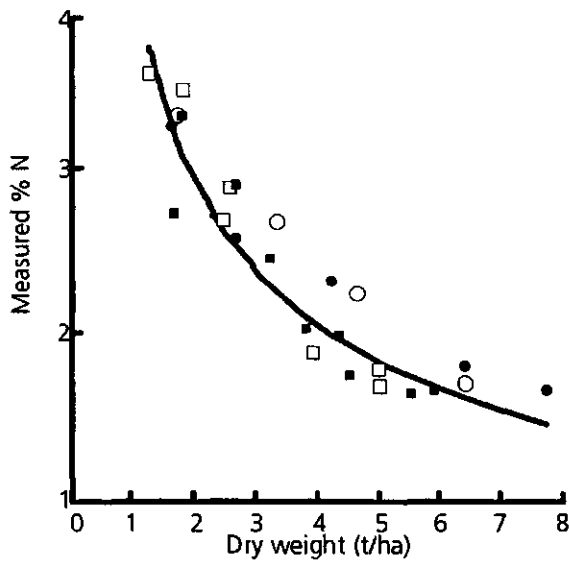
Figure 4 Measured % N and dry weights of some C4-crops
□ Represents setaria Guadeloupe, ■ sorghum Guadeloupe, ● maize France, and O maize Guadeloupe

12.3.3 Hydraulic conductivity

The original WAVE model offers a broad range of soil hydraulic functions based on parameter estimation techniques. However, it is clear that for some soils the description of the soil hydraulic conductivity by these parameter estimation techniques is not valid (e.g. Leummens et al., 1995). The model was extended with an option to enter soil hydraulic conductivity data in a tabular form. During simulations this table was used to extract the hydraulic conductivity data and, if necessary, interpolate values not given in the table.

12.3.4 Macropore flow

The mobile/immobile concept offered by the original WAVE package is only used for the flow of solutes and has no effect on water transport. However, bypass flow, also denoted as preferential flow, can have a large impact on the total water balance, especially in structured soils with macropores (e.g. Booltink et al., 1993). A relatively simple module was added to simulate this bypass flow based on the concept of Booltink et al. (1993), but due to some generalisations a lower amount of input data were required. Calculations were made on a daily basis to ensure linkage with the other WAVE modules. Rainfall intensities were used as driving forces for preferential flow. Because rainfall intensities are not regularly available, a function between rainfall on a daily basis and global radiation was derived. Speed of water through macropores was assumed to be equal to rainfall intensity. The infiltration of water into macropores was limited by the volume of the macropores and the absorption of water into the soil matrix. The latter is defined as a function of the conductivity of the matrix, the pressure head of the matrix, and the contact areas between macropores and matrix.

12.4 Input requirements

Input variables are those variables by which the environment affects the delineated system, as represented by the model. Model parameters are constants in the mathematical relations present in the model. They determine the behaviour of the system and are specific for a location. In the input files no distinction is made between model parameters or model input variables, as both should be specified by the user.

The programme reads its input from external ASCII-files, which can be prepared with a conventional text editor. The input files have the extension .IN and can be summarised as following:

Filename	Description
GENDATA.IN	General information (simulation period, number of compartments etc.)
WATDATA.IN	Hydraulic characteristics of the various soil layers
SOLDATA.IN	Variables/characteristics for nitrogen transport
TEMPDATA.IN	Heat transport parameters
CLIMDATA.IN	Daily precipitation, radiation, potential evapotranspiration (irrigation)
NITDATA.IN	Variables/characteristics for nitrogen transformations/distribution
CROPDATA.IN	Crop characteristics

12.5 Model validation

The WAVE model consists of various existing simulation modules such as SWATRE, SUCROS, and SOILN, which have been tested and applied widely by many researchers. WAVE and the previous version, SWATNIT, have been validated in various studies throughout its development from individual components. A thorough model validation of the WAVE model has been carried out by Diels (1994). In this study the water, nitrogen transport, and nitrogen transforma-

tion modules were tested for various soil types in Belgium. The validation procedure used field as well as lysimeter data.

Direct model outputs such as the simulated actual evapotranspiration and drainage at the bottom of the soil profile, together with derived properties such as the number of workable days and a reduction factor for mineralisation were included in a deterministic (changing one parameter at a time) and stochastic simulation procedure in which a Monte Carlo procedure was used to draw input parameter sets from parameter distributions. Diels (1990) concluded that the soil physical properties such as conductivity and retention characteristics of the soil types considered were the most influential model inputs.

A test of the WAVE model including all modules is described by Vanclooster (1995). This study also included a test on the effects on nitrogen leaching when using mobile/immobile and solute transport under cropped soils. In his study Vanclooster used a holistic modelling approach to simulate field as well as lysimeter data on water and nitrogen transport to judge model performance.

Some other relevant publications with respect to WAVE are described by Vereecken et al., (1990) and Vanclooster et al., (1993).

12.6   Acknowledgement

Model and model input descriptions in this manuscript are mainly based on the WAVE Reference and User's manual by M. Vanclooster, P. Viaene, J. Diels and K. Christiaens. Institute for Land and Water Management K.U. Leuven, Belgium.

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III   The ecologist's perspective

13 Needs, development and experiences with an interactive tool for planning of manure allocation and feed supply on organic dairy farms

J.P. Hansen & I. Sillebak Kristensen
Danish Institute of Animal Science, Department for Agricultural Engineering and Production Systems, Research Centre Foulum, Denmark

13.1 Summary

A programme with the purpose of operationalising the interdependencies between crop and livestock production at farm specific level in organic dairy farming has been developed. The programme is seen as a means of communication to be used by advisors together with the farmer, as the planning process is valued more important than the resulting plan itself. The programme has proven to be a valuable tool as facilitator of discussion of alternatives based on ongoing information of agronomical and environmental consequences.

13.2 Introduction

Organic dairy farming in Denmark is moving away from a farming method of a few idealistic farmers to an option considered and chosen by a growing number of conventional dairy farmers. At present about 3% of the dairy farms is certified as organic producers. Society demands and supports this evolution and as a result of this, a unit for research in Production Systems (PSu) at the Danish Institute of Animal Science (DIAS) has since 1987 been involved in systematic research in organic farming. The research is based on studies in 23 private owned mixed organic farms, with milk production as main activity.

These organic farms had a considerable N surplus of 124 (88-158) kg N ha^{-1} $year^{-1}$ (Halberg et al., 1995). The overall goal of the research project is to reduce the nutrient surplus on organic farms, primarily by altering the crop rotation, feed ration and use of manure.

13.3 The problem

Normally, agricultural production systems are managed effectively and efficiently using heuristics. The farmers' rule sets are developing through long experience and learning by customisation to technological components, locations and farming systems (Cox et al., 1995).

When former conventional farmers transform to organic farming, a substantial amount of their explicit and tacit knowledge can no longer be used - their heuristic models become useless. In addition, an organic dairy farm as a system has fewer options than a conventional

farming system. E.g., use of supplementary fertiliser is not allowed and there are restrictions on buying feed (Text box 1), which results in nitrogen being the primary delimiting factor in crop production (Magid & Kølster, 1995). Therefore, interdependencies between crop and livestock production is stronger in the organic than in the conventional system.

A premium price for organic milk in Denmark makes high milk production per cow most profitable. The high milk production is achieved by feeding a ration with 45 % easily degradable feeds - cereals, beets and concentrates (Kristensen et al., 1994). E.g., 17 organic mixed dairy farms in Denmark grew 47 % of the crop rotation area with small grain crops (mainly cereals and peas) (Halberg & Kristensen, 1995). Besides the crop rotation area, 11 % of the area was under permanent low-productive grassland. A typical crop rotation is:

- *barley + pea + undersown grass/clover*
- *grass/clover or lucerne (only on clay soil)*
- *grass/clover or lucerne (only on clay soil)*
- *winter cereal*
- *potatoes/fodder beets or spring cereal*

On the above 17 farms, the pure cereals were fertilized with 30 tons animal manure ha^{-1}, corresponding to 36 kg mineral N ha^{-1} (Kristensen & Halberg, 1995), so it is obvious that soil-N from previous crops is very important when N-demanding crops are grown on organic farms in Denmark. The average yields were 3900 kg grain ha^{-1}. Halberg & Kristensen (1995) found a 21-37% lower grain yield on organic than on conventional farms.

When a farm has to be mainly selfsupporting with feed, the stocking rate per area has a major influence on the crop rotation. The maximum allowed stocking rate in Denmark is 1.4 livestock unit (LSU) ha^{-1}; the variation between the investigated organic dairy farms is from 0.8 to 2.0 LSU ha^{-1}. The farms with high stocking rates are using a large proportion of the area for grass/clover and the farms with low stocking rates are using a large proportion of the area for cash crops.

The organic farms on sandy soils (<10 % clay) either have a high stocking rate or the farmers are importing animal manure from conventional farms (max. covering 25% of need for N), mainly because it is difficult to maintain N and K in the shallow root zone from year to year.

Text box 1   Organic dairy farming in Denmark

13.4   The solution

A programme with the purpose of operationalising the interdependencies between crop and livestock production systems and the environment have been developed. The programme is seen as a means of communication to be used by advisors practising computer-aided advising (Hansen, 1992), realizing that the process of creating environmentally and profitable sound plans in agreement with the farmers' goals is as important as the resulting plan itself. By bringing together farmer, advisor and computer it is possible to substitute learning in a simulated world for learning in the real world (Chatelin et al., 1992; Joyce & Showers, 1980) leading to a rebuilding of heuristic models.

13.4.1   Programme functionality

The functionality of the programme covers user-directed creation of operational and tactical feeding plans and creation of operational plans for land use and nutrition management on a per field basis (Figure 1). There are no optimisation or "guiding" restrictions in the pro-gramme. Instead, the consequences of ideas or alternatives put into the programme will on an ongoing basis be presented to the user. In this way, the advisor and the farmer can work their way towards the best solution by combining the scientifically based results from the pro-gramme with the farmer's knowledge of farm specific conditions and own preferences.
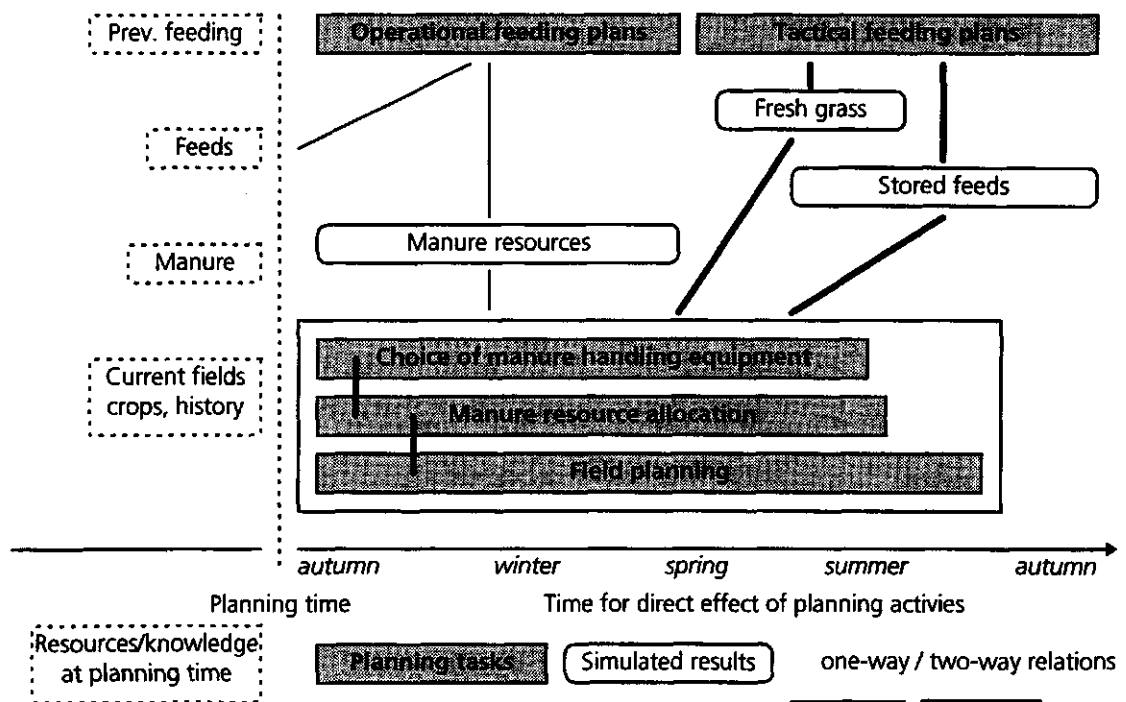
Figure 1   Relations between planning tasks covered by the programme and the time for fulfilment of plans

Creation of feeding plans is supported by pop-up windows showing accordance with standards and expected milk production. Manure resources are calculated on the basis of feeding plans, and volumes and concentrations can be verified and modified. Creation of field plans and allo-cation of manure to specific fields in different months is supported by ongoing information concerning manure resources in different storages, amount of leftover N per field, calculated effect of applied manure and resulting crop yields. Sources of N losses can be shown and nu-trient balances can be analysed at field, crop, herd and farm level in accordance with Halberg et al. (1995). The programme allows easy shifts between working with feed planning and with crop planning, including manure allocation.

13.4.2   Processes

The functionality of the programme is based on synthesis of a number of models each describing important processes in the farm system.

Expected milk yield in the first part of lactation is calculated by using a production function (Thysen, 1983) which simultaneously includes energy, protein and fat. The result is adjusted for amount of AAT (amino acids absorbed from the small intestine) and PBV (protein balance in rumen) in the ration in accordance with the new Nordic protein evaluation system (Aaes et al., 1991), and for amount of ad libitum feed (Hansen & Kristensen, 1994). Estimating milk yield in the second part of lactation is based on standard feeding adjusted for feed efficiency according to Østergaard et al. (1994).

Body weight gain is expressed using standards according to Kristensen et al. (1994).

Manure production is estimated as a function of animal, feeding, production level, and housing system. Nitrogen intake is calculated from the ration's protein content and apparent digestibility according to Thomsen (1979). The quantity and form of N, the volume of urine/ slurry and the faecal dry matter production, adding of straw and excess water and losses of N are calculated according to assumptions of Laursen (1994) in his work with estimating standard values for animal manure.

Ammonia losses from stored manure is calculated in a simple way according to Laursen (1994).

Ammonia losses during application and from applied manure is calculated by use of a model developed by Hansen et al. (1990). Determining variables are application and cultivation methods and time between these, soil type, temperature, weather conditions and pH, and dry matter content of the manure.

Turnover of N in soil is at present handled by a simple model operating at daily time steps and including nitrogen in three forms, different root zone capacities, weather data, evaporation and resulting N leaching and N-min in soil for plant uptake.

Influence of previous crops on a specific field is at present limited to effect of leftover N. Net mineralised N is estimated by using lumped functions with crop type, soil type and time as variables. For example 70 kg N ha^{-1} is mineralised in the first year after two years with grass/ clover. On sandy soil the net mineralisation would be lower than 20 kg N ha^{-1} after 2 years, on clay soil after 5 years.

Expected crop yields as a function of N from animal manure and N from previous crops are estimated using soil specific quadratic production functions according to Nielsen & Kristensen (1991).

13.5   The development environment

Development of the programme took place in an interdisciplinary research project with the purpose to study nutrient management in a manner similar to Lanyon & Beegie (1989). Activi-

ties have involved systematic data and knowledge collection from 24 farms certified as organic producers through locally placed technicians. In the cooperation with the farmers, the researchers from PSu equipped with the programme have played the role of farmer's advisors. It has been a very fruitful and stimulating development environment with direct communication between scientists, users and system developer.

13.5.1 The methods and tools used

Object-oriented methods influenced by the conceptual framework underlying the BETA language (Lehrmann et al., 1993) were used. The BETA framework states that analysis, design and implementation are all programming or modelling activities, but at different abstraction levels, and defines that a programme execution should be regarded as a physical model simulating the behaviour of either a real or imaginary part of the world. Programming of the first character-based prototype taken out in real use by fellow researchers were done in Borland Pascal. Now this prototype is being reprogrammed for Windows using the Delphi environment to improve the ease of use of the programme.

13.5.2 User participation

Evolutionary prototyping has been the name of the game. Prototyping provides a communication basis for discussions among people involved in the development process, especially between users and developers. In addition, prototyping enables us to adopt an approach to software construction based on experiment and experience (Budde & Züllighoven, 1992).

Our development environment has made it possible to go through an evolutionary development process based on an almost paperless communication between developer and users. Response times have been very short - from a new version to critic and following enhancements. This helps keeping everybody engaged in the process.

13.6 Experiences

A character-based prototype was developed and used as a tool by researchers in advising sessions (autumn) on 12 organic dairy farms involved in a research project. The purpose of these visits was to discuss and create feeding plans for the coming winter season and field plus fertilizer plans for the coming growing season. The purpose of using the programme was to clarify the appropriateness of the programme regarding functionality and scope.

The programme showed its strength as a facilitator of discussions of alternatives based on ongoing information of agronomical and environmental consequences. These findings were expected as the principle of its use is similar to a successful feeding planning tool (Kristensen & Hansen, 1989).

Needs concerning usability were revealed for optional levels of focus. In the development of the prototype focus had been on actions related to the single field. This is a common "scientific approach" mistake caused by concerns about getting all the details right (Cox et al., 1995). When moving out in real life the users of the programme were faced with farms with

up to 40-50 fields. The programme handles this number, but the users loose the overview when trying to allocate manure resources to such a large number of individual fields.

Needs were also revealed for support of analysis at strategic levels of alternative cropping systems. Some farmers would have liked to evaluate the effect of alternative cropping and feeding systems on recycling of nutrients when looked upon in static balance without considering the present system. Such analysis could give them information regarding directions for future changes in their overall system.

13.6.1   Future work

Our work aims at developing a *useful* medium of communication to be used by farmer and advisor in the process of creating feeding and field plans. *Useful* encompasses userfriendliness, addressing the problems of the user, and dealing with these problems in a realistic manner. The latter means that we will on an ongoing basis update the programme with the most suitable elements from scientific models.

Hutchings et al. (1996) have recently developed a dynamic model to predict ammonia volatilization from livestock farms under grazing. Elements from this model describing ammonia losses from animal houses to losses from applied slurry and urine patches will be included in the programme.

Olesen (pers. communication) is at present testing a simplified version of the DAISY soil-N model. This model will replace the current rather simple representation of soil water and nitrogen dynamics.

The P soil contents are typically low on organic clay farms due to low P surplus during many years. On sandy soil leaching of K is often causing a low K soil content. To represent these circumstances, simple functions for yield responses to P and K will be implemented in the model.

We would like to include major effects of the rotation system (N leftover, weed and disease pressure, long-term effect on soil fertility) in the model. Our aim is not to calculate precise quantitative information, but to assure that the model will show directions for how major biological, economical and environmental variables will be affected, so to give the decision maker a basis for making a choice.

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14 Lovinkhoeve: a research facility for organic farming

J.J. Schröder
Research Institute for Agrobiology and Soil Fertility (AB-DLO), The Netherlands

14.1 Introduction

Most researchers are aware that a farming system is more than the sum of individual crops. The performance of any crop results from the combination of the various measures taken in that crop, and residual effects of (the measures taken in) preceding crops. This concept is probably even more valid in organic farming systems where preventive instead of curative measures are the rule rather than the exception and measures may have a cumulative nature which only becomes visible after repeated applications. Organic farming systems claim to contribute to the development of a more sustainable agriculture. This alone justifies to study effects for more than just a few seasons.

These considerations made AB-DLO decide to convert the Lovinkhoeve farm from integrated farming to organic farming. From August 1995 agro-chemicals as defined by EC-regulation Nr. 2092/91 will no longer be used. The Lovinkhoeve is an arable farm of 38 ha located on a loamy clay soil in the Noord-Oost Polder. It is held by AB-DLO since 1954. The farm management team is already familiar with multidisciplinary approaches and concepts of system analysis, as research during the last 10 years has been directed at the development of integrated farming systems (Lebbink et al., 1994; Van Faassen & Lebbink, 1994).

14.2 Goals on a whole farm level

Future research on the Lovinkhoeve, starting this year, will focus on the optimisation of cropping techniques of individual crops in an organic setting. This implies that there is no room for a simultaneous comparison of different farming systems or rotations. Hence, decisions had to be made, at least for the near future, about the crop rotation. This emphasis on crops rather than rotations, does not mean, however, that no goals were defined on a whole farm level. These goals can be summarised as follows:
1. Annual nutrient losses to be limited to 80 kg N and 0 kg P per ha.
2. Maintenance of the chemical, physical and biological soil fertility (i.e. preclusion of a gradual increase of yield-reducing agents (weeds, pests, pathogens), accumulation of nutrients, heavy metals and organic matter, depletion of nutrient reserves and organic matter).
3. Development of an ecosystem both within fields and on the borders of fields, up to a level needed to support the farm management (stability, self-regulation) or desired from e.g. a landscaping point of view.
4. Balance between the nutrient outputs to other compartments of the society and the inputs through 'wastes' returning from these compartments (compost, sewage, excrements) whilst accounting for inevitable 'losses'.

So far it is not clear how large the difference between nutrient inputs and outputs should be to maintain the soil fertility at present levels on the one hand and to keep losses below environmentally acceptable levels on the other hand (Van Eck, 1995; Oenema & Van Dijk, 1995). Goal 1 may thus require concessions to goal 2.

Nutrient balance sheets will be established annually and pool changes (nutrients, organic matter, etc.) will be monitored in the various crops. Results from individual crops will be aggregated to a whole farm level. Serious attempts will be made to allocate the calculated N loss to various terms (temporal storage, denitrification, leaching, ammonia volatilization).

It is extremely difficult to quantify goal 3, not at least because there is still much confusion about the net result of border strips, hedges, etc. Support from colleagues from other disciplines is welcomed.

Goal 4 implies that there is a kind of upper and lower boundary for the amounts and nature of the wastes that can be used. Many commercial organic farms tend to select only those crops and wastes that fit them best from an economic point of view. Such a policy doesn't work, however, when larger regions would decide to convert to organic farming.

14.3   How to define a rotation?

Having set the goals, different crops and nutrient inputs have to be selected and put into a time sequence. To our present knowledge, no tools are as yet available that can perform this task in an automated manner. Therefore, we couldn't do anything but rely on common sense and semi-quantitative rules, some of which were proposed by Vereijken (1992; 1995):

- Alternate crops with negative and positive effects on the physical soil fertility as affected by the duration of crop cover, rooting characteristics, position of harvested plant parts (mowing vs. lifting), harvest date.
- Alternate crops with large and small nutrient demands.
- Alternate crops with large and small nutrient transfers to the next season.
- Alternate crops with large and small moisture demands (not relevant in the Noord-Oost Polder).
- Consider to insert perennial mown crops (e.g. leys) for the suppression of weeds.
- Link the choice of crop species to the choice of wastes (e.g. vegetables x urban compost; forage crops x animal wastes).
- Consider crops with an early harvest date allowing tillage operations under dry conditions, weed control and a successful establishment of cover crops.
- Select crops with large recoveries and nutrient harvest-indices for an effective conversion of wastes into produce.
- Avoid crops to be assigned to a field adjacent to the field where the crop was grown in the previous year.
- Grow as many legumes as needed for the supplementation of N in addition to the N derived from wastes (when N demands are fully met with wastes only, this will inevitably lead to P and K accumulation).
- Check feasibility of crop sequences in terms of labour and growing degree days.
- Limit the frequency of a crop species to < 16.7%.
- Limit the frequency of a crop group (i.e. genetically and/or phytopathologically related crops) to < 33%.

Especially the latter two rules have an intuitive and arbitrary character. They may be prudent from a soil fertility point of view (growing a species only once per century would be even better, probably), but may not yield rotations producing goods in agreement with society's needs for fats, starch, protein and fibre.

14.4   General setup of the Lovinkhoeve

We used the aforementioned rules to construct a rotation for the Lovinkhoeve consisting of 7 crops that will all be present at equal frequencies in 7 so-called crop blocks (Table 1). Organic wastes will be predominantly applied on cereal stubbles (combined with green manure) and to a lesser extent on cereals themselves. The anticipated balance sheet of nutrient inputs and outputs is given in Table 2. The ratio of N outputs and inputs amounts to 64% indicating that the utilization target is ambitious. This will probably mean that techniques such a spring application and or row application of manure, both uncommon on clay soils, have to be seriously considered. In addition to that, we are expecting more from green manures than what they have proved to be able of, so far. We hope to augment the contribution of green manures by concessions to preceding crops (especially their harvest dates) and by an improvement of their management (manipulation of C-N ratios, incorporation methods and timing).

Table 1   Crop rotation of the Lovinkhoeve

Year	Crop
1	lucerne-grass mixture
2	lucerne-grass mixture (last cut to be incorporated)
3	sugar beets or vegetables
4	cereal with non-leguminous green manure
5	ware potatoes
6	winter cereal with undersown red clover
7	onions, tulips, chicory or carrots

Table 2   Anticipated nutrient inputs, outputs and surplus on the Lovinkhoeve (kg ha^{-1} yr.$^{-1}$)

			N	P	K
Input	fertilizer	cattle slurry	54	10	56
		pig slurry	20	5	17
		urban compost	16	3	9
	fixation	lucerne	76		
		clover	13		
	deposition		49	1	4
	seeds		3	< 1	2
	Total		**230**	**19**	**90**
Output	products		147	20	100
Surplus			83	< 1	-11

Each of the seven crop blocks will be split into two parts: 25% of the area will be dedicated to the production of crops according to 'best ecological practice' and 75% of the area will be assigned to experimentation. In the latter part one will still find 'classical' experiments in terms of their design (i.e. replicated, randomized, factorial) to overcome problems of confounding as frequently encountered in on-farm research (e.g. Schröder et al., 1996). For 1996 we have planned research on cover crop management in one of the cereal blocks, research on organic matter sources x tillage in the onion block, and research on plant densities in the potatoes block.

Goals on a whole farm level can be achieved in different ways. Selecting crops and adjusting their cropping frequencies is only one method. Goals may, however, be achieved just as well through adjustments within crops. We expect the nutrient availability to be one of the major instruments within crops. Therefore is was decided to superimpose three nutrient input levels on all 7 crop blocks. The source and amount of nutrients within each nutrient input level may vary with the crop types grown on a specific block. Qualitatively, however, the nutrient levels will have fixed positions on each block to account for their cumulative effects. Consequently, experimental treatments (e.g. weed control, cover cropping, plant densities) can always be executed at 3 levels of soil fertility (i.e. in split plot manner). In this way we hope to collect data with a broader range of validity which may help modellers to construct alternative rotations. The Lovinkhoeve's setup is summarised in figure 1.

14.5   Concluding remarks

From an ecologist's point of view, I would say that a crop rotation model should be able to link crop species into a temporal sequence and explore the short- (one season) and long-term (decades) consequences for input needs (labour, nutrients, water, energy, capital) and outputs (marketable products, fate of nutrients, fate of water, CO_2, impact on pool sizes (weeds, pests, pathogenic inocula, nematodes, water, nutrients, heavy metals, organic matter)), impact on the physical soil status (compaction, erodability).

There is no such thing as a unique cropping technique for a specific crop, as a crop can be grown in numerous ways and an input-output matrix is needed for each of these crop variants. Therefore, it is not just the choice of crop species that determines whether a rotation is sustainable or not, but just as much the cropping technique within one species (e.g. fertilizer input, planting and harvesting date, destruction date of green manure, preceding crop(s), control measures). Last but not least, a crop rotation model should be able to check whether crop sequences are feasible in terms of calendar days or growing degree days.

LUCERNE CEREAL

BEETS
ONIONS

CEREAL
LUCERNE

POTATOES

< whole farm (1:7)

'Best ecological practice' >

N2		
N1	N3	N2
N3	N2	N1
N2	N1	N3

I

Experimentation >   II

III

< sub plots within nutrient level plot
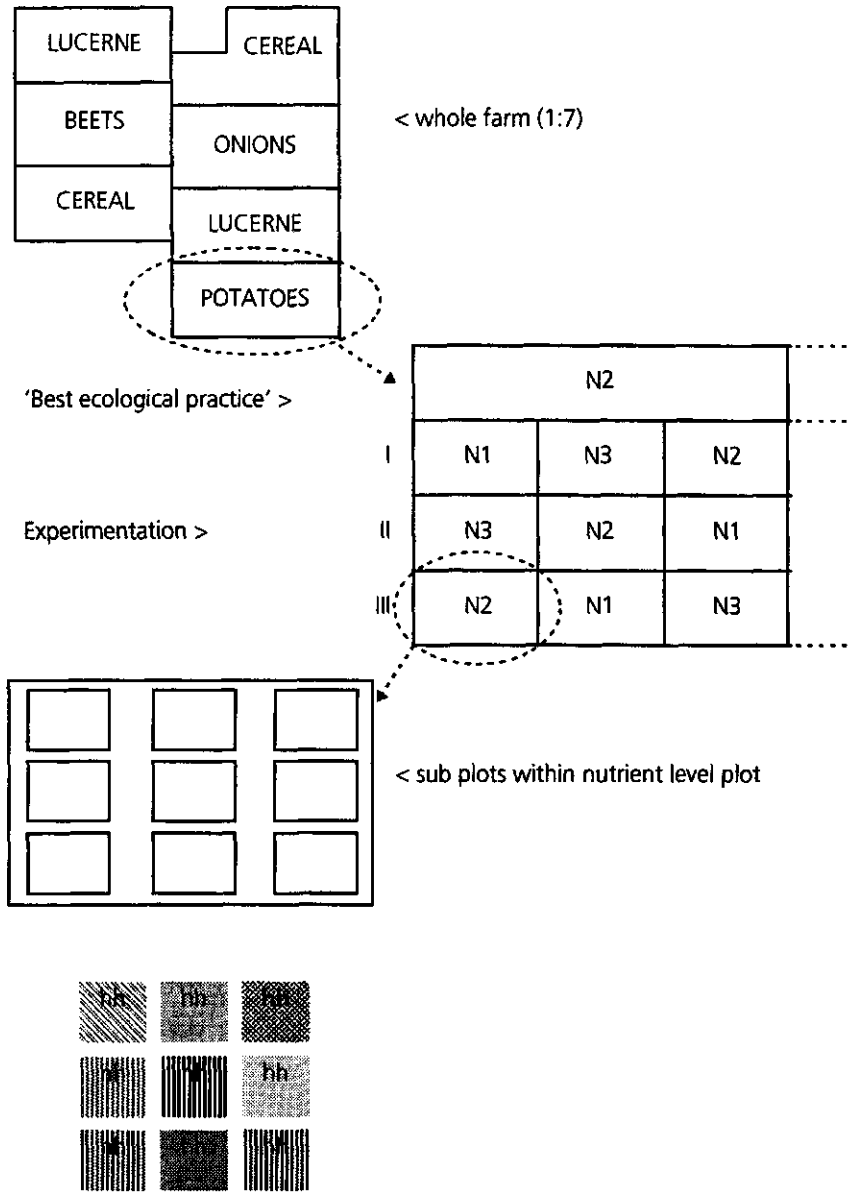
Figure 1   Experimental setup of the Lovinkhoeve farm

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15 An approach to a place for models in designing alternative cropping systems

T. Doré & J.M. Meynard
Institut National de la Recherche Agronomique, Laboratoire d'Agronomie, Paris-Grignon, France

15.1 Introduction

The economic changes affecting agriculture (e.g. the decrease of some product prices), the growth of new regulations (e.g. those concerning the environment), the enlargement of the markets for agricultural products (e.g. the development of crops for fuel production), have profoundly modified the context in which farmers produce in northern France during the past ten years. As partners of farmers and their advisors, research workers are requested to propose new cropping systems. We present the approach we use to achieve this, with emphasis on the needs and the uses of models.

15.2 The general framework

Due to the changes mentioned above, farmers must be able to manage cropping systems with different aims: it is clear for instance that high-yielding crop production and environment-friendly crop production are very likely to be different (Meynard & Girardin, 1991). The many other examples which justify changes in cropping system management due to new and various constraints include: increasing farm size forces some farmers to adopt time-cheap cropping systems, and set-aside modifies the constraints concerning crop protection. As changes are numerous and frequent, farmers cannot use their own experience to adapt their practices, and they need tools for helping them in decision-making; policy makers are also interested in such tools so as to be able to anticipate the changes in regulations.

Our purpose is to build and validate such decision tools for crop management and two-crop succession management at a strategic level. Three stages are usually used for this type of tool.

15.2.1 A diagnosis stage

The main aim of this stage is to assess and understand the variability of the conditions under which farmers produce, by identifying the main factors affecting production and the environmental impact of the cropping systems. This allows identification of the range of validity necessary to include in the construction of decision support tools. This stage takes entirely place in farmers' fields, and has already been largely described elsewhere (for example Meynard & David, 1992; Meynard & Doré, 1992; Doré et al, 1996).

15.2.2   A design stage

Quite often the design of new strategies by experiment has been abandoned. However, this approach may still be used when the diagnosis stage showed that few changes are sufficient to attain the objectives of the new strategies, and that the decision rules will be simple enough not to require heavy modelling. This was the case for example when designing new crop management strategies for malting barley in northern France (Le Bail, 1994). More often the design of new strategies is based on models, using either simulation or optimisations. The models used in this stage are chosen according to the diagnosis stage results. They must allow simulation of the effects of the main limiting factors on yield, and the effects of the cropping systems on the environmental variables. We believe that on-farm validation of very simple models (for example: nitrogen balance-sheet method; models of soil structure changes ...) under farmers' conditions is important. These models are sometimes included in decision support systems (see above).

15.2.3   A validation stage

This stage includes various steps:
1. Testing the global models (how do the observed measurements differ from the outputs of the model?)
2. Testing the cropping system management strategies obtained by using the model (are the aims achieved with such strategies?)
3. Testing the decision support system (is the decision maker really helped by the system?)
Much of this validation stage takes place in farmers' fields, and analysis of the disagreement between observed and simulated data can make a large contribution to model improvement feedback.

15.3   An example of a decision support system for wheat management: DECIBLE

The software DECIBLE (Figure 1) is the result of collaboration between agronomists, economists, and specialists working on farmers' decision making.

It allows to simulate the effects of crop management on wheat yield, gross margin, protein content, soil mineral nitrogen at harvest, at a field scale. Each plot is defined by cropping history and soil type; simulation is possible for a range of 20 years climatic data. Such a simulation enables to compare different crop management systems, and to identify which is the most relevant for a given set of objectives and constraints (for example extensive wheat production with low input and time required, or wheat for bioethanol production, which requires a definite quality and which price is very low). DECIBLE does not address tactical decision making (such as choosing a fungicide application date) but strategic decision making (such as intensification level, or coherence between sowing date and density, fertilisation, and crop protection).
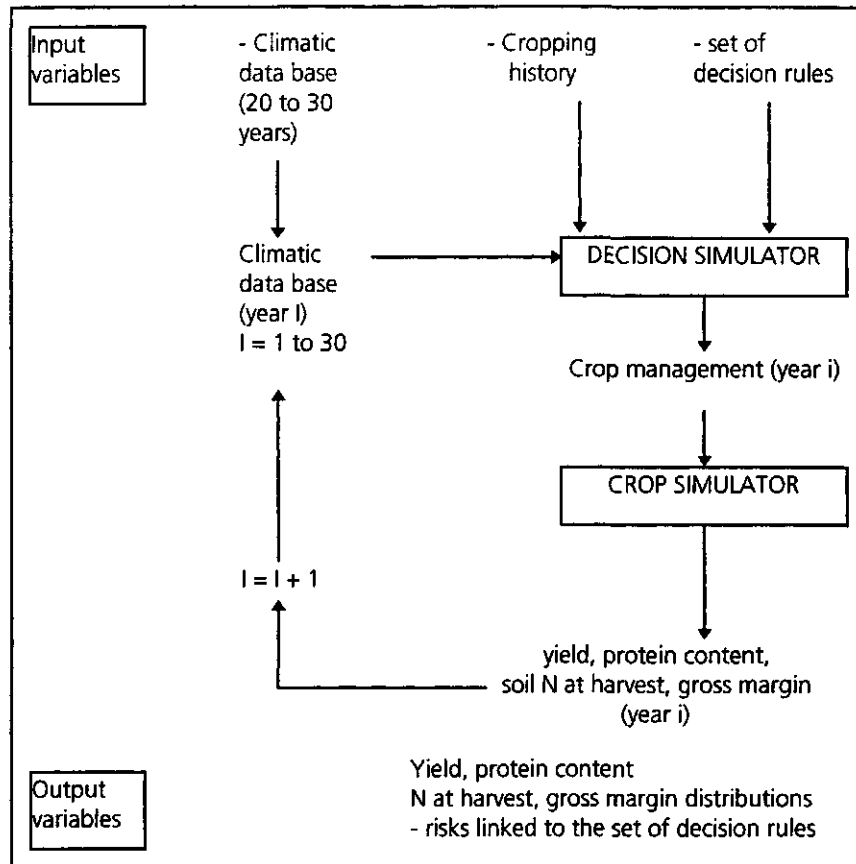
Figure 1   Simplified diagramme of the decision support system for wheat management DECIBLE (Aubry et al., 1992)

Crop management is described by a set of decision rules (<< *if* condition *then* action >>), translated for a particular crop and a particular year as sowing and fertiliser application dates, sowing density, variety choice, fertiliser rate and so on, using a << decision simulator >>. The simulated crop management which is the output of the decision simulator is also the input of a crop simulator including various submodels (including yield components, protein content, nitrogen accumulation, water balance, soil structure changes, and lodging and disease risks). These modules are quite simple, using few parameters, so as to be easily tested and adapted to new varieties and different areas in France. The DECIBLE software is a research object about linking crop models and decision models in decision support systems.

15.4   Example of on-going work on the management of two-crop successions

We recently enlarged our work in building decision tools towards aid to managing two crops succeeding on a plot. This is a different purpose than that of determining a crop succession. Here the succession is given, and we think, like for one crop management, that the management of this succession must be different according to the different constraints that may affect the farmers. Moreover, the management of a succession can not be reduced to the juxtaposition of each crop management (Doré & Debaeke, 1996). The management of the following

crop can (and often must) be adapted to the environmental changes caused by the previous crop. And the management of the previous crop could (and often should) be adapted after assessment of its likely effects on the following crop. For example in a maize/wheat succession, irrigation management of the maize will take into account the effects on maize growth and yield, but it could also take into account the subsequent effects on the wheat crop, which might be strong. The stronger the effect of the previous crop management on the environment left for the following crop, the greater the need for global management of the crops. Figure 2 gives and example of the variability of the environment left by the previous crop (here the nitrogen uptake by unfertilised wheat following a pea crop) largely due to the management of this crop.
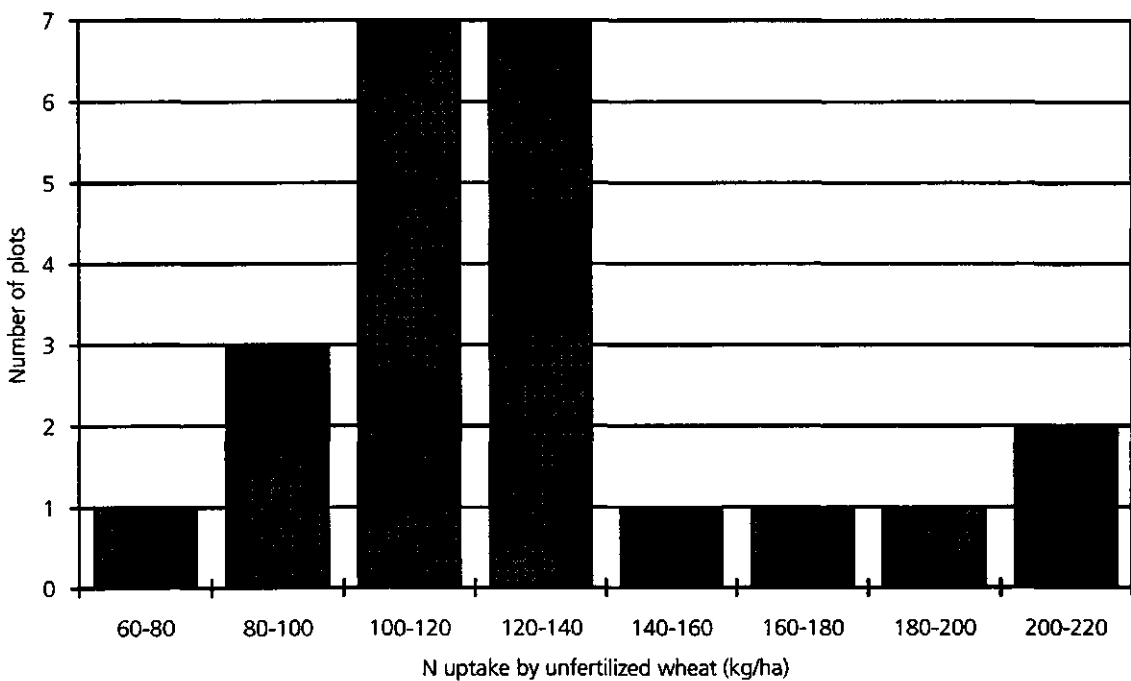
Figure 2   Variability in nitrogen uptake by unfertilised wheat crops after pea crops (farmers' plots, Northern Seine-et-Marne district)

The main programme in our laboratory as far as this subject is concerned is the design of a global model fort he management of the set-aside/wheat succession. It is helpful for answering questions like << which management of the set-aside/wheat succession minimises nitrate leaching during the succession? >> or << which management of set-asides minimises the risk of not achieving desired aims for the following wheat crop? >>. The diagnosis stage has already been performed. A hierarchy of the soil processes which have to be modelled has been established: nitrogen and water fluxes, weed flora changes and seed production, soil-borne diseases, soil structure. Changes in soil processes under set-aside (for example changes in weed dynamics) which must be taken into account during modelling (Doré & Dulout, 1996) have also been identified. Special effort in model building will be attributed to biological processes, as no relevant models are available. Moreover, the integration of different modules in a global model has to take into account heterogeneity of the models: some are dynamic with a daily-basis time step (nitrogen and water), others are dynamic with a management-basis time step (soil structure, weeds), or static either qualitative or quantitative (soil-borne diseases).

15.5   Perspectives

Our team in Paris-Grignon aims to produce genuinely useful references for cropping systems management. This leads to two important specifications in modelling cropping systems:

1. we address the variability of the farmers' fields, using the three-stage method described above,
2. we try to link agronomic and cognitive knowledge in our decision tools.

Our aims include developing these issues, by focusing on different topics, such as: uncertainty in farmers' fields modelling; use of artificial intelligence methods (such as constraint satisfaction problems method) in decision tools; and improvement of validation methods.

15.6   Conclusion

It is obviously necessary to predict ecological consequences of different cropping systems on a long-term basis, using rotation models, for improving the sustainability of agriculture. However, in northern France, ecological agriculture is not the only possibility in the short/medium-term future. Our purpose is to be ready for various needs corresponding to different constraints on crop production, rather than to help radical conversion from high yielding agriculture to ecological agriculture.

Moreover, the adoption of fixed rotation by the farmers is unlikely, due to an opportunistic behaviour when facing rapid changes in economics and regulations. This is why we focus more on the flexibility, the ability to take into account uncertainty and the range of validity or our models, than on their capability to determine the best ecological rotation.

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IV Model evaluations and plans for future experiments, data and model sharing, model development

16 Suggestions for priority issues and future cooperation

16.1 Input data and tools to accessing them; model structure; exchangeability

The discussion started with the observation that model exchangeability is largely dependent on common data structures and input file formats; if submodules or components per se are to be exchanged, then there must be a common framework into which shared components can be slotted. The sharing of component code or modules is one end of the spectrum; more often, sharing will involve the algorithm or other information concerning the processes being modelled.

It was noted that there are a number of constraints to model exchangeability. First, there are often no funds available for co-operative efforts. Research administrators may be enthusiastic about co-operation in theory, but are rarely willing to support it. Related to this is the issue of intellectual ownership; some administrators would see co-operation and model sharing as giving away a comparative advantage. Researchers clearly need to present a better case concerning collaboration to research administrators, but it was not obvious how this situation can be improved in the short run. Second, there would be a considerable "start-up" time for the development of appropriate tools that permit the exchanging of submodels or model components.

On the other hand, the benefits of exchanging submodels are clear, in theory: faster implementation of models that are sensitive to a wide range of factors, and the harder-to-quantify but still important benefits of synergy that arise when groups and individuals collaborate and work together.

On balance, a number of members of the discussion group felt that currently the constraints to model exchangeability outweigh the benefits. Some thought this too negative a conclusion, but beyond the sharing that continues among individuals anyway, it is hard to see how to foster this further without a lot of time and resources.

The discussion then turned to the issue of model structure as related to the farm scale. There was evidence of a considerable gap here between the ecologists and those who would apply the models at the farm level, and those more directly involved in building such models. As discussed on the previous day, there is currently a lack of models that are appropriate at the farm scale. Our present models tend to look at comparatively simple systems; the models that have been developed to deal with these are both simple (for instance, a mathematical programming model to study resource use at a regional level – the basic system as studied, as well as the model, may be rather simple) and complex (a highly detailed biophysical simulation model at the field scale, dealing with a monocrop and only water and N limitations, for example). The farm level is much more complex, and amounts to more than a simple addition of models simulation each field (as any systems person will point out).

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It is clear that dynamic, process-based models at the farm level that can answer detailed and wide-ranging questions as to the management of ecological farming systems are many years away. While complex models of complex systems such as a farm are not yet feasible, simpler models certainly are, although it must always be borne in mind that simplifying a complex model may lead to the situation where errors in the model outweigh the "treatment effects" (i.e., the things that the user wants to study) in the real world.

Three summary points were made with regard to these types of "interim" models:

- Dynamic models can and should be used only to provide additional information to farm-scale models. This follows directly from the consideration above, that complex models stuck together are not necessarily a feasible way of modelling complex systems.
- Farm-scale models may thus be based on local experience (perhaps in the guise of rule-based systems), available information, and the various constraints that are paramount in the situation under study (economics, environment, etc.). These interim models are not necessarily dynamic, although they may be.
- The level of complexity of a dynamic model is limited by the availability of information -- without information of some sort no process model can be built, but more importantly, in terms of the input data required to run it.

There is an enormous amount of work to be done, down both paths of this parallel approach to farm models; on the one hand, there is a continuing need for the building of dynamic process-based subcomponents, and on the other, there is also room for great creativity and innovation in representing and linking together available information in a way that can provide information to those who need it to make more informed decisions concerning the operation of farming systems.

16.2   Validation procedures and objectives

Summary of discussion group 2, Thursday 18 April, 1996
Reporter: W.A.H. Rossing, Wageningen Agricultural University, Dept. Theoretical Production Ecology, The Netherlands

Given the wealth of information (e.g. CAMASE_NEWS Extra Edition, November 1995) on technical aspects of validation, or rather evaluation, the discussion focused on philosophical aspects of validation in relation to model purpose.

16.2.1   The nature of validation

Validation of models aims at establishing credibility for a model with its developer, with colleagues and with the end-user. This involves a test of effectivity (is the aim of modelling achieved) in a scientific as well as social sense. To enable validation, clear definition of objectives of modelling is required. In addition, a description of best available knowledge at the start of the research project is needed. In this way, both the satisfaction of project objectives and the increase in operational knowledge is made apparent during model validation.

16.2.2 Aspects to be considered during validation

- Are the correct processes included in relation to the objective of modelling? Here, consideration may be given to short-term and long-term processes, and their interactions.
- Has Ocham's Razor been applied successfully? Or, has complexity been added only when necessary?
- In relation to sustainability aspects, especially long-term processes related to e.g. soil organic matter require attention.

16.2.3 Level of accuracy required

The level of accuracy of model output depends on the purpose of the model. Penning de Vries distinguishes three categories of purposes: research, advice and education. With respect to model accuracy he distinguished model truthfulness, the degree to which reality is represented correctly, and model usefulness, the degree to which model results lead to better decision making. In research, model accuracy is dictated by the accuracy of the empirical data on which the model is based, and model truthfulness is emphasized. With respect to advice (prediction), model usefulness is more important than model truthfulness. A model may be called useful when it provides additional or better information than the currently used basis for decision making. Finally, in education trends, rather than absolute numbers, are to be accurately produced by a model.

A serious pitfall in application of research results is striving for truthful models. We advocate a pragmatic approach in which a level of accuracy is aimed for which is needed to just obtain technical, scientific and social credibility, thus maximising interaction between analysis and synthesis of knowledge.

17   The models by themes

Discussion on the crop rotation models presented (weak and strong points)

17.1   Nutrients and water balances

Reporter: J.U. Smith
Rothamsted Experimental Station, IACR AFRC, United Kingdom

17.1.1   What is needed in rotation models for ecological farming?

The requirements for simulating crop rotations using nutrient and water models differ between ecological farmers and ecological planners.

Priority requirements of ecological farmers are estimates of:
* carbon and nitrogen fluxes throughout the year,
* the effects of applying organic manures,
* the influence of legumes in the rotation.

Nutrients and water should be modelled as part of the complete farming system. This means that the influence of economics, machines, labour etc. should also be included in any comparison of the viability of different rotations. It also requires that the system be considered at a number of different scales:

FIELD - FARM - CATCHMENT - REGIONAL - NATIONAL

When manure applications and legumes are included in the rotation, it is particularly important to consider additional nutrients to nitrogen, such as phosphorous and potassium. Long-term changes in soil structure should be described through changes in factors such as water and organic matter content. Modifications to nutrient and water balances due to pests, diseases and weed infestations could initially be described using simple reduction coefficients. Integration of arable simulations with descriptions of animal systems will be necessary for simulation of complete rotations. Dynamic simulation of carbon and nitrogen turnover in animal systems may be difficult due to effects such as "hotspots" of carbon and nitrogen in discrete patches where an animal has defecated.

Ecological planners, on the other hand, require models that allow crop rotations to be planned over long periods of time and for large regions of the country. Linear programmeming is likely to be an especially useful tool for this purpose. When working in conjunction with linear programmes and at such large temporal and spatial scales, static models can become more valuable due to:
* averaging of field results over the larger spatial and temporal scales,
* time constraints in optimising possible combinations of rotations.

Dynamic models are, however, of some value to ecological planners. Having selected the optimum rotation, it is essential to check what effect this rotation has at the smaller scale. In addition, it is necessary to develop the details of best management strategy at the field, or at least the farm scale.

17.1.2   What issues are currently being addressed in nutrient and water balance models?

The following issues are currently being addressed in the models present:
*   microbial biomass,
*   organic manures,
*   green manures,
*   soil structure,
*   biological nitrogen fixation,
*   animal-arable systems,
*   set-aside,
*   other effects (due to pest, diseases, weeds etc),
*   long-term planning.

17.1.3   What issues should be addressed?

Rotation modelling requires more than a sequential simulation of nutrient and water dynamics under different crops. Long-term changes in soil characteristics such as organic matter and depth must be simulated with respect to the continuing rotation. These interactions are generally included in the models present. However, the interaction of many other long-term processes, such as build-up of pests, diseases and weeds on nutrients and water have not been considered. Initially, it will be more feasible to simulate these interactions by combining process-based models with simple rules or reduction coefficients. In the long term, greater understanding of the processes involved might be obtained by developing comprehensive process-based models. Systems for linking models will be a great help in the development of such models. However, further basic research into the interactions between different parts of the system (eg. nutrients and pests; water and diseases) may also be necessary.

Economics should be incorporated. Ecological farming considers the quality of production in terms of both the quality of the product and the quality of the production method. Such systems are encouraged by feedback from consumers and government legislation. Models have a key role to play in assessing the whole system costs and benefits. Such information is essential if ecological farmers are to receive realistic payments for protecting the environment. For instance, ecological farming may result in higher leaching of nitrates due to use of organic manures, but losses of carbon dioxide to the atmosphere may be reduced. By incorporating a full economic assessment, the net costs or benefits of ecological farming may be calculated.

A sociological assessment may be of value in assessing likely errors in the calculations. For instance, the farmer who cares more about livestock than crops will provide more accurate information for assessing losses of nitrogen from the animal houses than from organic manure applications to the crops.

The application of existing models at different scales is complicated by the shortage of data, changes in the processes that should be incorporated in the models, and computational logistics. The changes necessary when a particular model is applied at a different scale should be considered further.

Finally, detailed evaluation of models is essential. Models are usually evaluated, but the boundary conditions of the evaluations are not stated. The greatest sources of errors in the model should be identified, and the simulations of those aspects of the system improved as a priority. It seems likely that these sources of errors will NOT be directly related to the nutrient or water simulations, but instead be due to other parts of the system, such as pest, diseases and weeds.

17.2   Weeds, pests and diseases

Reporter: R.E.E. Jongschaap
Research Institute for Agrobiology and Soil Fertility (AB-DLO), Dept. Agrosystems Research,
The Netherlands

Ecological farming strategies for crop and soil health are executed in the total absence of any artificially produced or chemical product. Thus the problem of growth and development of weeds, pests and diseases is tackled in different ways than in conventional farming systems. Additional problems can be expected by the lay-out of the farming system, and the choice of crop rotations.

Crop rotations in ecological farming systems take place in a finite area assembled by the fields for crop growth and non-productive (but perhaps green) parts of the farm. This area with its soils can be seen as a continuous factor and a base for the development of all kinds of positive and negative factors for crop growth.

The environmental conditions outside the farm bounderies may influence the occurrence of weeds, pest and diseases, as transportation of weed seeds and agents of pests and diseases can cross farm bounderies easily. These transport processes can either be passive (wind, machinery, manure) or active migration.

The occurence of weeds, pest and diseases on a single field is dependent on former crop growth and infestations from outside the farm, from adjacent fields or non-productive areas and transportation within the farm by machinery and the spreading of manure.

17.2.1   Important issues

Considering the mechanisms in rotation cropping for ecological farming systems, the most important issues according to the discussion group are mentioned here.

Source of weeds, pests and diseases
Weeds, pests and diseases can be either related to the crop rotation (intra- and inter-field) or not (invasion from outside the farm system bounderies). Both groups are of great importance in ecological farming systems and need to be specified. The spreading of weeds, pest and diseases within the farm system bounderies (inter-field) is related to crop rotation strategies.

Mechanisms such as active migration or inactive migration by wind, machinery or the spreading of manure over the farm can serve as possible sources of weeds, pests and diseases.

Dynamics of weeds, pests and diseases inside a single field

Numerous species of weeds, pests and diseases exist in a particular ecological setting. Determination of important pathogens for certain cropping systems is needed. Population dynamics of these actors are of interest as the total quantity of antagonisms determines the degree of infestation of the crop. A clear description of mechanistic relations between population dynamics and environmental conditions such as weather and soil characteristics, but also the impact of management practices on population dynamics is considered essential.

Impact of weeds, pests and diseases on crop growth and development

The occurrence of weeds, pests and diseases in time or on crop development scale are of major importance for the degree of damage inflicted on crop growth and/or development. The impact of weeds, pests and diseases can be more or less severe in certain periods.

Positive and negative antagonisms in survival areas

In ecological farming systems, special areas are retained for the survival of positive factors for crop growth. Undoubtedly, negative factors will persevere as well. The growth and development of both species and their interaction is of importance for the inter-field spreading of both groups.

17.2.2 Issues (im)possible to address through modelling

Not all of the mentioned issues can be addressed easily through modelling. In the next few paragraphs a short explanation will be given of potential problem areas.

Source of weeds, pests and diseases

The existence of weeds, pests and diseases outside the farm sytem bounderies is not always known, and the possible invasion of these is even more difficult to grasp. In order to simulate these effects, a weeds, pests and diseases generator could provide some specimen, with which growth and development can be picked up at field level.

The enormous variety of weeds, pests and diseases for various cropping systems makes it difficult to tackle each one of them individually. Characteristic groups can be considered and focused on.

Dynamics of weeds, pests and diseases inside a single field

Population dynamics of weeds, pests and diseases are not expected to cause a lot of problems for dynamic simulation as long as clear descriptions of these dynamics exist. Some work is already done in the area of seed bank development. The spread of inocculum and aphids, and the residence time of, e.g., sclerotia could be handled like-wise.

Impact of weeds, pests and diseases on crop growth and development

Clear insight in the relationship between the occurence and infestation degree of weeds, pests and diseases, and its impact on crop growth and development is lacking. Once these relationships are determined they could be incorporated into simulation models.

17.2.3 Approach

A conceptual model to handle the impact of weeds, pests and diseases on crop rotation strategies could be constructed as follows:

- definition of cropping system by physical bounderies,
- simulation of crop growth for 2 or 3 fields simultaneously,
- simulation of 2 or 3 characteristic groups of weeds, pests and/or diseases, and
- inclusion of non-productive areas for interactions of positive and negative factors.

17.3 The current capability of simulating crop rotations and related issues

Reporter: H. Meinke
DPI/CSIRO, Agricultural Production Systems Research Unit, Australia

The current capability of simulating crop rotations and related issues were discussed in a group session. This section attempts to briefly summarise the discussion.

There was consensus among group members that the current modelling capability can address some important issues related to crop rotations, while other, equally important aspects, are completely lacking. To make dynamic simulation models useful tools at the farm level, they need to consider water and nutrient balances, in particular nitrogen (organic and inorganic) and phosphorous. Further, they need to handle crop growth and crop rotations, management effects (i.e. tillage), erosion and the fate of chemicals in the system. Most of these aspects can be covered through existing modelling capabilities. However, other factors are often not considered by dynamic simulation models (e.g. pest and disease dynamics as affected by crop rotation, carry-over effects, biodiversity, soil structure, weed dynamics and nutrient flows across different enterprises). Frequently such factors are pivotal when farm management decisions have to be made.

This raised the question whether it is desirable (i.e. productive) to add such a level of complexity to the existing dynamic simulation models. To answer this, it is important to clearly address the issue of scale in models and review successful model applications. Two scales need to be considered: (a) a temporal scale that ranges from single season issues up to problems exceeding the life time of individuals and (b) a spatial scale that ranges from point data / single paddock issues to global problems. Although it is self-evident that the choice of an appropriate model for a particular application depends largely on the scale at which the model is to be applied, the multitude of scale combinations can make model identification difficult. Figure 1 presents a few key examples of the types of agricultural issues where a simulation approach might contribute to better decision making. The boundaries of the three decision categories (crop / farm / policy) are a convenient but arbitrary way of categorising a continuum. Likewise, circles drawn around management issues to indicate their sphere of influence will vary strongly from situation to situation.

However, the diagram helps to approximately determine the relative positions of some management issues. It shows that the problems addressed by this workshop fall mainly into the

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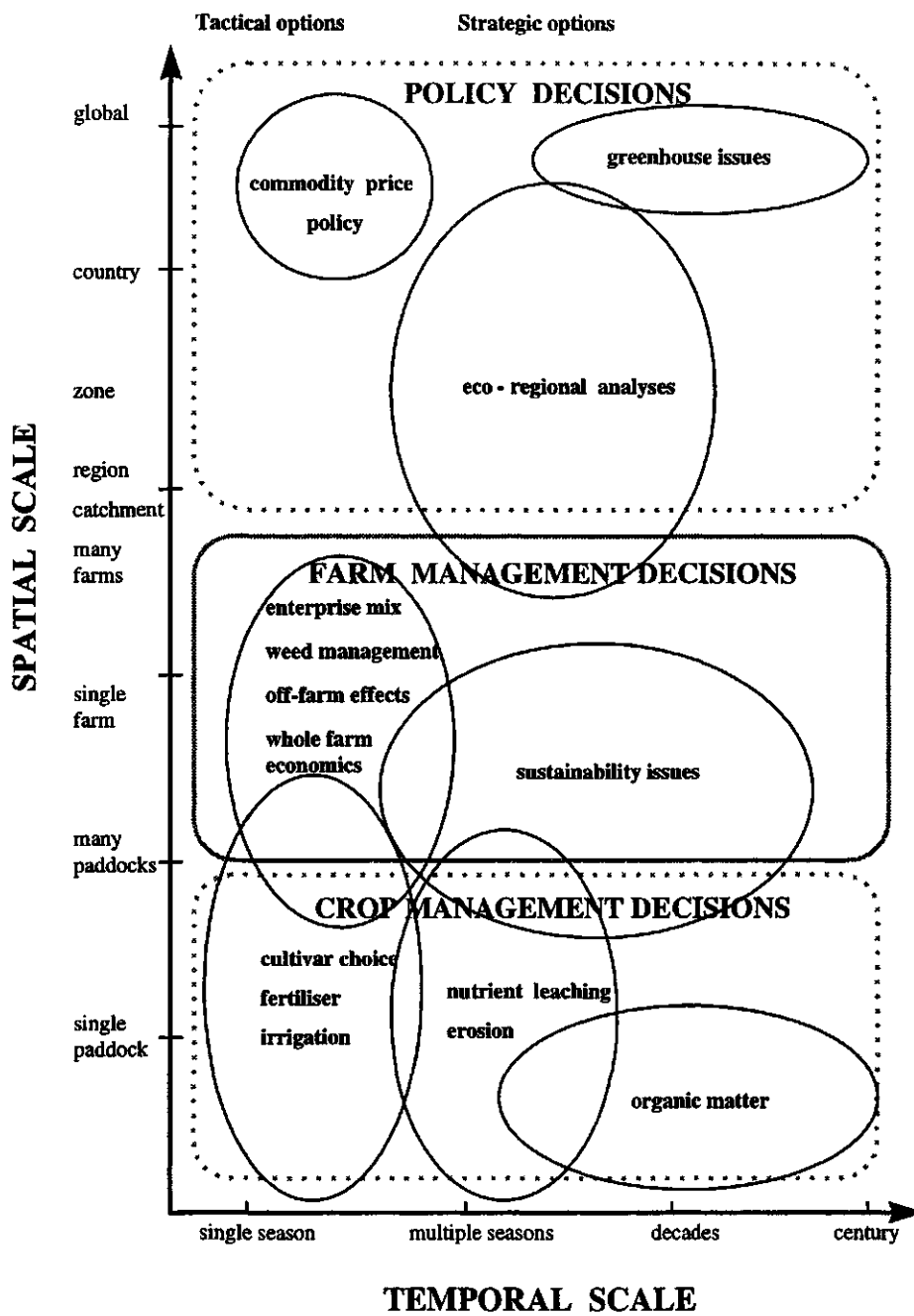
Figure 1   Schematic representation of some key management issues that could be addressed using a simulation approach and their relative position on a temporal and spatial scale. The boundaries of the three decision categories (crop / farm / policy) are a convenient but arbitrary way of categorising a continuum. Likewise, shape and size of circles drawn around management issues indicate their sphere of influence and will vary strongly from situation to situation.

intermediate category on the spatial scale and cover the low and medium range on the temporal scale. Investigating the diagram further, it becomes apparent that most of the successes in applying dynamic simulation models are either at the high (policy) or low (crop) end of the spatial scale. Rather than through dynamic models, farm management issues are often addressed by using tools such as linear programming or simple spreadsheet models.

An explanation for this is attempted in Figure 2 which shows schematically the successful application of dynamic models and the complexity of the agricultural system as a function of spatial scale.

At the single point / paddock level, the relative system's complexity is low and necessary input parameters to drive dynamic simulation models can be derived with reasonable accuracy. As the spatial scale increases, so does the number of input variables needed to apply dynamic models. Additionally, individual parameter variability and uncertainty also increases. The system's complexity, as measured by the number of input parameters needed and their associated uncertainty, reaches a maximum around the single farm scale. Increasing the spatial scale even further reduces complexity due to the "averaging effect" - e.g. field-to-field variations in soil type become less important as the spatial resolution decreases, as long as the key driving variables (mostly weather and climate) are captured well. It is no coincidence that the successful application of dynamic simulation models is inversely related to the system's complexity. After all, modellers are a sensible lot and know the limitations of their tools.

It seems unlikely that simply adding detail to existing crop simulation models will ever lead to major successes at the farm level. A more promising approach might to be to use the simulation capability to analyse individual farm enterprises. This increases our understanding of systems components and, when coupled with spreadsheet models, linear programming or rule based decision aids, might then lead to better and more integrated decision support tools that might deal with whole farm issues more effectively.
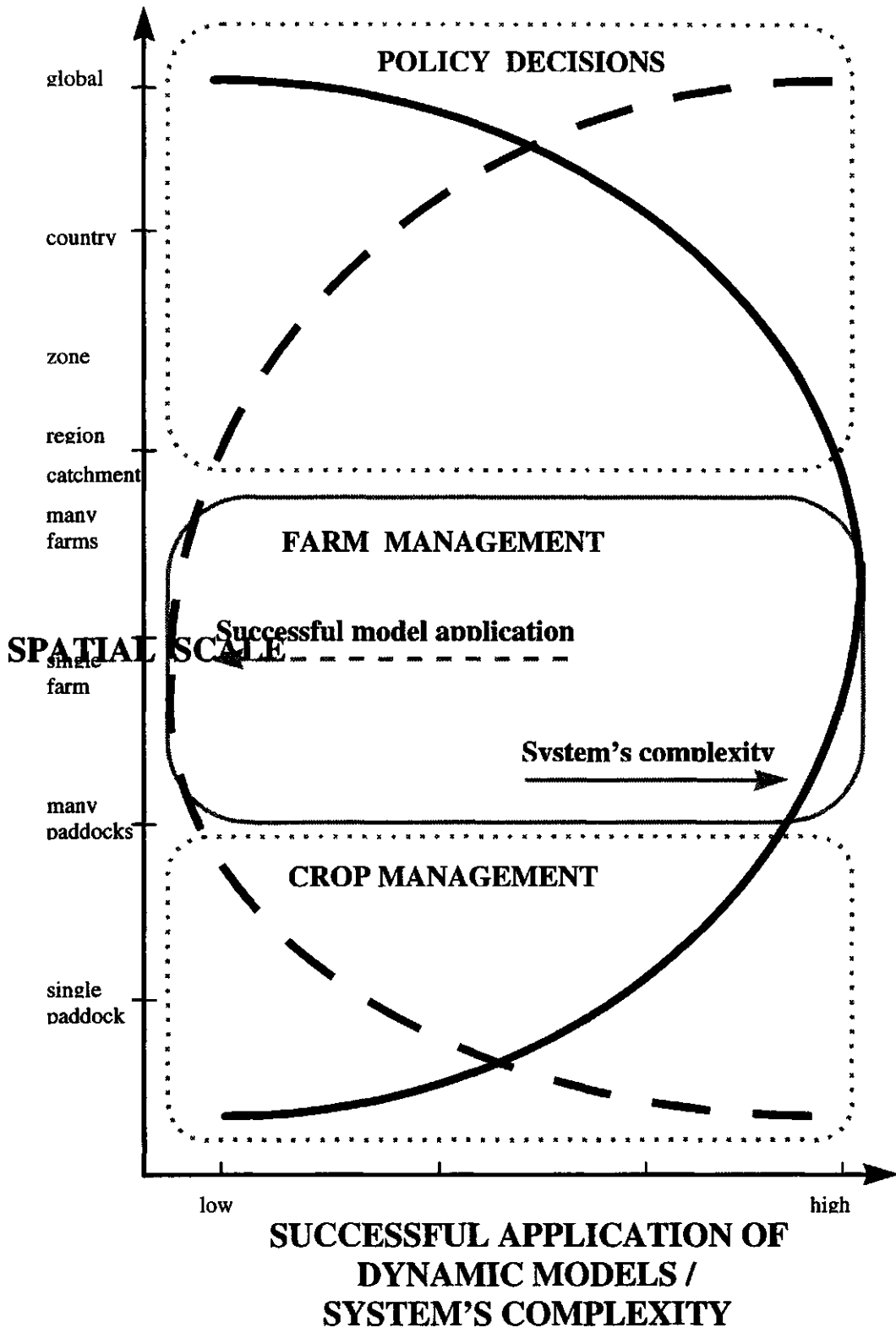
Figure 2   Successful application of dynamic simulation models and the system's level of complexity as a function of spatial scale.

17.4   Conclusions by working groups

Three working groups discussed aspects of the modelling of crop rotations: features and key processes already covered in the different models, crucial aspects of rotation models for decision support systems, and crucial aspects of models for research on crop rotations.

A review of the key features and processes is presented in Tables 1 and 2. For Table 1, it is important to note that while crop sequences are simulated in all models, few deal with parallel crops. In other words: all models can be used to handle questions about what happens to the soil when a series of crops 'passes', but few can handle farm-level limiting resources (such as labour). As a result, economic aspects are not really dealt with in these models. Participants recognised this as a shortcoming when model use was aimed at decision support. For Table 2, it is very clear that the history of rotation models is largely in soil and crop science, and little in crop protection. In fact, ways and extents by which pests, diseases and weeds can cause crop losses receive insufficient attention to deal realistically with crop rotations.

Table 1.   Features of the simulation models presented in the workshop (x: present; !: absent but really needed; *: being developed)

	APSIM	CropSyst	DAISY	DSSAT	EPIC / Almanac	NDICEA	ROTASK	SUNDIAL	WAVE
Crop sequence	x	x	x	x	x	x	x	x	
Parallel crops	x			!	x		!	!	
Economics	*			(x)	(x)				x
Optimisation	x						x	x	
Statistics (performance evaluation)	x						!	x	
Tracer								x	
Data base (evaluation experiments)	*							*	

Models that are to be used to support decision making on experimental or commercial farms need to be:
- robust, comprehensive (mechanistic) and flexible,
- simple and transparent.
Many do not yet meet these qualifications. One reason for needing simpler crop and soil models is that also important extensions are needed for several applications. These include:
- application of manure,
- feeding plans (for livestock farming),
- carry-over of weeds, pests and diseases between parallel crops,
- procedures to optimise cropping sequences,
- integration of decision rules.

It was also found that rotation models should allow running for long periods ('100 years') to evaluate development of soil organic matter. It is impossible to run dynamic weed and pest population models for such periods, because the properties of these organisms can adjust to new conditions, lessening the effects of measures to control them. All participants felt that lack of procedures to estimate the consequences of uncertainty in input parameters was limiting the applicability of the models.

With respect to models as tools in the research process of crop rotations, attention was asked for models in the process of upscaling information of single farms to 'the average farm in a region'. This is required when a model is found satisfactory for one (experimental) farm, and attemps are made to generalise its results. In explanatory models, much more understanding is required on soil fertility (soil structure, depth, biological activity and organic matter), on weed responses to nutrients in the short and the long term. These models should be able to accommodate spatial heterogeneity, as this is seen as an important modifier of the behaviour of the model. Benefits of 'precision agriculture' cannot be fully evaluated without dealing with heterogeneity in the farmed field.

Table 2. Processes covered by different simulation models

Process	APSIM	CropSyst	DAISY	DSSAT	EPIC	NDICEA	ROTASK	SUNDIAL	WAVE	Others Decible
Nutrients										
N										
mineral	x	x	x	x	x		x	x	x	x
organic										
1 pool						x			?	x
>= 2 pools	x	x	x		x	x	x	x		
microbiological			x					x		
P				(x)	x					
K										
Water										
cascading	x	x		x	x	x	x	x		x
finite difference	x	x	x	-						
subzero temperatures		x	x		x			x		
preferential flow	x	-	x	-	x					
Soil structure dynamics			x							(x)
Pests/weeds										
pests				x			x			x
weeds					x					
pesticide breakdown	x	x	(x)		x					
Crop simulation										
crop growth	x	x	x	x	x	x	x		x	x

Appendix I: Addresses participants

Addresses participants CAMASE/PE workshop "Rotation models for ecological farming" 15-19 April 1996

Dr. G. Bellocchi (Gianni)
Dipartimento di Agronomia e Gestione dell'Agroecosistema
via S. Michele degli Scalzi, 2
56124 Pisa
ITALY
Phone: +39.50.599111
Fax: +39.50.540633
E-mail: gianni@sssup1.sssup.it

Mr. M.S. Bernardes (Marcos)
Wageningen Agricultural University
Dept. Theoretical Production Ecology
P.O.Box 430
6700 AK Wageningen
THE NETHERLANDS
Phone: +31.317.475766
Fax: +31.317.484892
E-mail: doct30@rcl.wau.nl

Dr.Ing. H.W.G. Booltink (Harry)
Wageningen Agricultural University
Dept. Soil Science and Geology
P.O.Box 37
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.482422
Fax: +31.317.482419
E-mail: booltink@rcl.wau.nl

Ir. H.J. Bos (Bert)
Wageningen Agricultural University
Dept. of Agronomy
P.O.Box 341
6700 AH Wageningen
THE NETHERLANDS
Phone: +31.317.483040
Fax: +31.317.484575
E-mail: Bert.Bos@AKKER.AGRO.WAU.NL

Mr. J.F.F.P. Bos (Jules)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
Dept. GVK
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475...
Fax: +31.317.423110
E-mail: ..@ab.dlo.nl

Prof.dr. J. Bouma (Johan)
Wageningen Agricultural University
Dept. Soil Science and Geology
P.O.Box 37
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.484438
Fax: +31.317.482419

Dr. Ph. Debaeke (Philippe)
INRA, Centre de Recherches de Toulouse
Station d'Agronomie
B.P.27
31326 Castanet-Tolosan Cedex
FRANCE
Phone: +33.61.285016
Fax: +33.61.735537
E-mail: debaeke@toulouse.inra.fr

Dr. M. Donatelli (Marcello)
Istituto Sperimentale Agronomico - Sezione di Modena
Via le Caduti in Guerra, 134
41100 Modena
ITALY
Phone: +39.59.230454 /223853
Fax: +39.59.214957
E-mail: mdon@pianeta.it

Mr. T. Doré (Thierry)
Institut National de la Recherche Agronomique
Laboratoire d'Agronomie
16, rue Claude Bernard
75231 Paris Cedex 05
FRANCE
Phone: +33.1.44081683
Fax: +33.1.44081657
E-mail: dore@inapg.inra.fr

Ing. P. Droogers ()
Wageningen Agricultural University
Department of Soil Science and Geology
P.O.Box 37
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.484145/484410
Fax: +31.317.482419

Dr. C. Grashoff (Kees)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
Crop physiology and ecology
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475853
Fax: +31.317.423110
E-mail: grashoff@ab.dlo.nl

Ir. A.S.J. Habets (Jan)
Palenbergstraat 53
6415 RB Heerlen
THE NETHERLANDS
Phone: +31.45.5720173

Ir. M.J.D. Hack-ten Broeke (Mirjam)
DLO Winand Staring Centre (SC-DLO)
Dept. Systematic Land Information
P.O.Box 125
6700 AC Wageningen
THE NETHERLANDS
Phone: +31.317.474756
Fax: +31.317.424812
E-mail: hack@sc.dlo.nl

M.Sc. J.P.H. Hansen (Jens Peter)
Danish Institute of Animal Science
Research Centre Foulum
P.O.Box 39
DK 8830 Tjele
DENMARK
Phone: +45.89991388
Fax: +45.89991300
E-mail: jens=peter=hansen%kvaeg%husdyr1@sh1.foulum.min.dk

Ir. R.E.E. Jongschaap (Raymond)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
Dept. Agrosystems Research
P.O.Box 129
9750 AC Haren (Gr.)
THE NETHERLANDS
Phone: +31.50.5337314
Fax: +31.50.5337291
E-mail: r.e.e.jongschaap@ab.dlo.nl

Ir. D.W.G. van Kraalingen (Daan)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475949
Fax: +31.317.423110
E-mail: d.w.g.vankraalingen@ab.dlo.nl

Prof.dr. M.J. Kropff (Martin)
Wageningen Agricultural University
Dept. Theoretical Production Ecology
P.O.Box 430
6700 AK Wageningen
THE NETHERLANDS
Phone: +31.317.475858
Fax: +31.317.484892
E-mail: kropff@tpe.wau.nl

Dr.ir. P.A. Leffelaar (Peter)
Wageningen Agricultural University
Dept. Theoretical Production Ecology
P.O.Box 430
6700 AK Wageningen
THE NETHERLANDS
Phone: +31.317.483918 / 482141
Fax: +31.317.484892
E-mail: peter.leffelaar@staff.tpe.wau.nl

Mr. H. Meinke (Holger)
DPI/CSIRO
Agricultural Production Systems Research Unit
P.O.Box 102
Toowoomba
QLD 4350 AUSTRALIA
Phone: +61.76.314378
Fax: +61.76.332678
E-mail: holgerm@apsrusg.sth.dpi.qld.gov.au / meinkeh@tbacrm001.prose.dpi.qld.gov.au

Prof. Dr. N.E. Nielsen (Niels Erik)
The Royal Veterinary & Agricultural University
Dept. Agricultural Sciences
40 Thorvaldsenvej, DK-1871 Frederiksberg C
Copenhagen
DENMARK
Phone: +45.35.283383
Fax: +45.35.283460
E-mail: niels.erik.nielsen@agsci.kvl.dk

Ir. G.J.M. Oomen (Gerard)
Wageningen Agricultural University
Dept. Ecological Agriculture
Haarweg 333
6709 RZ Wageningen
THE NETHERLANDS
Phone: +31.317.484675 / 483522
Fax: +31.317.484995
E-mail: gerard.oomen@users.eco.wau.nl

Prof. Dr. F.W.T. Penning de Vries (Frits)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
Dept. Agrosystems Research
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475960
Fax: +31.317.423110
E-mail: pdvries@ab.dlo.nl

Ing. M.C. Plentinger (Marja)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
Dept. Agrosystems Research
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475961
Fax: +31.317.423110
E-mail: m.c.plentinger@ab.dlo.nl

Dr.ir. W.A.H. Rossing (Walter)
Wageningen Agricultural University
Dept. Theoretical Production Ecology
P.O.Box 430
6700 AK Wageningen
THE NETHERLANDS
Phone: +31.317.484766
Fax: +31.317.484892
E-mail: walter.rossing@staff.tpe.wau.nl

Dr. G. Russell (Graham)
The University of Edinburgh, School of Agriculture
Institute of Ecology & Resource Management
West Mains Road
Edinburgh EH9 3JG
SCOTLAND
Phone: +44.131.5354063
Fax: +44.131.667.2601
E-mail: graham.russell@ed.ac.uk

Ir. J.J. Schröder (Jaap)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475965
Fax: +31.317.423110
E-mail: schroder@ab.dlo.nl

Dr. J.U. Smith (Jo)
Rothamsted Experimental Station
IACR AFRC
Harpenden
Herts AL5 2JQ UNITED KINGDOM
Phone: +44.1582.763 133
Fax: +44.1582.760 981
E-mail: jo.smith@bbsrc.ac.uk

Dr. J.H.J. Spiertz (Huub)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
director AB-DLO
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475750/5751
Fax: +31.317.423110

Mr. H. Svendsen (Henrik)
The Royal Veterinary & Agricultural University
Dept. Agricultural Sciences
40 Thorvaldsenvej, DK-1871 Frederiksberg C
Copenhagen
DENMARK
Phone: +45.35.283383
Fax: +45.35.283460

Dr. P.K. Thornton (Philip)
International Fertilizer Development Center (IFDC)
P.O.Box 2040
Muscle Shoals
Alabama 35662 UNITED STATES
Phone: +1.205.381 6600
Fax: +1.205.381.7408
E-mail: p.thornton@cgnet.com

Dr. P.H. Vereijken (Pieter)
Research Institute for Agrobiology and Soil Fertility (AB-DLO)
P.O.Box 14
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.475952
Fax: +31.317.423110

Ms.c. J. Verhagen (Jan)
Wageningen Agricultural University
Dept. of Soil Science and Geology
P.O.Box 37
6700 AA Wageningen
THE NETHERLANDS
Phone: +31.317.482422
Fax: +31.317.482419

Ms. L. Willocquet (Laetitia)
Wageningen Agricultural University (temporarily address)
Dept. Theoretical Production Ecology
P.O.Box 430
6700 AK Wageningen
THE NETHERLANDS
Fax: +31.317.484892

Appendix II: The CAMASE project

The CAMASE project

CAMASE: a Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment. CAMASE is financially supported by the European Community Specific Programme for Research, Technological Development and Demonstration in the Field of Agriculture and Agro-industry, including Fisheries (Concerted Action AIR 3-CT93-1721).

Background of CAMASE

Development and testing of quantitative methods for research on agricultural systems and the environment requires dynamic simulation models of crops, animals and agricultural systems.

In the models, current knowledge and insights from different disciplines (including crop physiology, agrometeorology, soil science, agronomy, phytopathology) are integrated in a consistent, quantitative and process-oriented way. These models are used to test alternative hypotheses, analyse current production techniques, and predict the effect of changes in environmental conditions, crop management practices and new design of plant-type. Through associated experimental research, the models continue to be refined and expanded.

Decision support systems aid in strategic and tactical decision-making at the farm level. They allow users to combine technical knowledge contained in assessment and economic analysis of farming enterprises. To determine such optimal strategies and tactics by experimentation would be practically impossible.

Planning land use and rural development requires evaluation of a large number of alternatives for agricultural and non-agricultural land use, with their consequences for the corresponding physical, chemical, biological and socio-economic inputs and outputs. Multiple goal linear programming is such an aid for policy decisions.

Aims of CAMASE

Quantitative methods for research on crop and animal production, agricultural systems and the environment have developed slowly and unevenly in different organisations and different countries over the past to decades. Several models that emerged have now reached a level where they can be applied to some practical problems of agricultural production and environmental problems. Lack of standardisation and documentation is now an important bottle-neck for further application. Currently, many groups in Europe are active in crop modelling. Sharing information among them must be stimulated.

Research on methods and models at the level of agricultural production systems (multiple crops in time, space, arable farming and animal husbandry, involvement of sociological and economic factors at a farm of regional scale) is still at an early stage. Effective linkages with other sciences are to be forged, particularly with economics sciences, and additional techniques are to be employed and/or developed. A concerted action to share more intensively results of ongoing research will accelerate progress for setting research priorities and exploring options for policy decisions.

CAMASE is a concerted action of five European groups that are leading in the area of production systems research. The core groups for CAMASE are:
- the Copenhagen research team (Denmark): leading Drs. Niels Erik Nielsen, Sören Hansen, Henry E. Jensen (The Royal Veterinary and Agricultural University); strength in modelling nitrogen losses and crop growth and production.
- the Toulouse research team (France): leading Dr. Philippe Debaeke and Mr. Maurice Cabelguenne (Institut National de la Recherche Agronomique); strength in modelling crop production systems.
- the Cordoba research team (Spain), leading Dr. Francisco Villalobos (Universidad de Cordoba, Dept. Agronomy) and Dr. Luciano Mateos (CSIC, Instituto de Agricultura Sostenible); strength in modelling irrigation systems.
- the Edinburgh research team (U.K.): leading Prof.Dr. Barry Dent and Dr. Graham Russell (University of Edinburgh); strength in farm household modelling and expert systems.
- the Wageningen research teams (The Netherlands), coordinated by Dr. Peter Leffelaar (Wageningen Agricultural University, Dept. of Theoretical Production Ecology), Dr. Aad van Wijk (DLO Winand Staring Centre for Integrated Land, Soil and Water Research), Prof.Dr. Frits Penning de Vries and Ing. M.C. Plentinger (DLO Research Institute for Agrobiology and Soil Fertility); strengths in modelling crop and soil processes, dynamics of pests and weeds, crop production systems, methodology, training.

The objectives of CAMASE are to advance quantitative research on agricultural systems and their environment in the EU-countries, by improving systems research in participating institutes through exchange and standardization of concepts, approaches, knowledge, computer programmes and data. Specific objectives are:
- to produce a newsletter,
- to produce a register of models, and
- to stimulate research on production systems.

CAMASE started in November 1993, and was funded for three years. Marja Plentinger and Frits Penning de Vries coordinate the project.

Further information can be obtained from:
F.W.T. Penning de Vries
DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO)
P.O. Box 14
6700 AA Wageningen
The Netherlands
Phone: (+)31.317.475960
Fax: (+)31.317.423110
E-mail: CAMASE@ab.dlo.nl