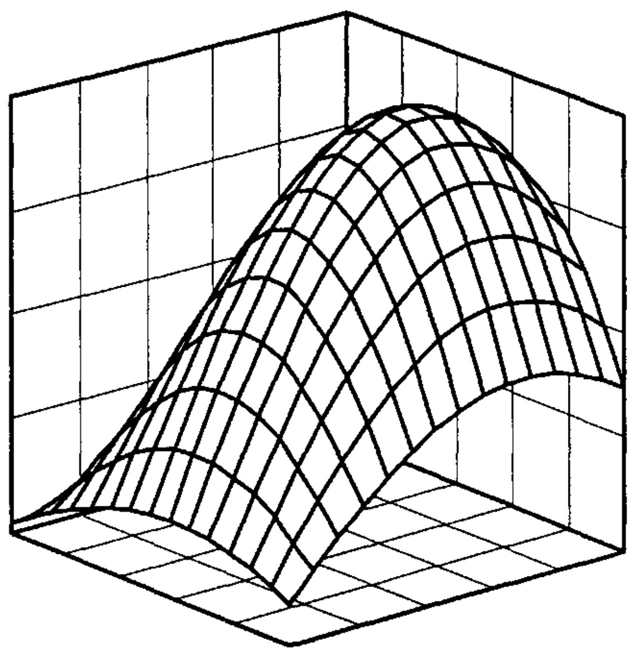
Active Methodology

Proceedings of a seminar series 1997/1998



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A. Stein, M.K. van Ittersum & G.H.J. de Koning (Eds)

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Preface

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Methodology is crucial to derive valid conclusions in research. When a research school as the C.T. de Wit Research School for Production Ecology starts to do new research, it has to put active attention into the use and development of methodology. For production ecology, the challenges were to find a sound methodology at the edge between competitive production in an environmental friendly way. More practical, the methodology should emphasize how to formulate new research hypotheses, how to develop and validate models and how to collect and organize data. Further, a methodology was needed for a sound quantitative statistical approach, and to optimally use information systems. In particular in cross- and inter-disciplinary research new and active ways for methodology and methodology development had to be found: the methodology is hence active and often determines instead of follows the research.

In this volume that follows the series of PE-seminars 'Active Methodology', we emphasize the role of methodology for sound research on production ecology. The series is a sequel to previous series 'Data in Action' (1996) and 'Models in Action' (1997). Again we aim at a volume which extends beyond the disciplinary context. We focus on four unifying concepts in which various elements of production ecology can be identified: precision farming, integrated past and nutrient management, information systems, and decision support systems. Traditional disciplines like agronomy, soil science, statistics, information science and others are still clearly visible at the background. The volume reflects the contributions of oral presentations. The speakers are therefore underlined and their names appear as headers above the papers, even if they are not the principal authors.

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References:

Stein A, Penning de Vries FWT and Schotman P (1996) Models in Action. Proceedings of seminar series 1995/96. Quantitative Approaches in Systems Analysis No. 6, DLO Research Institute for Agrobiology and Soil Fertility and C.T. de Wit Graduate School for Production Ecology, June 1996

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Table of Contents

1. The various perspectives for precision farming at different scales

A world-wide view for production ecology

In this chapter precision farming will be addressed as it is currently applied or applicable. The American, the European and the African perspective will be sketched. The basic questions are primarily the same: spatial and temporal variability has to be addressed in an efficient and cost-effective way. The scales, however, are totally different: in the US large scales prevail, Europe takes an intermediate position and in Africa the scale at which management decisions are taken is usually rather small. In the US and Europe availability of resources is not a primary issue, whereas in the African context resources are scarce. In all situations precise and timely application of resources is crucial, both from agronomical, economic and environmental perspective.

1.1 Multi-scale study of nutrient stocks and flows in sub-saharan Africa

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Studies on nutrient stocks, nutrient flows and integrated nutrient management (INM) in sub-Saharan Africa revealed that, on average, soil fertility is declining. Although this may sound and actually is alarming for some regions and farming systems, examples of good and sustainable INM (at plot and niche level) are many, and scattered all over the continent. Rather than painting a gloomy picture of (average) soil fertility decline, researchers should rather zero in on the positive examples and try to understand the driving forces behind them. Nonetheless, INM is rapidly gaining attention on the continent, as the poorly endowed regions (West Africa in particular) already have very low nutrient stocks and, as a consequence, little left to lose.

1. Introduction

Over the past two decades, attention in soil fertility research has moved away from agricultural production *per se* towards sustainable production, both in the temperate zones as well as in the tropics. During the 1970s and before, the research focus was largely on the increased use and efficiency of mineral fertilisers with, in the tropics, FAO's Fertiliser Trials as the most conspicuous exponents. Empirical point models were developed to predict crop yields as a function of soil chemical properties and fertiliser application, often relating to just one nutrient, and not valid for any area apart from the site where the experiment was located. Presently, however, the role of different spatial and temporal scales in agricultural and ecological sciences has received wider acceptance (Fresco and Kroonenberg, 1992). Soil fertility is no longer treated as a mere stock of nutrients, derived from a rather haphazardly taken "representative profile", and portrayed by a number of routinely determined soil tests. Advanced soil sampling strategies and spatial interpolation techniques have become available which enable us to portray soil fertility patterns three-dimensionally and at every spatial scale.

Soil fertility has also been given a much stronger temporal dimension. Next to nutrient stocks, we now address positive and negative nutrient flows, which cause the nutrient stocks at t_1 to be different from the nutrient stocks at t_0. It is no longer soil fertility *per se*, but rather imbalances between nutrient inputs and outputs over a period of time, and their very different environmental consequences that hit the headlines. Examples are the emissions of nutrients to the atmosphere and to aquifers in the high-input, West-European agriculture, potassium and micronutrient mining in high N-input, irrigated Asian agriculture, and mining of most nutrients in low-input, rainfed African agriculture. Studies at macro- and meso-level indicated that nutrient depletion was severe in Southern Mali (Van der Pol, 1992), Kenya's Kisii District (Smaling et al., 1993), West Africa as a whole (Pieri, 1989), and sub-saharan Africa as a whole

(Stoorvogel et al., 1993). At farm and plot level, however, Prudencio (1993), Brouwer et al. (1993), Bouma et al. (1995) and De Steenhuijsen Piters (1995) recently showed how risk-averse farmers in West Africa cherish and exploit spatial variation in soil fertility. In other words, every spatial scale has its own heterogeneity, and where agronomists and soil scientists traditionally preferred only to address macro variability, the concern of African farmers generally does not go beyond the boundary of their holding.

It is clear that traditional rate-response research must be replaced by a more holistic approach of integrated nutrient management (INM), conceptualised here as the judicious manipulation of nutrient stocks and nutrient flows, i.e., the different nutrient inputs and outputs that keep these stocks change constantly (Smaling and Fresco, 1993). This chapter provides an overview of current knowledge on nutrient stocks and flows and their management in sub-saharan Africa.

2. Nutrient stocks

Although spatial variation has been studied for long, the emphasis up to the 1980s has largely been on systematic variation (landforms, soil-forming factors) rather than "random" (but in fact partly spatially correlated variation) and on macro-variability (visible on air-photos and satellite images) rather than micro-variability (Wilding and Drees, 1978). At present, however, different sampling designs for geo-statistical interpolation are available that can provide quantitative predictions of soil test values at unsampled sites for systems of different levels of aggregation (Burrough, 1989; Oliver and Webster, 1991; Stein, 1991; Bregt, 1992). Moormann and Kang (1978) stated that "agronomic research, if it is to be realistic and applicable to the practice of farming in tropical areas, has to give more attention to the interplay between micro-variability of soil and related factors and the response of crops under different weather conditions". Prudencio (1993) for Burkina Faso, Brouwer et al. (1993) for Niger, De Steenhuijsen Piters (1995) for Cameroon, and Carter and Murwira (1995) for Zimbabwe recently showed not only how right Moormann and Kang were, but also how deliberate risk-averse farmers cherish and exploit spatial variation.

2.1 Macro-level

The mineral nutrient stocks of West Africa's vast interior plains and plateau's are low because, in a geological time horizon, the area is "old". It has undergone various erosion cycles, but lacked the volcanic rejuvenation that is typical of East Africa's Rift Valley area. As a consequence, soils are often strongly weathered and leached, and often overlie ironstone hardpans (*Fr: cuirasses*), which even feature at the surface in places. Table 1 shows a summary of work published in Windmeijer and Andriesse (1993), who collated nutrient stocks of 86 soils across the West-African agro-ecological zones. Differences between zones are very marked. High rainfall in the Equatorial Forest Zone enhanced weathering and leaching of bases, leading to low-pH soils. On the other hand, high biomass production causes the area to possess relatively favourable soil organic carbon and N and P contents, as compared to the drier zones.

Table 1. Nutrient stocks and other fertility indicators of granitic soils in different agro-ecological zones in West Africa (Source: Windmeijer and Andriesse, 1993).

Agro-ecological zone	Depth (cm)	pH-H_2O	Organic C (g/kg)	Total N (g/kg)	Total P (mg/kg)	Cation Exchange Capacity (mmol/kg)	Base Saturation (%)
Equatorial	0-20	5.3	24.5	1.60	628	88	21
Forest Zone	20-50	5.1	15.4	1.03	644	86	16
Guinea	0-20	5.7	11.7	1.39	392	63	60
Savanna Zone	20-50	5.5	6.8	0.79	390	56	42
Sudan	0-20	6.8	3.3	0.49	287	93	93
Savanna Zone	20-50	7.1	4.3	0.61	285	87	90

In Kenya, fertiliser recommendations used to be of the blanket type, i.e. one bag of whatever fertiliser available per acre. These days recommendations have improved much and are specific for zones of similar agro-ecology and soil classification order, but still based on 1:100,000 or smaller scale soil and climate maps (Smaling and Van de Weg, 1990). Data for the 1990 long rainy season in the Fertiliser User Recommendation Project (FURP) show that differences between the response of maize to N and P for a Nitisol, Vertisol and Arenosol are, however, already quite striking at this scale (Table 2). Maize on the red, volcanic Nitisol responded vigorously to P. Maize on the black Vertisol, however, responded only to N, whereas the crop grown on the sandy soil responded only to the combination of N and P.

2.2 Micro-level

Nutrient stocks of individual plots within farms and village territories can differ considerably. Reasons range from differences in soil texture, land use/fallow history to microclimatic differences. Farmers, notably those in the drier AEZs, tend to cherish micro-variability.

Table 2. Yields and NPK uptake of maize on three Kenyan soils as a function of soil type and fertiliser treatment (long rainy season, 1990).

Soil	Treatment	Yield (ton/ha)	Nutrient uptake (kg/ha)		
			N	P	K
Nitisol	$N_0 P_0$	2.1	42	5	30
(red,	$N_{50} P_0$	2.3	50	6	36
clayey)	$N_0 P_{22}$	4.9	79	12	58
Vertisol	$N_0 P_0$	4.5	63	24	95
(black,	$N_{50} P_0$	6.3	109	35	126
clayey)	$N_0 P_{22}$	4.7	70	23	106
Arenosol	$N_0 P_0$	2.5	38	7	42
(brown,	$N_{50} P_0$	2.2	45	7	47
sandy)	$N_0 P_{22}$	2.3	38	11	68
	$N_{50} P_{22}$	3.7	66	16	77

Heterogeneity at plot level is often seen as an asset by those who are resource-poor, risk-averse, and after food security rather than bumper harvests. An example is the use of (abandoned) termite mounds, representing spots of relatively high fertility. Another striking example of farm-level variation is in the ring management systems in semi-arid West Africa (Prudencio, 1993; Sédogo, 1993). Of the three subsystems shown in Table 3, the fields around the homestead receive substantial amounts of nutrients from animal manure and household wastes. Hence, soil productivity remains at a relatively high level.

Table 3 Nutrient stocks of different subsystems in a typical Upland farm in the Sudan-Savanna Zone (after Sédogo, 1993).

	PH-H_2O	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Exch. K ($mmol\ kg^{-1}$)
Homestead fields	6.7-8.3	11-22	0.9-1.8	20-220	4- 24
Village fields	5.7-7.0	5-10	0.5-0.9	13- 16	4- 11
Bush fields	5.7-6.2	2-5	0.2-0.5	5- 16	0.6-1

Table 4 shows spatial variation of some FURP experimental sites in Kenya, which were researcher-managed, but located on farms. Prior to experimentation, each 0.8 ha rectilinear experimental site was divided into four quarters of equal size, from each of which a composite soil sample was taken (mixture of six sample points). To study local practices, similar samples were taken from eight neighbouring farmers' fields. Unlike the experimental site, plot history was not taken into consideration here. From Table 4, one can derive that (i) spatial variation was particularly great for available P (modified Olsen) and, to a lesser extent, organic carbon and exchangeable potassium, (ii) for the farmers' fields, with different land use and management histories, deviation from the mean was considerably greater than for the experimental sites, and (iii) differences between average (modified Olsen) P values for experimental sites and farmers' fields were great and inconsistent.

3. Nutrient flows

3.1 Subcontinental scale

In the late 1980s, FAO replaced its fertiliser-driven philosophy by an INM approach, which amongst others triggered the debate on high versus low external input farming. In this context, FAO commissioned a study on nutrient balances in agricultural systems in SSA, with the aim to create awareness on not just the state but also the dynamics of soil fertility in the subcontinent. The nutrient balance study for 38 SSA countries (Stoorvogel and Smaling, 1990; Stoorvogel et al., 1993) involved the partitioning of the continent into rainfed cultivated, irrigated and fallow land, for which FAO provided hectarages and yields. Rainfed land was further divided on basis of the length of growing period, and the Soil Map of Africa, at a scale of 1 : 5 000 000 (FAO/UNESCO, 1977). The basic spatial unit was the land use system, for which 5 nutrient inputs and 5 nutrient

Table 4. Spatial variation of soil and temperature data for fertiliser trials in Kenya (after Smaling and Braun, 1996)[‡]

District	Site[†]	Properties of unfertilised soil (0-20 cm layer)						Temperature	Soil Classification
		y (%)	rganic C (g/kg)	Total N (g/kg)	mod. P-Olsen (mg/kg)	Exch.K (mmol/kg)	pH-H_2O		
Busia	a1	65	14.7 ± 1.7	2.1 ± 0.2	2.1 ± 0.3	8.2 ± 1.6	6.5 ± 0.6	22.4	ferralo-chromic Acrisol
	a2		14.0 ± 2.4	1.8 ± 0.3	3.9 ± 0.9	7.7 ± 1.7	5.5 ± 0.8		
Kwale	b1	10	5.1 ± 0.1	0.5 ± 0.1	4.8 ±1.4	2.7 ± 0.5	6.7 ± 0.2	25.4	orthic Acrisol
	b2		5.4 ± 1.8	0.5 ± 0.1	9.1 ± 5.0	3.6 ± 1.8	6.5 ± 0.3		
Kilifi	c1	6	4.4 ± 0.8	2.0 ± 0.3	3.6 ± 1.5	3.2 ± 0.4	7.5 ± 0.4	24.9	cambic Arenosol
	c2		5.4 ± 1.3	0.7 ± 0.2	2.9 ± 1.3	4.6 ± 1.5	7.8 ± 0.1		
Kakamega	d1	56	17.3 ± 0.7	2.3 ± 0.2	21.0 ± 15.2	5.2 ± 0.6	6.2 ± 0.3	20.3	nito-humic Ferrralsol
	d2		13.6 ± 2.2	1.8 ± 0.2	6.2 ± 3.4	5.2 ± 3.3	7.2 ± 0.3		
Lamu	c1	28	8.9 ± 0.3	0.7 ± 0.0	28.0 ± 1.4	5.9 ± 0.4	7.0 ± 0.4	26.1	chromic Luvisol
	c2		10.9 ± 2.6	0.9 ± 0.2	50.4 ± 33.0	5.7 ± 1.8	7.0 ± 0.4		
Nyandarua	f1	38	33.9 ± 1.6	4.1 ± 0.3	44.3 ± 14.5	8.0 ± 4.8	7.3 ± 0.2	11.0	nito-chromic Luvisol
	f2		34.9 ± 4.0	4.6 ± 0.5	22.4 ± 8.7	8.1 ± 2.3	6.5 ± 0.4		
Kisii 1	g1	54	30.1 ± 3.3	2.7 ± 0.8	3.7 ± 1.2	11.8 ± 3.6	6.2 ± 0.5	20.1	mollic Nitisol
	g2		30.4 ± 3.9	2.6 ± 0.8	4.5 ± 1.9	13.9 ± 7.4	5.9 ± 0.6		
Kisii 2	h1	43	24.1 ± 0.7	3.0 ± 0.3	6.4 ± 1.0	6.3 ± 0.6	5.2 ± 0.1	19.2	humic Nitisol
	h2		23.8 ± 1.5	2.7 ± 0.1	5.6 ± 1.3	7.9 ± 2.8	5.5 ± 0.5		

‡ sampled in 1985, 1986 or 1987
† the fertiliser trial site is indicated by 1, i.e. a1, b1, etc. and the farmers' field by 2, i.e. a2, b2, etc.
mean ambient temperature during growing period

outputs were calculated or estimated (Table 5). For this exercise, many country statistics, maps, reports and literature were scrutinised. A detailed account of the information gathered and interpreted is annexed to the main document (Stoorvogel and Smaling, 1990).

Table 5. Nutrient inputs and outputs calculated in continental and district studies.

- Nutrient inputs	
IN 1	Mineral fertilisers
IN 2	Organic inputs (manure, feeds, waste)
IN 3	Atmospheric deposition in rain and dust
IN 4	Biological nitrogen fixation
IN 5	Sedimentation by irrigation and natural flooding
- Nutrient outputs	
OUT 1	Harvested products
OUT 2	Crop residue removal
OUT 3	Solute leaching
OUT 4	Gaseous losses
OUT 5	Runoff and erosion

The amount of data available to calculate the five inputs (*IN 1-5*) and the five outputs (*OUT 1-5*; Table 5) varied largely between and within countries. As a consequence, much available detail had to be dropped and discrete ratings had to be developed for variables that normally represent a continuum. Also, average values were used for properties that showed wide ranges, such as crop nutrient contents. Quantitative information on atmospheric deposition, leaching and gaseous losses was very scarce. Instead of going by educated guesses, transfer functions were built (Bouma and Van Lanen, 1987; Wagenet et al., 1991). These are regression equations, in which the nutrient flow is explained by parameters that are easy to measure. For leaching, for example, the equations represent the best fit for a series of point data on leaching which were accompanied by such building blocks as rainfall, soil fertility class, and fertiliser and manure use. Soil fertility classes were merely rated low (1), moderate (2), high (3), on the basis of soil taxonomy (sub)orders. Mollisols, for example, were ranked 3, whereas Psamments were ranked 1. For erosion, quantitative information on soil loss was amply available, but its translation into nutrient losses was hardly ever studied. Moreover, the studies were often done at miniplot level, the results of which cannot be linearly scaled up to the watershed.

The results can be portrayed per land use system, per agro-ecological zone, per country and also per nutrient for the entire continent. The average N, P and K balances for SSA were -22, -2.5 and -15 kg ha^{-1} yr^{-1}. Nutrients exported in harvested products, in runoff, and eroding sediments were high and caused the balances to be negative. The implication of the figure is that on average, soils in SSA have to supply 22 kg N ha^{-1} each year to balance the ledger, leading to a decline of the N stocks. The mountainous and densely populated countries in East and Southern Africa have the highest depletion rates. This is caused by high values of nutrients in harvested products and erosion, and also by the relatively high inherent fertility of the soils.

3.2 Subnational scale

The Subcontinental scale and uneven data availability implicitly brought about a considerable amount of generalisation, simplification and aggregation. As a follow-up, similar studies were done at subnational scales, i.e., in the 2200 km^2 sub-humid Kisii District in Kenya (Smaling et al., 1993) and in the 12230 km^2 semi-arid region of Southern Mali (Van der Pol, 1992). Primary data were available on climate, soils and land use, mineral fertilisers and farmyard manure, crop yields and residues and their nutrient content, and to a lesser extent on erosion. Kisii soils are predominantly well drained, very deep and rich in nutrients (Nitisols, Phaeozems, Luvisols; FAO/UNESCO, 1988), with the exception of P (see also Nitisol in Table 2). Mean annual rainfall ranges between 1350 and 2050 mm. Major food crops in the district are maize (*Zea mays*) and beans (*Phaseolus vulgaris*), often grown in association. Major cash crops include tea (*Camellia sinensis*), coffee (*Coffea arabica*) and pyrethrum (*Chrysanthemum cinerariaefolium*). Most farm holdings in addition comprise small improved pastures for livestock. Less than 5% of the land is left fallow during a year. In Southern Mali, millet (*Eleusine coracana*; 20%), sorghum (*Sorghum vulgare*; 17%) and cotton (*Gossipyum hirsitum*; 15%) are the major crops of the region, which is mainly made up of Ultisols. Smaller portions of maize and groundnuts (*Arachis hypogea*) are grown. An approximate 29% of the arable land is left fallow in a year.

Calculations revealed that nutrient depletion in the Kisii District was 112 kg N, 2.5 kg P, and 70 kg K ha^{-1} yr^{-1}, whereas in Southern Mali, values of 25 kg N, 0 kg P, and 20 kg K ha^{-1} yr^{-1} were found. In Kisii, removal of nutrients in harvested product was the strongest contributor to the negative balance, followed by water erosion and, for N, leaching. Use of mineral fertilisers and manure in Mali is much less than in Kenya, but crop production is also lower, reflected in lower values of the output of above-ground crop parts (*OUT 1*). Because of lower rainfall and flatter topography, losses due to leaching, denitrification and erosion were also smaller in Mali.

At the crop level, conclusions drawn from the Kisii study revealed that pyrethrum is the big nutrient miner (-147 kg N, -24 kg P, -96 kg K ha^{-1} yr^{-1}), whereas tea has the most favourable nutrient balance (-67 kg N, +6 kg P, -30 kg K ha^{-1} yr^{-1}). Pyrethrum receives little mineral or organic fertiliser, has a high nutrient content per unit harvested product and protects the surface poorly against erosion. Tea, however, receives substantial amounts of mineral fertiliser and offers good protection to the topsoil. In Southern Mali, millet is the big nutrient miner (-47 kg N, -3 kg P, -37 kg K ha^{-1}), whereas cotton has the most favourable nutrient balance (-21 kg N, +7 kg P, -9 kg K ha^{-1}). Millet receives virtually no mineral or organic fertiliser, and has a high nutrient content per unit harvested product as compared to sorghum. Cotton, however, receives substantial amounts of fertiliser.

3.3 Farm and field scale

The Subcontinental and subnational studies revealed that N and P are, on average, moderately to strongly mined. In the Kisii District, soils are still rich enough to produce high agricultural output. But for how long? And how to tell a farmer not to go for high crop yields when he can obtain them? Should the farmer apply N fertiliser when the N balance is as negative as -112 kg ha^{-1}? These questions have been posed by many interested parties after publication of the Subcontinental and subnational studies, and triggered the development of a proposal for a nutrient monitoring programme (NUTMON) at farm scale (Smaling and Fresco, 1993; Smaling et al., 1996).

In 1995, a Rockefeller Foundation-sponsored NUTMON pilot project started in 26 farms in three agro-ecologically and ethnically different districts in Kenya (Kisii, Kakamega, Embu). The initial phase included interpretation of satellite images and identification of more or less homogenous land use zones. In each zone, rural appraisals were then held which led to the identification of characteristic farm types for each land use zone, and the subsequent selection of pilot farms. For each farm, an initial inventory was done on household composition, farm and field architecture, agricultural activities and nutrient stocks. This was then followed by monthly monitoring of farm management activities related to nutrient flows and related economic factors (De Jager et al., 1998a). For this purpose, the nutrient balance of Table 5 had to be extended (Table 6). Particularly the inclusion of 'internal flows' *(FL 1-5)* is important here, as they are a reflection of farmers' efforts to recycle nutrients within the farm. At the higher spatial scales, these flows are treated as a black box. As much of the produce is eaten on the farm, losses of nutrients through urine and faeces also needed to be recognised separately (*OUT 6*).

Results so far indicate an average negative N balance of -71 kg ha^{-1} for the three districts (Van den Bosch et al., 1998). It appeared that input through manure derived from communal lands where animals graze during daytime is quite an important nutrient input at the farm level. These communal lands are virtually absent in densely-populated Kisii, explaining the lower N balance value. One major methodological constraint was that a number of flows was actually measured, whereas others such as leaching and gaseous losses were estimated. Yet, they influence the value of the balance very much.

Relations have also been established between economic performance indicators, the socio-economic environment, farm management practices and the nutrient balances. It was found that net farm income shows no relation with the nutrient balance (De Jager et al., 1998b).

Table 6. Nutrient inputs and outputs and internal flows at farm level.

- Nutrient inputs	
IN 1	Mineral fertilisers
IN 2	Organic inputs, subdivided into:
IN 2a	concentrates for livestock and fish
IN 2b	other organic feeds for livestock and fish
IN 2c	urban and agro-industrial waste
IN 2d	manure obtained from outside the farm
IN 2e	manure from farm livestock grazing outside the farm during part of the day
IN 2f	food for the farm family obtained from outside the farm
IN 3	Atmospheric deposition in rain and dust
IN 4	Biological nitrogen fixation in leguminous species (including free-living bacteria and mycorrhiza)
IN 5	Sedimentation as a result of (i) irrigation, (ii) natural flooding or (iii) partial re-sedimentation of soil materials eroded from upper slopes
IN 6	Subsoil exploitation by trees and other perennial crops
- Nutrient outputs	
OUT 1	Harvested crops, meat, milk, and fish, leaving the farm
OUT 2	Crop residues and manure leaving the farm
OUT 3	Leaching below the root zone
OUT 4	Gaseous losses (including de-nitrification, ammonia volatilisation, and losses as a result of burning)
OUT 5	Runoff and erosion
OUT 6	Human faeces ending up in deep pit latrines
- Internal flows	
FL 1	Crop residues fed to tethered farm animals or applied to certain plots
FL 2	Biomass from plots under pasture and fallow eaten by roaming farm animals
FL 3	Animal manure from within the farm applied to certain plots
FL 4	Crops, milk, meat and fish obtained from the farm, eaten by the farm family
FL 5	Food remnants and farmyard manure applied to certain plots

A high degree of market orientation, however, correlated well and negatively with negative N and K balance. The market-oriented farms located in the densely populated areas and characterised by intensive crop and livestock activities import nutrients through fertilisers and animal feeds, but insufficient to compensate the outflow through marketed products, leaching and erosion. Subsistence farms in the less populated areas (drier parts of Kakamega and Embu) have a relatively successful strategy to concentrate nutrients through grazing of cattle in communal lands. Off-farm income also proved very important for households to survive. Without this source of income, 54% of the farms in the sample would be below what the World Bank considers to be the poverty line. The replacement costs of mined nutrients amounted up to 35% of the average net farm income.

3.4 Comparing results at different scales

The Kisii District study yielded nutrient loss values of -112 kg N and -3 kg P ha^{-1} yr^{-1}. In the Subcontinental study, the extrapolated nutrient balance for Kisii District would have been -75 kg N and -5 kg P ha^{-1} yr^{-1}. In the latter study, all soils would have been in fertility class 2 (moderate), characterised by 1 g N and 0.2 g P kg^{-1} soil. In reality however, the soils have higher N contents, which could be adequately covered in the district study. On crops, pyrethrum turned out to be the major nutrient miner in the district study, but it was not included in the supranational study due to lack of importance at that scale. Hence, the differences between the results of the two studies are differences in resolution.

In the NUTMON pilot project, farm-determined nutrient balances for Kisii were -102 kg

N, -2 kg P and -34 kg K ha^{-1} yr^{-1}, which compare well with the subnational estimates (Van den Bosch et al., 1998). Variation around the mean, however, was considerable. Nutrient stocks used in the subnational study were average values for land units on a 1:100,000 scale soil map for Kisii District (Smaling et al., 1993). The six farms in Kisii District had total N concentrations between 1.5 and 4.6 g kg^{-1} soil and total P concentrations of 0.9 to 1.3 g kg^{-1} soil.

4. Managing stocks and flows

When Van Keulen and Breman (1990) discussed overexploitation of agricultural land in West Africa, they concluded that increased productivity of the land, both in animal husbandry and in arable farming will require at least inputs of P from outside the system. They argued that recycling of crop residues, manure and household waste, regeneration of degraded rangeland, anti-erosion measures, etc., may at best prevent further deterioration of the land resource, but are insufficient to improve soil fertility. Against this background, it becomes useful to distinguish between nutrient management technologies that:

- **save** nutrients from being lost from the system, such as erosion control, restitution of residues, recycling of household waste and animal manure
- **add** nutrients to the system, such as the application of mineral fertilisers and amendments, concentrates for livestock, organic inputs from outside the farm, and N-fixation in wetland rice and by leguminous species.

As the technical options to restore soil fertility eventually have to be adopted by the farm household, the farm will be taken as the focal system level. To obtain high and sustainable agricultural production in sub-saharan Africa, internal flows of organic materials (*FL 1-5*), and inputs that are free-of-charge (*IN 3,4,6*) should be maximised, non-useful losses (*OUT 2-6*) should be minimised, whereas the use of external inputs should be optimised with respect to capital and labour (*IN 1,2*). INM-based technologies that are most relevant to sub-saharan Africa and their major characteristics have been listed in Table 7.

5. Conclusions

The nutrient balance results obtained for the Subcontinental study paint a rather gloomy picture. Soil fertility is really at stake. However, it is risky to draw conclusions from low-resolution, aggregated studies. Generally, the largest unit for which soil nutrient balances can be quantified is the field, whereas larger spatial scales can only be dealt with through generalisation and aggregations (Stoorvogel and Smaling, 1998). For nutrient balances, aggregation is a very delicate issue, as the balance itself is made up of at least ten parameters (Table 5 and 6) which are in some cases outcomes of regression analysis on again more basic parameters. Also, a negative balance not necessarily means that crop production declines instantly as soils may have a large buffering stock of nutrients, sufficient to keep production going for many years (Smaling et al., 1996).

Based on this, we suggest that the Subcontinental results should be treated as general awareness raisers, i.e., that soil fertility decline in SSA is a threat and needs attention, just like nutrient accumulation in parts of Europe needs attention. At the national and subnational level, results are meant to alert national and subnational policy makers and other stakeholders. Research and development efforts can be better targeted, but again the results do not reveal much on differences in farmers' management and strategies. This only becomes visible during

Table 7. Some characteristics of INM-based components of farming systems in sub-saharan Africa.

Mineral (high-reactivity) fertilisers

- increasing IN 1 and OUT 1, reducing OUT 3-5
- applying the right type and amount of mineral fertilisers at the right time to the right crop, based on knowledge of inherent soil fertility and pH, may considerably raise production per unit area
- if combined with nutrient-saving techniques such as manuring and erosion control, mineral fertilisers are used more efficiently

Mineral soil amendments

- increasing IN 1 and OUT 1
- rock phosphates is a slow-release, but a cheap and perfectly sound alternative to mineral fertilisers, having a lasting residual effect, and not acidifying the soil
- rock phosphates perform best in combination with organic inputs, when applied to leguminous species, in wetland cultivation, and in slightly acid conditions
- lime and dolomites redress acidity, and add Ca and Mg to the soil

Organic inputs

- increasing IN 2c,d,e, reducing OUT 2, OUT 6, maximising FL 1-3 and FL 5
- organic inputs can be from within the farm (saving nutrients) or from without (adding nutrients)
- wide array of organic materials to be applied/recycled; farmers' perceptions on importance and type of organic inputs differ from place to place

Improved crop-live stock systems

- increasing IN 2a,b (and OUT 4), reducing OUT 3, OUT 5, maximising FL 3, FL 4
- cross-bred dairy cattle in East Africa is kept in zero-grazing units and fed farm-grown fodder grasses, and purchased concentrates; a large percentage of the nutrients involved is recycled as manure
- if fodder grasses are planted on contour bunds, water erosion can be strongly reduced; similarly, the absence of free range saves nutrients as anti-erosion structures are not damaged, whereas manure does not reach the land in patches
- kraaling of cattle in West Africa on cropland is more nutrient-efficient and labour-efficient than stalling

Improved crop-tree systems (trees, rotations, green manures, improved fallows)

- increasing IN 4, IN 6, reducing OUT 2, OUT 3, OUT 5
- trees potentially provide building poles, fuelwood, fodder, fruits, shade, etc.; species such as *Calliandra, Sesbania, Leucaena* (all leguminous species) and *Grevillea* are highly valued in Kenya
- legume-cereal rotations generally outyield intercropping systems
- interactions between tree-crop-grass system components are still poorly quantified (presently one of the key research areas of the International Centre for Research on Agro-forestry).

Soil conservation

- increasing IN 4, reducing OUT 5
- government policies and extension service have to play (and have played) a crucial role, as there is no direct socio-economic incentive for the farmer
- few attempts have been made to turn data on annual soil loss per hectare into nutrient and productivity loss; physical data on land degradation are of little use to decision-makers unless transformed into units comparable with the cost of soil conservation.

Combined technologies

- Combination of mineral fertilisers, rock phosphates and organic inputs: because nutrients from organic inputs are released slowly, one can minimise losses (OUT 3-5) by synchronising the release of nutrients with momentary crop nutrient demand (Myers et al., 1994). Synchronisation tools are the manipulation of rate, quality, timing and placement of organic inputs. When organic inputs are not sufficient, mineral fertiliser nutrients can complement nutrients released from organic sources, thus increasing fertiliser use efficiency

farm-level monitoring activities, as carried out during the NUTMON pilot (Van den Bosch et al., 1998), and projects that are currently underway under the NUTMON aegis. Similar work going on in several African countries will soon be available in a Special Issue of *Agriculture, Ecosystems, Environment.* This will include cases from Kenya (Shepherd and Soule, 1998), Mali (Defoer et al., 1998), Ethiopia (Elias et al., 1998), and Tanzania (Baijukya and De Steenhuijsen Piters, 1998). In the recent past, different authors (e.g., Prudencio, 1993; Brouwer et al., 1993; Carter and Murwira, 1995; De Steenhuijsen Piters, 1995) have shown how risk-averse farmers in West and Southern Africa cherish and exploit spatial variation in soil fertility. Analogies in the field of soil and water conservation are also plentiful (Tiffen et al., 1994; Rey et al., 1996), and clearly signal a warning to those who tend to only rely on averages and smoothness of trends. Apparently, survival strategies of SSA farmers are underestimated (Scoones and Toulmin, 1998). Research should therefore be geared towards those farmers who are innovative in the field of INM, and who can play a guiding role in getting their colleagues to invest in INM.

References

Baijukya FP and De Steenhuijsen Piters CB (1998) Nutrient balances and their consequences in the banana-based land use systems of Bukoba District, North-west Tanzania. In: E.M.A. Smaling (Ed). Nutrient Flows and Balances in sub-saharan African Agro-ecosystems. Agric. Ecosystems Envir. (Special Issue)

Bouma J and van Lanen HAJ (1987) Transfer functions and threshold values: from soil characteristics to land qualities. In: KJ Beek, PA Burrough and DE McCormack (Eds), Quantified Land Evaluation Procedures. ITC Publication 6, pp106-110

Bouma et al. (1995) Eco-regional approaches for sustainable land use food production. Proceedings of a symposium on eco-regional approaches in agricultural research. ISNAR.

Bregt AK (1992) Processing of soil survey data. PhD Thesis Wageningen Agricultural University The Netherlands.

Brouwer J, Fussell LK and Herrmann L (1993) Soil and crop growth micro-variability in the West African semi-arid tropics: a possible risk-reducing factor for subsistence farmers. Agric. Ecosystems Envir. 45:229-238

Burrough PA (1989) Matching spatial databases and quantitative models in land resource assessment. Soil Use Manag. 5: 3-8

Carter SE and Murwira HK (1995) Spatial variability in soil fertility management and crop response in Mutoko Communal Area Zimbabwe. Ambio 24:77-84

Defoer T, De Groote H, Hilhorst T, Kanté S and Budelman A (1998) Participatory action research and quantitative analysis for nutrient management in Southern Mali: a fruitful marriage. In: E.M.A. Smaling (Ed) Nutrient Flows and Balances in sub-saharan African Agro-ecosystems. Agric. Ecosystems Envir. (Special Issue)

De Jager A, Nandwa SM and Okoth PF (1998a) Monitoring nutrient flows and economic performance in African farming systems (NUTMON). I Concepts and methodologies. In: EMA Smaling (Ed) Nutrient Flows and Balances in sub-saharan African Agro-ecosystems Agric. Ecosystems Envir. (Special Issue)

De Jager A, Karachi I, Matter FM, Odendo M and Wanyama JM (1998b) Monitoring nutrient flows and economic performance in African farming systems (NUTMON). IV Linking farm economic performance and nutrient balances in three districts in Kenya. In: EMA Smaling (Ed) Nutrient Flows and Balances in sub-saharan African Agro-ecosystems. Agric. Ecosystems Envir. (Special Issue)

De Steenhuijsen Piters CB (1995) Diversity of fields and farmers: explaining yield variations in northern Cameroon. PhD. thesis Wageningen Agricultural University

Elias E, Morse S and Belshaw DGR (1998) Nitrogen and phosphorus balances of Kindo Koisha farms in southern Ethiopia. In: EMA Smaling (Ed) Nutrient Flows and Balances in Sub-Saharan African Agro-ecosystems. Agric. Ecosystems Envir. (Special Issue)

FAO/UNESCO (1977) FAO/Unesco soil map of the world 1: 5 000 000. Vol VI Africa. UNESCO Paris

FAO/UNESCO (1988) FAO-Unesco Soil map of the world: revised legend. World Soil Resources Report 60 FAO Rome

Fresco LO and Kroonenberg SB (1992) Time and spatial scales in ecological sustainability.

Land Use Policy 9: 155-168
Moormann FR and Kang BT (1978) In: M. Drosdoff et al. (Eds) Diversity of Soils in the Tropics. ASA Special Publication Number 34. American Society of Agronomy Madison WI
Myers RJK, Palm CA, Cuevas E, Gunatilleke IUN and Brossard M (1994) In: Woomer, PL and MJ Swift (Eds.). The biological management of tropical soil fertility. Wiley & Sons Chichester
Oliver MA and Webster R (1991) How geo-statistics can help you. Soil Use Manage. 7: 206-217
Pieri C (1989) Fertilité des terres de savanes. Ministère de la Coopération et CIRAD-IRAT Montpellier France
Prudencio CY (1993) Ring management of soils and crops in the West African semi-arid tropics: The case of the mossi farming system in Burkina Faso. Agric. Ecosystems Envir. 47: 237-264
Rey C, Scoones I and Toulmin C (1996) Sustaining the soil. Indigenous soil and water conservation in Africa. Earthscan Publications Ltd London
Scoones I and Toulmin C (1998) Soil nutrient balances: what use for policy? In: EMA Smaling (Ed.). Nutrient Flows and Balances in Sub-Saharan African Agro-ecosystems Agric. Ecosystems Envir. (Special Issue)
Sédogo PM (1993) Evolution des sols ferrugineux lessivés sous culture: Incidence des modes de gestion sur la fertilité. PhD Thesis University of Abidjan Cote d'Ivoire
Shepherd KD and Soule MJ (1998) Soil fertility management in West Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. In: EMA Smaling (Ed) Nutrient Flows and Balances in Sub-Saharan African Agro-ecosystems. Agric. Ecosystems Envir. (Special Issue)
Smaling EMA and Fresco LO (1993) A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). Geoderma 60:235-256
Smaling EMA and Van de Weg RF (1990) Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. Agric Ecosystems Envir 31:263-274
Smaling EMA, Stoorvogel JJ and Windmeijer PN (1993) Calculating soil nutrient balances in Africa at different scales. II. District scale. Fert. Res. 35:237-250
Smaling EMA and Braun AR (1996) Soil fertility research in sub-Saharan Africa: new dimensions, new challenges. Commun. Soil Sci Plant Anal. 27:365-386
Smaling EMA, Fresco LO and De Jager A (1996). Classifying, monitoring and improving soil nutrient stocks and flows in African agriculture. Ambio 25: 492-496
Stein A (1991) Spatial interpolation. PhD. Thesis, Wageningen Agricultural University, The Netherlands
Stoorvogel JJ and Smaling EMA (1990) Assessment of soil nutrient depletion in sub-Saharan Africa, 1983-2000. Report 28 DLO Winand Staring Centre for Integrated Land Soil and Water Research (SC-DLO) Wageningen The Netherlands
Stoorvogel JJ, Smaling EMA and Janssen BH (1993) Calculating soil nutrient balances at different scale. I. Supra-national scale Fert. Res. 35:227-235
Stoorvogel JJ and Smaling EMA (1998) Research on soil fertility decline in tropical environments: Integration of spatial scales. Nutrient Cycling in Agro-Ecosystems (in press)
Swift MJ, Seward PD, Frost PGH, Qureshi JN and Muchena FN (1994) Long-term experiments in Africa: developing a database for sustainable land use under global change. In: FA Leigh and AE Johnston (Eds) Long-term experiments in agricultural and ecological sciences, pp 229-251
Tiffen M, Mortimore M and Gichuki F (1994) More people, less erosion. Environmental Recovery in Kenya. John Wiley & Sons New York US

Van den Bosch H, Gitari JN, Ogaro VN, Maobe S and Vlaming J (1998) Monitoring nutrient flows and economic performance in African farming systems (NUTMON). III Monitoring nutrient flows and balances in three districts in Kenya. In: EMA Smaling (Ed) Nutrient Flows and Balances in Sub-Saharan African Agro-ecosystems. Agric. Ecosystems Envir. (Special Issue)

Van der Pol F (1992) Soil Mining: An Unseen Contributor to Farm Income in Sothern Mali. Bulletin 325, Royal Tropical Institute (KIT), Amsterdam The Netherlands

Van Keulen H and Breman H (1990) Agricultural development in the West African Sahelian region: a cure against land hunger? Agric. Ecosystems Envir. 32: 177-197

Wagenet RJ, Bouma J and Grossman GB (1991) Minimum data sets for use of soil survey information in soil interpretive models. In: MJ Mausbach and LP Wilding (Eds) Spatial variabilities of soils and landforms. SSSA Special Publication Number 28. Madison, Wisconsin

Wilding, L.P. and L.R. Drees, 1978. Spatial variability: A pedologist's viewpoint. In: M. Drosdoff et al. (Eds.) Diversity of soils in the tropics. ASA Special Publication Number 34. American Society of Agronomy, Madison, WI.

Windmeijer PN and Andriesse W (1993) Inland valleys in West Africa: An Agro-Ecological Characterization of Rice-Growing Environments. Publication 52. International Institute for Land Reclamation and Improvement (ILRI) Wageningen The Netherlands

1.2 Precision farming for large farms: The role of Measurements and equipment

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Precision farming, more accurately spatially variable crop production is practised on large farms with sophisticated equipment and techniques. The research and commercialisation of these equipment and techniques is generally described from both historical and contemporary perspectives with an emphasis on field mapping and variable crop input application. Some technical considerations are identified.

1. Introduction

It has long been recognised that crops and soils are not uniform within a given field. Astute farmers have always responded to such variability by taking appropriate actions. But the large acreage's and high level of mechanisation of modern, western crop production make such actions less frequent than they should be. At the same time, the larger fields and groves on such farms make inherent variability greater within any of those larger fields or groves. For over a dozen years, there have been technical methods to utilise modern electronics to respond to field variability. These methods go by many names, often a two-word combination. The first may be such terms as spatially variable, GPS-based, prescription, soil-specific, site-specific, or precision. The second might be crop production, agriculture, or farming. It seems that the correct term should probably be spatially variable crop production as that is more accurate and descriptive than precision farming, the most popular term.

Whatever the technology area is termed, the concept is similar. Variations occur in crop or soil properties within a field. These variations are noted, and often mapped. There then may or may not be some management action taken as a consequence of the spatial variability within the field. A description and taxonomy of some of the types of responses to the variability are included in Schueller (1992). Five types are identified as:

1. Homogeneous
2. Automatic
3. Temporally Separate
4. Multivariate
5. Historical

Homogeneous is not responding to the spatial variability and treating the field as a uniform entity. It is the default system of most contemporary crop production. Multivariate and Historical are enhancements of the Temporally Separate and a discussion of them is beyond the scope of this manuscript. Both types involve measurement, accumulation, and use of greater amounts of data.

Automation of field equipment to respond to spatial variation of crops and soils has a long history. The self-levelling hillside combine responded to topographic variations. The famous Ferguson system varied tractor three-point hitch height to maintain a relatively constant load on the tractor in varying soil draft conditions while plowing or performing other tillage operations. But notice the philosophy. The automation is machinery-centred in that it counters difficulties the machinery is having in separating the grain under varying yields or providing enough power for tough spots. Another example is the sprayer controller which varies boom pressure in response to changing forward travel speeds. When advocates of spatially variable crop production refer to Automatic control, however, they are referring to something that is agronomy-centred. For example, herbicide application to the soil may be controlled with input from an organic matter sensor. Or anhydrous ammonia side dressing may be guided by real-time sensing of nitrate levels. Another example would be a planter who varies planting depth in response to soil moisture. In these situations the machine is responding to the agronomic needs, rather than its own deficiencies.

The automatic response to spatial variability is being widely researched and marketed. In fact, a real-time, simple, reliable, accurate nitrate sensor is the most-desired goal of sensor research in the U.S.A. Corn Belt. Such a sensor would reduce crop production costs and nitrate pollution by allowing the optimum amount of additional nitrogen fertiliser to be applied. Development of sensors which are reliable and accurate in the rough and heterogeneous agricultural conditions is difficult, but is being widely researched.

Most discussions of spatially variable crop production or precision farming however deal with temporally separate control. One or more quantities such as crop yield or soil nutrient levels are measured and mapped. At a later time, some cropping operation is controlled based upon the maps or their derivatives. Operations in temporally separate spatially variable crop production will therefore be discussed here.

2. Mapping programs

Generation of maps of crop or soil properties is the first and most important step in spatially variable crop production. These maps allow spatial variability to be understood and provide the basis for spatially variable control of current or subsequent crop production. Mapping operations can be classified into:

1. Remote Sensing
2. Field Operations
3. Manual

Based upon how the information used to generate the maps is gathered.
Remote Sensing measures the visible or non-visible optical properties of a field or groups of fields. The most-known procedure is to take images from satellites such as LANDSAT or SPOT. These images, if properly ground-truthed, may allow mapping of crop, pest, or soil properties within a field. The images may be gathered from a wide variety of platforms, including satellites, aeroplanes, remotely piloted vehicles (RPVs), or even bucket trucks. Different devices including sensors, film cameras, digital cameras, and video recorders may gather them. Gathered images must then be manipulated to correct for errors, such as geometric or chromatic distortion. Finally a useful map is generated, assuming that point measurements have been taken in the field to ground-truth (verify) the accuracy and calibration of the measurement. Remote sensing has existed for many years and is used for such large-scale tasks as predicting the crop production for large regions. Many attribute the lack of similar commercial success in documenting within-field variabilities to below-needed resolutions and slowness in information transfer to the farmers. New one-meter satellites and Internet delivery may make remote sensing a commercially successful part of spatially variable crop production.

Measurements may also be taken during normal field operations. The most common one is measurement of yield during harvesting. Measuring soil properties during tillage or planting is another example. Since a field operation is already being performed, the costs involved in the measurements are reduced. Unfortunately, this requires that measurements for mapping be completed under the constraints of the other operation. Usually this implies that the operations are performed at specific times and that mapping measurement activities cannot adversely affect time-critical field operations.

Manual measurements may be taken by farm workers or hired service providers specifically to gather information. Manual mapping measurements can be taken at the particular time and location to provide the most accurate and useful information. The most common measurement of this type is taking of a soil sample. Another is scouting of pests. Unfortunately, time and financial cost of such activities is often problematic. So the number of measurements which can be economically justified is limited. Mapping then demands interpolation, which can have accuracy problems given the characteristics of soil variabilities.

2.1 Grain Yield Mapping

One of the areas of greatest interest in machinery-centred automatic controls for agricultural equipment was the automatic control of grain harvester travel speed. Schueller et al. (1983) and van Loo (1977) are examples. The speed of the harvester varies so that a harvester encounters a constant flow-rate of material despite spatial variation of yield within the field being harvested. This is desirable due to the highly non-linear (exponential) relationship between flow-rate and threshing and separation losses (e.g., Huisman, 1977) within the harvester. The control of the harvester is rather straightforward. The greater difficulty is to accurately measure the flow. So flow-rate sensors have been widely researched.
These same flow-rate sensors can be used to generate yield maps, although there is a difference in that the material floweret most affecting harvesting efficiency is typically the material-other-than-grain (MOG) while yield mapping requires the flow-rate of just the grain. Grain flow-rate and MOG flow-rate tend to be correlated, but not totally. But if the flow-rate is divided by the harvester travel speed and multiplied by the effective harvesting width, the yield per unit of area is determined. Harvesting width is usually an approximately fixed number and width sensors or harvester path post-processing are under development. Therefore, the easy measurement of harvester travel speed makes mapping easy once the grain flow-rate is accurately measured.

The most popular method of measuring flow-rate is to direct the stream of clean grain on its way from the separating mechanism to the grain tank against some sort of target or plate. The force of the grain hitting the plate at a fixed velocity is then proportional to the mass of the grain. The force is then measured. This is the basis of the CaseIH and John Deere sensors, as well as popular after-market sensors, such as Ag-Leader and Micro-Trak.

The flow-rate may also be measured on a volumetric basis. One such method is to measure the amount of time a light beam is intercepted by grain on the clean grain elevator. Another volumetric method is to measure the speed of a paddle wheel of fixed displacement in the grain stream (Searcy et al., 1989).

Tests (and theory) have indicated that the most accurate method is to pass the grain between a gamma radiation source and a radiation detector. The attenuation of the radiation is proportional to the mass of grain.

There are various other methods to measure the grain flow-rate. Electromagnetic methods are useful if the effects of moisture can be removed.

2.2 *Other Crop Yield Maps*

Yield mapping for other crops has occurred later than for grains and soybeans. The greatest research effort in the U.S.A. appears to be in cotton. The impact force method has been less successful. Other methods include light interruption and measuring changes in the weight of the basket. The light interruption method is used on the two sensors commercially marketed in the U.S.A.

Potato yields have been measured with load cells on the harvester. Sugar beet and sugar cane yield has similarly been measured. Peanut combine yield mapping has also been demonstrated. In most of these particular systems the mass flow-rate of the separated harvested material is measured on some conveyor chain by measuring the weight of the travelling loaded chain over some length. Alternatively, the change rate of the weight of the storage tank or bin is measured. The difficulty with the latter approach is that a small change in a large value must be accurately measured. Both systems require good sensor signal processing to avoid the effects of the harvester moving on rough surfaces.

Crops, which are harvested in discrete, rather than continuous, quantities, can also be mapped. Recording the locations of such items as hay bales or full citrus bins does this. This is a simple way to generate maps in which the density of dots or spots on a map indicates yield. Greater accuracy measures the mass of the item (e.g. Whitney et al. 1998) or the mass accumulation rate (e.g. Wild 1998).

2.3 *Pest and Crop Maps*

Locations and relative levels of pests can also be mapped. In fallow fields or young crops, presence of weeds can be easily detected by presence of green vegetation. In more mature crops, they can only be detected by more sophisticated means, such as vision or sensor systems which discriminate on the basis of plant physical characteristics or colour.

Other pests, as well as nutritional or water problems, can generally only be detected by observing health or growth of the crop plants. This observation may occur by operation of sensors during other field operations, by remote sensing measurement of light reflectance characteristics, or by manual samples. Since many potential causes exist for health or growth problems, significant management intervention is necessary for cause determination and calibration.

2.4 *Soil Maps*

Soil maps are available for agricultural land in many countries. These however, were generally made for purposes other than spatially variable crop production. Accordingly, scale, accuracy, and usefulness may be limited. Maps of such quantities as nutrient levels, moisture, topography, soil type, and texture have also been made.

A common simple type of mapping applies an GPS-equipped all-terrain vehicle (ATV) to circumnavigate the boundary and thereby generates a map of the boundary of the field. But the most common spatially variable soil map is the map of soil characteristics (nutrient, pH, cation exchange capacity, organic matter, etc.) based upon individual soil tests. It is now common to extract soil cores with a hydraulic or electromechanical device mounted on an ATV or pickup truck. Human interaction is however, required to drive to each site and to bag the samples. Due to costs for taking samples and processing them, interpolation, including geo-statistical methods (kriging) or inverse distance weighting, is often used in map generation.

2.5 *Needed Technical Capabilities*

No matter what type of mapping is being done, the crucial element seems to be measuring of the quantity to be mapped. Accurate, reliable sensors are needed to convert the physical or biological quantity into some sort of electronic data value. The sensor reading needs to be predictably related to the quantity being measured without being affected by other quantities or environmental conditions. The dynamic response, or speed, of the sensors is also important. Slowly reacting sensors will tend to smooth the data and will result in averaging of the dynamic data. Slow sensor data must also be treated properly in mapping to insure proper registration.

Mapping also requires accurate locators to unequivocally establish the geographical location of the quantities being measured. There are several methods such as dead reckoning and radio wave trilateralation to establish location in a field. But the dominant method in spatially variable crop production is the use of the Global Positioning System (GPS), more correctly differential GPS (DGPS) because GPS without differential correction has insufficient accuracy for most agricultural mapping.

Finally, there needs to be some sort of computer system to record and store both the data from the sensor measurements and the location data. Theoretically, these two types of data could be stored on different computers and merged when mapping. But usually merging occurs during data gathering and the measured quantity data is immediately given location attributes. In some cases the locations attributed are modified later, especially if the differential corrections are made in post-processing.

2.6 *Use of Maps*

The use of soil or crop maps can be categorised into:

1. Information acquisition
2. Strategic decisions
3. Tactical spatially-variable control

Information Acquisition provides information on the soil or crop variability to the farm operator. It alerts him to the variations, which are in the fields, and allows him to better understand the spatiality of his farm.

Perhaps the greatest benefit from mapping at the lowest cost will be from the strategic decisions the farm manager is able to make. The farm manager is able to change the field boundaries so that the optimum crops were planted in the optimum locations. Or mapping may show that a portion of a field should have artificial drainage installed. Yield mapping has led to significant additional drainage being constructed in existing fields. The first yield map of Searcy et al. (1989) demonstrated yield loss due to machinery traffic compaction and that machinery traffic should be routed around the field. Mapping provides the information necessary to evaluate problems and potential opportunities due to management changes.

Tactical spatially variable control is the map-based temporally separate control, which to most people exemplifies precision agriculture. It according is dealt with in the next section.

3. Control programs

Maps document spatial variability within fields. Field operations are often controlled to mitigate or take advantage of the variability. These may attempt to respond to the variability in soils, crops, or pests.

The most common response has been to control fertiliser application. Fertility levels and yield goals vary within fields. Usually based upon maps generated from interpolation of soil tests, fertilisers are often spread in a spatially variable manner. Commercial equipment to perform this task has been available for over a dozen years (Lullen, 1985; Elliott, 1987) based upon the Ortlip (1986) patent. Variability in soil organic matter has been similarly used to control application rates of herbicides, which are sensitive to organic matter (Gaultney, et al., 1988). Soil moisture conditions may be used to control irrigation or planting depth or population. Of course, soil type and topography maps may also be used to control fertiliser application, pesticide application, irrigation, or planting depending upon what makes the most agronomic sense.

Maps of crop yield, size, or colour can be similarly useful. For example, remote-sensing maps of crop stress can be used to guide spatially variable interventions, if the cause of the stress can be determined. Spatially variable operations such as patch spraying, variable irrigation, or variable nitrogen side dressing can be guided with such information.

Pest infestation maps can be used to guide application. Patch sprayers use such maps. Herbicides can be added at needed locations while applying fertilisers. There are many questions as to strategy. Will spraying boundary areas contain a pest? Will maintaining a small population in untreated field portions delay the development of pesticide resistance? More research is needed to develop both the strategic and tactical strategies for all these operations.

3.1 Needed Technical Capabilities

Control of field operations in a spatially variable manner, such as controlling fertilisation, pesticide application, irrigation, tillage, or planting, is essentially the reverse of the mapping operations. A map in a computer is used to control the actuation of some piece of field equipment.

The field equipment will need the following items:

1. Control computer
2. Locator
3. Actuator

The control computer will co-ordinate the field operation. It has a map of desired activity as a function of geographic location. It receives the equipment's current location from the Locator and decides what to do based upon the map in its memory or data storage. The control computer then issues a command to the actuator.

Dynamic response is very important. Otherwise, delays from information transfer and actuator and equipment dynamics will result in a control action being performed long after it was desired. For example, good fertiliser applicators mix and transport fertiliser not based upon the current location of the applicator, but rather upon the predicted location of the applicator when that portion of fertiliser hits the soil. Modern microprocessors can easily perform these tasks, if they are programmed with the proper algorithms. Although this type of algorithm (referred to in control theory as feed-forward compensation) is useful, care must be taken in mechanical equipment design to speed dynamic response, thereby reducing potential inaccuracies. Without feed-forward control and good dynamics, temporally separate control can be no better than homogeneous control.

Requirements for location determination in control are similar to those in mapping. Post-processing however cannot be done to remove noise or add differential or other corrections. The accurate location must be available immediately. Reliable, accurate DGPS without delay is a necessity.

The command from the control computer must be converted into a change of actions of the equipment. Usually, this means converting an electrical signal into some sort of displacement or force. Electro-hydraulic or electromechanical systems are typically used. For example, a proportional solenoid hydraulic valve can be stroked to vary the hydraulic oil flow to a hydraulic motor turning a centrifugal fertiliser pump, thereby varying liquid fertiliser flow. The actuator system must act as commanded and must act quickly. Generally, getting the desired mechanical output is not a major problem if good mechanical design principles are followed. The greater difficulty is to insure that mechanical output corresponds to correct agronomic output, such as to insure accurate control of fertiliser flow at varying compositions and temperatures or of planting depth in variable soil conditions.

4. Contemporary situation

Spatially variable crop production has achieved commercial success in the United States. Although there is no systematic means of evaluating the extent of its adoption, anecdotal evidence and some limited studies have shown it to becoming popular with farmers. At one time, one major grain harvester manufacturer claimed one-third of its new combines was leaving its North American factory equipped with yield monitors. A 1996 survey commissioned by CaseIH found that about 19% of the North American farmers with 200 ha or more are currently using GPS with 90% expecting to adopt the technology in the next five years (Finck, 1996). AgChem has sold a significant number of their SOILECTION units for map-based fertiliser and pesticide application.

The most common technology is grain harvester yield mapping. Between units sold by combine manufacturers and by after-market suppliers, a large percentage of grain harvesters is capable of yield mapping. Advices of university personnel, availability of equipment from multiple sources, and inherent utility and aesthetic appeal of yield maps to farmers have contributed to its popularity. It is now an accepted technology, although tests of accuracy have been called for (Schueller, 1995). It has been estimated that there were 17,000 combines with yield monitors in operation in North America during the 1997 harvest. This might represent around 6,250 000 ha of grains and soybeans.

Yield mapping for other crops is in various stages of development and commercialisation depending upon crop and location. The primary difficulty has been development of accurate sensors. A load-cell system for potato harvester conveyors and other similar applications is one of the items commercially available. Two commercial systems for cotton have been recently introduced. Other yield mapping systems are close to commercialisation, but more research is needed for improved performance and additional crops.

Soil fertility maps are widely commercially used to guide application of chemical fertilisers. Generally these are produced from rather intensive soil samples subjected to laboratory analysis. The sampling process has been aided by sampling machines attached to vehicles. There is currently a healthy debate about how much other knowledge such as topography and soil type should guide sampling and map generation. One opinion is that co-variates can reduce sampling and sampling costs. Another holds that regular (although systematically unaligned) grid sampling minimises sampling errors and produces more reliable results, especially in soils with long histories of human intervention.

There has been much commercialisation of remote sensing technology. Some have achieved success, although that success might be considered limited. Issues of timeliness, resolution, ground-truthing, and cost have caused difficulties.

AgChem is the current owner of the Ortlip (1986) patent on applying fertiliser according to digital maps. They sell various equipment, primarily based upon their FALCON controller, to apply fertilisers, pesticides, and manure in a spatially variable manner. Some manufacturers, such as Tyler, have use of the patent. Others manufacture equipment, which can easily be used or modified to perform spatially variable application, but explicit claims to do so appear to be affected by the patent situation, especially in the U.S.A.

Controllers are commercially available to vary the planting population. This is a relatively easy, low-cost task, but there has been debate of the usefulness with current seed varieties. One opinion is that variable planting rates are only justifiable in fields with significant patches of low yields.

Many researchers and developers in both public and private sectors are working on developing additional technologies for spatially variable crop production. New or more accurate methods of sensing soil, crop, and pest situations are eagerly anticipated. A wide variety of machinery to vary seeding, fertilisation, pest control and soil tillage is also under development. It is difficult to predict where the next innovations will come from.

It must be restated here that spatially variable crop production can use automatic control as well as temporally separate control. In those cases, the locator and several functions of the control computer (e.g., map storage and Locator correction) can be dispensed with. Of course, automatic control demands a good, fast sensor and a known consistent relationship between sensed quantity and desired control action. Perhaps a combination of automatic and temporally separate control might prove the best. For example, a nitrogen side-dressing rig in corn could have stored map data on spatially variable soil type and other limiting factors. Real-time sensors would measure current crop condition and soil nitrate level and then meter just the right amount of nitrogen according to algorithms, which consider the map data.

It may be remembered as well that there is a variety of means of achieving spatially variable crop production without use of electronics. For example, reorienting field boundaries or forming contour strips on hillsides achieves more uniform areas, which can be treated in different manners. Wiping or re-circulating applicators which apply herbicides to tall weeds do so only where the herbicides are needed.

5. Conclusions

Spatially variable crop production, often known as precision farming, has become widespread and has generated widespread equipment and management research and development. Various equipment and measurement systems have been developed and commercialised to generate field maps, especially of crop yield. The spatially variable application of crop inputs has also had some commercial success. The component engineering technologies include sensors, actuators, locators, and computer controls.

References

Elliott C (1987) Fertilizing-blending and spreading on-the-go using computerized soil maps and radar guidance. SAE paper 871676

Finck C (1996) On tap for technology. Farm J 112(13):24

Huisman W (1977) Moisture content, coefficient of friction and modulus of elasticity of straw in relation to walker losses in a combine harvester. Proceedings First International

Grain and Forage Harvesting Conference Ames Iowa. Pp 49-54.

Lullen WR (1985) Fine-tuned fertility: tommorrow's technology here today. Crops and Soils 38(2):18-22

Ortlip EW (1986) Method and apparatus for spreading fertilizer. US Patent 4,630,774. December 23

Schueller JK (1992) A review and integrating analysis of spatially-variable control of crop production. Fert Res 33:1-34

Schueller JK (1995) We need Nebraska Tests for spatially-variable agriculture. Resource 2(5):40

Schueller JK, Mailander MP and Krutz GW (1983) Computer control of combine forward speed and rotor speed. Proceedings, ASAE Conference on Agricultural Electronics Applications. Chicago. December 11-13. pp 99-108

Searcy SW, Schueller JK, Bae YH, Borgelt SC and Stout BA (1989) Mapping of spatially-variable yield during grain combining. Trans ASAE 32(3):826-829

Van Loo IJ (1977) An automatic feed rate control system for a combine harvester. Wageningen University, Department of Agricultural Engineering

Whitney JD, Wheaton TA, Miller W, Schueller JK, and Salyani M (1998) Precision agriculture applications in Florida citrus. Proceedings, First International Conference on Geospatial Information in Agriculture and Forestry. Orlando 1-3 June

Wild KJ (1998) Satellitengestützte arbeitszeiterfassung und ertragsermittlung in rundballenpressen. Dissertation, Institut für Landtechnik der Technischen Universität München

1.3 Models and scenario studies for precision farming

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1. Introduction

The aim of precision agriculture is to adjust and fine-tune resource application addressing spatial and temporal variable conditions. Precision farming implies that management practices should vary within fields reacting to local soil and crop conditions. Local optimisation of resources benefits both the farmer in economic terms and the environment in terms of reduction of pollutants.

De Wit (1992) pointed out that the optimum law of Liebscher[1] has a general validity because agriculture requires the management of growth and production processes in a partly controlled environment. De Wit concludes that most production resources are used more efficiently with increased yield level due to optimisation of growing conditions. When fine-tuning the application of agro-chemicals to the plant the efficient use of these compounds is improved. Fine-tuning of farm management measures, in terms of time and space, is therefore the core activity of precision agriculture (Bouma, 1997). Strategic research that is to serve both agriculture and its environment should be directed mainly towards the search for the minimum of each production resource that is needed to allow maximum utilisation of all other resources.

This paper focuses on the optimisation of N fertiliser application, taking into account spatially variable soil conditions. When searching for optimal N fertilisation levels combining low leaching quantities with high production levels, simulation models are powerful tools. Simulation models for point data in combination with geo-statistics are used to address soil quality issues at field level. We always have to look simultaneously at quantity and quality of agricultural production and to environmental quality, as well, as they are important elements of sustainable agricultural production systems (Bouma, 1997). In this paper both items are addressed in quantitative terms, separating conditions in the growing season from those in the wet winter season when most leaching occurs. Finally, the issue is addressed as to how threshold-values for N contents at the end of the growing season, as defined by winter leaching, influence management during the growing season. The study area is a 2.5 ha field of an experimental farm in the Wieringermeer polder in the northwestern part of the Netherlands. Before reclamation in 1930, the experimental farm was part of a tidal mudflat. Because of the dynamic sedimentation environment, both horizontal and vertical soil-spatial variability are high. The soils are strongly layered with textures ranging from sand to silty clay. The individual texture lenses vary in thickness from 1 mm to 50 mm. During a previous survey on the same farm, soils were classified as fine-loamy, calcareous, mesic Typic Udifluvents (Finke and Bosma, 1993).

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[1] Liebscher's law is known as the law of the optimum and states that a production factor that is in minimum supply contributes more to production the closer other production factors are to their optimum.

2. Spatial variable conditions

Soil variability is a key element in precision agriculture. Variability should be dealt with in terms of space and time, both for point observations and characterisations for areas of land more particularly, fields. The simplest way to obtain such characterisations is to make direct observations or measurements of variability for a period of time. Measurements focus on elements of importance for site specific management, such as crop growth and soil water and soil nutrient contents during the year.

An attractive alternative to measurement of crop growth and solute fluxes is dynamic simulation modelling to predict crop growth and nutrient fluxes. Model runs can be based not only on actual but also on historic weather data. Historic data can be used to make predictions for future conditions using statistical techniques. Of course, results of simulation runs should always be validated with field data, obtained by measurements as mentioned above, for a limited period of time, e.g. a few growing seasons.

Of particular interest, when discussing site-specific management, are predictions of soil behaviour in different areas of a field. The spatial patterns in fields relate to yield differences, occurrences of pests, diseases, etc. Soil science, and particularly soil survey, has had a long history of providing patterns, as they are shown on soil maps. The basis for these patterns is pedological differences as expressed by the legend of the map, which is based on criteria from soil classification. As stated above, we are not really interested in pedological differences but, rather, in functional differences within fields, which are relevant for precision agriculture. So rather than use patterns of existing soil maps, we prefer to model for point data and use interpolation techniques to extend results to areas of land (e.g. Finke, 1993). Spatial soil variability of the farm field was characterised using 65 augerings on a regular grid including short distance observations to allow geo-statistical analyses, see Figure 1.

To model variability requires first a proper definition of variability. Variability of what? Soil parameters vary, but variation may not be significant in a functional sense. For instance, variations in soil texture may not result in significant differences among the corresponding hydraulic characteristics. Sometimes pedologically identical soils behave differently, sometimes-different soils behave the same. Management practices can have a major effect on soil properties in a given soil series (e.g. Bouma, 1989). Introduction of "functional" soil horizons, which are a combination of different pedological horizons with identical behaviour, is an attractive procedure as it simplifies modelling by requiring fewer input data. Wösten et al. (1985) considered the hydraulic behaviour of soil horizons and could reduce data demand by a factor three. For the farm field four functional layers are identified ranging from sandy (F1) to clayey (F3), functional layer (F4) represents the loamy/clayey topsoil. Figure 2 presents a cross section of the central transact, using the concept of "functional layers", clearly showing the change from the sandy profiles at the left side of the field to the loamy and clayey profiles at the right part of the field. This sequence is a general characteristic of the field.

Besides spatial variability the temporal variability over a period of different growing seasons is very important for precision agriculture, because weather conditions in any given year determine the most appropriate precision agriculture procedure. Simulation modelling is

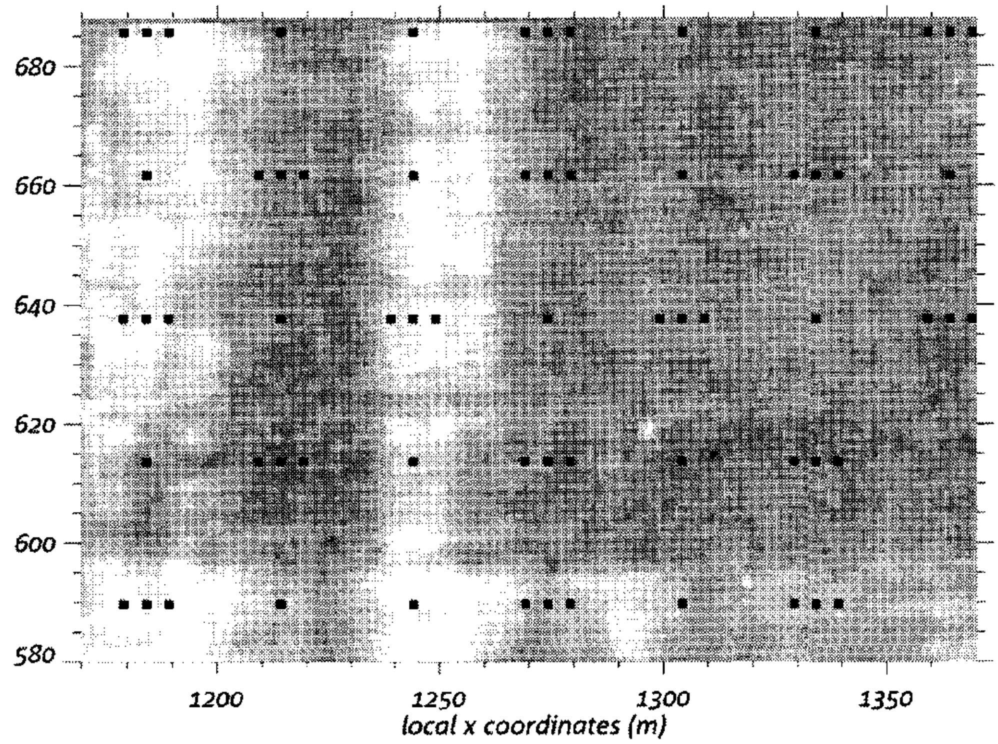

Figure 1. Layout of sampling design superimposed on an aerial photograph of the bare soil at the experimental field. The light coloured areas mark the sandy parts.

a particularly attractive way to make Multi-year runs for production and associated solute fluxes. The following paragraph deals with the temporal stability of the spatial pattern.

3. Stable spatial patterns

Maps are needed to guide site specific management. Such maps, when to be used in farm management, should display areas with relative uniform behaviour in different years with respect to crop growth and leaching. To explore the spatial and temporal behaviour of the field a mechanistic deterministic simulation model was used to calculate water-limited production levels for the 1988 - 1994 period. Figure 3 shows the simulated water--limited potato yield patterns for the period 1989 - 1994, in 1988 no spatial differences were found.

From Figure 3 we see that patterns for water-limited yield are comparable for the years 1989, 1990 and 1992-1994. The 1991 growing season started quite wet, which resulted in an inverse pattern where relatively high yields were obtained on sandy spots while yields in the more clayey spots were clearly depressed by oxygen deficiencies. Data in Figure 3 illustrate use of modelling to express variability of crop yield within a field, demonstrating the major impact of different weather conditions. Following the approach by Davis (1986), Van Uffelen et al. (1997) developed a procedure to compare different maps. Using this technique a general or prototype pattern for the experimental field was extracted from the simulated water limited yields. This prototype patterns is shown in Figure 4.The stable pattern from Figure 4 can be used as a base map for site-specific management. In the following section we will explore the validity of this map by comparing conventional and site-specific fertiliser application.

4. Production levels and nitrate leaching related to N fertiliser dose

The prototype pattern as displayed in Figure 4 is based on calculated water-limited productions for seven years. These production levels can be used to estimate the N requirement (Neeteson and Wadman, 1987) and hence provide a basis for fertiliser maps. This pattern is not necessarily the optimal fertiliser pattern; when taking nitrate leaching into account the optimal pattern may be different. In this section we address both production level and nitrate leaching to compare the effects of the different fertiliser applications. The optimal fertiliser pattern for 1994 is defined and is compared to the conventional uniform fertiliser application and the site specific fertiliser application using the prototype pattern. The effects are studied by calculating the production level and the amount of nitrate leached for all 65 points for 7 fertiliser levels. Figure 5 presents the relationships between fertiliser application, yield and leaching. High production levels and high nitrate losses are associated with high fertiliser rates. Low fertiliser doses result in low production levels and consequentles low nitrate uptake, which has a negative effect on, nitrate leaching.
Fertiliser recommendations in the Netherlands are based upon nitrogen content in early spring. These recommendations were established some 20 years ago using plot experiments and aimed to provide maximum yields with low risk. Apart from the soil N content rooting depth is also taken into account. The recommended fertiliser dose for the field for 1994 is a uniform dose of 250-kg N ha^{-1}. This dose clearly results in high production levels but the leaching threshold value is exceeded for the entire field. The spatial effect of three selected uniform fertiliser applications can be seen in Figure 6.

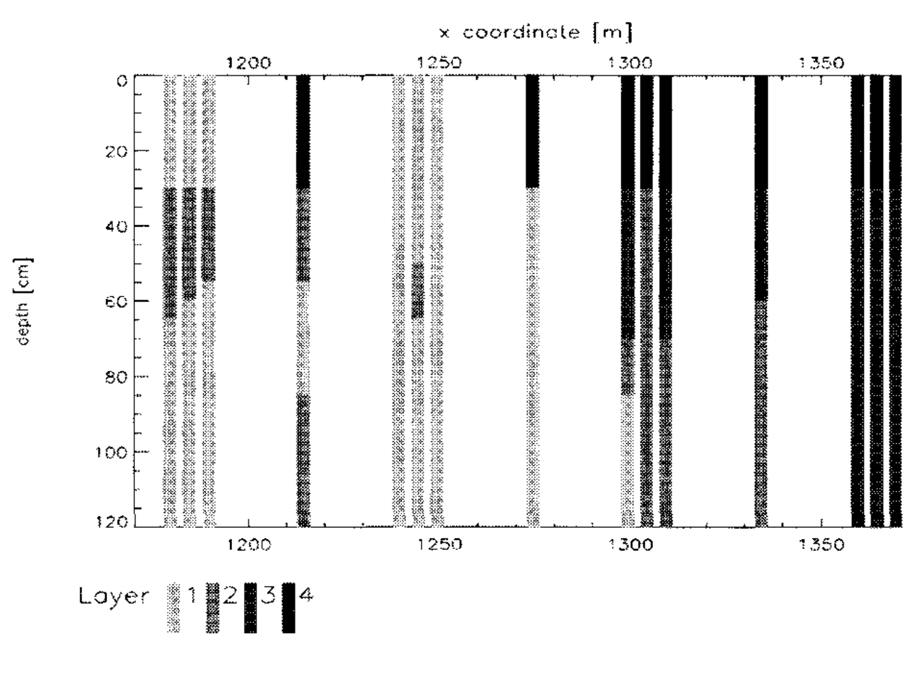

Figure 2. Cross section of the central transact.

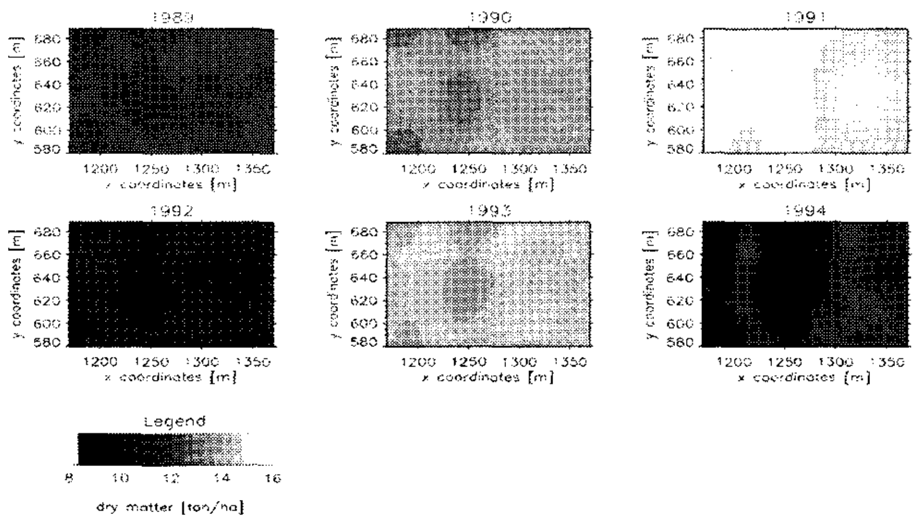

Figure 3 Simulated water-limited production levels of potatoes for six years.

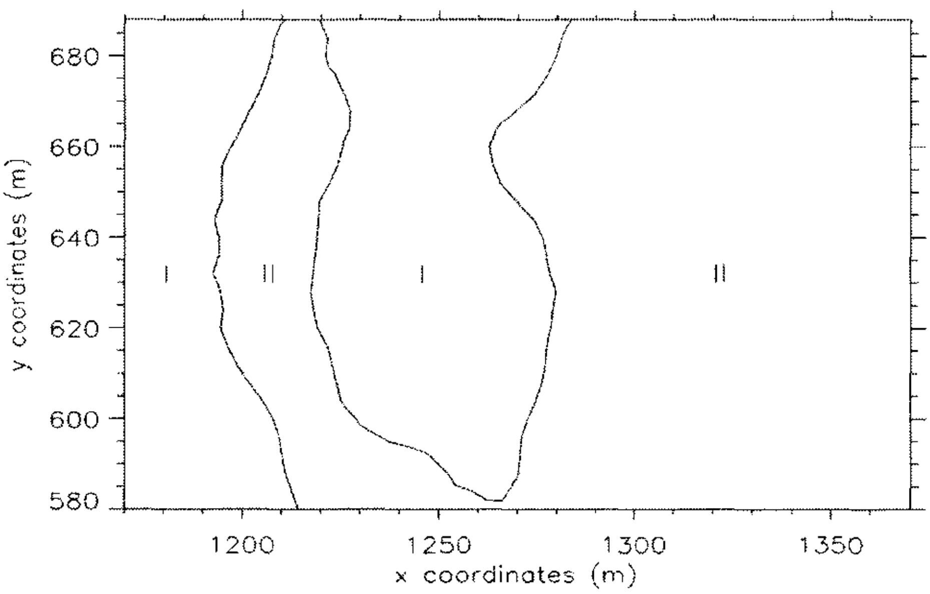

Figure 4. Site-specific management units based on seven years-simulated water limited productions (After Van Uffelen et al., 1997).

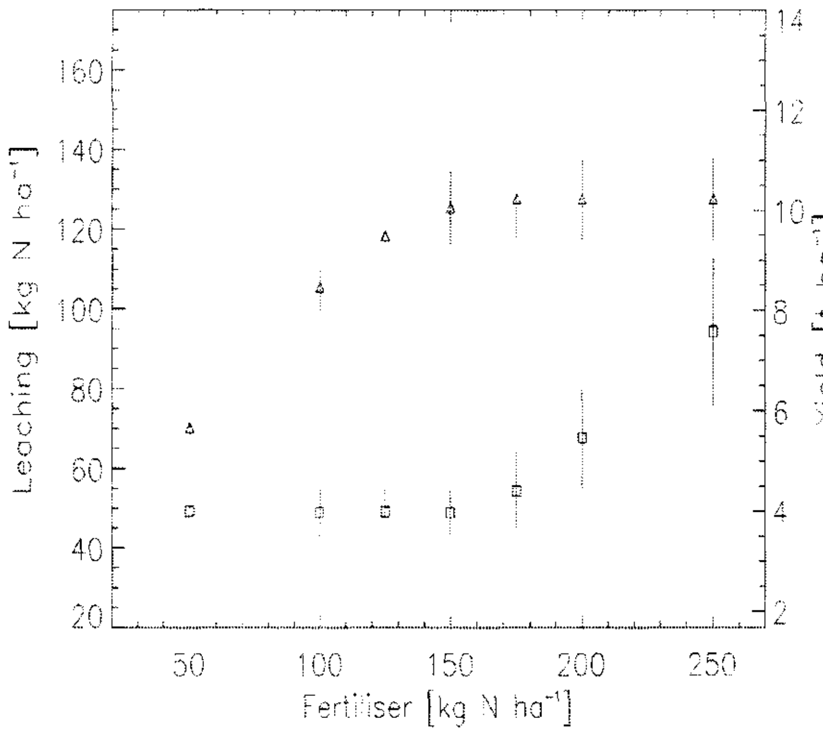

Figure 5. Effect of fertiliser application on yield and leaching quantities for the individual scenarios. Triangle: yields [t ha^{-1}]; square: leaching quantities [kg N ha^{-1} yr-1]; the vertical bar indicates the standard deviation.

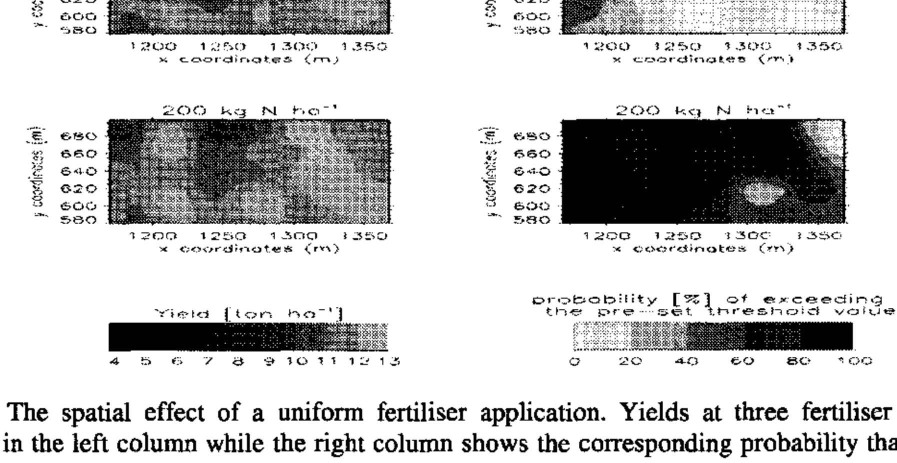

Figure 6. The spatial effect of a uniform fertiliser application. Yields at three fertiliser rates in 1994 are displayed in the left column while the right column shows the corresponding probability that a threshold value for nitrate leaching is exceeded

The nitrate leaching patterns were created with indicator kriging taking 50-mg nitrate dm^{-3} (critical concentration in drinking water) as threshold value. Nitrate concentrations for a given soil, management type, and year is based on the total leached nitrate dissolved in the precipitation surplus. This concentration is compared with the threshold value.

The site-specific fertiliser map for 1994 based on the data presented in Figure 5 taking both the production level and nitrate leaching into account are presented in Figure 7. The high producing clayey part (unit III) receives the highest fertiliser dose whereas the low producing sandy part (unit I) receives much lower amounts of fertiliser. The loamy area (unit II) takes an intermediate position.

This previous analysis is based on one growing season looking back in time. Yield patterns differ strongly among years. The prototype pattern, expressing temporal variation, claims to be valid for 5 out of 7 years. Using this prototype pattern as a guideline for fertiliser management is an attractive alternative to uniform application.

The results of the three-fertiliser applications are displayed in Table 1. The results show that both site-specific fertiliser scenarios display a dramatic improvement in leaching risk as compared to the recommended fertiliser scenario.

Table 1. Comparison of recommended and site-specific fertiliser scenarios.

Scenario	Area	Rate [kg N ha^{-1}]	Average Yield [t ha^{-1}]	sd	Average NO_3 leaching [kg NO_3 ha^{-1}]	sd
Recommended	field	250	11.57	1.10	95.9	24.1
Prototype	I	125	9.78	0.76	47.3	5.7
	II	175	12.17	0.64	36.4	6.0
	field		11.29	1.34	39.7	7.0
Optimal	I	125	9.65	0.83	46.1	6.4
	II	150	11.47	0.98	40.9	5.0
	III	175	12.06	0.56	33.8	3.5
	field		11.13	1.21	39.3	6.9

5. Environmental risk

Modern agriculture not only focuses on high production but also is increasingly concerned with the negative environmental side effects. Goals are set for the nitrate concentration in the groundwater which may not exceed 50 mg l^{-1} in the year 2000 (VROM, 1989). With an average annual precipitation surplus of 300 mm in the Netherlands this means that only 35 kg N ha^{-1} yr^{-1} is allowed to leach. This section will not discuss the validity of the pre-set threshold values but will focus on how to work with the imposed boundary conditions.

In the Netherlands, N leaching occurs mainly in the winter season ranging from 15 September to 15 April. Risk analyses, including aspects of spatial and temporal variability should therefore focus on this period. Soil mineral nitrogen after harvest is the major source of nitrogen pollution of the groundwater (Corré, 1994; Van der Ploeg et al., 1995; Booltink and Verhagen, 1997). Farm management should aim at an N profile in autumn which has a low risk of exceeding a pre-set leaching limit during the wet season.

To achieve the goal of reduced nitrate leaching, farm management has to re-evaluate the use of N fertilisers. Implications of this reasoning are studied using Multi-annual runs of a validated dynamic simulation model.

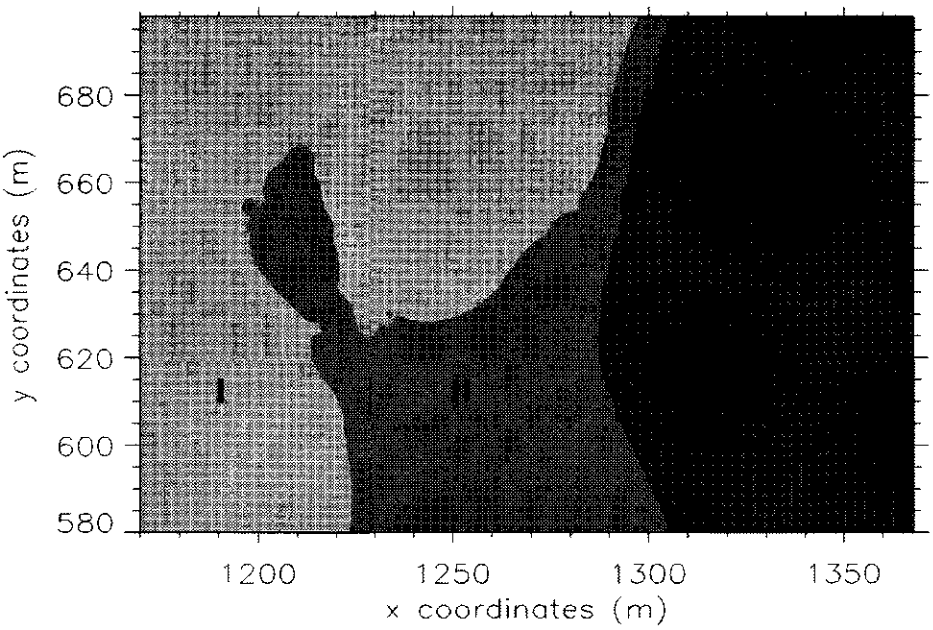

Figure 7. Site specific fertiliser recommendation based on optimising production levels and minimising leaching probability for 1994. Unit I: 125 kg N ha^{-1}, unit II: 150 kg N ha^{-1} and unit III: 175 kg N ha^{-1}.

The simulation model is used to calculate expected nitrate losses during the wet season, ranging from 15 September to 15 April. Leaching risk is assessed for five different initial N profiles namely: 15, 30, 60, 90 and 120 kg N ha^{-1}, while N distributions in the soil profiles are based on the October 1994 measurements. Temporal variation was expressed by calculating leaching for 20 wet seasons. The database created contains information on nitrate leaching for 5 different N-initial scenarios for 65 points for 20 periods.

For each location risk is expressed using cumulative distribution functions. Figure 8 displays the probability at any locations (based on 20 years of data) that nitrate is leached for the 5 initial N scenarios. No risk, when leaching never exceeds the threshold value, is indicated by the 1.0 level while at the 0.0 level the threshold values is exceeded for all periods. Allowing 10 % of the periods to exceed the threshold value the 0.9 probability level is read. Example: a threshold value of 50 kg nitrate per ha. For profile 105 the scenarios with 15 and 30 kg N ha^{-1} m^{-1} result in nitrate leaching which for all periods is below the threshold value. The 60-kg N ha^{-1} m^{-1} intersects with the threshold value at 0.5 indicating exceedance for 50 % of the periods. Both the 90 and 120-kg N ha^{-1} m^{-1} scenarios always result in leaching quantities above the threshold value. For profile 201 the threshold value is exceeded for 90 % of the periods for the 90-kg N ha^{-1} m^{-1} scenario. The scenarios of 15, 30 and 60 kg N ha^{-1} m^{-1} do not exceed the set threshold of 50-kg nitrate while the 120-kg N ha^{-1} m^{-1} scenario does exceed the threshold for all periods.

Using Figure 8 critical N values for 100 cm of soil at September 15 can be determined for a given risk level. The spatial pattern of the required 15 September N profile based on the 65 points (Figure 9) was created by ordinary kriging (Journel and Huijbregts, 1978). For two threshold values, the national 35 kg NO_3 ha^{-1} and local 42 kg NO_3 ha^{-1} and three risk levels, comparable patterns, were observed: relatively low N concentrations are located on the left part of the field, corresponding with the sandy area, while higher N concentrations are found on the right part of the field, corresponding with the clayey area.

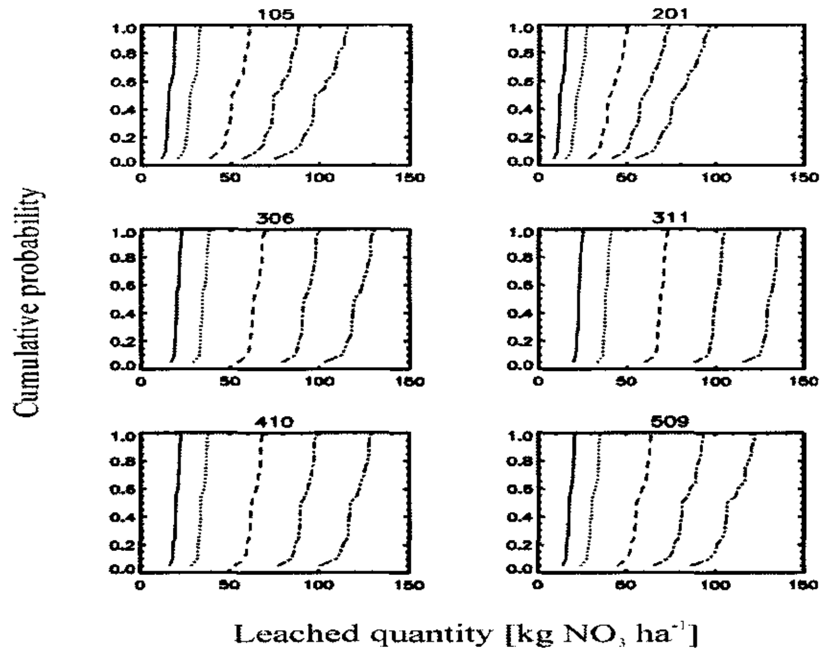

Figure 8. Leaching probabilities (based on 20 years) given an initial N profile for six representative profiles. Initial N profiles at 15 September: ---------- 15 kg N ha^{-1} m^{-1}, ... 30 kg N ha^{-1} m^{-1}, -- -- -- -- -- 60 kg N ha^{-1} m^{-1}, --. -- . --. 90 kg N ha^{-1} m^{-1}, ...--- ... 120 kg N ha^{-1} m^{-1}.

Depending on the defined threshold and accepted risk level the autumn N-profile can be set as a target for farm management. Reacting to local differences, fertiliser rates and frequency can be set to achieve the set target (Booltink et al., 1997).

6. Balancing production and environmental requirements

This section will discuss the effects of fertiliser applications on crop production and leaching during both the "dry" growing season (April - September) and the "wet" season (September - April). The leaching potential during the "wet" season is based on critical N contents at September 15. The key aspect is the question as to how the critical N contents on September 15 can be translated into management measures for N during the growing season, thus linking the requirements dictated by the "wet" season with those for N management in the "dry" growing season.

The areas with different leaching potential as presented in Figure 9 are stable in space and time. All patterns reveal the same spatial pattern, only the absolute levels differ. The pattern presented in Figure 4 is related to production and is used to define fertiliser inputs for the farm field. Both patterns are soil-related. The patterns do not match perfectly, because crop growth is mainly affected by the topsoil layers (rooting zone) while losses of nitrate to the groundwater are also governed by conditions in the lower soil layers.

Both patterns are complementary and not conflicting. Because the pattern presented in Figure 10 reveals the most detail, representative soil profiles for further analysis are selected based on this pattern. An assessment of the effect of fertiliser level on three soil quality indicators was made: (1.) post-harvest N, (2.) N leaching and (3.) potato production. For the three soils an initial N profile of 30 kg ha^{-1} 0.6 m^{-1} is defined. This initial N profile and N distribution over the profile is based on measured N profiles during two years of monitoring. The recommended fertiliser dose calculated according to national guidelines is 250-kg ha^{-1}. In addition, also fertiliser doses of 150, 175, 200 and 225 kg N ha^{-1} were included in the scenario analyses. For the three profiles each scenario was calculated for 11 "dry" seasons (1984 - 1994). The results of the scenario analysis are presented in Figure 11.

Figure 11 A shows that fertiliser doses above 200 kg N ha^{-1} have a dramatic impact on post-harvest N. N uptake by the crop does not increase (see figure 11 C) so either the added N above 200 kg N ha^{-1} contributes to the post-harvest N (figure 11 A) or to leaching during the "dry" growing season (Figure 11 B). Temporal variation (Figures 11 a, b and c) is highest for all three indicators for soil 1. Different climatological conditions have a larger impact on this soil as compared to the other two. Soils 2 and 3 are stable with respect to all the three indicators. The recommended fertiliser rate (250-kg N ha^{-1}) results in high production levels for all three soils but post-harvest N values are unacceptably high.

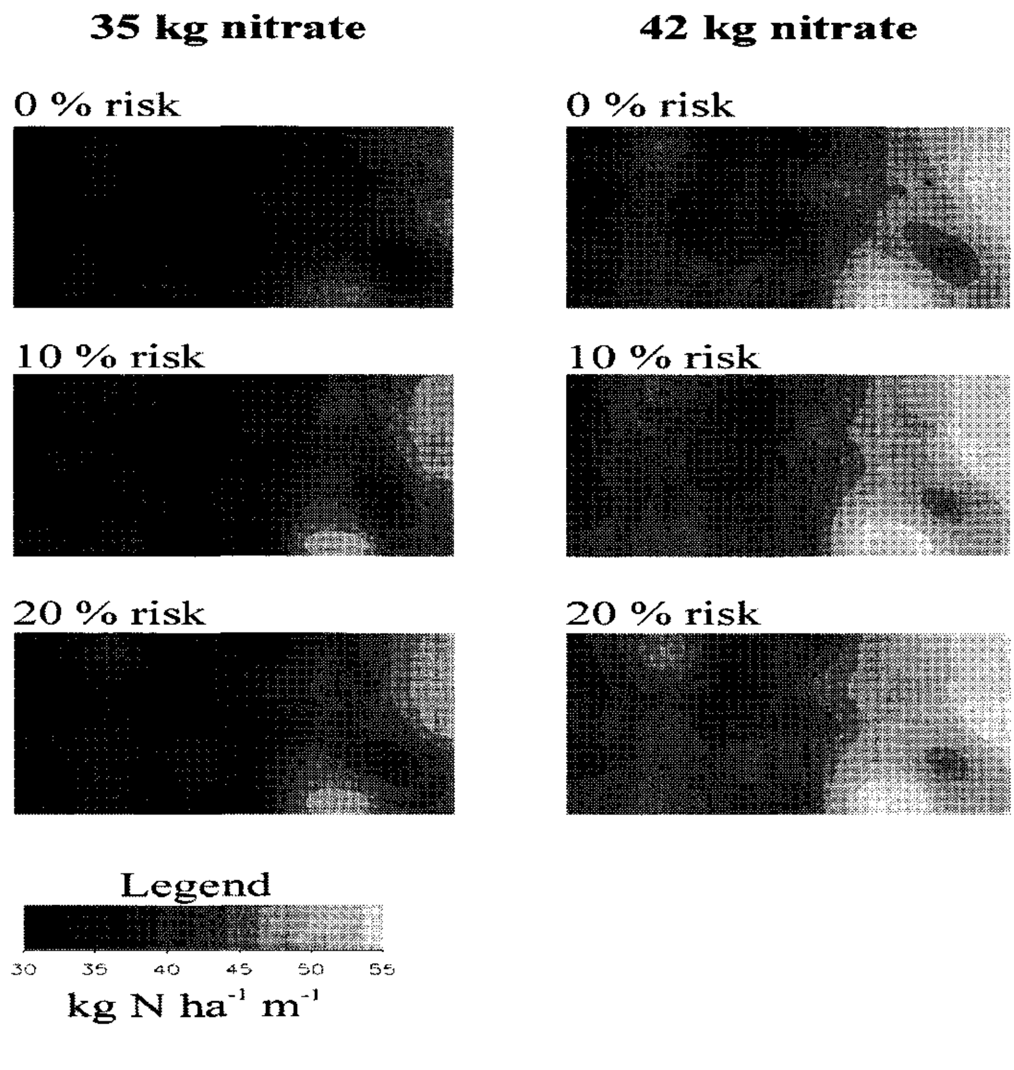

Figure 9. Target maps of the N profile (kg ha^{-1} m^{-1}) at September 15 for two threshold leaching values and three risk levels of exceeding these threshold values of 35 kg N ha^{-1} and 42 kg N ha^{-1}.

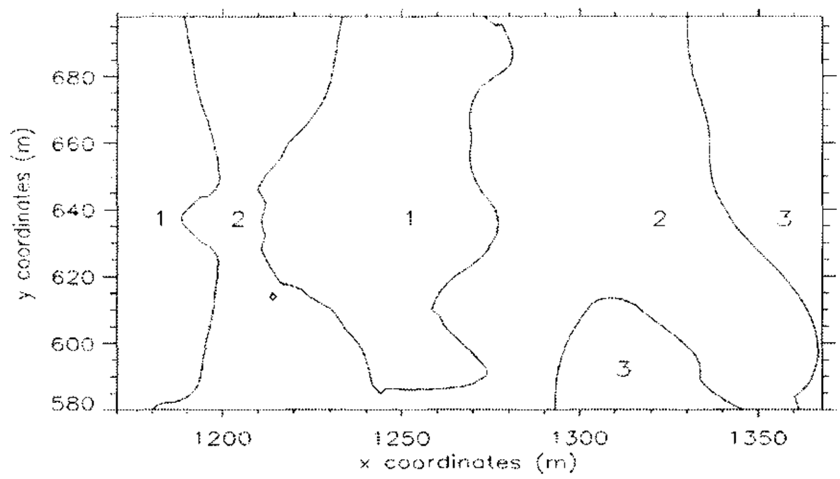

Figure 10. Post-harvest N map based on 20 years simulated leaching during the September 15 - April 15 period (after Verhagen and Bouma,1997).

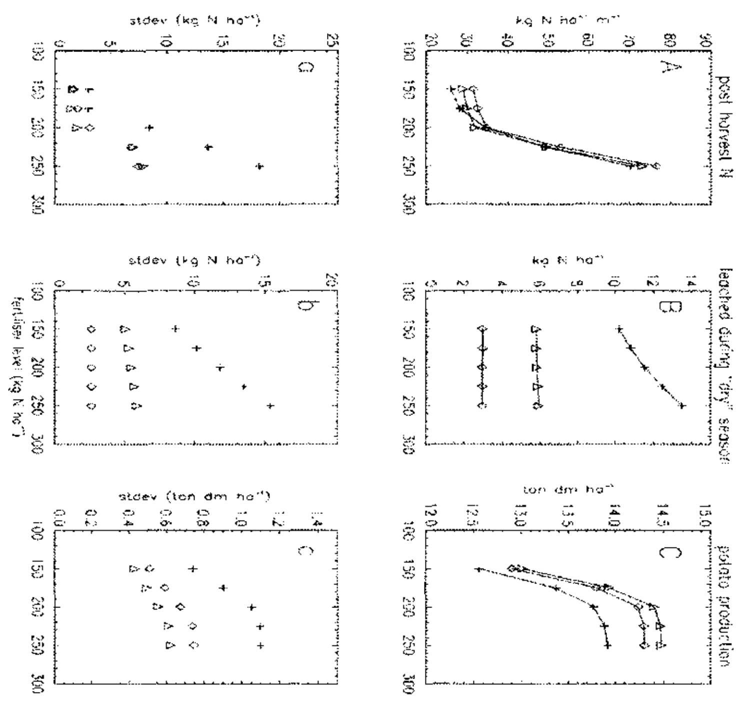

Figure 11. Average (A, B, C) and standard deviation (a, b, c) of post-harvest N, leached N during the "dry" season and potato production levels for the three soils. Average and standard deviation are based on 11 years of simulated data. + indicates soil 1, triangle indicate soil 2 and diamond indicates soil 3.

7. Conclusions

1. Variability of physical soil properties has a significant impact on both crop production and nitrate leaching.
2. Dynamic simulation models are crucial in quantifying both crop production and the associated nitrate leaching for point data. Geo-statistical interpolation techniques allowed the step from points to areas.
3. Temporal variation could be expressed by exploratory running of the model using weather data for a number of years.
4. A comparison of maps showing yields and leaching for a number of years, has indicated that soil-related patterns can be defined for a field that are stable in space and time.
5. Definition of threshold values for nitrate leaching should reflect spatial and temporal variation by defining such thresholds in terms of probability of exceedance under various weather conditions.
6. Adjusting N fertiliser application, taking into account spatial variable conditions, can significantly reduce leaching without lowering the production level.

References

Booltink H, Thornton P, Verhagen J and Bouma J (1997) Application of simulation models and wheather generators to optimize farm management strategies. Madison,Wis USA Soil Sci. Soc of America Spec Publ., pp 343-360

Booltink HWG and Verhagen J (1997) Using Decision Support Systems to Optimize Barley Management on Spatial Variable Soil vol 2 pages 219 - 233. Kluwer Academic Publishers, Dordrecht/Boston/London

Bouma J (1989) Using soil survey data for quantitative land evaluation. Advances in Soil Science vol 9, pp 177-213 Springer Verlag New York

Bouma J (1997) Precision agriculture: introduction to the spatial and temporal variability of environmental quality. CIBA-EERO Symposium on Precision agriculture. Bock G and Lahe J, editors, pp 5-17

Corré WJ (1994) Bepaling van de hoeveelheid minerale stikstof in de bodem in het najaar als instrument voor het te voeren stikstof beleid. Akkerbouwgewassen en vollegronds-groente, AB-DLO rapport 21

Davis CD (1986) Statistics and data analysis in geology - second edition. John Wiley and Sons, New York

De Wit CT (1992) Resource use efficiency in agriculture. Agricultural Systems 40:125-151

Finke PA (1993) Field scale variability of soil structure and its impact on crop growth and nitrate leaching in the analysis of fertilizing scenarios. Geoderma 60:89-109

Finke PA and Bosma WJP (1993) Obtaining basic simulation data for a heterogeneous field with stratified marine soils. Hydrological Processes 7:63-75

Journel AG and Huijbergts CJ (1978) Mining Geostatistics. Academic Press, London

Neeteson JJ and Wadman WP (1987) Assessment of economic optimum application rates of fertilizer N on the basis of response curves. Fertilizer Research 12:37-52

Van der Ploeg RR, Ringe H and Muchalla G (1995) Late fall site-specific soil nitrate upper limits for groundwater protection purposes. J Environ Qual 24:725-733

Van Uffelen CGR, Verhagen J and Bouma J (1997) Comparison of simulated crop reaction patterns as a basis for site specific management. Agricultural Systems 54:207-222

Verhagen J and Bouma J (1997) Defining threshold values: a matter of space and time. Geoderma

VROM (1989) Nationaal Milieubeleidsplan Ministerie van Volkshuisvesting, Ruimtelijke Orening en Milieubeheer. Tweede Kamer vergaderjaar 1989-1990

Wösten HJW, Bouma J and Stoffelsen GH (1985) The use of soil survey data for regional soil water simulation models. Soil Sci Soc Amer J 49:1238-1245

2. Integrated Pest Management

Towards integrated and efficient means for environmentally friendly farming

Yield-reducing factors can be controlled by chemical, mechanical, ecological and biological means. Integrated Pest Management (IPM) aims at an optimum combination of these means to meet both agronomical, economic and environmental objectives. Development of IPM requires careful diagnosis and specification of pest and disease problems at the crop and cropping system level. Next, a quantitative understanding of the impact and damage of the pest or disease is useful for a targeted development of biological, ecological and chemical technology to protect the crop against yield-reducing factors. The foregoing is necessary but not sufficient for a successful application and dissemination of IPM.

2.1 Economic specification for production ecology: consideration of dynamic and intergenerational aspects in pest management research

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1. Introduction

Crop protection experts appreciate economists if they help them to demonstrate the importance of crop protection in agriculture. In fact, results of economic research helped to „prove" that without pesticides crop losses would be at unacceptable levels. By calculating the marginal return of pesticide use some economists even have tried to show that in fact more pesticides should be used. A figure of US $ 3 to 5 per every US $ spent on pesticides is quoted widely (Headley, 1968). Contrary to that, others showed that pesticide use could be rather uneconomical, as is the case for insecticide use in tropical rice (< biblio >).

In theory, economic analysis should provide information on the net benefit of pest management strategies at the level of the individual farmer and the national economy. In practice, as noted by Oskam (1994) there are a number of limitations for example in estimating pesticide productivity. Among these are difficulties to specify a production function for pesticides in the same way as this is widely done for determining the optimal rate of mineral fertiliser use Mostly, when production functions have been estimated for pesticides, the marginal value product exceeds their marginal costs by several times. Following the theory, these results suggest that pesticides are under-utilised. Lichtenberg and Zilberman (1986) have first pointed out the flaw in this kind of analysis. They noted that analysts have misspecified the functional form for estimating pesticide productivity as a result of ignoring that pesticides are damage control agents, and not - as assumed in production theory - direct productive inputs. This causes problems in specifying the functional form for productivity estimation. Carrasco-Tauber and Moffitt (1992) analysed aggregated data from the U.S. agricultural sector and showed that the marginal value product of pesticides ranges between US $ 0.11 and around US $ 7 per US $ spent, dependent on the functional form used. Therefore, no definite conclusions on pesticide productivity could be concluded.

Another complication in the economic analysis of pest management decisions is based on the fact that pest control interventions in the agro-ecosystem during prior production periods influence the options available for promising interventions in current periods. In relation to pesticide use, crop protection experts have named this phenomenon the chemical spiral. From an economic perspective, the theory of path dependence of the use of technologies may contribute to an explanation (David, 1985; Arthur, 1989). When sunk costs are implied or positive network externalities influence the adoption rate, economic processes can become self-reinforcing and may lead to a sub-optimal outcome. Cowan and Gunby (1996) analysed developments in cotton and citrus production where pesticide use continued to rise because of a lock-in situation for individual decision-makers although the technology had been less economically viable than its alternative.

The third area where economic analysis is potentially useful stems from the negative environmental and health effects of pesticide use. Responding to the concerns widely advocated by the general public opinion, economists refer to the theory of external effects. An economic assessment of negative side-effects can be useful in determining the net benefit of programmes that aim at reducing these costs. Environmental economic assessment can also be used as a basis for regulatory decision making.

Economic analysis in crop protection should do more than simply calculate „crop loss minus costs equals net gains". It has to take into account the relationship between human interference, host, pest and the environment if it shall help the crop protection science in setting priorities for research and development. The application of questionable methodologies can result in completely misleading information and oversimplification. One recent example is formed by the conclusions drawn by Oerke et al. (1994). The authors claim the existence of a huge difference between attainable yield and yield level without pesticide use. In their view, the world's food security problem can be solved by a higher use of plant protection products. The simple conclusion of Oerke et al. (1994) that "for the foreseeable future agro-chemicals continue to be an indispensable weapon in the battle to protect crops" offers a challenge to economists to do a more scientifically based analysis.

In this paper three examples are presented that show an application of economic approaches that take some of the above-mentioned specifications of the problem into account. In the first part of the paper, results of an analysis of the external costs caused by pesticide use in Germany are presented. In the second part of the paper, some evidence of the dependence of the agricultural sector in Germany on pesticides is presented. Next, an example is shown how the principles of resource economics can be applied to support decision-making in regulatory matters using the case of banning the herbicide atrazine. Finally, some conclusions for crop protection research are drawn.

2. The assessment of external costs

Externalities associated to pesticide use are costs, which are not borne by the farmer but nevertheless appear and have to be borne by the society. External costs occur because the market is unable to internalise these costs into the price of resources and products. The reason for this is mainly found in two factors:

(a) the nature of affected resources and goods

(b) institutional failure

An example for (a) is the destruction of beneficial organisms. For example, spiders and lady beetles are non-marketable goods. They are also non-rival goods because nobody competes for them. Additionally, they are non-exclusive because „deadly" access by pesticide applicators cannot be prevented as beneficial do not respect field, farm, or even state boundaries. Effective institutions can help to prevent the occurrence of external effects, misguided institutions increase their likelihood and their extent.

A good example for institutional failure is pesticide regulation. For example, Germany claims to have one of the most advanced crop protection laws in the world. The German pesticide law by definition excludes external effects because of two assumptions:

(1) pesticides are only registered if after standardised laboratory and field tests only „acceptable" risks can be identified. Based on the result of such risk assessment they are then declared safe under conditions of normal use,

(2) farmers are supposed to use pesticides according to good agricultural practices.

The problem with the first assumption is a rather philosophical one. The proof that substances have no effects cannot be made but only assumed. Since there is no complete objectivity in science the probability used in defining risk is always based on subjective likelihood. However, currently it is expert opinion that decides on behalf of the society how much risk has to be accepted. Consequently, acceptance of such decisions by the society is often low. Democratic principles require that the major interest groups, which are affected by a pesticide regulatory decision, be equally made part of that decision.

The second assumption is questionable, as law enforcement is costly. According to the German crop protection law, farmers are supposed to base their pesticide applications on economic thresholds as essential component of integrated pest management (IPM) principles. The use of economic thresholds is part of it. However, the neglect of IPM principles, and the use of prophylactic treatments instead is not subject to sanctions. Consequently, adoption of IPM is low. Socio-economic research on farmer's practices has shown that less than 10 % of the farmers in Germany practice what could be called Integrated Pest Management (Lütke-Entrup and Hensche, 1995). Therefore, it is likely that currently pesticides are not used in an economic way and external costs can not be ruled out.

In a cost-benefit analysis of pesticides use in German agriculture (Waibel et al., 1998) the following results were obtained:

- External costs resulting from negative side-effects of pesticide use amount to at least 252 million DM per year, i.e. for every DM spend on pesticides another 0,25 DM has to be borne by the society. Monitoring, avoidance and mitigation of pesticide residues in water resources cause the lion share of these costs. Other negative side effects of pesticide use include chronic effects on human health, long term effects on the sustainability of agricultural production and soil fertility as well as induced preference changes of consumers for drinking water. Various external effects could be identified, but currently not be assessed in monetary terms. The "True" long-term costs to the society are definitely above the calculated value.
- Using a regional factor demand and product supply model based on duality theory, in terms of a benefit cost ratio it was found that every DM spent on pesticides results in a benefit of 1.47 DM. This is significantly less than what has been found in previous studies.
- Although major cutbacks of cereal and oilseed prices took place following the reform of the Common Agricultural Policy of the European Union in 1992, the share of pesticide costs in total production costs continues to rise. While during the 1960s for every DM spent on fertiliser farmers spent 0.05 DM on pesticides this ratio has changed to 1: 0.35 in the nineties.

The limited economic benefit of current pesticide use levels supports the hypothesis that farmer's pesticide use may be inefficiently high (Lichtenberg and Zilberman, 1986). Since marginal net benefit is below average benefit, marginal benefit could well be negative. The results of the study invariably lead to the conclusion that German plant protection policy should reconsider its sole reliance on a command-and-control approach. Despite the established sophisticated regulatory framework, which was designed to exclude external costs, these definitely occur at an intolerable level.

The existing command-and-control policy has probably helped to reduce the number of pesticide compounds but has failed to reduce pesticide use intensity and external costs. Regulatory instruments are also not offering any mechanisms to reduce pesticide dependence. Excessive pesticide use is being stimulated by a general lack of transparency in the decision-making processes of regulatory institutions. The pesticide and agribusiness industry, farm managers and farm labourers, researchers and extension workers, consumers, various government agencies (agriculture, natural resources, health and environment) and, sometimes non-governmental organisations participate in policy formulation. Potentially, all groups provide information and exert political pressure to the regulatory agency (Cropper et al. 1992). The various groups have different interests in regulatory decisions and can thus gain or loose from such decisions. Their impact on the regulatory agency, however, depends on how effective they are in organising themselves. The actual power structure among the groups favours the unilateral use of pesticides. In Germany it is the chemical industry that so far represents its interest with the necessary pressure, clarity and advocacy.

3. The resource cost problem in pest management

Applying pesticides is interference in nature, which ultimately affects natural resources. One such resource is the susceptibility of pest populations to control by pesticides (Hueth and Regev, 1974). Resistance, a process that continuously takes place ever since pesticides are being used, is the expression of depleting this resource. The economic implications of resistance are that either the dose level has to be increased or new, more expensive pesticides have to be used. Carlson (1979) has shown that the marginal physical product of cotton insecticides is declining over time as a result of resistance. The case of cotton (Archibald, 1988) and vegetable production in Asia (Waibel and Setboonsarng, 1993) are good examples of the implications brought about by pesticide resistance.

The second natural resources, which can become affected by pesticides, are beneficial organisms. Natural enemies of pests act as a biological control factor available to growers as common property resource. As a side effect, pesticides tend to destroy beneficial organisms by reducing their numbers or even causing their extinction in certain ecosystems. These negative off-time externalities lead to the depletion of the natural resource „beneficial organisms“. This influences the costs and returns of alternative pest management strategies that rely on such self-regulating forces of the agro-ecosystem, e.g. IPM. Decisions on pesticide use taken in past periods thus lower the profitability of IPM strategies in the future.

Internalising the true costs of using both types of natural resources, i.e. susceptibility of pest populations and abundance of beneficial organisms into a market process, faces two fundamental problems of economic analysis. Both, susceptibility towards pesticides and presence of beneficial organisms, are common property resources. Also, the cause and effect relationship between resource stock and depleting factors can not always be established in a direct manner. Besides direct toxic effects from pesticide use, species diversity is also affected by the general trend towards specialisation and intensification in cropping systems, which of course is again facilitated by pesticides. These factors prevent that a resource like the abundance of natural enemies can easily be priced. Even if scarcity exists individuals owning the resource can make no capital gains.

The second problem is that scarcity of these resources cannot be observed on a short term. The effect of a depleted ecosystem resulting in more frequently occurring pest outbreaks is not necessarily perceived as a result of prior pesticide use. Some empirical evidence for such processes is indicated by the results of global crop loss assessment (Oerke et al., 1994) which show tendency to increase. As these effects occur in the long run only, a model is needed that takes into account inter-temporal competition for natural resources. Economists can then assess the inter-temporal opportunity costs of the resource depletion, which is currently excessive, i.e. at the expense of tomorrow's farmers. The implicit resource price is the result of a simulated inter-temporal optimal allocation showing the resource rent, also

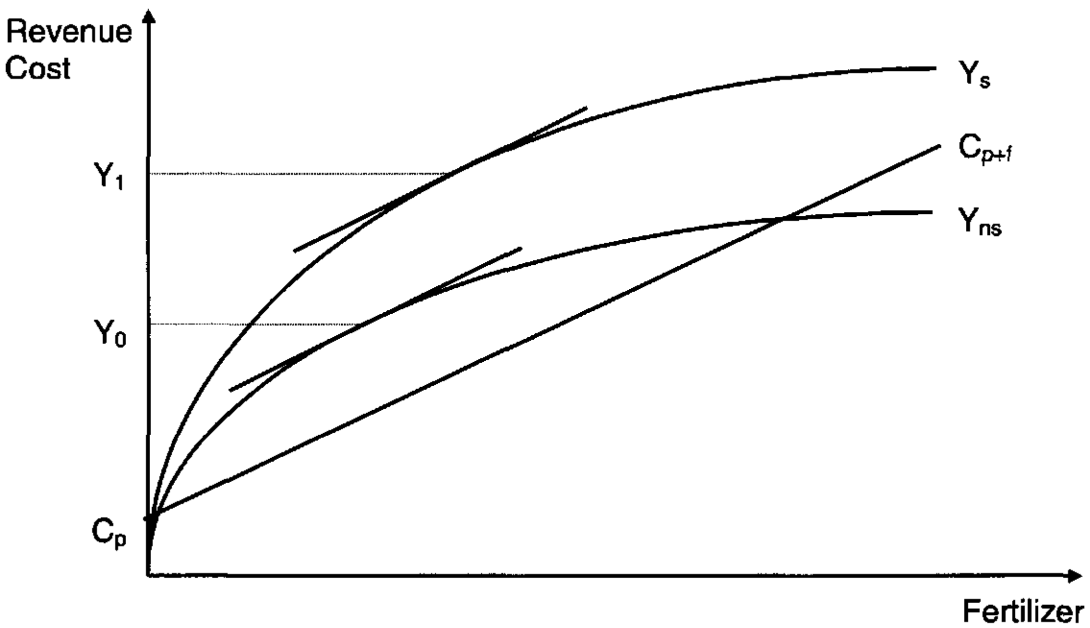


Figure 1a. Costs and revenues of pesticide use in t_0. The economics of pesticide use over time.

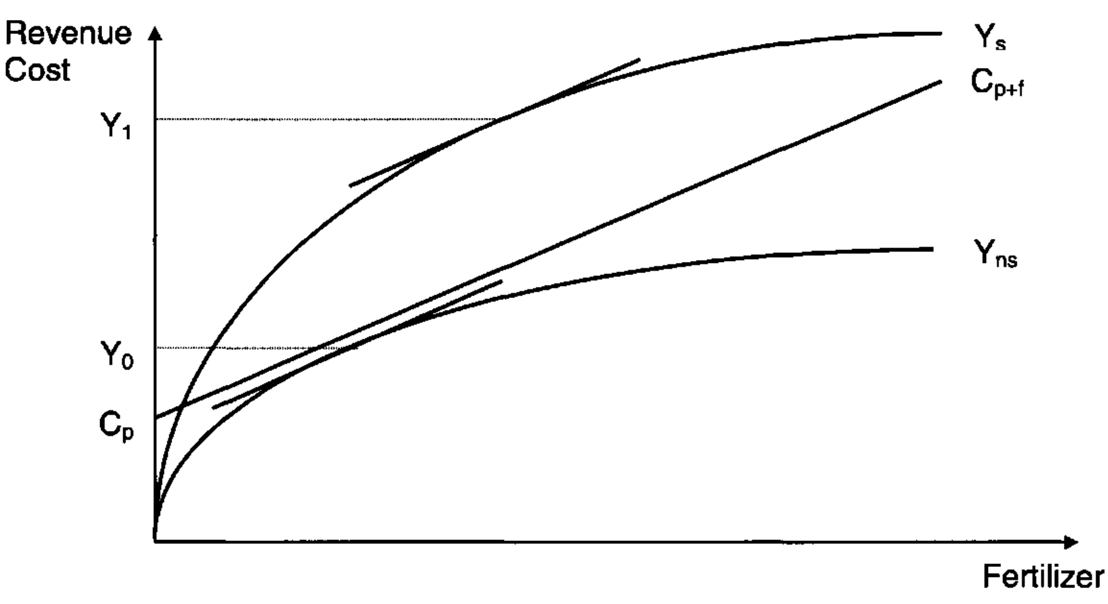


Figure 1b. Costs and revenues of pesticide use in t_1.

ns = non spray	*p* = pesticide	*f* = fertiliser	*Y* = Yield
s = spray		*C* = Cost	

called user costs. User costs have to be added to the price of pesticides resulting in a social price, i.e. the market price of pesticides plus user costs (ignoring all other external costs attributable to that pesticide). Following the Hotelling rule (Pearce and Turner, 1990) user costs (R_t) depend on the rate of interest (s) of alternative assets as expressed in Hotelling's (1931) basic equation:

$$R_t = R_o e^{st}.$$

The path of the resource price over time reaches its maximum when it intersects the price of an alternative technology, say a new pesticide or another, non-chemical control method. Ignoring user costs would cause a sudden shift in the costs of a technology by the time the resource is depleted.

The theoretical effect of resource depletion on pesticide productivity for the case of natural enemies is illustrated in Figures 1a and 1b. Figure 1a shows the conventional fertiliser production function under a with and without situation. The shift in the yield/revenue curve is supposed to be the result of applying pesticides. The cost of pest control is the intercept of the fertiliser cost curve. Hence, net benefits of pesticide use equate to the difference in the revenue curve minus pesticide costs. Higher pest pressure as a result of pesticide application in prior periods will make the revenue curves to drift apart (Figure 1b). As long as the divergence in the revenue curve is larger than the increase in the cost curves, the marginal product of pesticide use will increase. Hence, pesticides appear to become more profitable over time. The process is stopped when the net revenue curve of the current cropping system falls below an alternative, presumably less pesticide-intensive system. From a private producer's point of view, a change in the cropping system is not economical before that point is reached, hence the farmer has become dependent on pesticides. This dependency is shown in an increase in the marginal product of pesticides relative to other input factors when taking the farmer's point of view within the framework of a partial analysis. Under a resource economic framework this additional „benefit" is actually an expression of the depletion of natural resources and thus has to be interpreted as costs.

Some indications for the existence of user costs of pesticides could be shown by a study of the agricultural sector of Germany. The analysis uses time series and cross sectional data from the annual report of the state of agriculture in Germany. This report is based on farm accounting data of sample farms located in different agro-ecological zones (BML, various years).

Differing from the yield differences in Figure 1, we use in the model the amount farmers spend on pesticides over time in order to test the hypothesis of pesticide dependency of the cropping system. The model explains the trend in pesticide use over time across a wide range of farming environments expressed in different farming systems. The basic idea of the model - based on economic theory - is to include the major determinants of pesticide use, i.e. as far as they are available from the agricultural statistics. In addition to the economic variables, proxies for the state of the ecosystem, which predetermine the economic need for pesticide use must be found.

In a formal expression the model we used includes the following variables :

$\ln PS_t = f(\ln PS_{t-1}, \ln F_t, \ln Yw_t, P_c/P_{ps}, Yw_{rel}, D_m, T)$

where

PS_t: amount spent on pesticide in DM/ha in period t

PS_{t-1}: amount spent on pesticides in the prior year

F_t: the amount of fertiliser spent in t

P_c/P_{ps}: ratio of the index of cereal prices to pesticide prices

Yw_t: yield of winter wheat in t

Yw_{rel}: proportion of wheat in the total crop area

D_m: dummy for mixed farms

T: trend variable

The lagged variable PS_{t-1} is used as the proxy for the inter-temporal pesticide dependency. Partially this effect would also show up in the trend variable, which however will also include any changes in the technical efficiency of pesticide use.

The variable F_t is based on a two variable production function with an assumed positive relationship between the intensity levels of fertiliser and pesticides. Similarly, P_c/P_{ps} is based on production theory assuming non-zero price elasticity under profit maximisation behaviour. Further, Y_{wt} is taken as a proxy for technical progress in crop production, while Yw_{rel} would indicate the vulnerability of the cropping system towards pest attack as a high share of wheat in the rotation tends to increase the pressure from diseases and weeds. The dummy variable for mixed farming system is to be interpreted in the same manner. Cropping systems of mixed farms are supposed to show a better self-regulating capacity and thus have a lower degree of pesticide dependency.

Data for the model calculations were obtained from the Ministry of Agriculture's database of farm accounting data and cover the period of 1981/82 to 1990/91 (before German unification). The database covers 41 agro-economic zones differentiated by seven farming systems and two organisational groups namely part-time and full-time managed farms. For the analysis only full-time farms of two systems types, namely cash crop farms (mainly cereal-sugar beet cropping systems) and mixed (integrated) farming systems were selected.

Preparation of the data for the analysis required introducing some assumptions in order to specify the variables. For example, the amount of organic fertiliser which plays an important role especially in the mixed farms, was based on the amount of manure converted into nutrient contents and valued at replacement costs. Expenditures on pesticides were related to the area of field crops as pesticide use in grassland is negligible.

In the following some model calculations results are shown in order to investigate the plausibility of the hypothesis on which the model is based. In Table 1 results for whole Germany (before unification) and for the state of Lower Saxony are presented. The equation for whole Germany is statistically significant but shows a coefficient of determination of only 0.588. The equation for Lower Saxony however gives a satisfactory statistical fit ($R^2 = 0.78$). In both models most of the variables have positive signs. The lagged variable of pesticide use in prior periods is, as expected, positive and highly significant with similar results for both areas. The same is true for the trend variable. The economic variable P_c/P_{ps} confirms the assumption of a positive reaction of farmers to an increase in the ratio of crop prices to pesticide prices but price elasticity seems to be low. As expected, the yield level of wheat has a positive influence on pesticide use with a moderate elasticity. Somewhat surprising is the negative sign for the fertiliser variable. A possible explanation is that those farms with higher fertiliser levels are more efficient pest managers. The dummy for mixed farms shows the expected sign but is not significant in the equation for all areas. In both cases the variable has a surprisingly low value. This might be related to the fact that mixed farms are more likely to overuse pesticides. Knowledge and access to information might be less in mixed farms who are more likely to belong to the group of late adopters of a technology.

Growth rates of pesticide and fertiliser inputs derived from the slope of a general growth function showed that in some agro-ecological zones pesticide growth rates are higher in mixed, i.e. diversified farming systems as compared to the more specialised cash crop farms (Waibel and Fleischer, 1997). This is more pronounced in the hilly-upland areas where adjustment to the ratio of crop prices to factor prices set by the agricultural policy during that period (i.e. before CAP reform) occurred with some delay. The negative average growth rate for fertiliser confirms the general observation that farmers gradually reduced the overuse of fertiliser.

Several variations of the model for different groups of agro-ecological zones did not change the direction of the results. The hypothesis that there exists an inter-temporal relationship in pesticide use therefore cannot be rejected. Of course a more solid conclusion could be reached if the database could be amended by information on long-term agro-ecological trends. For example, if information on the changes in the pest population patterns

Table 1. Results of regression estimates to explain pesticide use in German agriculture.

Variables	All agro-ecological zones		Lower Saxony	
	Regression coefficient	Prob. level	Regression coefficient	Prob. Level
Constant	-0.14	0.7	1.25	0.07
PS_{t-1} (ln)	0.643	0.001	0.6	0.001
F_t (ln)	-0.068	0.03	-0.113	0.03
Y_{wt} (ln)	0.384	0.001	0.094	0.375
P_c/P_{ps}	0.644	0.012	0.867	0.002
Yw_{rel}	-	-	0.450	0.004
D_m	-0.025	0.245	-0.080	0.048
T	0.040	0.001	0.044	0.001
R^2	0,588		0.785	
N	599		120	

Source: own calculations

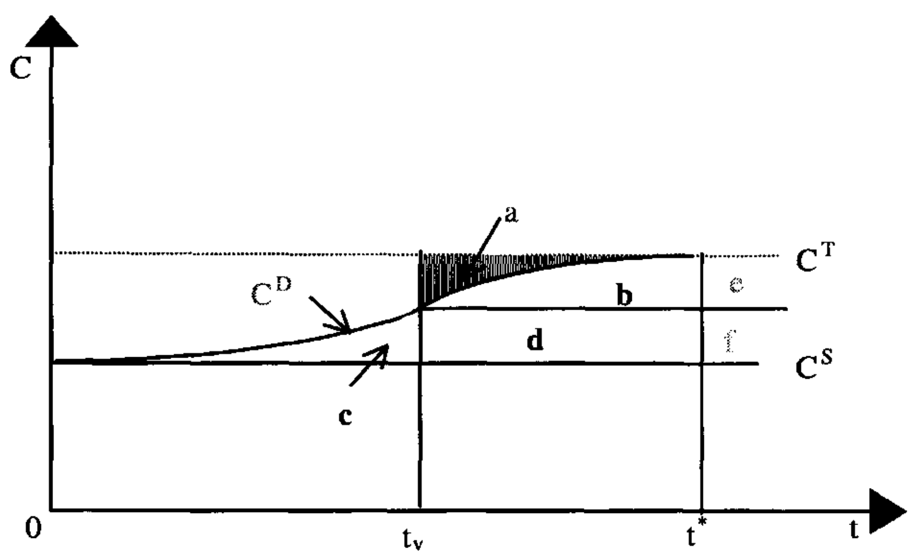
as well as their beneficial organisms were available a refined analysis based on agro-ecological zones will make the model more realistic. Nevertheless, based on the theory of natural resources it can concluded that in the assessment of pesticide productivity a framework is required which takes into account the state of nature of an ecosystem. In this framework all available options of control have to be considered including especially non-chemical options such as the crop management practices.

4. Case study of the resource costs of atrazine use in maize

Indications of the existence of resource costs and pesticide dependency were given for the level of the total agricultural sector. However, the analysis is constrained by the unavailability of appropriate ecosystem variables that can adequately describe the change in the expected value of pest attack and the overall state of resistance against pesticides. Therefore results of such aggregate analysis remain less convincing.

To show clearer evidence for the existence of resource costs case studies are more appropriate. Fleischer (1998) has recently completed a case study for the herbicide atrazine. Until its ban in German agriculture in 1991, atrazine was the most important herbicide in maize cultivation. In fact, it has much facilitated the increase in the share of maize in the rotation. During the eighties residues in ground water were discovered, and as a result a political decision was made to ban atrazine. Predictions were made that maize production would loose in competitiveness because of the assumed high economic value of atrazine from the farmer's point of view. However, if resource costs of atrazin were considered the economic loss due to the atrazine ban is much smaller.

Theoretically, a herbicide with a high frequency of use is likely to develop resistance. Susceptibility of weed populations towards chemical control decreases, and resistant individuals spread. Hence, costs for chemical weed control will increase over time as other, more expensive control options have to be used. C^S in Figure 2 shows the costs of sustainable weed control. Costs relative to other economic factors would remain constant if no resistance would occur. In reality the real costs of weed control due to herbicide resistance increase following a polynomial curve (Zwerger and Walter, 1994) as indicated by C^R in Figure 2 until



C^S = Costs of crop protection at sustainable resource use
C^D = Costs of crop protection under resource degradation (e.g. resistance)
C^T = Costs of substitute control technology
t^V = Timing of ban for a pesticide
t^* = Timing of technology change without ban
Source: Fleischer (1998)

Figure 2. Impact of pesticide ban on the resource costs of pest control.

they have reached the costs of a substitute technology C^T. Areas *b, c* and *d* are then the resource costs attributable to resistance development, while areas e and f represent the loss of control options as susceptibility is considered to be a non-renewable resource. If a pesticide is being banned at a time t^V for political or environmental reasons, i.e. before the resource has been used up in t^*, additional costs occur as indicated by the shaded area *a*.

Those farmers which have used less resources, pay a higher penalty than those who have used the compound more intensively and have thus actually caused the negative external effects that may have prompted the regulatory authorities to impose the ban.

Resistance to atrazine is caused by a high frequency of applications (Zwerger and Walter, 1994) as a result of a high share of maize in the cropping pattern. For calculating the resource costs of atrazine use, plot-specific panel data collected by a market research company were used (Anonymous, 1996). The sample included weed control inputs on 1428 plots over a period of 1987 to 1993. The data were grouped according to the share of maize in the cropping area and divided in high, medium and low maize intensive cropping patterns.

To estimate resource costs by cropping pattern the time period between the point of departure from the sustainable cost path (low maize intensity) and the maximum level of resource costs has been simulated by maximising the coefficient of determination for alternative adjustments of the panel data to the theoretical resistance curve. As expected the time span for resource depletion decreases with increasing maize share in the rotation. For high maize intensity cropping this point is reached after about 11 years whereas it takes about 20 years in the medium maize intensity. Knowing the time span, the shape of the resource cost curve and the respective maize areas we may calculate the resource costs as well as the adjustment costs to be borne by farmers as a result of an atrazine ban.

Table 2 shows the adjustment costs caused by an atrazine ban taking into account the resource costs. Because adjustment costs can only be considered until the resource susceptibility would have been fully used, the group that practices „sustainable" weed control in maize is given the highest burden, while the high maize intensity farmers pay less. Because these costs are future costs, discounting becomes necessary. Depending on the discount rate which is an expression of the society's time preference the present value is high if society considers the resource „susceptibility" to atrazine to be important. In fact, a value of an infinite rent can be computed if the option of conserving the effectiveness of the compound exists (Table 2).

Table 2. Adjustment costs to atrazine ban in maize, in mill DM per hectare (Germany before reunification).

Rate	R 1[1]		R 2		R 3		Total	
Discount rate	PV[2]	rent[3]	PV	rent	PV	Rent	PV	rent
0.01	412.5	4.1	153.9	1.5	27.9	0.3	**594.3**	**5.9**
0.05	283.2	14.2	122.8	6.1	25.1	1.3	**431.2**	**21.6**
0.1	193.4	19.3	96.6	9.7	22.3	2.2	**312.3**	**31.2**

1 share of maize in crop rotation: R1 < 30 %, *R2* = 30 - 60 %, *R3* > 60 %
2 present value of adjustment costs (PV = Σ ($a_t \cdot q^{-t}$)); a = adjustment costs, q = 1*+i; I = discount rate
3 infiniterent ($a = K_o * i$); a = rent , K_o = total cost, I = interest
Source: Fleischer (1998)

This case study shows that ignoring resource costs leads to an overestimation of the foregone benefits of atrazine use as a result of a ban. Undoubtedly the ban of atrazine, a compound , which had been used by over 70 % of farmers in Germany, increased the costs in maize production considerably in the first year after the ban. However, subsequently farmers realised efficiency gains in weed control, which partly offset the additional costs. The real issue of the atrazine ban, however, is that under the current regulatory framework, farmers that practice sustainable crop protection with a more careful use of natural resources are being punished by the non-sustainable practices of their high intensity farmer companions. Non-sustainable crop protection becomes a public bad (the opposite of a public good) that needs to be given much more attention in crop protection research.

5. Implications for research

The three case study results have shown some application of economic analysis in crop protection that is different from conventional „costs and returns". Some conclusions can be drawn as to possible research gaps in crop protection.

The first case, which deals with external costs of pesticides in German agriculture, questions the general philosophy that is currently followed in chemical oriented crop protection. The existing paradigm of searching for solutions within narrowly set limits on the one hand and of trying to define limit values that suggest safety, does not meet the criterion of sustainable crop protection. It puts crop protection scientists into reactive position and draws resources away from more fundamental questions. The existence of significant external costs despite of sophisticated regulatory procedures calls for more interdisciplinary interaction. Pesticides are no longer only technical problems but have long become a social problem. The registration process of chemical pesticides should be amended by an economic analysis of the long-term effects on the farming sector. Charging a risk premium for chemical pesticide use could mitigate the inevitable problem of resistance development.

The second example demonstrates that myopic optimisation overestimates pesticide productivity. The long-run assessment of pesticide productivity requires the comparison with non-chemical options. Economic models need to incorporate the state of the ecosystem. This creates a demand to crop protection scientists to come up with studies that indicate dynamic changes in the ecosystem, e.g. by a probability distribution of pest levels over time.

The third example clearly points to the implications of equity and intergenerational distribution of chemical pest control. Good agricultural practices of the frontier farmers may cause externalities to farmers that follow a more sustainable path. Research must address these issues by identifying the basic ecosystem interactions in relation to human interference. Participatory approaches that foster the understanding of farming communities for ecological processes and their likely economic implications require a new type of farmer and ecosystems oriented research.

The intergenerational issue in pest management demands to consider option values. New pest control technologies like genetically modified plants must be checked towards their „susceptibility" for path dependence. There is some danger that gene-tech may suffer a similar fate as it happened to chemical pesticides because the technology has been introduced in the agricultural sector in a short period of time without carefully designed pilot testing and subsequent evaluation. There is always the danger that benefits of new and dramatic technologies become overestimated. Research emphasis in pest management in future should pay more attention to the potential and actual benefits of technology by comparing real alternatives.

References

Anonymous (1996) Panel Data on Maize Herbicide use 1987 to 1993 in Germany. Produkt und Markt Wallenhorst (Germany) unpublished

Archibald SO (1988) Incorporating Externalities into Agricultural Productivity Analysis. In Agricultural Productivity - Measurements and Explanation, ed. by SM Capalbo and JA Antle Washington DC

Arthur B (1989) Competing Technologies, Increasing Returns and Lock-in by Historical Events. The Economic Journal 99: 116-131

BML (Federal Agricultural Ministry) Farm Accountancy Network Data. Bonn, various years

Carrasco-Tauber C and Moffitt LJ (1992) Damage Control Econometrics - Functional Specification and Pesticide Productivity. American Journal of Agricultural Economics 75: 158-162

Carlson GA (1979) Long Run Productivity of Insecticides. American Journal of Agricultural Economics 56: 543 - 548

Cowan R and Gunby P (1996) Sprayed to Death - Path Dependence, Locked-in and Pest Control Strategies. The Economic Journal 106: 521-542

Cropper ML, Evans WN, Berardi S, Dulca-Soares U and Portney PR (1992) The Determinants of Pesticide Regulation. A Statistical Analysis of EPA Decision Making. Journal of Political Economy Vol 100 (11): 175-197

David P (1985) Clio and the Economics of QWERTY. American Economic Review, Proceedings 75: 332-337

Fleischer G (1998) Economic Analysis of Pesticide Policy - The Case of Registration Decisions (in German). In: Landwirtschaft und Umwelt, Kiel (in press)

Headley JC (1968) Estimating the Productivity of Agricultural Pesticides. American Journal of Agricultural Economics 50: 13-23

Hotelling H (1931) The Economics of Exhaustible Resources. Journal of Political Economy 39: 137-175

Hueth D and Regev U (1974) Optimal Pest Management with Increasing Resistance. American Journal of Agricultural Economics 56: 543 - 552

Lichtenberg E and Zilberman D (1986) The Econometrics of Damage Control: Why Specification Matters. American Journal of Agricultural Economics 68: 261-273

Lütke-Entrup N and Hensche H. (1995) Umweltrelevante Verhaltensmuster der Landwirte - Umsetzungsstrategien und Transferdefizite für den integrierten Pflanzenbau in Nordrhein-Westfalen. Gesamthochschule Paderborn-Soest

Oerke EC, Dehne HW, Schönbeck F and Weber (1994) Crop Production and Crop Protection - Estimated Losses in Major Food and Cash Crops. Elsevier Amsterdam.

Oskam AJ(1994) Pesticides the Issue at Stake for Agricultural Economists. In Michalek J and CH Hanf (eds) The Economic Consequences of a Drastic Reduction of Pesticides in the EU Kiel

Pearce DW and Turner RK (1990) Economics of Natural Resources and the Environment. John Hopkins University Press Baltimore

Rola AC, Pingali PL (1993) Pesticides Rice Productivity and Farmers' Health - an Economic Assessment. International Rice Research Institute (IRRI) Los Baños Philippines

Waibel H and Fleischer G (1997) The Incorporation of User Costs in the Assessment of Pesticide Productivity. In: AJ Oskam and RAN Vijftigschild (eds): Policy Measures to Control Environmental Impacts from Agriculture Workshop on Pesticides Wageningen August 24th - 27th, 1995. Proceedings and Discussions. Wageningen Agricultural University Department of Agricultural Economics and Policy May 1997

Waibel H and Setboonsarng S (1993) Resource Degradation Due to Chemical Inputs in Vegetable-based Farming Systems in Thailand. Journal of the Asian Farming Systems Association Vol 2 (1): 107-120

Waibel H und Fleischer G (unter Mitarbeit von) Becker und Runge-Metzger A (1998) Kosten und Nutzen des chemischen Pflanzenschutzes in der deutschen Landwirtschaft aus gesamtwirtschaftlicher Sicht Kiel

ZwergerP und Walter H (1994) Modelle zum Management herbizidresistenter Unkrautpopulationen. Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz, Sonderheft XIV 409-420

2.2 Development of bio-control technology using a Systems approach

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A model has been developed which simulates the temporal and spatial dynamics of greenhouse whitefly and the parasitoid *Encarsia Formosa* in a tomato crop. The pest-parasitoid interaction is based on the local searching and parasitization behaviour of individual parasitoids in the whitefly-infested crop. The model comprises several sub-models for (a) the parasitoid's foraging behaviour, (b) the whitefly and parasitoid population development, (c) the spatial distribution of whitefly and parasitoid in the crop, and for (d) leaf production. The model will allow us

(1) to explain why the parasitoid can control whiteflies on some crops and not on others in large commercial greenhouses,
(2) to improve introduction schemes of parasitoids for crops where previous control was ineffective,
(3) to predict effects of changes in cropping practices (e.g. greenhouse climate, choice of cultivars) on the reliability of biological control, and finally
(4) to develop criteria for the selection of natural enemies.

1. Introduction

Greenhouse and sweet potato whitefly (*Trialeurodes vaporariorum* and *Bemisia tabaci*) is very common, highly polyphagous pest insects worldwide. Biological control of greenhouse whitefly with the parasitoid *Encarsia Formosa* has been applied with great commercial success during the past 20 years. One of the problems was that in some key greenhouse crops (e.g. tomato) results were very reliable, while on other important crops (e.g. cucumber) control often failed. Another, more recent problem, is that *E. Formosa* does not seem to be a suitable parasitoid for the control of *Bemisia* and new natural enemies need to be evaluated. Modelling has always played an important role in the process of selecting and improving the efficacy of releases of natural enemies, but often biologically unrealistic simplifications were part of these models which strongly limited their predictive value.

We started a long-term project consisting of modelling and experimentation, with the aim to obtain quantitative understanding of this tritrophic system to explain failure or success of biological control. Because of the multitude of relationships between the trophic levels, the most important quantitative factors can only be traced after integration of all relevant processes. Systems analysis and simulation are powerful tools for this purpose. The study aims at integrating existing knowledge on the major processes known to affect the whitefly-parasitoid interaction in a crop by means of an explanatory simulation model. In this paper we summarise the work of the first phase, which was limited to the tritrophic system tomato-greenhouse whitefly-*Encarsia Formosa*.

We developed a model which is unique in that it is individual-based (Judson, 1994) and simulates the local searching and parasitisation behaviour of individual parasitoids in a whitefly-infested crop. The model includes stochasticity and spatial structure based on location co-ordinates of plants and leaves. This model comprises several sub-models for (a) the parasitoid's foraging behaviour, (b) the whitefly and parasitoid population development, (c) the spatial distribution of whitefly and parasitoid within and between plants in the crop, and for (d) leaf production. With the model we can simulate temporal and spatial dynamics of pest and natural enemy. The model will allow us

2. Direct observation experiments on foraging of *E. Formosa*

When the present research project started, the behaviour of *E. Formosa* had been observed in various experiments (for a review see Noldus & van Lenteren, 1990). *E. Formosa* is a solitary larval parasitoid: females lay one egg per host during an oviposition. Like in other synovigenic parasitoids new eggs mature when the egg load of the parasitoid drops below the storage capacity, which is 8-10 mature eggs for *E. Formosa.* About ten days after oviposition the immature parasitoid pupates in the host pupa, which (in case of greenhouse whitefly) then turns black and parasitism can easily be seen from the outward appearance of the whitefly. Female parasitoids produce daughters parthenogenetically. Males are rarely observed.

The parasitoid searches for the sessile whitefly immatures by flying or hopping from leaf(let) to leaf(let), without distinguishing between infested and clean plants or leaves before landing. Once on the leaf she starts walking and drumming the leaf with her antennae. Hosts are encountered randomly and the walking pattern is not changed after an encounter with a host. After an encounter, four behaviours on that host can be distinguished: the parasitoid may reject the host after an inspection with the antennae (antennal rejection) or after insertion of the ovipositor (ovipositorial rejection), she may parasitize (oviposition) or she may use the host as a food source (host feeding).

These earlier experiments however, did not lead to a complete picture of foraging behaviour. Quantitative data on some aspects were lacking, such as on the parasitoid's searching or walking activity between host encounters, and on the effect of temperature on the foraging processes. In many of the earlier experiments parasitoids were confined to an experimental area, and therefore little was known about the time allocation of the parasitoid on leaves, such as the time until leaving, the time spent on upper and lower leaf side, and how these are affected by encounters with or ovipositions in hosts.

Before developing simulation models these gaps in our knowledge were identified and studied experimentally. Experiments were carried out where individual parasitoids were observed continuously until they flew away, either on clean tomato leaflets, on leaflets with honeydew, or on leaflets with unparasitized and parasitized whitefly larvae (Van Roermund & Van Lenteren, 1995a,b; Van Roermund et al., 1994). The parasitoid's residence time on leaflets, its leaving tendency and effects of temperature and several experiences with hosts were quantified. Other basic aspects of foraging that have been quantified were the parasitoid's walking speed and walking activity, the probability of each handling behaviour to occur after an encounter with a host and the host handling times. These data enabled quantification of the parasitoid's foraging process from landing on a leaf until its departure. This work resulted in the following conclusions:

- The parasitoid *E. Formosa* searches at random without a preference for the edge or the middle of a leaf, or for the upper or lower leaf side, whereas its hosts, the whitefly immatures are present only on the lower side of a tomato leaflet.

- The median residence time of the parasitoid on uninfested tomato leaflets (or giving up time, GUT) is 18.6 min at 20, 25 and 30°C and equal to that on infested leaflets on which no hosts are encountered.
- Parasitoids are arrested on the leaf by encounters with, and especially by ovipositions in unparasitized hosts, by encounters with parasitized (unsuitable) hosts and by contact with honeydew. The time since latest host encounter until departure (GUT) is again 18.6 min, whether the hosts were already parasitized or not. It increases to 40 min after the first

oviposition in an unparasitized host occurring on the leaflet.
- Parasitoids are arrested on the lower leaf side by encounters with hosts, and especially by ovipositions in unparasitized hosts. The median time since the arrival on a particular leaf side or, if it occurred, since the latest host encounter on that leaf side until changing to the other side (time until changing, TUC) is 11.6 min, but drops to 5.7 min when the parasitoid has visited both sides of the leaflet. After the first oviposition in an unparasitized host, TUC on the lower leaf side (where hosts are present) becomes twice as long.
- Parasitoids usually leave from the upper leaf side, because no hosts will be encountered there.
- The leaving behaviour of the parasitoid on a leaf can be described by a stochastic threshold mechanism, which is characterized by a certain tendency (probability per time) to leave. The parasitoid leaves after the host encounter rate falls below a certain threshold (encounters per time, which is the reciprocal of GUT). This threshold is not fixed, but shows a great variation and is expressed as a probability.
- The parasitoid's walking speed increases linearly between 15 and 25-30°C.
- The parasitoid's walking activity (% of time walking on the leaf surface compared to the total time on the leaf without handling hosts) is very low at temperatures below 18°C and increases to about 75% at 20, 25 and 30°C. The walking activity is not affected by host encounters, but decreases with decreasing egg load after 4 ovipositions.
- The percentage of encounters resulting in an oviposition is about 75% for the most preferred stage (unparasitized L4 larva), but decreases with decreasing egg load.
- Host handling behaviour and handling time is not influenced by the host plant.
- The total handling time (including drumming etc.) for antennal rejection of an unparasitized hosts is about 20 s, for oviposition and for ovipositional rejection about 6 min, and for host feeding about 15 min. These handling times slightly differ when hosts are parasitized.
- Self-superparasitism is not observed. Conspecific-superparasitism occurs in 14% of the contacted hosts containing a parasitoid egg, but is not observed anymore when the parasitoid egg had hatched.
- No difference is observed in host handling behaviour between naive and experienced parasitoids.
- Many inactive parasitoids are observed when the barometric pressure had decreased over a time span of at least 12 h.

3. Simulation models of foraging behaviour of *E. Formosa*

The information described above was used as input in the simulation models of *E. formosa*'s foraging behaviour (van Roermund et al., 1996, 1997a,b). Foraging behaviour is analyzed using Monte Carlo simulation at three spatial scales: in a small experimental arena, on a tomato leaflet and on a tomato plant. Foraging behaviour is first studied at these small spatial scales, to better understand the quantitative effects of parasitoids on whitefly populations as observed in a crop. The above simulation models are *mechanistic*, that is, they explain *how* parasitoids, in terms of searching efficiency, host handling and available eggs, realize the observed level of parasitism. Mechanistic explanations can help to understand failure or success of biological control in practice. The models do not provide a *functional* explanation of the observed behaviour.

The simulated number of hosts encountered, parasitized and killed by host feeding, and the residence times on leaflets were validated with experimental data and the simulation results agree well with these observations. According to the model, *E. Formosa* can parasitize 16 hosts per day on average at 25°C on a tomato leaflet if they start searching with a full batch of mature eggs and if host density is not limiting. Thus about 7 new eggs mature during the day (16 h) at that temperature. From the second day onwards, the parasitoid can parasitize 11 hosts per day, due to egg limitation. If the parasitoid laid all eggs the preceding day, only 4 eggs mature during the night (of 8 h) at 25°C, so the parasitoids do not have a full batch of mature eggs the next morning.

The model shows that at a density of one L3 larva per tomato leaflet, 15.7% of the parasitoids discover the larva before they leave. Also at higher host densities, not all hosts are encountered and patches (leaflets) are not depleted after one visit. Variation in number of encounters and ovipositions between parasitoids is considerable, mainly caused by the random encounter of hosts, the variation in handling behaviour of an encountered host and by the variation in GUT and TUC.

In greenhouses, whiteflies show a clustered distribution over plants and leaves and average numbers are usually very low. The models show that at such conditions the number of parasitizations on tomato leaflets or plants is strongly affected by the leaf area, the parasitoid's walking speed and walking activity, the probability of oviposition after encountering a host, the initial egg load (egg load at the beginning of the experiment) and the ratio of search times on both leaf sides. At extremely high host densities, the egg storage capacity and the initial egg load of the parasitoid are most important, and on plants with a clustered host distribution also the parasitoid's GUT plays an important role.

At all tested spatial scales, the number of encounters, ovipositions and host feedings increase with host density with a decelerating rate until a maximum level is reached. This shape of the curves resemble a Holling Type II 'functional response', which is caused by the parasitoid's decreasing walking activity and smaller probability of oviposition after encountering a host, when egg load decreases. This is predominant at all levels, and even a change in GUT from 18.6 to 40 min after the first oviposition on the leaf does not result in an accelerating increase of the curve. The shape of the curves, describing the effect of host density on parasitism as a result of the basic processes, helps to understand the dynamics of the host-parasitoid interaction at the population level. In case of a Type II functional response, the percentage of parasitism declines with increasing host density and parasitism is inversily dependent density dependent upon a high host density thus reduces the per capita parasitization pressure caused by one parasitoid.

According to theory, inverse density dependence tends to have a destabilizing effect on the dynamics of host and parasitoid (see, e.g., Murdoch & Oaten, 1975; Oaten & Murdoch, 1975). However, the functional response or the parasitization pressure caused by one parasitoid is only one factor in determining the dynamics at the population level. Another factor is the number of parasitoids on the leaf. For *E. Formosa*, the effect on the population level depends on the balance between the parasitization pressure caused by one parasitoid and the arrestment and subsequent aggregation of parasitoids on leaves with high host density (see below).

4. Life-history parameters of greenhouse whitefly and *e. Formosa*

Life-history parameters of the greenhouse whitefly and *E. Formosa* are reviewed in Van Roermund & Van Lenteren (1992a,b). Data from literature were selected on development rate of each immature stage, percentage mortality of each immature stage, sex ratio, longevity, pre-oviposition period, period of increase of daily oviposition, fecundity and oviposition frequency. Most of these experiments have focused on the effect of temperature with little attention to other environmental factors such as humidity or light. Using these data, the relationship between the life-history parameters and temperature was assessed by non-linear regression. For each life-history parameter five different curves were fitted, the best being selected on the basis of the coefficient of determination (R) and on visual comparison, which was necessary to check whether a curve was biologically realistic, particularly the tails. Coefficients to describe the mean of each life-history parameter as a function of temperature are summarized in these papers. Coefficients of variation (*cv*: sd/mean) among individuals are also given. These coefficients are used as input in the submodels of population development of whitefly and parasitoid (see below).

For greenhouse whitefly, the life-history parameters depend very much on the host plant.

For *E. Formosa*, data for several host plants were combined. The high R^2 values indicate that host plant effects can be disregarded for the parasitoid's life-history parameters, except for oviposition at low host densities, which is caused by differences in the parasitoid's walking speed and walking activity on leaves with a different morphology. The immature development rate and immature mortality of the parasitoid is strongly affected by the host instar which was parasitized. The development rate is calculated as the reciprocal of the stage duration. For all immature stages of whitefly and parasitoid the relationship between development rate and temperature is described by the Logan curve: just above the lower threshold temperature, the development rate increases exponentially to an optimum, whereafter it declines sharply until the upper lethal temperature has been reached. The relationships of longevity, fecundity, and oviposition frequency with temperature are described by the Weibull curve: they increase exponentially from the lower lethal temperature to an optimum, whereafter they decrease exponentially. Only for *E. Formosa*, the longevity decreases exponentially with temperature and an optimum was not found at greenhouse conditions. No relationship with temperature was found for the immature mortality, the sex ratio and the *cv* values of the life-history parameters of whitefly and parasitoid.

5. Simulation model of whitefly-parasitoid interaction in a crop

The final model simulates the population dynamics of the pest insect-parasitoid interaction in a tomato crop (Van Roermund, 1995; Van Roermund & Van Lenteren, 1995c; Van Roermund et al., 1997c). The model is based on the parasitoid's searching and parasitization behaviour and on developmental biology of the two insect species. This model comprises several submodels, such as the submodel for whitefly population development, for parasitoid population development, for the parasitoid's foraging behaviour on tomato leaflets (Van Roermund et al., 1997a), for spatial distribution of whitefly and parasitoid in the canopy based on dispersion of adult whiteflies and parasitoids from leaf to leaf, for leaf production and a submodel for checking simulation errors. Life-history parameters of Van Roermund and Van Lenteren (1992a,b) are used as input in the submodels for population development of whitefly and parasitoid on tomato. The model is unique in that it is an individual-based model which simulates local searching and parasitization behaviour of a large number of individual parasitoids in a whitefly-infested crop. The model includes stochasticity and spatial structure which is based on location coordinates of plants and leaves.

The model was validated with population counts from experiments on tomato with and without introduction of *E. Formosa* in small greenhouse compartments and in a large commercial greenhouse. The simulated population increase of greenhouse whitefly in the *absence* of parasitoids agree well with the observations. This result can for an important part be explained by the accurate estimates of the life-history parameters, which are based on many experiments at a wide temperature range (see Van Roermund and Van Lenteren, 1992a,b).

With these life-history parameters as input in the model, the intrinsic rate of increase (r_m) of both insect species was simulated. The r_m of *E. Formosa* is much higher than that of the greenhouse whitefly above 14°C. The r_m of a parasitoid however, plays a limited role in biological control, because it is only valid when all parasitoids can lay their daily egg load. This can only happen at extremely high host densities when the parasitoids do not have to spent much time searching for hosts. In greenhouses whitefly densities are usually much lower and the realized whitefly density depends on the parasitoid's searching efficiency. Therefore, to evaluate and understand success or failure of biological control, r_m values are inappropriate and it is essential to built models, which include searching and parasitization behaviour of the natural enemy at very low host densities.

Also in the *presence* of parasitoids, the simulation results agree well with greenhouse observations on tomato. Apparently, the hypothesised random host encounter of *E. Formosa* in a tomato crop is reliable. In the model, the parasitoid does not distinguish between uninfested and infested leaflets before landing, the parasitoid searches randomly for hosts once on the leaflet, and shows a strong arrestment effect on the leaflet once a host is encountered. Simulations show that the adult parasitoid-whitefly ratio is very high and can even reach 250:1. As a result, whiteflies are suppressed rather than regulated by the parasitoids at extremely low host densities (< 0.3 unparasitised pupae per plant), but never become extinct. These whitefly densities are much lower than the economic damage threshold for greenhouse whitefly. Percentage black pupae fluctuates between 40 and 70%. According to the model, the parasitoid adults reach high densities of 7.4 per plant, but due to the low whitefly density not more than 1% of the parasitoids is searching on infested leaflets.

The giving up times (GUT) of *E. Formosa* vary to a large extend (van Roermund et al., 1994). The degree of whitefly control is very sensitive to those GUT's lower than 800 s of the parasitoids. The whiteflies are suppressed at much lower densities when the parasitoids stay *at least* five minutes on each leaflet (infested or uninfested) and after each host encounter. This minimum time increases the arrestment effect and the resulting percentage of parasitoids on infested leaflets, thereby reducing the chance that clustered hosts escape from parasitism. When variation in GUT is excluded in the model, the whitefly population becomes less stable and nearly goes extinct. Variation in GUT on leaflets induces host refuges from parasitoid attack. Also from more theoretical studies, host refuges are known to stabilise populations (Murdoch and Oaten, 1975; Chesson and Murdoch, 1986).

Whitefly adults migrate to young leaves in the top of the plant. A slower leaf production results in a longer stay and more ovipositions of whitefly adults on a particular leaflet. Thus, the same numbers of hosts are distributed over fewer leaflets, resulting in a more aggregated host distribution. Whiteflies are then suppressed by *E. Formosa* to much lower numbers, according to the model. Parasitism of one *E. Formosa* female on a tomato leaflet is inversely density-dependent, which is caused by a decreasing walking activity and smaller probability of oviposition after encountering a host, when egg load decreases (Van Roermund et al., 1996, 1997a,b). Host aggregation thus 'dilutes' the per capita parasitization pressure caused by one parasitoid on the leaflet. The effect on the population level, however, depends on the balance between this 'dilution' effect and the strength of the arrestment and aggregation of *E. Formosa*. Therefore, the stronger whitefly reduction when whiteflies are more aggregated is caused by a stronger parasitoid arrestment on infested leaflets. As a result, the relative number of parasitoids searching on these leaflets increases.

This shows that differences in whitefly distribution among crops are one factor in causing differences in success of biological control. Other factors are the size, number and surface (hairiness) of leaves in the canopy. Leaf size and total leaf area have a strong effect on whitefly control according to the model, caused by their direct effect on host density. Furthermore, leaf size and leaf surface strongly affect the efficiency of *E. Formosa* by changing the parasitoid's arrestment effect (GUT) and the walking speed and activity, respectively.

Another important factor is the whitefly development duration on the crop. The model shows that plant resistance breeding aimed at an increase in egg-to-adult duration of the whiteflies is very efficient in causing a severe reduction of whitefly numbers, when biological control is applied. Observed development times of whitefly differ very little between tomato genotypes, and a much larger difference is found for whitefly longevity, oviposition rate and immature mortality. These parameters have a smaller effect on whitefly population development.

The important factors or crop properties affecting the success of biological control cannot be compared independently. For instance crops with large leaves usually have a lower number of leaves which are produced at a lower rate than crops with small leaves or leaflets. It is particularly the combined effect of these important factors that can be tested with this model for different crops or plant varieties.

In biological control programs, parasitoids are usually tested in small-scale experiments at high host densities before introduction in the field. As a result, maximum daily oviposition of parasitoids is measured, whereas this study shows that egg storage capacity and egg maturation rate of *E. Formosa* is not important for the level of whitefly control. In commercial greenhouses, whitefly densities have to be very low for biological control to be regarded, as successful, therefore effective host searching is the most essential process. When selecting parasitoids for biological control, attention should be focused on the parasitoid's arrestment effect (minimum GUT), walking speed, walking activity, the probability of oviposition after encountering a host, the ratio of search times on both leaf sides and on longevity, when comparing different synovigenic and solitary parasitoid species with random search. These characteristic attributes of parasitoids are easily measured in laboratory studies. Again, they cannot be compared independently, however, because the attributes of natural enemies are often found in particular combinations. The combined effect of these important attributes of a parasitoid can be tested with this model.

6. Conclusions

The study aimed at integrating existing knowledge on the major processes known to affect the whitefly-parasitoid interaction in a crop. Because of the multitude of relationships between the three tropic levels (crop-pest-parasitoid), it was decided to follow a combined experimental-simulation approach. The goal was to obtain quantitative understanding of the tritrophic system to explain failure or success of biological control. With the model we now unravelled the ability of *E. Formosa* to reduce whitefly populations on greenhouse tomato. The study resulted in understanding of the relative importance of basic processes that affect the population interaction of whitefly and natural enemy. The life history of parasitoids often summarised in a r_m value, less important than the parasitoid's searching capacity. This shows that in addition to the traditional selection criteria, a criterion based on searching efficiency is essential. The study further generated knowledge on foraging behaviour of *E. Formosa.* A large effect of variation in patch times of individual parasitoids on the whitefly population in the greenhouse shows that individual-based models which include stochasticity and local searching behaviour are a necessity when developing models of host-parasitoid interaction at extremely low host densities and aggregated host distributions.

One of the questions was to identify the main causal factors for differences among crops in success of biological control of whitefly. The parasitoid is more successful on tomato than on cucumber or gerbera. The present study showed that attention should be focused on differences in the parasitoid's arrestment effect (GUT), the parasitoid's walking speed and activity, the whitefly development duration and the number, size and production of leaves in the canopy. When adapting the parameters in the model for gerbera and cucumber we are able to

(1) explain the lower ability of the parasitoid to reduce whitefly populations on these crops,
(2) improve introduction schemes of parasitoids for these crops, and
(3) predict effects of changes in cropping practices (e.g. greenhouse climate, choice of cultivars) on the reliability of biological control.

Further, the model is being used to evaluate effects of temperature and day-length on biological control and yield of a tomato crop. As a result, greenhouse climate control may not only be based on crop characteristics (yield, quality, timing) and production costs, but also on prevention of production risks like the environment-friendly control of pests. With the model, recent problems with the use of *E. Formosa* in greenhouses during autumn/winter will be tried to solve by evaluating effects of increased temperatures during short periods of the day. In another project, the model is being used to evaluate several parasitoids of the silverleaf whitefly (Drost et al., 1996). The model thus assists in identification of the characteristics, which compose an efficient natural enemy. Good evaluation criteria allow for a choice between useless and potentially promising natural enemies. Systems analysis and simulation are important tools for integration of criteria, but go beyond the mere comparison of parasitoids, as they also take characteristics of the pest, the crop, and the environment into account.

References

Chesson P and Murdoch WW (1986) Aggregation of risk: relationships among host-parasitoid models. Am. Nat. 127: 696-715
Drost YC, Fadl Elmula A, Posthuma-Doodeman CJAM and Van Lenteren JC (1996) Development of. selection criteria for natural enemies in biological control: parasitoids of Bemisia argentifolii. Proc Exper Entomol, NEV Amsterdam, 7: 165-170
Judson OP (1994) The rise of the individual-based model in ecology. Tree 9: 9-14
Murdoch WW and Oaten A (1975) Predation and population stability. Adv Ecol Res 9: 2-131
Noldus LPJJ and Van Lenteren JC (1990) Host aggregation and parasitoid behaviour: biological control in a closed system. Mackauer M, Ehler LE and Roland J (eds) Critical Issues in Biological Control. Intercept Andover pp 229-262
Oaten A and Murdoch WW (1975) Switching functional response and stability in predator-prey systems. Am Nat 109: 299-318
Van Roermund HJW (1995) Understanding biological control of greenhouse whitefly with the parasitoid Encarsia Formosa. From individual behaviour to population dynamics.
PhD Thesis Wageningen Agricultural University The Netherlands 243 pp
Van Roermund HJW and Van Lenteren JC (1992a) The parasite-host relationship between Encarsia Formosa (Hymenoptera: Aphelinidae) and Trialeurodes vaporariorum (Homoptera: Aleyrodidae) XXXIV. Life-history parameters of the greenhouse whitefly Trialeurodes vaporariorum as a function of host plant and temperature. Wageningen Agric Univ Papers 92.3: 1-102
Van Roermund HJW and Van Lenteren JC (1992b) The parasite-host relationship between Encarsia Formosa (Hymenoptera: Aphelinidae) and Trialeurodes vaporariorum (Homoptera: Aleyrodidae) XXXV. Life history parameters of the greenhouse whitefly parasitoid Encarsia Formosa as a function of host stage and temperature. Wageningen Agric Univ Papers 92.3: 103-147
Van Roermund HJW and Van Lenteren JC (1995a) Foraging behaviour of the whitefly parasitoid Encarsia Formosa on tomato leaflets. Entomol Expl Appl 76: 313-324
Van Roermund HJW and Van Lenteren JC (1995b) Residence times of the whitefly parasitoid Encarsia Formosa Gahan (Hym., Aphelinidae) on tomato leaflets. J Appl Ent 119: 465-471
Van Roermund HJW and Van Lenteren JC (1995c) Simulation of biological control of greenhouse whitefly with the parasitoid Encarsia Formosa on tomato. Proc Exper and Appl Entomol, NEV Amsterdam 6: 153-159
Van Roermund HJW, Hemerik L and Van Lenteren. JC (1994) Influence of intra-patch experiences and temperature on the time allocation of the whitefly parasitoid Encarsia Formosa (Hymenoptera, Aphelinidae). J Insect Behav 7: 483-501
Van Roermund HJW, Van Lenteren JC and Rabbinge R (1996) Analysis of the foraging behavior of the whitefly parasitoid Encarsia Formosa (Hymenoptera: Aphelinidae) in an experimental arena: a simulation study. J Insect Behav 9: 771-797
Van Roermund HJW, Van Lenteren JC and Rabbinge R (1997a) Analysis of the foraging behavior of the whitefly parasitoid Encarsia Formosa on a leaf: a simulation study. Biological Control 8: 22-36
Van Roermund HJW, Van Lenteren JC and Rabbinge R (1997b) Analysis of the foraging

behaviour of the whitefly parasitoid Encarsia Formosa on a plant: a simulation study. Biocontrol Science and Technology 7: 131-151

Van Roermund HJW, Van Lenteren JC and Rabbinge R (1997c) Biological control of greenhouse whitefly with the parasitoid Encarsia Formosa on tomato: an individual-based simulation approach. Biological Control 9: 25-47

2.3 Integrated pest management: the case of flower bulb Production in the Netherlands

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1. Introduction

In the second part of this century the bulb-growing industry in the Netherlands and in other bulb-producing countries had to cope with two major societal changes. Between roughly 1950 and 1980 a sharp increase in the costs of labour without a concomitant rise in bulb-selling prices forced farmers to scale up, to intensify and to replace labour by capital-intensive machinery. The concurrent introduction on the market of various groups of pesticides with a then unprecedented efficacy and reliability compensated for the additional risks emanating from intensification, mechanical handling and reduced attention to the crop.

Since the early eighties the bulb-growing industries have to cope with a second major challenge: the society. The markets are becoming increasingly demanding, not only with regard to product quality, but also with regard to the quality of the production process. Application of improved analytical techniques showed that pesticides or their break-down products occur in low but detectable amounts in almost all environmental compartments, e.g., in soil, ground and surface water, and in the air (Faasen, 1992; Van Aartrijk et al., 1995; MJP-G, 1996; Jansma and Linders, 1995; Hopman et al., 1992). Eco-toxicological effects of such contaminations have been shown. To avoid further ecological damage, the regulations set by governments for the registration of existing and new pesticides have been tightened. As a consequence, the number of available, registered active compounds is decreasing and will presumably show a further decline in the future, especially for smaller crops. This development is stimulated further if target organisms become resistant against specifically acting pesticides.

A new concept for crop protection in the future was formulated in the late eighties in The Netherlands. This concept aims at reducing the dominant role of pesticides in crop protection and consists of four strategies:

- a reduction of the dependence on pesticides,
- a reduction of the volume of detrimental pesticides used,
- a reduction of the emissions to environmental compartments, brought about by pesticide applications, and
- a re-evaluation of the registration of the pesticides used.

This article summarises part of the progress and problems in the process of adjustment of the bulb industry in the Netherlands.

2. Characterization of the flower bulb industry

The acreage of flower bulbs in the Netherlands is increasing slowly but steadily, and amounted to 18,650 ha in 1996 on 3000 farms (Voortgangsreportage, 1997). Most of the flower bulbs are still grown in the coastal sandy regions of the provinces of North and South

Holland and Flevoland, but there is a tendency of spreading to heavier soils and other regions (Table 1).

Table 1. Acreage of flower bulbs in different regions in the Netherlands.

Province	Acreage (ha)	Acreage (% of total)
North Holland	11,265	60
South Holland	2,685	14
Flevoland	2,052	11
Brabant/Limburg	1,044	6
Gelderland/Utrecht	339	2
Zeeland	290	2
Other	975	5

With regard to the acreage, tulips and lilies are the most important crops (Voortgangsreportage, 1997), as illustrated in Table 2. Flower bulb culture is a knowledge- and capital- intensive process (planting stock, suited soils, buildings, storage cells, and machinery). Annual yields per ha may amount to Dfl 10,000 - Dfl 100,000. Consequently, growers tend to avoid unnecessary risks as much as possible. Inputs of pesticides have been and are regarded as effective means of reducing production risks. In 1988 (Anonymous, 1991) annual inputs of pesticides were estimated to be 123 kg a.i. per ha. Major changes in the production process, such as required in disease management, increase the grower's perception of production risks. Therefore, changes are generally realised in a step-by-step manner.

Table 2. Acreage of flower bulbs for different crops.

Crop	Acreage (ha)	Acreage (% of total)
Tulip	8,747	47
Lily	3,289	17
Gladiolus	1,569	8
Narcissus	1,473	8
Hyacinth	1,067	6
Iris	677	4
Other	1,828	10
Total	18,650	100

3. Organisation of the turn-around process

Realisation of major changes in the organisation of a single firm with a clear hierarchy generally requires much effort and perseverance. This is the more so for large, diffusely organised structures as the bulb industry, consisting of thousands of private farms. Therefore, at first the Dutch bulb industry has created a broad forum, the so-called 'Milieuplatform', to co-ordinate measures and the policy on pesticide use. Then, the joint bulb industry and various national and local authorities formulated and signed a covenant on reduction of pesticide use and emissions to the environment (Convenant, 1995). In regular consultations of the various organisations (such as ministries, provinces, municipalities, water-boards, 'Milieuplatform') decisions are taken on priorities and measures. This so-called

'Doelgroepoverleg' publishes an Annual Report describing the progress and the problems in the process.

If progress is hampered by a lack of knowledge or techniques, projects are formulated and carried out to gather the necessary information. Disease management in the future, which will be less dependent on pesticide use, requires a lot of knowledge to be produced in research programmes carried out by various organisations. In the next chapters an overview will be given of recent developments with regard to the various strategies.

4. Independence of pesticides

Realisation of this strategy is very time-consuming. Various approaches can be distinguished:

4.1 Breeding techniques and resistance breeding

Increased attention is paid to the improvement of breeding techniques - especially in tulip and lily - in order to extend the options for genetic recombination. Transformation and genetic modification were realised for lily (Langeveld et al., 1995; Langeveld, 1996; Van der Leede-Plegt et al., 1995), tulip (Wilmink et al., 1995), and gladiolus (Kamo et al., 1995a; Kamo et al., 1995; Straathof et al., 1997). Crossing barriers between distantly related species of tulip and lily were analysed and *in vitro* techniques were developed to overcome such barriers. As a result, crosses could be made between -until recently- incompatible species (Kerckhoffs and Meyer, 1993). Cultivation *in vitro* of microspores of tulip resulted in the regeneration at low frequency of haploid offspring (Van den Bulk et al.,1994), which offers a perspective for acceleration of breeding programmes in this crop.
Resistance breeding programmes were carried out in lily, gladiolus, and tulip. The main emphasis is on diseases caused by more or less specialised pathogens such as
- formae speciales of *Fusarium oxysporum* in lily (Straathof et al., 1994; Straathof et al., 1994), gladiolus (Straathof et al., 1996; Straathof et al., 1997) and narcissus (Linfield, 1994),
- viruses (tulip breaking virus, lily symptom-less virus), and
- *Botrytis tulipae* in tulip.

4.2 Biological control

A completely different approach, i.e. biological control in its broadest sense, was chosen to control some other, generally less specialised parasites.

The first biological control agent introduced into practical flower bulb culture is the predatory mite *Hypoaspis aculeifer*, which was shown to be very effective against *Rhizoglyphus* mites in lily (Lesna et al., 1996). The gladiolus thrips *Taeniothrips simplex* can be controlled equally well by various predators, such as *Amblyseius barkeri* (Conijn, 1993). Economic barriers have prevented practical application in this crop as yet. Similar approaches offer good perspectives for the control of the dry bulb mite *Aceria tulipae* in tulips.

Polyphagous nematodes such as the tobacco rattle virus (TRV) -transmitting Trichodoridae and the root-lesion nematode Pratylenchus were controlled by preventive soil fumigation in the past. Results in recent years (Asjes et al., 1996) showed that Trichodorids are attracted to roots by root-produced chemical stimuli, the reach of which is dependent on soil type and soil-water flux. Laboratory and field experiments have shown that interception of the stimulus, e.g., by organic matter, prevented nematode migration and, consequently, TRV transmission and plant damage. Inter-cropping of subsequent bulbous crops with specific non-hosts, e.g. easy to grow *Tagetes spp.* against Pratylenchus and black raddish against Trichodorids and TRV, can also considerably reduce risks on bulb yield and quality (Asjes et al., 1996; Conijn, 1994).

Sandy soils used for flower bulb or bulb flower cultivation in the Netherlands appear to be relatively conducive to the soil fungus *Pythium spp.*, especially after soil treatments such as steam sterilisation, fumigation, or flooding and if suitable nutrient sources are available in the soil (Van Os, 1995; Van Bruggen and Duineveld, 1996). In the laboratory, well-timed introduction of a specific antagonist *(Laetisaria arvalis)* or a less-defined mixture of mesofilic organisms in compost could render suppressiveness against Pythium, thus reducing risks on infection. Ongoing experiments will make clear whether these effects can also be realised under greenhouse and field conditions.

A similar approach was chosen for the control of *Rhizoctonia solani* (Schneider et al., 1996).

4.3 Healthy mother stock

Special attention to disease-free mother stock is a common feature in bulb cultivation and very effective for the control of a broad range of menacing organisms.

In a long-term program, efforts were and are made to improve the virus situation in bulbous crops. In recent years, application of ELISA-tests on dahlia tubers used for the production of cuttings resulted in a sharp decline of tomato spotted wilt virus (TSWV)-incidence in this crop, thus preventing a possible need for intensive crop sprays to prevent spread of this virus by thrips vectors (Asjes and Blom-Barnhoom, 1997; Derks and Lemmers, 1996; Van Schadewijk-Nieuwstadt and Derks, 1995). Virus-free plantlets were produced by meristem culture of hyacinth cultivars bearing hyacinth mosaic virus. An improved technique was developed for meristem culture of bulbous iris (Van Schadewijk-Nieuwstadt M and Derks 1995).

Hot-water treatments are already successfully applied on a large scale to control stem nematodes (*Ditylenchus spp.*) and various insects and mites. Such treatments were optimised in recent years for lily to control root-borne *Pratylenchus penetrans* (Conijn, 1996) and are being developed or modified for a number of special crops, such as *Allium spp.*, Hippeastrum, Colchicum, Fritillaria, Galanthus, Erythronium and various other geophytes (e.g., Aconitum, Hosta, Phlox) (Muller, 1994; Van Leeuwen and Van der Weijden, 1994; Van der Meij, 1998; Van Leeuwen and Van der Weijden, 1993; Van Leeuwen et al., 1993).

4.4 Diagnosis

Reduced availability or use of pesticides also emphasises the need for rapid and discriminative tools for diagnosis. In the past few years a computer-based expert diagnosis system EXSYS was developed for bulbous iris (Kramers et al., 1997). This system is now being tested by potential users. Extension of EXSYS to other crops awaits the results of this testing period.

Improved identification techniques were developed, often on subspecies level, for various viruses (Derks et al., 1994; Derks and Lemmers, 1996; Langeveld et al., 1997), fungi (formae speciales of *Fusarium oxysporum,* AG-groups of *Rhizoctonia solani,* and *Pythium spp.*) (Mes et al., 1994a; 1994b, Schneider et al., 1997), and for *Xanthomonas campestris* pv. *hyacinthi*, the cause of yellow disease in hyacinth (Van Doorn, 1993; Van Doorn, 1995).

5. Reduction of pesticide volume

This strategy is still based on the use of pesticides, be it in dosages and application frequencies as low as possible and with pesticides selected for relative environmentally friendly characteristics. A few approaches can be distinguished. Generally, these approaches are less knowledge-intensive and their development less time-consuming. Major steps can be made and have been made in a relatively short period.

5.1 Guided control

A computer model is developed and tested, that based on a regional 5-day leaf-wetness forecast calculates as to whether the Botrytis-infection risk will exceed a threshold level, taking into account genotype susceptibility and moment of the last pesticide treatment. Additionally, if a crop spray is calculated to be necessary, the related 5-day weather forecast also allows the selection of a suited spraying period. Such a guided control system for 'fire' has been tested for several years in lily, tulip, and gladiolus. Preliminary results indicate that adequate control can be realised using 20-100% less fungicides (Bastiaansen et al., 1997). In 1998, such a warning system for lilies will be introduced on the market. Other examples of guided control relate to Pratylenchus and TRV. A decision as to fumigate soils (or to apply other control measures) is made only when the population density of Pratylenchus or the TRV-infection pressure in the soil exceeds set threshold values. Both control systems show clear perspectives but have to be optimised yet.

A final example of a guided control system is in weed control. Instead of preventive treatments with soil herbicides crop sprays with very low herbicide concentrations are applied when a 'flux' of tiny germinated weeds can be observed. In gladiolus and iris, some of the crops for which the technique has been developed already, a reduction of roughly 50% in herbicide use is possible (Koster et al., 1996; Koster et al., 1994). Except for tulip and hyacinth, the technical prospects for other crops are good.

5.2 Reconsideration of existing recommendations and techniques

Considerable reduction of pesticide volumes and emissions were also achieved by critical reconsideration and fine-tuning of existing recommendations. To give some examples:

- adjustments of the recommended crop treatments for the control of Botrytis allowed a lower crop-spraying frequency and a 50% or more reduction in active compounds sprayed (Koster and Van der Meer, 1992; Koster et al., 1994).
- decreased susceptibility for viruses after flowering of lily allowed a 50% lower frequency of sprays against aphid-transmitted viruses after flowering (Asjes, 1993).
- changing from specific to more or less uniform bulb disinfection treatments for the various bulb crops reduced the amount of fungicides required and of immersion-bath remnants.
- Site-specific application of pesticides. Examples are in furrow treatments instead of field applications of soil fungicides against *Rhizoctonia spp.* (Koster and Van der Meer, 1988) and plant row instead of field treatments with herbicides. The latter system is being investigated now in combination with mechanical weed control in between the plant rows and in the paths.

6. Reduction of emissions

This strategy aim at the reduction of emissions of pesticides to environmental compartments in addition to the reductions brought about by the decrease in pesticide use. Extensive field experiments revealed that the most important emission pathways to surface water are related to spray-drift and to farm buildings. Leakage of pesticides to soil and surface water is of minor or no importance for most pesticides (Van Aartrijk et al., 1995). Various studies are carried out to reduce these sources for emissions (Van IJzendoorn et al., 1995; Beltman and Boesten, 1996; Wondergem, 1995; Porschkamp et al., 1997).

7. (Re)evaluation of pesticides

Based on criteria that are uniform in all countries of the European Union ('uniform principles') all existing and new pesticides will be reregistered resp. registered. In the Netherlands, applications of registered compounds will not be allowed to exceed threshold levels in various compartments. It is yet unclear for many applications what the consequences of this policy will be. It may well be that (applications of) certain registered compounds will be prohibited.
Moreover, the number of applicable compounds may also be limited by a purely commercial development: the registration of pesticides for application in minor crops becomes unprofitable for phyto-pharmaceutical industries. Probably, a system of 'off-label use' may contribute to solving this problem.

8. Evaluation and perspectives

The applied volume of pesticides in the bulb industry in the Netherlands decreased ever since 1988. In 1996 a reduction was realised of 43% compared to 1988 (after correction for changes in the acreage of various crops (Voortgangsrapportage, 1997)).

In experimental 'integrated farming' systems the actual reductions amount to 80 - 95%, depending on the crops grown, and new improvements are regularly introduced (Wondergem et al., 1997). At present, priorities are in control of virus diseases of lily, in weed control and in bulb disinfecting treatments.

Most of the bulb growers have invested in improved equipment for bulb disinfecting and in spray-drift reduction in order to reduce emissions to surface water. A large and rapidly increasing number of farms have received a so-called 'WVO-license' from water-boards to conduce their farms. Compulsory registration of pesticide use has given a clear insight in the application of pesticides. On the other hand, in 1996 and based on data from 'monitoring studies' no improvement of surface water quality could yet be established. These studies will be continued in coming years.

The process of reducing pesticide inputs by the bulb industry has shown to be slow and stubborn, due to its complexity, to risk perception and to resistance of vested interests. However, substantial progress has been made in the last 5 years and there is an increasing willingness for further adjustments. To realise further reductions, the economic situation of the farms must be adequate and emphasis should be given to demonstration and extension of new techniques and recently obtained knowledge. In 1998, in a large project called 'Bollenteelt 2000', a number of bulb farms will be intensively trained and guided in order to introduce principles of 'integrated farming' systems on these farms.

9. References

Anonymous (1991) Meerjarenplan Gewasbescherming. Staatsdrukkerij The Hague
Asjes CJ (1993) Virusverspreiding en -bestrijding in lelies: Complex van factoren bepaalt virusverspreiding. Bloembollencultuur 104 (12): 26-27
Asjes CJ and Blom-Barnhoorn GJ (1997) Incidence and control of thrips-borne tomato spotted wilt virus in dahlia in the Netherlands. Acta Hortic 430: 625-632
Asjes CJ, Zoon FC, de Hey A, de Boer FA and Maas PWTh (1996) Geïntegreerde beheersing van trichodoride aaltjes en tabaksratelvirus via tussengewassen en organische toevoegingen. Gewasbescherming 27: 17-18
Bastiaansen C, Koster AThJ, Van de Meer LJ, Van de Ende E, Pennock I, Groen NPA and Buurman FPM (1997) Vuurbestrijding: waarschuwingssysteem klaar voor praktijktest. Bloembollencultuur 108 (7), 26-27
Beltman WMJ and Boesten JJTI (1996) Emissies van bestrijdingsmiddelen bij het spoelen van bloembollen. Report 429 SC-DLO Wageningen The Netherlands
Conijn CGM (1993) Biological control of the gladiolus thrips Taeniothrips simplex on gladiolus corms in storage rooms with Amblyseius barkeri and Orius insidiosus. Med Fac Landbouww Univ Gent 58 (2a): 391-396
Conijn CGM (1994) Cultivation of *Tagetes patula* to control root rot in narcissus and lily caused by *Pratylenchus penetrans*. Med Fac Landbouww Univ Gent 59 (26): 807-811
Conijn CGM (1996) Lelieplantgoed: warmwaterbehandeling en invriezen doden veel wortellesie-aaltjes. Bloembollencultuur 108 (1), 36-37
Convenant ' Overeenkomst uitvoering milieubeleid bloembollensector' (1995). Doelgroepoverleg Bloembollensector Hillegom The Netherlands
Derks AFLM and Lemmers MEC (1996) Detection of tospoviruses in bulbous crops and their transmissibility by vegetative propagation. Acta Hortic 432: 132-139
Derks AFLM, Lemmers MEC and Van Gemen BA (1994). Lily mottle virus in lilies: characterization, strains, and its differentiation from tulip breaking virus in tulips. Acta Hortic 377: 281-288
Faasen R (1992) Landbouwbestrijdingsmiddelen in oppervlaktewater een situatieschets. H_2O 25(2): 30-33
Hopman R, Janssen HMJ, Van Beek CGEM and Puijker LM (1992) Speurtocht naar bestrijdingsmiddelen in de bronnen voor de drinkwaterbereiding. H_2O 25(7): 176-185
Jansma JW and Linders JBHJ (1995) Volatilization of pesticides from soil and plants after spraying. Repno 67910203. National Institute of Public Health and Environmental Protection Bilthoven The Netherlands
Kamo K, Blowers AD, Smith F and Van Eck J (1995a). Stable transformation of Gladiolus by particle gun bombardement of cormels. Plant Science 110: 105-111
Kamo K, Blowers AD, Smith F, Van Eck J and Lawson R (1995a) Stable transformation of Gladiolus using suspension cells and callus. J Amer Soc Hort Sci 120: 347-352
Kerckhoffs DMFJ and Meijer B (1993) New genetic variation in Lilium and tulip by wide hybridization. Proc XVIIth Eucarpia Congress San Remo Italy pp141-149
Koster AThJ and Van de Meer LJ (1988) Veurbehandeling tegen Rhizoctonia kan nog efficiënter. Bloembollencultuur 99 (20): 26-27
Koster AThJ and Van de Meer LJ (1992). Control of Botrytis spp. in tulip with reduced input of chemical crop protectants. In: Recent advances in Botrytis research. Proceedings Xth Int Botrytis Symp Heraklion Greece pp277-281
Koster AThJ, Brooymans EACM, Bastiaansen C, Van de Meer LJ, Buurman FPM and

Schouten CAM (1994) Vuurbestrijding lelie: Allure goede vervanger voor zineb/maneb. Bloembollencultuur 105 (11): 34-35

Koster AThJ, Van de Meer LJ, Buurman FPM and Schouten CAM (1994) Onkruidbestrijding in gladiool: minder middel nodig met lage-dosering-systeem. Bloembollencultuur 105 (8): 44-45

Koster AthJ, Van de Meer LJ, Kok H and Van Aanholt H (1996) Besparing op middelen mogelijk: lage-dosering-systeem biedt perspectief bij onkruidbestrijding iris. Bloembollencultuur 107 (5): 44-45

Kramers M, Conijn CGM and Bastiaansen C (1997) EXSYS, an expert system for diagnosing flowerbulb diseases. Acta Hortic 430, 651-656

Langeveld SA (1996) Introductie van virusresistentie in lelie door middel van genetische modificatie. Report Bulb Research Centre The Netherlands

Langeveld SA, Derks AFLM, Konicheva V, Munoz D, Zhinnan C, Denkova ST, Lemmers MEC, Boonekamp PM (1997) Molecular identification of potyviruses in Dutch stocks of Onarcissus. Acta Hortic 430 641-648

Langeveld SA, Marinova S, Gerrits MM, Derks AFLM and Boonekamp PM (1995) Genetic transformation of lily. Acta Hortic: 430, 290

Lesna I, Sabelis MW and Conijn CGM (1996) Biological control of the bulb mite *Rhizoglyphus robini* by the predatory mite *Hypoaspis aculeifer* in lilies: predator-prey interactions at various spatial scales. J Appl Ecology 33: 369-376

Linfield CA (1994). An investigation into the detection, identification, differentiation and pathogenicity of *Fusarium oxysporum* f sp *narcissi*. PhD Thesis University of Reading UK 227 pp

Mes JJ, Van Doorn J, Roebroeck EJA, Boonekamp PM (1994a) Detection and identification of Fusarium oxysporum f sp gladioli by RFLP and RAPD analysis. In: Schots A Dewey FM and Oliver R Modern Assays for plant pathogenic fungi Identification detection and quantification. CAB International Oxford UK

Mes JJ, Van Doorn J, Roebroeck EJA, Van Aartrijk J and Boonekamp PM (1994b) Restriction fragment length polymorphisms, races, and vegetative compatibility groups within a world-wide collection of Fusarium oxysporum f sp gladioli Plant Pathology 43: 362-370

MJP-G Emissie-evaluatie (1996) Report IKC-LNV Ede The Netherlands

Muller PJ (1994) Aconitum napellus, bladaaltjes goed te bestrijden met warmwater-behandeling. Bloembollencultuur 105 (22): 11

Porskamp HAJ, Michielsen JMGP and Van de Zande J (1997) Driftbeperkende spuittechnieken voor de bloembollen. Report 97-08, IMAG-DLO Wageningen The Netherlands

Schneider JHM, Dijst G and Schilder MT (1996) Rhizoctonia solani in tulp en iris in relatie tot de bodemreceptiviteit. Report 96-05. IPO-DLO Wageningen The Netherlands 42pp

Schneider JHM, Salazar O, Keijer RV and Keijer J (1997) Identification of Rhizoctonia solani associated with field-grown tulips using ITS rDNA polymorphism and pectic zymograms. Eur J Plant Pathol 103, 607-622

Straathof ThP and Van Tuyl JM (1994) Genetic variation in resistance to Fusarium oxysporum f sp lilii in the genus Lilium. Ann appl Biol 125, 61-72

Straathof ThP, Jansen J, Roebroeck EJA and Löffler HJM (1996) Fusarium resistance in gladiolus:selection in seedling populations. Plant Breeding 116: 283-286

Straathof ThP, Löffler HJM, Linfield CA, Roebroeck EJA (1997) Breeding for resistance to Fusarium oxysporum in flowerbulbs Acta Hortic 430 477-486

Straathof ThP, Roebroeck EJA and Löffler HJM (1994). Screening for Fusarium resistance in seedling populations of Asiatic Hybrid lily. Euphytica 78: 43-51

Van Aartrijk J, Groenendijk P, Boesten JJTI, Schoumans OF and Gerritsen R (1995) Emissies van bestrijdingsmiddelen en nutriënten in de bloembollenteelt Report 387 SC-DLO Wageningen The Netherlands

Van Bruggen AS and Duineveld TLJ (1996) The effects of Laetisaria arvalis and compost on *Pythium ultimum* root rot in a tulip forcing system. Proc 4th 10BC/EFPP Workshop Dijon France. IOBC Bulletin 19(6)

Van den Bulk RW, De Vries-Van Hulten HPJ, Custers JBM and Dons JJM (1994) Induction of embryogenesis in isolated microspores of tulip. Plant Science 104: 101-111

Van der Leede-Plegt LM, Kronenburg-Van de Ven BCE and Franken J (1995) Pollentransformatie: een methode voor de produktie van transgene lelies. Report CPRO-DLO Wageningen The Netherlands

Van der Meij J (1998) Warmwaterbehandeling van vaste planten ter bestrijding van wortelaaltjes. Report Bulb Research Centre Lisse The Netherlands

Van Doorn J (1993) LBO ontwikkelt nieuwe monoklonalen: verbeterde toetsing op geelziek in hyacinteblad. Vakwerk 67 (12): 10-11

Van Doorn J (1995) Detectie van geelziek: van sera naar DNA. Bloembollencultuur 106 (9): 24-25

Van IJzendoorn MT, Van Koster AThJ, Schouten JAM (19??) Spuiten: evenveel middel, minder drift. Bloembollencultuur 106 (13): 38-39

Van Leeuwen PJ and Van der Weijden JA (1993) Galanthus, warmwaterbehandeling effectief tegen stengelaaltje. Bloembollencultuur 104 (9): 29

Van Leeuwen PJ and Van der Weijden JA (1994) Allium giganteum and A. aflatunense zonder schade koken, voorwarmte noodzakelijk. Bloembollencultuur 105 (12), 23

Van Leeuwen PJ, Van der Weijden JA and Muller PJ (1993) Fritillaria imperialis: bladaaltjes zijn met een warmwaterbehandeling goed te bestrijden. Bloembollencultuur 104 (11), 36-37

Van Os GJ (1995) Pythium-aantasting: het gevolg van een verstoord biologisch evenwicht. Report Bulb Research Centre, Lisse The Netherlands 38 pp

Van Schadewijk AR (1996) Detection of tomato spotted wilt virus in dahlia. Acta Hortic 432: 384-391

Van Schadewijk-Nieuwstadt M and Derks AFLM (1995) Virusvrij maken iris: meristeem en bolbewaring bepalen rendement. Bloembollencultuur 106 (12): 22-23

Voortgangsrapportage Doelgroepoverleg Bloembollencultuur 1996-1997 (1997) Hillegom, The Netherlands

Wilmink A, Van deVen BCE, Custers JBM, Van Tuyl JM, Eikelboom W and Dons JJM (1995) Investigations on the genetic modification of tulip. In: Bajaj UPS (ed) Biotechnology in agriculture and forestry, Vol. 34 'Plant Protoplasts and genetic engineering VI', 296-303

Wondergem MJ (1995) Gewasbeschermingsmiddelen en nutriënten in compost en percolaatwater. Report 95 Bulb Research Centre Lisse The Netherlands

Wondergem MJ, Jansma JE and Snoek AJ (1997) Geïntegreerde bedrijfssystemen Bloembollenteelt. Jaarverslag 1995/1996 Bulb Research Centre, Lisse The Netherlands

3. On-the-road information systems

The additional value of information technology to management and planning, including uncertainties

Modern production ecology increasingly depends upon geographical information systems for 1) the optimal use of data and 2) an integrated approach to data use at various levels and scales. GPS and models, even meta-models, are necessary to apply at the field scale. Remote sensing may allow improved planning facilities. The development of technology allows to better incorporate these data into production ecolopgy. Uncertainty is always present and has to be optimally dealt with.

3.1 Geo-statistical and sampling design applications in precision agriculture

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1. Introduction

Precision agriculture involves characterising and managing the spatial variability in agronomic properties such as crop yield, soil fertility, or weed and pest populations. In precision agriculture, heterogeneous fields are not managed according to their mean characteristics, rather they are subdivided into relatively homogeneous management units. Each management unit is treated differently, according to its unique properties and characteristics, including water supply and storage capacity, soil nutrient availability, or weed and insect pressure.

Precision agriculture is dependent upon the accurate delineation of spatial patterns in the soil, landscape, and biological characteristics that control management decisions. Accurate delineation of these patterns relies, in turn, upon an appropriate sampling design and an appropriate procedure to estimate the attributes of unsampled locations. Spatial estimation is often achieved using geo-statistics. This paper will review some of the commonly used geo-statistical approaches for spatial interpolation, and some of the commonly used sampling designs. An example will be presented to illustrate the advantages and disadvantages of various strategies for spatial interpolation and sampling design.

2. Geo-statistics

Soil properties do not vary across the landscape in a random fashion. Typically, the values for a soil property from samples taken at close spacing will be similar or spatially correlated (Oliver, 1987). Soil properties from large sample spacing will typically be dissimilar and spatially uncorrelated.

Thus, we are often interested in knowing the spatial correlation structure of the population. The spatial structure of a population can be estimated using approaches developed in a branch of non-classical statistics known as geo-statistics (Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989; Cressie, 1991). Geo-statistics is a branch of applied statistics that quantifies spatial dependence and spatial structure of a measured property and in turn uses that spatial structure to predict values of the property at unsampled locations. These two steps typically involve spatial modelling (variography) and spatial interpolation (kriging).

In the jargon of geo-statistics, a random function is a property such as soil moisture or soil hydraulic conductivity, which can be sampled. This random function has a value at every point within the region to be studied, and successive samplings of the region are different realisations of the sample population frequency distribution. One realisation of this sub-sampling is a regionalized variable $Z(x)$, having data values $z(x_i)$, or simply z_i, at sampling locations x_i. There can be many realisations of the regionalized variable if the region is sampled many different times, with each realisation being a sub-sample of the sample population.

2.1 Variography

Spatial dependence can be quantified and modelled using the semivariogram (Burgess and Webster, 1980a). The semivariogram • *(h)* is estimated using the equation:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z_i - z_{i+h}]^2$$

where h is the separation distance between locations x_i and x_{i+h}, z_i and z_{i+h} are the measured values for the regionalized variable at locations x_i or x_{i+h}, and n(h) is the number of pairs at any separation distance h.

The semivariogram can be modelled using any of several authorised models (Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989; Oliver, 1987). These models are commonly fit to the semivariogram data using non-linear least squares with either uniform weighting of points or weighting that favours data at small separation distances (Cressie, 1985) over data at large separation distances. The most common models are the linear, spherical, and exponential models. For example the spherical model is given by:

$$\gamma(h) = C_0 + 0.5\, C_1 [(\frac{3h}{a}) - (\frac{h}{a})^3] \qquad for\ h < a$$

and

$$\gamma(h) = C_o + C_1 \qquad for\ h \geq a$$

The semivariogram model and its parameters provide a quantitative expression of spatial structure for the measured property. In these models, the fitted parameters have the following definitions (Journel and Huijbregts, 1978; Oliver, 1987; Oliver and Webster, 1991).

- C_0 is the nugget parameter, a measure of the amount of variance due to errors in sampling, measurement, and other unexplained sources of variance.
- The sum of parameters C_o and C_1 is the sill, theoretically equal to the variance of the sampled population at large separation distances if the data have no trend. If the nugget parameter is about equal to the sample variance it is an indication that the sampled property has very little spatial structure or varies randomly. In this case, the semivariogram would be best described using a linear semivariogram with a slope of zero, often referred to as a pure nugget effect

model (Oliver, 1987; Isaaks and Srivastava, 1989).

- Probably the most important of the semivariogram parameters for decisions concerning the spacing between sample locations is the range *(a)* (Table 1). At separation distances greater than the range, sampled points are no longer spatially dependent. This has great implications for sampling design. If a region is being sampled in order to understand the spatial pattern of a given property, it is advisable that the sampling design uses separation distances smaller than the range parameter of the semivariogram. Preferably, the sample spacing is from one-fourth to on half of the range (Flatman and Yfantis, 1984). If distances greater than the range separate samples, there is no spatial dependence between locations. It is then inappropriate to use geo-statistics.

Table 1. Published values for the range parameter *(a)* of semivariogram models for several measured soil and agronomic properties (Jury, 1986; Warrick et al., 1986; Wollenhaupt et al., 1997; McBratney and Pringle, 1997).

Property	Range of spatial dependence (m)	Type of spatial dependence
Saturated hydraulic conductivity	1-34	short range
Saturated water content	14-76	short to moderate range
Sand content	5-40	short range
Soil pH	20-260	short to long range
Crop yield	70-700	moderate to long range
Soil Nitrate-Nitrogen	40-275	moderate to long range
Organic matter content	112-250	long range
Soil available P	68-260	moderate to long range
Soil available K	75-428	moderate to long range

2.2 *Interpolation by kriging*

Kriging is a general term describing a geo-statistical approach for interpolation at unsampled locations. There are several types of univariate kriging methods, including punctual (Burgess and Webster, 1980a), indicator (Journel, 1986), disjunctive (Yates et al., 1986a,b), universal (Webster and Burgess, 1980), and block kriging (Burgess and Webster, 1980b). A multivariate form of kriging is known as co-kriging (Vauclin et al., 1983). Conditional simulation has also been applied to kriging (Hoeksema and Kitanidis, 1985; Warrick et al., 1986; Gutjahr, 1991).

The science of kriging was developed for the mining industry by Matheron (1963), and first applied in the mining industry by Krige (1966). Geo-statistical techniques, including kriging, were introduced into the European literature of soil science by Webster and his colleagues in

1980 (Burgess and Webster, 1980a,b; Webster and Burgess, 1980). Nielsen and his colleagues published important work on geo-statistical methods in the American soil science literature during the early 1980's (Vauclin et al., 1982, 1983; Vieira et al., 1983). The first applications of kriging to precision agriculture were introduced by Mulla (1991, 1993).

Kriging is known as the best linear unbiased predictor (BLUP). No other interpolation method provides less bias in predictions (Burgess and Webster, 1980a). This is because the interpolated or "kriged" values are computed from equations that minimise the variance of the estimated prediction error. In fact, when interpolating at a location where a measurement exists, kriging will always generate a value equal to the measured value. For this reason, kriging is often loosely described as being a type of linear regression in which the regression line always passes through every measured data point.

Several studies have been conducted in which comparisons were made between kriging and classical methods for interpolation (Dubrule, 1984; Laslett et al., 1987) such as inverse distance weighting and cubic splines. As a general rule of thumb, kriging is equivalent or superior to classical methods when the data to be interpolated have well developed spatial structure, have a semivariogram without a significant nugget effect, are sampled at spacing less than the range of the semivariogram, and are sampled in clusters or at irregular spacing. Inverse distance weighting tends to be more suitable for use with data having short-range variability (Cooke et al., 1993) than with data having long-range spatial dependence (Gotway et al., 1996). Spline based interpolation is perhaps better than kriging only in situations where an abrupt change in measured soil property values occurs across a short distance (Voltz and Webster, 1990).

A key conclusion from comparisons by Gotway et al. (1996) is that interpolation accuracy is more dependent up on the adequacy of the sampling design than on the type of interpolator used. When intensive sampling is conducted on a regular grid, there may be only small differences in interpolation with kriging, inverse distance weighting, or cubic splines. In view of this, Warrick et al. (1988) suggested that kriging would be the best choice for an interpolator, because it is the only method that allows the variance of an interpolated point to be estimated. Whelan et al. (1996) suggests that inverse distance weighting interpolators will outperform kriging interpolators for small sample sizes collected at moderate intensity.

<u>Punctual kriging</u>

Punctual kriging is essentially a linear interpolator, which sums up weighted values for measurements at locations neighbouring the unsampled location. The expression used in kriging is:

$$z_o = \sum_{i=1}^{N} \lambda_i z_i$$

where z_o is the interpolated value, N is the number of points neighbouring the interpolated location, z_i are the measured values at neighbouring locations, and $_i$ are the kriging weighting factors for each of the neighbouring measured values. The weighting factors must sum to unity so that the expected value of the interpolated points minus the measured points is zero. To further illustrate this concept, if interpolation occurs at a location where a measured value exists, the weighting factor is unity for the measured point at the location to be interpolated, and the weighting factors for all neighbouring locations are zero.

Block Kriging

As the previous section shows, punctual kriging is a method for estimating the value of a property at an unsampled point location. There are times when it is more appropriate to estimate the average value of a property in a block or small region around an unsampled point location. For example, data from the Landsat Thematic Mapper satellite are typically available at a spatial resolution of 30 m. If data are missing from some sections of the image due to interference from clouds, it would be useful to be able to estimate the average value for the missing data in the unsampled blocks. Alternatively, we may wish to estimate the average value of a soil property for mapping units of the soil survey, or the effective permeability in a particular strata of the subsurface geology (Journel et al., 1986). The geo-statistical approach for estimating the average value of a property in an unsampled block is called block kriging (Burgess and Webster, 1980b).

Block kriging is analogous to punctual kriging in many ways. The average value of a block, $z_o(B)$ is estimated from a linear weighting of measured values inside and outside of the

$$z_o(B) = \sum_{i=1}^{N} \lambda_i z_i$$

block using the expression (Webster and Oliver, 1990):
where the weighting factors sum to unity. The weighting factors are estimated using the semivariograms between points and blocks, or within a block.

Cokriging

Cokriging is an interpolation technique that uses information about the spatial patterns of two different, but spatially correlated properties to interpolate only one of the properties (Vauclin et al., 1983). Typically, cokriging is used to map the property that is more difficult or expensive to measure (z_2) based on its spatial dependence with a property that is easier or less expensive to measure (z_1). An example of this is interpolation by cokriging of sparsely sampled soil test phosphorus levels using intensively sampled soil organic carbon content values (Bhatti et al., 1991; Mulla, 1997). Another example is interpolation by cokriging of sparsely sampled soil moisture content levels (Yates and Warrick, 1987; Mulla, 1988; Stein et al., 1988).

Cokriging requires that the semivariogram models $(\lambda_1(h), \lambda_2(h))$ be estimated for both of the measured properties. In addition, cokriging requires estimation of the cross-semivariogram model $(\lambda_{12}(h))$ describing spatial dependence between the two measured properties. This cannot be done unless measurements of the more intensively sampled property are available at each of the locations where the sparsely sampled property is measured.

The cross-semivariogram is estimated using the following expression:

$$\gamma_{12}(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z_{1i} - z_{1,i+h}][z_{2i} - z_{2,i+h}]$$

where z_{1i} and $z_{1,i+h}$ are the measured values for property 1 at locations i and $i+h$, respectively, and

z_{2i} and $z_{2,i+h}$ are the measured values for property 2 at locations i and $i+h$, respectively. Zhang et al. (1992) have proposed a method for estimating pseudo cross-semivariograms using data that are sampled at nearly the same, but not identical, locations.

Interpolation with cokriging involves an approach that is similar to that for kriging, with terms for weighting factors of both measured properties. Interpolated values for the second property (z_{2o}, the sparsely measured property) are obtained using the expression:

$$z_{2o} = \sum_{i=1}^{N_1} \lambda_{1i} z_{1i} + \sum_{j=1}^{N_2} \lambda_{2j} z_{2j}$$

where λ_{1i} is the weighting factor for property 1 at location i, λ_{2j} is the weighting factor for property 2 at location j, z_{1i} is the measured value for property 1 at location i, and z_{2j} is the measured value for property 2 at location j. Thus, the interpolated value is simply a linear combination of the measured values for both properties at locations that neighbour the unsampled location.

As in kriging, the cokriging predictor is the best linear unbiased predictor. Requiring that the weighting factors for property one sum to zero, and the weighting factors for property two sums to unity ensures this.

2.3 Sampling Design

The variability and spatial structure of a sample population are of great importance in developing a valid soil sampling design. Soil sampling design is concerned with developing a statistically rigorous and unbiased strategy for collecting soil samples (Brown, 1993; Carter, 1993). The main considerations in sampling design include determining the optimal number of samples to collect, and determining the spatial arrangement of the samples to be collected (Wollenhaupt et al., 1997). A rigorous sampling design ensures that sampling points are representative of the region studied (ASTM, 1997a), meaning that the mean of the sampled points is a good estimate for the population mean. It also minimises the bias or systematic error caused by human judgement. Sample designs may also be developed to provide quality control and quality assurance, involving replicate measurements and split samples (ASTM, 1997b). Finally, the sampling design should provide the basis for accurate identification of spatial patterns in the measured property.

To avoid bias in sampling a statistically rigorous arrangement of sample locations is needed. Several strategies for determining sample locations have been developed, including geo-statistical sampling, systematic sampling, and targeted sampling. Each of these approaches will be described below.

Geo-statistical Sampling

In geo-statistical sampling there are two primary concerns. The first concern is systematic sampling for the purposes of accurate interpolation by kriging to produce spatial pattern maps. A regular grid with square, triangular, or hexagonal elements is most often used to achieve this objective (Webster and Burgess, 1984; Burrough, 1991; Wollenhaupt et al., 1997). For a regular grid-sampling program, the most efficient placement of sample locations is in the centre of each grid cell (Webster and Burgess, 1984; Burrough, 1991). Sample spacing for these grid cells should be less than half the range for the semivariogram (Flatman and Yfantis, 1984). The second concern is sampling for accurate estimation of the semivariogram (Russo, 1984; Russo and Jury, 1988). The semivariogram is useful as a tool for modelling spatial structure in a measured soil property, and is important for accurate interpolation by kriging. A typical approach for accurate estimation of the semivariogram is to supplement the systematic sampling grid with one or more transacts consisting has closely spaced sample locations. This helps to define the shape of the semivariogram at small separation distances.

One of the dilemmas in designing geo-statistically based sampling schemes is that the design depends upon the semivariogram, yet the semivariogram is often unknown until the study site is sampled. There are two approaches for solving this dilemma. The first is to use pre-existing information about the range of the semivariogram for the soil property of interest, whether this information is from study site, a nearby site, or a site in the same region. Once an estimate for the range is obtained, it can be used to set the approximate sample spacing in the sampling design of interest. The second approach is used if no pre-existing information about the semivariogram can be obtained. In this case it is necessary to conduct a preliminary sampling survey of the study site along several transacts (Flatman and Yfantis, 1984).

If the semivariogram is known, it is a powerful tool which can be used to evaluate various sampling strategies before any samples are collected (McBratney et al., 1981; Rouhani, 1985; Burrough, 1991). The first type of evaluation is determination of optimum spacing for sample locations (Rouhani, 1985; Warrick et al., 1986; Oliver and Webster, 1987; Burrough, 1991; Gutjahr, 1991). This is achieved by computing kriging estimation variances for a wide range of sample spacing and arrangements. Estimation variances can be computed even when no measurements are available at sample locations because the estimation variance depends only upon the semivariogram and separation distances between potential sampled and unsampled locations. The second type of evaluation is determination of the optimum number of composite or bulked samples to collect at each sample location (Webster and Burgess, 1984; Oliver et al., 1997). Significant reductions in estimation error are possible by mixing samples taken from small blocks around a sampled location and analysing the composite sample.

Systematic Sampling

To avoid clustered sampling and difficulties associated with finding randomly spaced locations in the field, many sampling designs use systematic sampling (Wollenhaupt et al., 1994). In this approach, sample locations occur either at the centre of regularly shaped grid cells or at the intersection of the grid lines. When samples are located at the centre of cells, the resulting values are thought to be representative of the soil within the grid cell. When they are located at the intersections of grid lines, all of the values along the edge of the grid cell can be averaged to obtain a representative value for the grid cell.

Grid cells can be of varying size and shape. The most common shapes are square grid cells, rectangular grid cells, hexagonal grid cells, and triangular grid cells. Triangular grid cells are widely considered to be more efficient than the other methods. Rectangular grid cells may be used when there is some reason to believe that the spatial variability in the sampled property exhibits anisotropy due to topographic, tillage, or other types of influences. The square grid cell is probably the most widely used approach in systematic sampling, and is often simply referred to as grid sampling.

One reason for the popularity of the square grid cell sampling design is the ease in finding or surveying sampling locations. On flat fields two parallel rows of sampling locations can be surveyed on adjacent transacts. Then starting at the midpoint of these two rows, two more columns can be surveyed in a direction perpendicular to the first two rows. Stakes or flags can be driven at each sampling location along the four transacts. All other sampling locations can then be found by sighting towards the two rows and the two columns until the two flags at the right sampling distance in those transacts are both perfectly lined up with your location. Alternatively, global positioning satellites, distance measuring devices, and dead reckoning can be used to find sampling locations.

The major disadvantage of systematic sampling is that the sample rows may be perfectly aligned with soil or management features that vary systematically (Wollenhaupt et al., 1997). For instance, alternating sample rows may be alternately aligned with irrigation furrows and then hills, or with tillage rows and then wheel tracks. In either case, the analysis of spatial patterns in the direction of the columns might show periodicity. To avoid this bias, random sampling may be done within cells.

Targeted or Directed Sampling

There are two major types of variation in soil properties, namely: those that can be seen and those that cannot. An example of the type that can often be seen by eye or with remote sensing is spatial variation in soil colour as a result of patterns in soil surface organic carbon content or moisture content. An example of the type that usually cannot be seen is spatial variation in soil nutrient availability caused by a management history of spatially varying cropping patterns, fertiliser applications, or manure applications.

A statistically rigorous sampling design is appropriate for the characterization of spatial patterns arising from unseen sources of variability such as soil nutrient availability. If, however, spatial patterns in the field arise from both unseen and visually obvious sources of variability, it may be advisable to supplement the statistically rigorous sampling design with some targeted or directed samples.

Targeted or directed samples are taken at locations where there is some visual evidence for a change in value of the measured property. For instance, an aerial photo taken prior to sampling (Bhatti et al., 1991) or during the early stages of crop growth (Ferguson et al., 1996) may show colour variations within the study site. A map of variation in crop yield may show small regions with either very poor or very good yields. Other sources of prior information about the study site may also be used to design a directed sampling strategy, including soil maps, digital elevation maps, ground penetrating radar maps, and electromagnetic induction maps (Pocknee et al., 1996). In these cases, a few sample locations may be added to the statistically rigorous sampling design strategy to find out how the measured soil property changes in the targeted region. This approach is particularly valid when the objective of the sampling program is to identify and characterise regions of the field which are distinctly different from the majority of the field, as is needed for Precision Farming (Francis and Schepers, 1997).

3. Example: Soil sampling and interpolation of soil test phosphorus levels

The advantages and disadvantages of the various interpolation techniques and soil sampling strategies described in this paper will be illustrated using an example involving the estimation of spatial patterns in soil test phosphorus from a field in eastern Washington state (Mulla et al., 1992; Bhatti et al., 1991; Mulla, 1997).

A commercial winter wheat farm on steep rolling topography was sampled using a geo-statistically based design involving four 655 m long parallel transacts with sample spacing at 15.24 m on each transact. Transacts were separated by 122 m. Three subsets of these data were considered:

- the entire set of 172 samples,
- a subset consisting of 24 samples on a systematic grid at spacing of 120 m, and
- a subset consisting of 51 targeted samples with about half the samples being located in regions where a remotely sensed Thematic Mapper image indicated low soil organic matter content.

Spatial patterns for kriged organic matter based upon 172-soil sampling locations (Figure 1) divide the field into three large and distinctly different sub-sections. In contrast, the spatial patterns for remotely sensed organic matter content (Figure 2) differentiate the field into about seven distinctly different sub-sections. Thus, satellite imagery of bare soil provides more detail about spatial patterns in organic matter content than intensive ground sampling.

Spatial patterns for kriged soil test phosphorus (Figure 3) show values less than 5 ppm that are located roughly in accordance with organic matter contents that are less than 2% (Figure 2). Soil test phosphorus levels higher than about 10 ppm do not always appear to be spatially consistent with patterns in organic matter content. It should be noted that this field has never received applications of manure.

Spatial patterns in soil phosphorus from cokriging with remote sensed estimates of organic matter content are shown in Figure 4. Many of the locations in the co-kriged map with soil phosphorus levels below 5 ppm are consistent with those in the kriged map.

Fig. 1:Kriged Organic Matter (%)

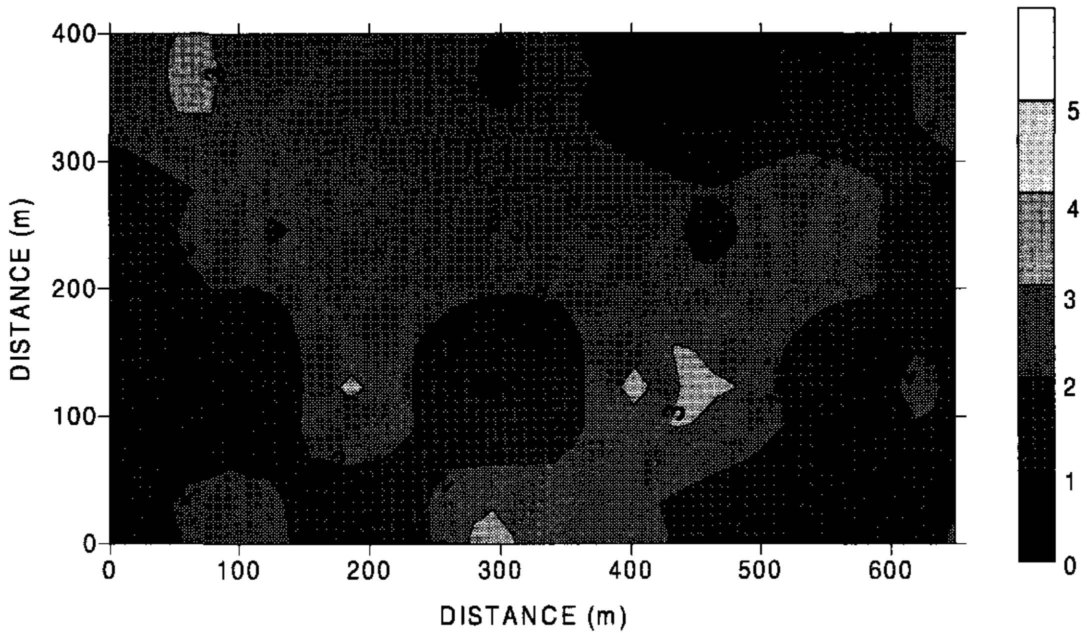


Fig. 2:Satellite Estimated Organic Matter (%)

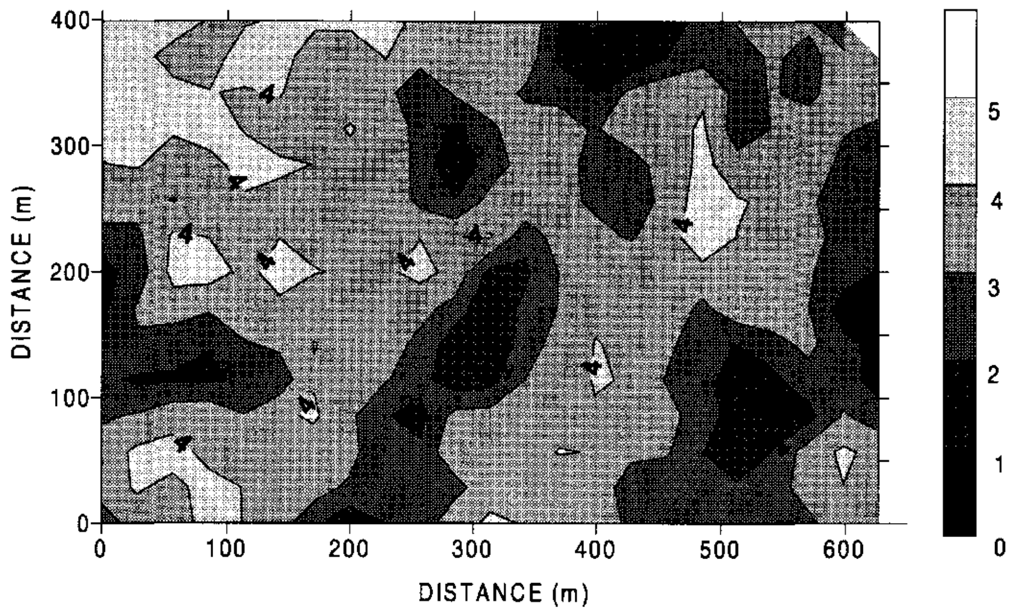


Fig. 3:Kriged Soil Test Phosphorus Levels (ppm)

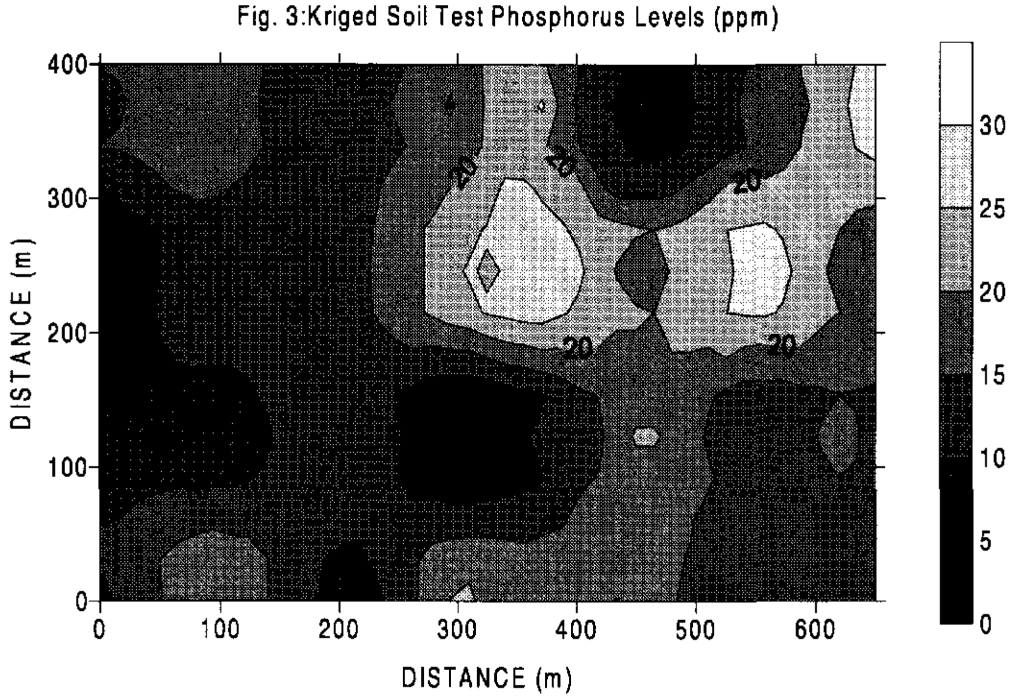


Fig. 4:Cokriged Soil Test Phosphorus Levels (ppm)

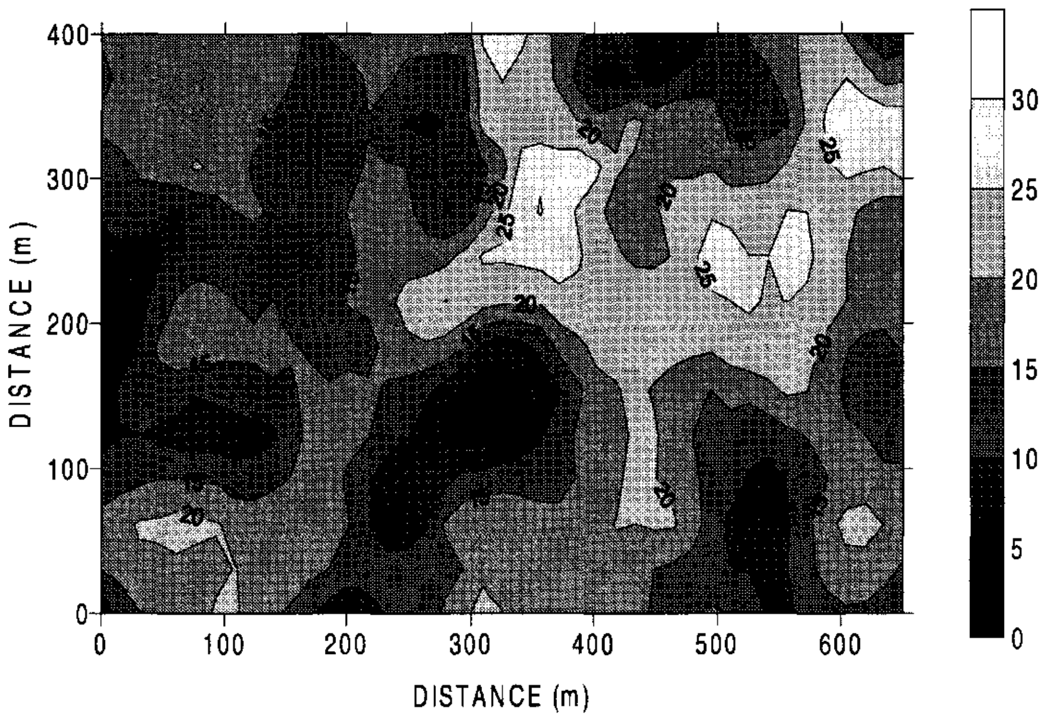


Fig. 5:Grid Sampled Kriged Phosphorus (ppm)

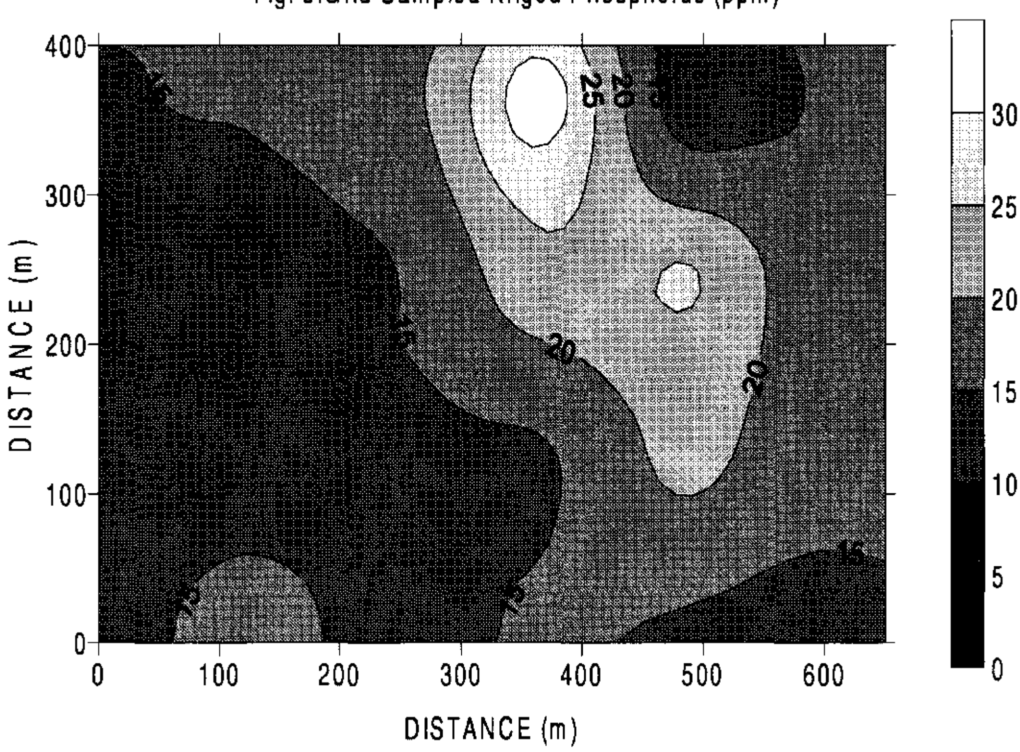
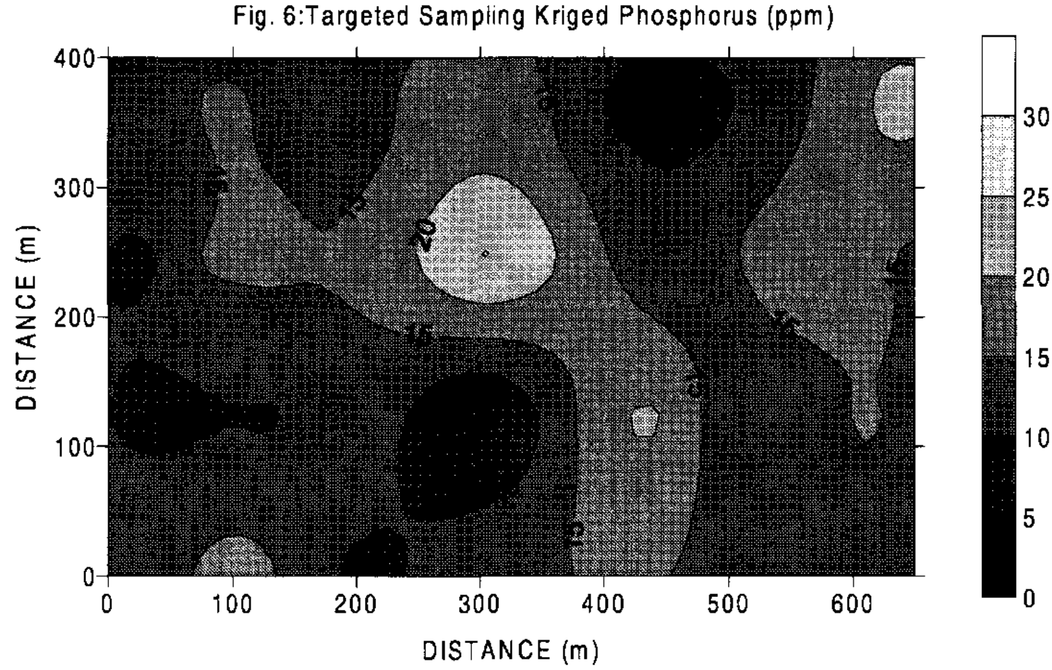


Fig. 6:Targeted Sampling Kriged Phosphorus (ppm)



There are however, locations with low phosphorus levels in the co-kriged map that did not show up in the kriged map. Similarly, there are locations with phosphorus levels above 25 ppm in the co-kriged map that was not correctly identified in the kriged phosphorus map. Thus, the use of cokriging from satellite images shows details for spatial patterns in soil phosphorus that are not possible to delineate in the kriged map that is based solely on ground sampling.

Precision farming consultants in rainfed regions typically sample fields on a regular grid at spacing of approximately 120 m. After kriging the 24 systematic grid points separated by 120 m spacing, the resulting spatial patterns (Figure 5) were found to be a poor representation of reality. Not only were the resulting spatial patterns unable to properly locate the regions of high soil test phosphorus, but there were no regions on the map with phosphorus levels lower than the 10 ppm at which phosphorus deficiencies are indicated. Thus, sampling on a 120-m grid for this field would have resulted in a recommendation to apply no phosphorus fertiliser anywhere. Clearly, sampling to identify fertility deficiencies requires careful attention to issues of sample spacing and location.

The spatial patterns in kriged soil test phosphorus resulting from a targeted sampling scheme involving 51 sampling locations are shown in Figure 6. These spatial patterns are not as complicated as those obtained by cokriging with remotely sensed organic matter (Figure 2). However, the locations having low soil test phosphorus levels are remarkably similar to the kriged targeted sampling map and the co-kriged map. The one exception is the failure to identify the low soil test phosphorus levels with targeted sampling at the co-ordinates surrounding (550,50). This is due to the absence of low organic matter contents at that location on the remotely sensed organic matter map (Figure 2).

4. Conclusions

Precision agriculture involves procedures for mapping and interpolating spatial patterns, and geographic information systems for overlaying and interpreting several soil, landscape, and crop attributes. The key component of precision farming is the map showing spatial patterns in field characteristics. Obtaining information for this map is often achieved by soil sampling and subsequent interpolation using geo-statistical approaches. Sampling design is critical, and must include both the appropriate number and arrangement of sampling locations. If not properly designed, sampling strategies can fail to provide the needed accuracy in identifying manageable spatial patterns, and they can be costly. Targeted soil sampling strategies can be developed without sacrificing accuracy by the use of cokriging techniques for interpolation with auxiliary data provided by satellite or air photo imagery. This approach is illustrated using spatial patterns in soil test phosphorus along with auxiliary information from Thematic Mapper imaging. Results from this example show that the combined use of remotely sensed images of bare soil, targeted soil sampling, and kriging or cokriging techniques provide an accurate assessment of spatial patterns in soil phosphorus deficiencies.

References

ASTM (1997a) Standard guide for general planning of waste sampling p 460-469. *In* J Azara, NC Baldini, E Barszcewski, L Bernhardt, EL Gutman, JG Kramer, CM Leinweber, VA Mayer, PA McGee, TJ Sandler and RF Wilhelm (ed) ASTM standards on environmental sampling. 2nd ed ASTM West Conshohocken PA

ASTM (1997b) Standard guide for sampling strategies for heterogeneous wastes p 521-537. *In* J Azara, NC Baldini, E Barszcewski, L Bernhardt, EL Gutman, JG Kramer, CM Leinweber, VA Mayer, PA McGee, TJ Sandler, and RF Wilhelm (ed) ASTM standards on environmental sampling. 2nd ed ASTM West Conshohocken PA

Bhatti AU, Mulla DJ and Frazier BE (1991). Estimation of soil properties and wheat yields on complex eroded hills using geo-statistics and thematic mapper images. Remote Sens Environ 37:181-191

Brown AJ (1993) A review of soil sampling for chemical analysis. Aust J Exp Agric 33:983-1006

Burgess T M and Webster R (1980a) Optimal interpolation and isarithmic mapping of soil properties. I The semi-variogram and punctual kriging. J Soil Sci 31:315-331

Burgess T M and Webster R (1980b) Optimal interpolation and isarithmic mapping of soil properties. II Block kriging. J Soil Sci 31:333-341

Burrough PA (1991) Sampling designs for quantifying map unit composition. p 89-125 *In* MJ Mausbach and LP Wilding (ed) Spatial variabilities in soils and landforms. SSSA Spec Publ 28 SSSA Madison WI

Carter MR (1993) Soil sampling and methods of analysis. Lewis Publ Boca Raton FL

Cooke RA, Mostaghimi S and Campbell JB (1993) Assessment of methods for interpolating steady-state infiltrability. Trans ASAE 36:1333-1341

Cressie N (1985) Fitting variogram models by weighted least squares. Math Geol 17:563-586

Cressie N (1991) Statistics for spatial data. Wiley Interscience New York NY

Dubrule O (1984). Comparing splines and kriging. Computers Geosci 10:327-338

Ferguson RB, Gotway CA, Hergert GW and Peterson TA (1996) Soil sampling for site-specific nitrogen management. p 13-22 *In* PC Robert, RH Rust and WE Larson (ed) Precision agriculture Proc 3rd Int Conf Minneapolis MN 23-26 June 1996. ASA CSSA SSSA Madison WI

Flatman GT and Yfantis AA (1984) Geo-statistical strategy for soil sampling. The survey and the census. Environ Monit Assess 4:335:349

Francis DD and Schepers JS (1997) Selective soil sampling for site-specific nutrient management. p 119-126 *In* JV Stafford (ed) Precision agriculture '97 Volume 1: Spatial variability in soil and crop. BIOS Scientific Publ Ltd Oxford United Kingdom

Gotway CA, Ferguson RB, Hergert GW and Peterson TA (1996) Comparison of kriging and inverse-distance methods for mapping soil parameters. Soil Sci Soc Am J 60:1237-1247

Gutjahr A (1991) Geo-statistics for sampling designs and analysis p 48-90. *In* RG Nash and AR Leslie (ed) Groundwater residue sampling design. Am Chem Soc Symp Ser 465 ACS Washington DC

Hoeksma RJ and Kitanidis PK (1985) Comparison of gaussian conditional mean and kriging estimation in the geo-statistical solution of the inverse problem. Water Resour Res 21:825-836

Isaaks EH and Srivastava RM (1989) An introduction to applied geo-statistics. Oxford University Press New York NY

Journel AG (1986) Constrained interpolation and qualitative information-The soft kriging approach Math Geol 18:269-286

Journel AG and Huijbregts JC (1978) Mining geo-statistics. Academic Press London England

Journel AG, Deutsch C and Desbarats AJ (1986) Power averaging for block effective permeability. Soc Petrol Engin Paper No SPE 15128 presented at 56th California Regional Meeting of the Soc Petrol Engin. Oakland CA

Jury WA (1986) Spatial variability of soil properties p245-269. *In* SC Hern and SM Melancon (ed) Vadose zone modeling of organic pollutants. Lewis Publ Chelsea MI

Krige DG (1966) Two dimensional weighted moving average trend surfaces for ore-evaluation. J South African Inst Mining Metall 66:13-38

Laslett GM, McBratney AB, Pahl PJ and Hutchinson MF (1987) Comparison of several spatial prediction methods for soil pH. J Soil Sci 38:325-341

Matheron G (1963) Principles of geo-statistics. Econ Geol 58:146-1266

McBratney AB and Pringle MJ (1997) Spatial variability in soil-implications for precision agriculture p3-31. *In* JV Stafford (ed) Precision agriculture '97. Volume 1 Spatial variability in soil and crop. BIOS Scientific Publ Ltd Oxford United Kingdom

McBratney AB, Webster R and Burgess TM (1981) The design of optimal sampling schemes for local estimation and mapping of regionalized variables. I Theory and method Computers Geosci 7:331-334

Mulla DJ (1988) Estimating spatial patterns in water content, matric suction, and hydraulic conductivity. Soil Sci Soc Am J 52:1547-1553

Mulla DJ (1991) Using geo-statistics and GIS to manage spatial patterns in soil fertility p 336-345 *In* G Kranzler (ed) Automated agriculture for the 21st century. ASAE St Joseph MI

Mulla DJ (1993) Mapping and managing spatial patterns in soil fertility and crop yield p 15-26 *In* PC Robert, RH Rust and WE Larson (ed) Site specific crop management. ASA Misc Publ ASA CSSA SSSA Madison WI

Mulla DJ (1997) Geo-statistics remote sensing and precision farming p100-114. In JV Lake, GR Bock and JA Goode (eds) Precision agriculture: spatial and temporal variability of environmental quality. John Wiley and Sons Chichester England

Mulla DJ, Bhatti AU, Hammond MW and Benson JA (1992) A comparison of winter wheat yield and quality under uniform versus spatially variable fertilizer management. Agric Ecosys Env 38:301-311

Oliver MA (1987) Geo-statistics and its application to soil science. Soil Use Manage 3:8-20

Oliver MA and Webster R (1987) The elucidation of soil pattern in the Wyre Forest of the West Midlands England. II Spatial distribution. J Soil Sci 38:293-307

Oliver MA and Webster R (1991) How geo-statistics can help you. Soil Use Manage 7:206-217

Oliver MA, Frogbrook Z, Webster R and Dawson CJ (1997) A rational strategy for determining the number of cores for bulked sampling of soil p155-162 *In* JV Stafford (ed) Precision agriculture '97. Volume 1: Spatial variability in soil and crop. BIOS Scientific Publ Ltd Oxford United Kingdom

Pocknee S, Boydell BC, Green HM, Waters DJ and Kvien CK (1996) Directed soil sampling p159-168. *In* PC Robert, RH Rust and WE Larson (ed) Precision agriculture. Proc 3rd Int Conf Minneapolis, MN 23-26 June 1996. ASA CSSA SSSA Madison WI

Rouhani S (1985) Variance reduction analysis. Water Resour Res 21:837-846

Russo D (1984) Design of an optimal sampling network for estimating the variogram. Soil Sci Soc Am J 48:708-716

Russo D and Jury WA (1988) Effect of the sampling network on estimates of the covariance function of stationary fields. Soil Sci Soc Am J 52:1228-1234

Stein A, Van Dooremolen W, Bouma J and Bregt AK (1988) Cokriging point data on moisture deficit. Soil Sci Soc Am J 52:1418-1423

Vauclin M, Vieira SR, Bernard R and Hatfield JL (1982) Spatial variability of surface temperature along two transects of a bare soil. Water Resour Res 18:1677-1686

Vauclin M, Vieira SR, Vachaud G and Nielsen DR (1983) The use of cokriging with limited field soil observations. Soil Sci Soc Am J 47:175-284

Vieira SR, Hatfield JL, Nielsen DR and Biggar JW (1983) Geo-statistical theory and application to variability of some agronomical properties. Hilgardia 51:1-75

Voltz M and Webster R (1990) A comparison of kriging, cubic splines and classification for predicting soil properties from sample information. J Soil Sci 41:473-490

Warrick AW, Myers DE and Nielsen DR (1986) Geo-statistical methods applied to soil science. p53-82. *In* A. Klute (ed) Methods of soil analysis. Part 1. 2nd ed Agron Monogr 9 ASA and SSSA Madison WI

Warrick AW, Zhang R, El-Harris MK and Myers DE (1988) Direct comparisons between kriging and other interpolators p 505-510. *In* PJ Wierenga and D Bachelet (ed) International Conference and workshop on the validation of flow and transport models for the unsaturated zone. 22-25 May 1988. Ruidoso NM New Mexico State Univ Las Cruces NM

Webster R and Burgess TM (1980) Optimal interpolation and isarithmic mapping of soil properties. III Changing drift and universal kriging. J Soil Sci 31:505-524

Webster R and Burgess TM (1984) Sampling and bulking strategies for estimating soil properties in small regions. J Soil Sci 35:127-140

Webster R and Oliver MA (1990) Statistical methods in soil and land resource survey. Oxford University Press New York

Whelan BM, McBratney AB and Viscarra Rossel RA (1996) Spatial prediction for precision agriculture p331-342. *In* PC Robert, RH Rust and WE Larson (ed) Precision agriculture. Proc 3rd Int Conf Minneapolis, MN 23-26 June 1996. ASA CSSA SSSA Madison WI

Wollenhaupt NC, Wolkowski RP and Clayton MK (1994) Mapping soil test phosphorus and potassium for variable-rate fertilizer application. J Prod Agric 7:441-448

Wollenhaupt NC, Mulla DJ and Gotway Crawford CA (1997) Soil sampling and interpolation techniques for mapping spatial variability of soil properties. p19-53. *In* FJ Pierce and EJ Sadler (ed) The state of site specific management for agriculture. ASA CSSA and SSSA Madison WI

Yates SR, Warrick AW and Myers DE (1986a) Disjunctive kriging. 1 Overview of estimation and conditional probability. Water Resour Res 22:615-621

Yates SR, Warrick AW and Myers DE (1986b) Disjunctive kriging. 2 Examples. Water Resour Res 22: 623-630

Yates SR and Warrick AW (1987) Estimating soil water content using cokriging. Soil Sci Soc Am J 51:23-30

Zhang R, Myers DE and Warrick AW (1992) Estimation of the spacial distribution of soil chemicals using pseudo-cross-variograms. Soil Sci Soc Am J 56:1444-1452

3.2 Use of remote sensing and GIS for sustainable Land management

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Remote sensing provides basic data to undertake inventory of land, as well as temporal information to monitor sustainable land management practices. In this paper, the current use of remote sensing for sustainable land management is reviewed, and the potential of future (new) satellite systems to contribute to sustainable development is explored. Other elements for successful sustainable development (i.e. good policy and participatory approaches) are compared and contrasted with information requirements.

1. Introduction

Sustainable land management refers to the activities of humans and implies that activity will continue in perpetuity. It is a term, which attempts to balance the often-conflicting ideals of economic growth and maintaining environmental quality and viability. Economic activities may range from intensive agriculture to management of natural areas.

It is argued that to effectively 'manage' resources, three policy tools must be present. These are information about natural resources, clear policies on how the resource may be managed (e.g. Acts of Government, policy papers, administrative procedures), and participation of everyone (including local people) with an interest or 'stake' in the land. In this paper we concentrate on methods to generate information about resources, with an emphasis on how recent innovations in remote sensing fit with sustainable land management methods. In particular we assess how remote sensing, and techniques and data may inventory resources, which may ascertain whether activity is indeed sustainable. A concluding section discusses how the information (generated from remote sensing) is linked to policy and local participation.

Thus, three specific questions are addressed. Firstly, what cover is present? This question requires that remote sensing provides information on land cover as well as terrain attributes such as slope, aspect and terrain position. The second question addresses whether the use (management) of the cover is sustainable. This question requires temporal data collection to monitor whether the environment is degrading, or otherwise changing. The third question is how remote sensing and GIS can contribute to the policy tools of generating policy, providing information, and ensuring participation by all stakeholders.

2. Sustainable development

Sustainable development has been defined in many ways; in fact there are 67 different definitions listed in the 'natural resource management' subject taught at ITC. Interestingly, none mention GIS and remote sensing as being necessary tools for sustainable development. Sustainable development is a term, which attempts to balance the often-conflicting ideals of economic growth and maintaining environmental quality and viability. As such, sustainability implies maintaining components of the natural environment over time (such as biological diversity, water quality, preventing soil degradation), while simultaneously maintaining (or improving) human welfare (eg. provision of food, housing, sanitation etc).

In any definition of sustainability, the key element is change. For example, Fresco and Kroonenberg (1992) define sustainability as the "...dynamic equilibrium between input and output". In other words, they emphasise that dynamic equilibrium implies change and that for a land system to be sustainable, its potential for production should not decrease. In other words the definition allows for reversible damage. This type of definition is most applicable when considering agricultural production systems, but may also be generalised to management of natural areas. A broader definition of sustainability, such as that proposed by Brown et al., (1987), includes persistence of all components of the biosphere, even those with no apparent benefit to society, and relates particularly towards maintaining natural ecosystems.

Other definitions emphasise increasing the welfare of people (specifically the poor at the 'grassroots' level) while minimising environmental damage (Barbier, 1987), which has an socio-economic bias. The necessary transition to renewable resources is emphasised by Goodland and Ledec (1987) who state that renewable resources should be used in a way which does not degrade them, and that non-renewable resources should be used so that they allow an orderly societal transition to renewable energy sources.

That changes continually occur at many spatial (eg. global, regional, local) and temporal (eg. ice ages, deforestation, fire) scales, is obvious to any observer. For example, change may occur in the species occupying a site, amount of nitrate in ground water, or crop yield from a field. Change may also occur to human welfare indices such as health or education. To assess whether such changes are sustainable is a non-trivial problem. Possibly the greatest advantage of the debate about sustainable development, is that the long-term capacity of the earth to sustain human life through a healthy and properly functioning global ecosystem, is becoming a normal political goal.

3. Review of remote sensing for resource inventory and monitoring

Since the launch of ERTS-1 (Landsat 1) in 1972, digital remote sensing has been used with some success to monitor natural resources and provide input to better manage the earth. Applications have included monitoring of deforestation, agro-ecological zonation, ozone layer depletion, food early warning systems, monitoring of large atmospheric-oceanic anomalies such as El Niño, climate and weather prediction, ocean mapping and monitoring, wetland degradation, vegetation mapping, soil mapping, natural disaster and hazard assessment and mapping, and land cover maps for input to global climate models. These techniques have been developed using rather rudimentary sensing systems, such as NOAA AVHRR, Landsat MSS and TM and SPOT panchromatic. Though developments have been broadly based across many divergent disciplines, there is still much work required to develop remotely sensed images suited to natural resource management, refine techniques, improve the accuracy of output, and demonstrate and implement work in operational systems.

3.1 Global mapping and monitoring

A number of satellite systems have been dedicated to monitoring the global environment. Probably the most commonly used for natural resource management has been the NOAA AVHRR which has a twice daily overpass, and can be freely downloaded by low cost ground receiving stations. It has a nominal pixel size of 1.1 km and records two spectral bands in the visible and near infrared. The data from the AVHRR has been used to map global land cover when degraded to a pixel size of 4 km. Land cover is an input layer to global climate models, in addition to being important for estimating the pattern of soil erosion over the earth. AVHRR imagery has been used to estimate global biomass production, as well as regional estimates of biomass. Apart from use in global models, the imagery is also effective in awareness building of the state of the earth's environment as well as policy development for government.

When used in a time series, the seasonal increase and senescence of vegetation may be related to agricultural and grassland production. The information forms the basis of food early warning systems in Africa; for example in 1997 the Kenyan government imported extra grain to avoid shortages caused by drought with the decision based partly on information derived from satellite images (Mr H. Mwandwa, DRSRS, Kenya, pers comm). The FAO produces a 10 day summary of NDVI (normalised difference vegetation index), an index indicating biomass. Another famous satellite is the total ozone mapping system (TOMS) which has had follow-on system. This satellite raised awareness of ozone depletion, and assisted agreements limiting the global use of ozone depleting chemicals. Finally, the daily use of the global meteorological satellite system (GMS) by weather forecasting agencies in familiar to most people. The GMS offers hourly updates and has 2 visible channels with pixel sizes of 1 km, as well as a thermal infrared channel of 5-km size.

3.2 Regional mapping and monitoring

The Landsat Multispectral Scanner (MSS) data series commenced acquisition in 1972, and has had an unbroken data record since then. For regional scale mapping and monitoring the instrument has been widely used. With a 60 by 80-m pixel and 4 bands in the visible and near infrared, Landsat MSS introduced multispectral remote sensing to earth resource scientists. A later sensor called the Landsat Thematic Mapper (TM), offered higher spatial resolution (30 by 30 m) as well as more spectral bands (7 channels). Similar remote sensing sensors have been launched by other nations, such as the Indian Remote Sensing (IRS) satellite system, and the French SPOT.

The Landsat MSS, TM, SPOT and IRS have had wide application in natural resource management, primarily in the inventory and measurement of natural resources, as well as monitoring change. Such information is essential for developing policy on the change in land cover as a result of human activity, and thereby indicating whether the activity is sustainable, from both a socio-economic and biophysical perspective.

3.3 Local mapping and monitoring

Local mapping has traditionally been undertaken using aerial photographs in combination with topographic maps (if available). The use of aerial photographs in a wide variety of applications is detailed in Colwell (1983).

4. New advances in remote sensing for sustainable development

Three recent innovations in remote sensing (*viz*. hyperspectral remote sensing radar and high spatial resolution) offer promising techniques to assist sustainable development. Hyperspectral remotely sensed data provide information on vegetation floristics, soil type and soil chemistry. Radar is frequently cited as a solution for mapping the structure of vegetation as well as the moisture of soils and geomorphological patterns. High spatial resolution images (formerly limited to 'spy satellites') will offer extremely high spatial resolution images (comparable to aerial photographs) within a few hours of acquisition. These innovations are reviewed, and their potential for monitoring and mapping sustainable land management is assessed.

4.1 New advances in remote sensing for sustainable development: Part I - Hyperspectral remote sensing

Hyperspectral imagery (also called high spectral resolution imagery) use scanners with very many narrow bands that span a wider section of the electromagnetic spectrum from the visible to the near infrared, compared with traditional multispectral scanners such as the Landsat MSS or TM. When the reflectance curve of vegetation is plotted against the broad bands of Landsat MSS, broad band scanners tend to average out important differences in reflectance over small spectral resolution. Also, spectral ranges where the broad bands are placed may not coincide with areas of maximum difference in the spectral curves for vegetation. This problem occurs with other surface covers; for example, minerals have specific absorption pits, which broad band sensors average out, or miss altogether. Hyperspectral remote sensing developed in the 1980s through airborne systems, and in the late 1990s a number of satellite systems are being launched. There are at least 35 operational airborne systems, in addition to a number of planned spaceborne systems.

The potential of hyperspectral for sustainable land management is large; it represents a leap in the ability to distinguish between cover types, and hence begin to accurately monitor land degradation through, for example, changes in vegetation composition and structure (cover), change in soil chemistry and structure, evapotranspiration and catchment hydrology, and forest depletion.

Main Principles

A recent success with hyperspectral imagery has been achieved using aircraft scanners. Hyperspectral scanners are passive; in other words they receive radiation reflected from the earth's surface. At an altitude of 500 km, a space borne sensor receives approximately 10000 times less radiation than an aircraft at 5 km. Therefore, much less signal (information) is received by satellite as compared to aircraft, with a lower signal to noise ratio. The signal to noise ratio is of prime importance in hyperspectral remote sensing. With aircraft sensors, it is possible to have small pixels (say 2-5 m) as well as narrow wavelength bands (usually around 10 nm). With satellite systems, a choice must be made between either narrow bands coupled with large pixels (e.g. ESA Envisat has larger pixels of 250 m and band widths of about 1 to 25 nm) or wide band widths and higher spatial resolution (e.g. SPOT XS has a pixel size of about 20 m but a few wide bands). The advantage of aircraft scanners is that spatial spectral resolution is high, and these sensors are therefore ideally suited for detailed local surveys. However, the cost of the data is high, unless a consortium can be formed, and there are problems with geometrical image correction due to the less stable aircraft platform.

In contrast, the cost of satellite data is substantially less, and will be better suited to environmental applications requiring more repetitive coverage. The challenge in the future will be to create space borne scanners with higher spatial and spectral resolution, while maintaining high signal to noise ratios.

Applications

Researchers have found relationships between vegetation properties and remotely sensed variables (Table 1). To summarise these diverse experiments in one Table, the 'cover' variable includes leaf area index, basal area and canopy cover, and the 'volume and productivity'

	Cover	Volume & Productivity	Type	Damage
Blue	• Franklin et al., 1991 - cover - TM	• Fiorella & Ripple, 1993 - AGE - TM	• Lillesand et al., 1985 - TM • Nelson et al., 1984 - TM	• Leckie et al., 1992 - TM
Green	• Brockhaus&Khorram, 1992 - BA - TM • Franklin et al., 1991: cover - TM	• Fiorella & Ripple, 1993 - AGE – TM • Brockhaus&Khorram, 1992: AGE- TM	• Lillesand et al., 1985 – TM	
Red	• Badhwar et al., 1984 - LAI - TM • Franklin et al., 1986 - LAI - TM • Franklin et al., 1991 - cover - TM • Tucker, 1979 - LAI - MSS • *Peterson et al., 1987* - LAI - TM • Spanner et al., 1990 - LAI - TM • Brockhaus&Khorram, 1992 - BA - TM • Nemani et al., 1993 - LAI - TM	• Skidmore et al., 1988 - AGE -TM • Brockhaus&Khorram, 1992: AGE- TM • Danson and Curran, 1993 - AGE • - AV HT • - DBH • - VOL	• Lillesand et al., 1985 - TM • Horler and Ahern, 1986 - TM	
pan visible		• De Wulf et al., 1990 - AV HT - S • De Wulf et al., 1990 - VOL - S	• Lillesand et al., 1985 - TM • Horler and Ahern, 1986 - TM • Nelson et al., 1984 – TM	
near-IR	• Hame et al., 1988 - BA - S • Brockhaus&Khorram, 1992 - BA- TM • Brockhaus et al. 1988 - BA - TM • Danson and Curran, 1993 - BA - TM • Badhwar et al., 1984 - LAI - TM • *Franklin, 1986 - LAI - TM* • Franklin et al., 1991 - cover - TM • Tucker, 1979 - LAI - MSS • Peterson et al., 1987 - LAI - TM • Spanner et al., 1990 - LAI - TM	• Fiorella & Ripple, 1993 - AGE - TM • Brockhaus&Khorram, 1992: AGE- TM • Turner et al., 1988 - AGE - S • - AV HT - S • Hame et al., 1988 - AGE - S • - VOL - S • - DBH - S • Leprieur et al., 1988 -TM - AGE - TM • Danson and Curran, 1993 - AGE -TM • - AV HT • - DBH • - VOL	• Lillesand et al., 1985 – TM • Horler and Ahern, 1986 - TM • Nelson et al., 1984 – TM	
middle-IR	• Brockhaus&Khorram, 1992 - BA - TM • Butera, 1986 - cover - TM • Franklin et al., 1991 - cover - TM	• Brockhaus&Khorram, 1992: AGE- TM • Leprieur et al., 1988 - AGE -TM • Horler and Ahern, 1986 - VOL -TM	• Lillesand et al., 1985 – TM • Horler and Ahern, 1986 - TM • Nelson et al., 1984 – TM • Tucker, 1979 – MSS	
Ratio	• Nemani et al., 1993: LAI - modified NDVI - TM	• Cook et al., 1989 - PROD - TM- MIR/NIR • - PROD - TM- MIR/blue • - PROD - TM- TIR/vis • Fiorella&Ripple, 1993 -AGE- TM - NIR/red • - AGE- TM- MIR/NIR		• Leckie et al., 1992 - NIR/red- TM • - *norm-diff* - TM • Defeo et al., 1987 - MIR/NIR - TM • Rock et al., 1986 - TIR/MIR - TM • Vogelmann&Rock,1986 - TIR/MIR – TM • Vogelmann&Rock, 1986 - TIR/NIR – TM • Vogelmann, 1990 -NDVI, MIR/NIR - TM

	Terrain			• Hall-Könyves, 1987 – gradient - TM • Karaska et al., 1986 - gradient - TM • Strahler et al., 1980 - gradient - TM • Hoffer, 1975 - elevation - Skylab • Strahler et al., 1980 - elevation - TM • - aspect • - gradient • Skidmore 1989 - TM - aspect - TM • Richards et al., 1982 - aspect - TM	

Key to abbreviations:
Forest Variables: BA - basal area; LAI - leaf area index; COVER - crown cover; AV HT - average stand height; VOL - stand volume; DBH - diameter at breast height; PROD - forest productivity;
Terrain Variables: gradient - slope gradient; elevation - altitude or elevation
Remote Sensing Bands: blue - visible blue; green - visible green; red - visible red; NIR - near-infrared; MIR - middle infrared
Remote Sensing Ratios: NIR/red - near-infrared to red ratio; MIR/NIR - middle-infrared to near-infrared ratio; TIR/MIR - thermal-infrared to middle-infrared ratio; TIR/NIR - thermal-infrared to near-infrared ratio; norm-diff - normalised difference
Remotely Sensed Data Source: TM - Landsat Thematic Mapper; S - SPOT; MSS - Landsat MSS; Skylab - NASA Skylab data

variable includes age, height, volume, diameter and density. In the body of Table 1, the vegetation variable is specified as well as the author of the study, date and type of remotely sensed data. For example, in Table 1 at the intersection of the 'cover' column, with the 'green' row, the key shows that Brockhaus and Khorram (1992) found a significant relationship between green TM band (2) with basal area of trees.

Table 1 leads to several general comments.

- The 'cover' variables of leaf area index, basal area and canopy cover have been correlated with the visible, near-infrared, and middle infrared. Red reflectance has a consistent negative correlation with leaf area index (LAI), biomass and canopy cover (Badhwar et al., 1984; Franklin, et al., 1986; Tucker, 1979; Peterson et al., 1987; Spanner et al., 1990; Nemani et al., 1993), and green and red reflectance with basal area (Brockhaus et al., 1988; Brockhaus and Khorram, 1992). These authors also report a weak or slightly positive correlation between LAI and near-infrared reflectance. For woodlands and savannah with sparse tree cover, Franklin et al. (1991) found blue, green and red bands were strongly negatively correlated with canopy cover. Hame et al. (1988), Brockhaus et al. (1988), Brockhaus and Khorram (1992) and Danson and Curran (1993) note inverse correlation's for tree basal area with the near- and middle-infrared, and Franklin et al. (1991) report negative correlation's for canopy cover. A more complicated situation is described by Spanner et al. (1990), where forests with canopy cover greater than 89 per cent exhibit positive correlation with the leaf area index, but open forests have a raised near-infrared response: Between these two extremes the near-infrared response was flat. The middle infrared wavelengths correlated with forest canopy closure (Butera, 1986) and leaf are index (Spanner et al., 1990). Peterson et al. (1987) reported a strong relationship between leaf area index and a near-infrared/red ratio, but Spanner et al. (1990) found a confused relationship with this ratio. The normalised difference vegetation index (NDVI) ratio was weakly correlated with canopy cover (Franklin et al., 1991). However, Nemani et al. (1993) concluded that NDVI cannot be used to estimate LAI for open canopy conditions
- With respect to the 'volume and productivity' variable in Table 1, Turner et al. (1988) and De Wulf et al. (1990), showed that SPOT bands in the visible were not significantly correlated with any forest plantation parameters, but De Wulf et al. (1990) noted that the SPOT panchromatic band, which spans the visible, correlated with stand density and average canopy height. In contrast, Danson and Curran (1993) reported that the red radiance correlated with age, density, DBH and height, and Fiorella and Ripple (1993) found a correlation between the visible bands and mature and old-growth forests. Skidmore et al. (1988) found that as age varied for coniferous plantations, different Landsat MSS responses were recorded.
- When considering the 'volume and productivity' variables at infrared wavelengths, Turner et al. (1988), Leprieur et al. (1988), Hame et al. (1988) and Danson and Curran (1993) reported that the near-infrared band had a significant negative relationship with age; however, Hame et al. (1988), reported that the near-infrared band was correlated with tree volume (which conflict with the results of Turner et al. (1988) and Leprieur et al. (1988)) as well as mean tree diameter. Again in contrast with the above results, Danson and Curran (1993) discovered the near-infrared correlated with density, DBH and height. The middle infrared wavelengths correlated with stem density (Horler and Ahern, 1986), while Leprieur et al.

(1988) concluded that middle-infrared reflectance decreases with increasing stand age. Thermal infrared was correlated with forest structural characteristics (Holbo and Luvall, 1989). More recent work by Fiorella and Ripple (1993), found that ratios of near-infrared/red and near-infrared/middle-infrared correlated with structural forms.

- Cook et al. (1989) discovered that vegetation productivity is more strongly related to band ratios than individual bands. Ratios of mid-infrared to near-infrared, as well as ratios of mid-infrared and visible (blue) were important. In mountainous sites, Cook et al. (1989) found that Landsat TM band 6 (thermal infrared), in varying ratios with visible bands, correlated significantly with productivity.
- Lillesand et al. (1985) found that TM near-infrared and middle-infrared yielded most information for discriminating species, while visible bands offered less discrimination. Horler and Ahern (1986) found the red, near-infrared and middle-infrared useful for discriminating Canadian forests. Nelson et al. (1984) analysed (simulated) TM data, and concluded most information about vegetation was contained in the blue, near-infrared and middle-infrared. Holbo and Luvall (1989) to map broad forest type classes used thermal infrared.
- Vegetation dieback and damage are best mapped by band ratios. Rock et al. (1986) and Vogelmann and Rock (1986) correlated thermal/middle-infrared and thermal/near-infrared ratios with dieback in high altitude spruce-fir forests, and Defeo et al. (1987) found the middle-infrared/near-infrared ratio significant. Vogelmann (1990) concluded that NDVI was more suitable for monitoring broadleaf forest damage, while a ratio of middle-infrared to near-infrared was best for both coniferous and broadleaf forests. Leckie et al. (1992) concluded that ratios and normalised differences of the spectral bands best discriminated spruce budworm damage.
- The impact of terrain on vegetation reflectance values has been widely reported, as forested areas often occur over rugged areas. For example, Hoffer (1975) improved the accuracy of remote sensing classifications by including elevation, while Strahler et al. (1978 and 1980) also improved mapping by incorporating topographic data (i.e. slope, aspect, elevation). Richards et al. (1982) and Skidmore (1989) used topographic information with Landsat TM data to improve forest type mapping .
- Areas which are shadowed as a result of topography will have lower mean and variance brightness values compared with areas which are sunlit (Holben and Justice, 1980; Justice et al., 1981). However, increasing the brightness of shadowed areas (that have a low variance) will not increase the amount of information content *per se*. Shadow in remotely sensed images is in part determined by the steepness of the topography (Hall-Könyves, 1987). Leprieur et al. (1988) also investigated the relationship between slope gradient and reflectance, but found the relationship was confused by variations in the vegetation cover. Aspect is an important terrain variable which influences remotely sensed reflectance; for example, Proy et al. (1989) found that well illuminated pixels are not influenced by scattered sky irradiance, but shadowed pixels require adjustment for this effect. Another problem highlighted by Karaska et al. (1986) was the percentage of tree and shrub cover, which masked the effect of topographic variables on spectral responses. There has been some debate whether Lambertian (i.e. light is scattered equally in all directions from a surface) or non-Lambertian models are more suited for modelling topographic shadowing (Malila et al., 1978; Justice et al., 1981), although Smith et al. (1980) and Holben and Justice (1980) showed that ponderosa pine and sand will exhibit both Lambertian and non-Lambertian

scattering at different sun incident angles. Thus, as Justice et al. stated back in 1981, reducing topographic effects in remotely sensed data by using digital terrain models is difficult; and even today this topic remains inconclusive.

- Two recent experiments have been undertaken by the authors in eucalyptus forests of NSW, Australia, and the rangeland of the Masai Mara Nature Reserve, Kenya. In both experiments the principle aim was to evaluate whether species may be distinguished based on the spectral response. In addition, work is underway to try and scale up the spectral response of the individual species to the response obtained for a pixel.
- The grassland studies at Massai Mara Nature Reserve show that there are significant differences between 8 grass species. In these experiments, the spectral position of maximum reflectance was at the visible-red (around 600-700 nm) and the near infrared-middle infrared (approximately 1200-1600 nm) (Figure 1). The statistical difference between the different grass species (as tested using the students t-test) is indicated on Figure 2; the vertical shading indicates the number of species, which had a statistically different reflectance for the various wavelengths. Note that with 8 species, a total of 28 possible combinations of species may be available. Another interesting result is that the area of the spectrum which best discriminates senescence of vegetation (based on a 2 week period when Themida triandra was 'haying off') was also at the same wavelengths (Figure 2). Clearly this has implications for the choice of suitable wavelengths for discriminating vegetation in scanners, and requires further study.

The geologists have made advanced use of hyperspectral data and developed the popular 'linear unmixing' method of classifying the percentage of cover components within a pixel (Boardman, 1989).

Hyperspectral data are frequently displayed as 'image cubes' where an image (usually a colour composite) represents the surface, and the bands (e.g. 224 for AVIRIS) are detailed on the sides of the cube, going from short wavelengths at the top of the cube to longer wavelengths at the bottom of the cube. The image cube may allow anomalies to be visualised.

Finally, hyperspectral data may be used for natural disaster monitoring, especially with aircraft borne systems, which permit rapid response. For major catastrophes, high spatial resolution panchromatic images (or serial photographs) may suffice (see below for the description of new high resolution satellite images). But if a detailed classification, such as the deposition of silt and sand after a flood, or the pattern of burnt vegetation after a fire, must be mapped, then hyperspectral data should provide a higher classification accuracy.

4.2 New advances in remote sensing for sustainable development: Part II - Radar remote sensing

Since the 1970s, imaging radar has been used to map natural resources, first from aircraft and since 1991 from satellite platforms. Few sensors in the microwave section of the spectrum work with the reflected/emitted radiation of the earth itself, like sensors in the optical and infrared section do. Most sensors used for mapping and monitoring natural resources are active sensors, receiving the reflection of the radiation they emit themselves. This has the advantage that the

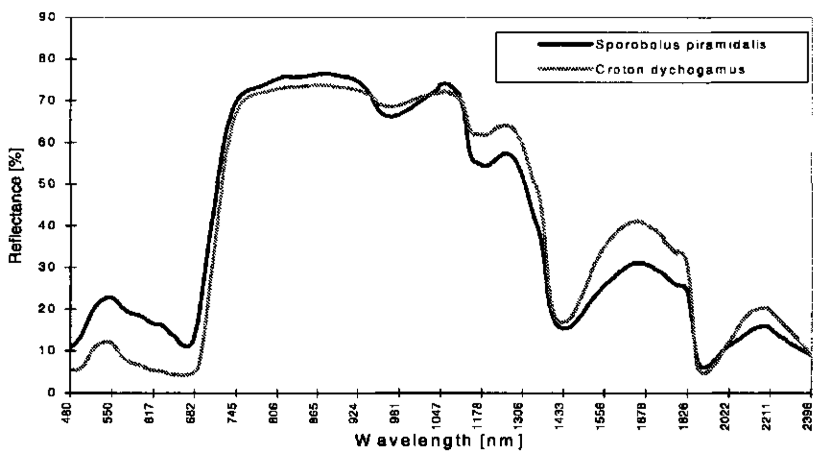

Figure 1. Difference between reflectance of grass and shrub in the Masai Mara Nature Reserve.

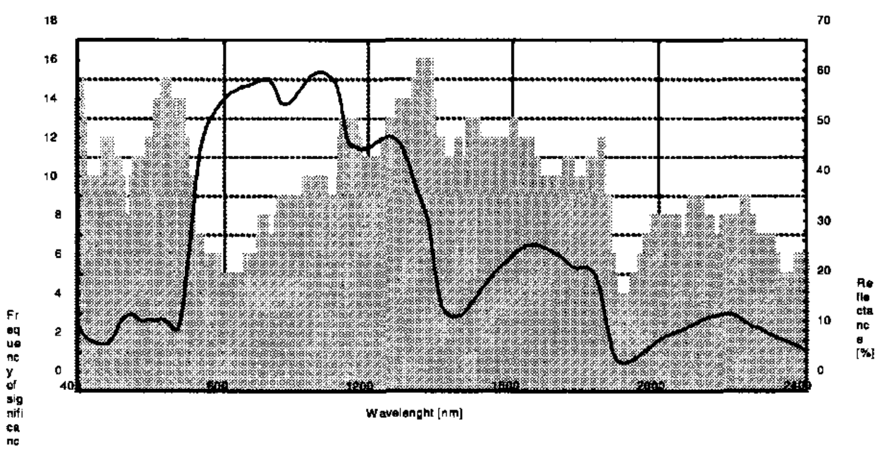

Figure 2. Frequency of significantly different medians between 8 species of vegetation in the Masai Mara Nature Reserve.

sensor can be used any time during night or day. As the wavelengths used are in the order of a few millimetres to nearly 70 centimetres, the radiation is not reflected or absorbed by clouds or haze. This is especially important in a large number of humid areas, where optical or infrared sensors are of limited use for mapping and monitoring natural resources because of clouds and haze.

Main principles

The microwave radiation emitted by the sensor reaches the surface and is scattered. Part of the scattered signal is received by the sensor, this is called the backscatter. The intensity of the backscatter depends on characteristics of the sensor and of the scattering surface. To start with the latter, generally backscatter increases with the amount of moisture in the soil and the vegetation and with the roughness of the surface (both canopy as well as soil surface). The longer the wavelength used, the deeper the waves will penetrate the vegetation or the soil surface. The backscatter in X- and C- band gives information on the upper few centimetres of a bare soil, or the upper part of the canopy of a closed forest. The L-band will penetrate a few decimetres into a bare soil, depending on the moisture content, and gives information on the larger branches of the trees in a closed forest. The P-band penetrates deeper into the soil, and gives information on the trunks in the forest, and on the understorey. This illustrates, that a combination of several wavelengths will allow to make moisture profiles in soils as well as to see differences in biomass distribution in forests. In vegetation with less biomass and/or a more open canopy, backscatter will be influenced by both soil as well as vegetation characteristics. Polarimetry refers to the study of how the polarised (horizontal or vertical) radar electromagnetic radiation is scattered by the surface. Traditional radar sensors could transmit microwaves in a vertical or horizontal mode, and then receive the reflected vertical or horizontal mode. In other words, there were 4 possibilities viz. V-V (i.e. transmit vertical and receive vertical), H-H (i.e. transmit horizontal and receive horizontal), H-V (ie. transmit horizontal and receive vertical), and finally V-H (ie. transmit vertical and receive horizontal). More recently, multipolarised images may be generated (based on the Stokes matrix) which allow all combinations of polarisation between vertical and horizontal to be simulated. The polarimetry images provide further insights to the structure and floristics of vegetation, soil properties and parent material. By using a time delay (difference) in recording a radar image as a satellite or aircraft proceeds along a flight line, a digital elevation model may be generated by interferometry. Finally, benefits of the satellite radar systems are stable platforms offering well-calibrated data. There is no problems with haze, smoke or cloud, and consequently atmospheric corrections are not required.

4.3 New advances in remote sensing for sustainable development: Part III - High spatial resolution imagery

By 1998, high resolution 'spy' satellite images will be available for a few hundred dollars with delivery within a few hours. Two competing American companies, Space Imaging EOSAT and Earthwatch, will launch satellites with pixels sizes of 1 m and 3 m respectively. A second satellite will be launched by Earthwatch and will have a resolution of 0.85 cm in 1999. These commercial systems are being built by the same companies, which developed spy satellites for the American military.

Main principles

The satellites have a telescope, which can be rotated up to 30 degrees off nadir, to point at targets nominated by customers with high precision. The sensors are arrays of charge coupled devices (similar to the SPOT sensor system). The closest current competitors are the SPOT panchromatic system, with a resolution of 10 m, as well as former Russian military photographs with a 3 m resolution. The Russian photographs have a limited coverage, and delivery is notoriously slow and difficult.

There is nothing particularly new about high spatial resolution technology; it has been known informally for many years that military satellites are able to resolve objects as small as 10 cm. The difference is that this high resolution imagery was only available through aerial photographs. Aerial photographs are expensive to obtain (or buy), and natural resource managers often have restricted access in developing countries due to 'security concerns'. The new satellites will offer lower resolution than the military systems, but will deliver imagery just as quickly. It is the ability to rapidly acquire images, which should be of most use for natural resource management and sustainable land use.

<u>Applications and potential for sustainable land use</u>
The use of aerial photographs in sustainable land use is widespread, and numerous applications have been developed. The high resolution space imagery will have two major benefits over aerial photographs - that is low cost and rapid availability allow repeatability in coverage of rapidly changing areas. The low cost of the imagery is an obvious advantage for natural resource managers, particularly in developing countries. Urban planners will also find the imagery of great interest. Another potentially useful application is its use for map making. Updating maps is slow and expensive, and a number of agencies have been using satellite imagery or orthophotographs as a base over which traditional cartographic line work (e.g. roads, rivers, cadastre etc) are placed.

Perhaps the greatest advantage of rapid delivery of images is for checking and control of human activities and impacts. This will allow users to monitor new developments, as well as to design methods to assess whether environments are degrading as a result of resource utilisation. Ironically, military applications may benefit as well, being considered by many as counterintuitive for sustainable land management. The images will allow strategic targets to be identified and mapped, as well as priming missile guidance systems with the necessary co-ordinate systems. On the other hand, publicly available data will make the build-up of arms much more transparent to the rest of the world.

5. Promising algorithms for sustainable development

Visualisation is an important tool for assessing the impact of a development. Such applications are useful for land suitability studies, change detection and obtaining knowledge about where in the landscape particular land cover, or land cover changes, are occurring. A second technique holding promise is the expert system (Skidmore et al., 1996). Export systems formalise knowledge about a resource as a set of rules, which may be used to classify digital spatial data. Operational accuracies have been achieved. These techniques may be particularly relevant when used in combination with information obtained from participatory rural appraisal (PRA) and Rapid Rural Appraisal (RRA) methods (see below for details).

6. Policy tools and information needs for sustainable development

In recent years, new approaches to natural resources management have emerged, based on participation of local populations, such as joint forest management, social forestry and eco-development projects. Approaches ignoring local knowledge and stakeholder interests have sometimes had poor conservation success, while simultaneously failing to meet the needs of the local population. Survey and planning techniques with a local focus have been termed 'PRA' (participatory rural appraisal), while 'RRA' (Rapid Rural Appraisal) are applicable for larger areas at higher administrative levels and map scales (Mukheree, 1995, 1997). But inclusion of socio-economic approaches and data must be consistent with conventional scientific methods in order to avoid bias, maintain credibility, and check the veracity of the output.

Indeed, both socio-economic and biophysical approaches may be combined, to provide data and information for decision makers and planning processes. Successful examples of biophysical studies at the local scale (eg. Skidmore et al., 1996) and regional scale (Tucker et al., 1978) have the potential to be used with socio-economic data collected at similar scales, (e.g. PRA for such as local (eg. Singh and Bhardwaj, 1994) and RRA at a regional level. Integration is facilitated though site specific data collection, where biophysical and land use data are collected for the same plot and are directly cross-checked and integrated.

For most natural resource applications (eg. forestry, agriculture, nature conservation), a people centred approach must be joined with a biophysical based approach, to balance use and conservation of natural resources. Both approaches may be supported by remote sensing and GIS. Some attempts at integrating participatory methods with remote sensing and GIS have been made (eg. Singh & Bhardwaj, 1994; Groten, 1996). Maps of biophysical resources for policy and district management plans are usually derived by aerial photographs (and more recently by digital image processing and GIS). Further research into issues of multi-scale interaction and communication between different planning levels represents a major challenge.

It should be emphasised however, that there are three essential components for any sustainable development. These are:

1. **Information:** Information on which to base planning and decision making, and to monitor whether the activity is indeed sustainable, through change detection. In recent times, less emphasis has been placed on good data and information supply by donor organisations, government and industry. An exception are wildlife and livestock records, as well as agricultural production figures, which have been collected for 20 years by the Department of Remote Sensing and Resource Assessment, Nairobi. From this time series data, conclusions may be drawn about the decline of wildlife, famine early warning systems, and increasing livestock populations.
2. **Policy**: Clear and unambiguous policy is required at global, national, regional and local levels, to guide planning and utilisation of resources.
3. **Participation**: Unless stakeholders (at all levels) are involved in considering the consequences of their actions, a development will not be sustainable.

Equally important is to have a well educated society, which can consider and debate the consequences of the development.

7. Conclusions

In this paper, a small selection of successful remote sensing applications in the area of sustainable development have been reviewed. Three recent remotely sensed imagery (hyperspectral, radar and high spatial resolution) are discussed, and their potentials outlined. Finally some methods for using and integrating these data with appropriate algorithms and planning environments are discussed. Any sustainable development should balance information supply, good policy and participation.

References

Badhwar GD and MacDonald RB et al. (1984) Spectral characterization of biophysical characteristics in a boreal forest: relationship between thematic mapper band reflectance and leaf area index for Aspen. Proc of the IGARSS symp, Strasbourg, France

Baumgardner M F, Silva LF, Biehl LL, Stoner ER (1985) Reflectance properties of soils. Adv Agron 38: 1-44

Banninger C (1986) Relationship between soil and leaf metal content and Landsat MSS and TM acquired canopy reflectance data. Remote Sensing for Resources Development and Environmental Management Proceedings of the 7th International Symposium on Remote Sensing for Resources Development and Environmental Management ISPRS Commission VII, ITC : Enschede The Netherlands, pp 195-200

Barbier EB (1987) The concept of sustainable development. Environmental Conservation 14(2): 101-110

Boardman JW (1989) Inversion of imaging spectyrometry dta using value decomposition. Proceedings IGARSS'89, 12th Canadian Symposium on Remote Sensing 4:2069-2072

Bridges RG and Dobbyns GR (1991) The dry schlerophyll silvertop ash stringybark forests of south-eastern NSW. Surrey Beatty and Sons Pty Ltd: Perth WA

Brockhaus JA and Khorram S et al. (1988) An evaluation of the utility of Spot and Thematic Mapper data for providing forest inventory information. Symp proc: Spot-1 Image Utilisation Assessment and Results. CNES, Cepadues Editions, Toulouse

Brockhaus JA and Khorram S (1992) A comparison of SPOT and Landsat-TM data for use in conducting inventories of forest resources. International J. of Remote Sensing 13(16): 3035-3043.

Brown BJ, Hanson M et al (1987) "Global sustainability: Towards definition." Environmental Conservation 11(6): 713-719

Butera AS (1986) A correlation and regression analysis of percent canopy closure versus TMS spectral response for selected forest sites in the San Juan national forest, Colorado. IEEE Trans on Geoscience and Rem Sens GE-24, 1:122-129.

Cipra JE, Franzmeier DP, Bauer ME and Boyd RK (1980) Comparison of multispectral measurements from some nonvegetated soils using Landsat digital data and a spectrometer. Soil Science Society of America Journal 44: 80-84

Coleman TL, Montgomery OL, (1987) Soil moisture, organic matter and iron content effect on the spectral characteristics of selected vertisols and alfisols in Alabama. Photogrammetric Engineering and Remote Sensing 53(12): 1659-1663

Colwell, RN (1983) Manual of remote sensing. Falls Church Virginia ASPRS. Baur GN 1965. Forest types in New South Wales. Forestry Commission of N S W Sydney

Cook EA, Iverson LR and Graham RL (1989) Estimating forest productivity with thematic mapper and biogeographical data. Remote Sens Environ 28: 131-141

Crist E P, and Kauth R J (1986) The Tasseled Cap de-mystified. Photogrammetric Engieering and Remote Sensing 52: 81-86

Crist EP and Cicone RC (1984) A physically based transformation of Thematic Mapper data. The TM Tasseled Cap. IEEE Trans on Geosci. and Remote Sensing GE-22: 256-263

Cumming RW and Elliot GL (1990) Soil chemical properties. Sydney University Press Sydney

Danson FM and Curran PJ (1993) Factors affecting the remotely sensed response of coniferous forest plantations. Remote Sens Environ 43: 55-65
Defeo NJ and Rock BN et al. (1987) Detection of forest damage on Whiteface Mountain, New York, using Landsat TM data. Proc 21st internatl symp on remote sensing of environment. ERIM, Ann Arbor, Michigan
De Wulf RR, Goosens RE, De Roover BP, and Borry FC (1990) Extraction of forest stand parameters from panchromatic and multispectral SPOT-1 data. International J Remote Sensing 11(9): 1571-1588
De Jong SM (1994) Applications of reflective remote sensing for land degradation studies in a Meditteranean Environment. Netherlands Geographical Studies, Utrecht, The Netherlands.
Escadafal R, Girard M and Courault D (1989) Munsell soil colour and soil reflectance in the visible spectral bands of Landsat MSS and TM data. Remote Sensing of Environment 27: 37-46
Fiorella M and Ripple WJ (1993) Determining successional stage of temperate coniferous forests with Landsat satellite data. Photogrammetric Engineering and Remote Sensing 59(2): 239-246
Franklin JF, Davis F W and Lefebvre P (1991) Thematic Mapper analaysis of tree cover in semiarid woodlands using a model of canopy shadowing. Remote Sens Environ 36: 189-202
Franklin J, Li X and Strahler AH (1986) Canopy reflectance modelling in Sahelian and Sudanian woodland and savannah 4-10 December 1986. Proceedings of the 20th International Symposium on Remote Sensing of Environment, Nairobi Kenya. ERIM: Ann Arbor Michigan pp1273-1281
Frazier BE and Cheng Y (1989) Remote sensing of soils in the eastern Palouse region with Landsat Thematic Mapper. Remote Sensing of Environment 28:317-325
Fresco LO and Kroonenberg SB (1992) "Time and spatial scales in ecological sustainability". Lans Use Policy 9:155-168
Goodland R. and Ledec G (1987) "Neoclassical economics and principles of sustainable development." Ecological Modelling 38:19-46
Groten SME (1996) Aerial Photographs as a means of communication in land use planning. Agriculture and rural Development 4:11 - 13
Hall-Könyves K (1987) The topographic effect on Landsat data in gently undulating terrain in southern Sweden. International Journal of Remote Sensing 8(2): 157-168
Hame T, Tomppo E and Parmes E (1988) Stand based forest inventory from SPOT Image. Symposium Proceedings: SPOT-1 Image Utilisation Assessment Results Toulouse France pp971-976 (CNES Cepadues Editions)
Helyar KR, Cregan PD and Godyn DL (1990) Soil acidity in New South Wales - current pH values and estimates of acidification rates. Aust J Soil Sci 28:523-537
Hoffer RM (1975) Natural resource mapping in mountainous terrain by computer analysis of ERTS-1 satellite data. Purdue University Indiana
Hoffer RM (1978) Biological and physical considerations in applying computer aided analysis techniques to remote sensor data. In: Swain PM and Davis SM (eds) Remote Sensing: The Quantitative Approach, McGraw-Hill, New York
Holben BN and Justice CO (1980) The topographic effect on spectral response from nadir-pointing sensors. PE&RS 46, 9: 1191-1200
Holbo HR and Luvall JC (1989) Modeling surface temperature distributions in forest landscapes. Remote Sensing of Environment 27:11-24

Horler DNH and Ahern FJ (1986) Forestry information content of Thematic Mapper data. Int. J. Remote Sensing 7(3): 405-428

Horvath EH, Post DF and Kelsey JB (1984) The relationships of Landsat digital data to the properties of the Arizona rangelands. Soil Science Society of America Journal 48: 1331-1334

Huete AR (1988) A soil-adjusted vegetation index. Remote Sensing of Environment 25: 295-309

Huete AR and Jackson RD (1988). Soil and atmosphere influences on the spectra of partial canopies. Remote Sensing of Environment 25: 89-105

Huete AR, Jackson RD and Post KF (1985) Spectral response of a plant canopy with different soil background. Remote Sensing of Environment 17: 35-53

Huete AR, Post DF and Jackson RD (1984) Soil spectral effects on 4-space vegetation discrimination. Remote Sensing of Environment 15: 155-165

Hurditch WJ (1990) The soil ecosystem, Pergamon Press, Sydney

Justice CO, Wharton SW and Holben BN (1981) Application of digital terrain data to quantify and reduce the topographic effect on Landsat data. International Journal of Remote Sensing 2(3): 213-230

Karaska MA, Walsh SJ et al. (1986) Impact of environmental variables on spectral signatures acquired by Landsat Thematic Mapper. IJRS 7, 12:1653-1667

Kauth RJ and Thomas GS (1976) The tasseled cap - a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, Laboratory of Remote Sensing Purdue University West Lafayette Indiana 47907

Keith DA and Sanders JM (1990) Vegetation of the Eden region, south eastern Australia. Species composition, diversity and structure. Journal of Vegetation Science 1: 203-232

Kornblau ML and Cipra JE (1983) Investigation of digital Landsat data for mapping soils under range conditions. Remote Sensing of Environment 13: 103-112

Korolyuk TV and Scherbenko HV (1994) Compiling soil maps on the basis of remotely sensed data digital procesing: soil interpretation. International Journal Remote Sensing 15(7): 1379-1400

Leckie DG and Yuan X et al. (1992) Analysis of high resolution multi-spectral MEIS imagery for spruce budworm damage assessment on a single tree basis. Rem Sens of Environ 40: 125-136

Lee K, Lee GB and Tyler EJ (1988). Thematic Mapper and digital elevation modelling of soil characteristics in hilly terrain. Soil Science Society of America Journal 52: 1104-1107

Leprieur CE, Durand JM and Peyron JL (1988) Influence of topography on forest reflectance using Landsat Thematic Mapper and Digital Terrain Data. Photogrammetric Engineering and Remote Sensing 54(4): 491-496

Lewis DT, Seevers PM and Drew JV (1975) Use of satellite imagery to delineate soil associations in the sand hills region of Nebraska. Soil Science Society of America Journal 39: 330-335

Li X and Strahler AH (1985) Geometric-optical modeling of a conifer forest canopy. IEEE Trans Geosci and Remote Sens GE-23: 705-721

Lillesand TM, Hopkins PF, Bucheim MP and MacLean AL (1985) The potential impact of thematic mapper, SPOT and microprocessor technology on forest type mapping under Lake

State conditions. Proceedings of Pecora 10 - Remote sensing in forest and range management Colorado State University Fort Collins Colorado. ASPRS: Falls Church Virginia pp 43-57

Little IP (1992) The relationship between soil pH measurements and calcium chloride and water suspensions. Aust J Soil Sci 30: 587-592

Long Y and Turner BJ (1994) The relationship between spectral characteristics of SPOT and TM and stand variables of a coniferous forest. In: P Woodgate and P Turner (Ed) Proc 7th Australasian Remote Sensing Conf Melbourne. Remote Sens & Photogrammetry Assoc Aust Vol 3: 97-102

Malila WA and Gleason JM et al. (1978) Applications of modelling to analysis and processing of Landsat data. Proc 12th internatl symp on remote sensing of environment. Ann Arbor, Michigan

Moore ID, Mackay SM, Wallbrink PJ, Burch GJ and O'Loughlin EM (1986) Hydrological characteristics and modelling of a small forested catchment in southeastern New South Wales. Pre-logging condition. Journal of Hydrology 83: 307-335

Mukherhee Neela (1997) Participatory Rural Appraisal . Methodology and applications. Nat Acad Of Administration Moussori Concept Publishing company New Dehli 160 pp

Mukherjee Neela (1995) Participatory Rural Appraisal and Questionnaire survey: comparative field experience and methodological innovations. Nat Acad Of Administration Moussoorie Natraj Publishers Dehra Dun,163 pp

Murphy RJ and Wadge G (1994) The effects of vegetation on the ability to map soils using imaging spectrometer data. International Journal Remote Sensing 15(1): 63-86

Musick HB and Pelletier RE (1988) Response to soil moisture of spectral indexes derived from bidirectional reflectance in Thematic Mapper wavebands. Remote Sensing of Environment 25: 167-184

Myers VI (1983) Remote sensing applications in agriculture. In: Colwell R N (ed) Manual of Remote Sensing Vol 2 Chapter 33. American Society of Photogrammetry: Falls Church Virginia

Nelson RF, Latty RS and Mott G (1984) Classifying northern forests using thematic mapper simulator data. Photogrammetric Engineering and Remote Sensing 50(5): 607-617

Nemani R, Running PS and Band L (1993) Forest ecosystem processes at the watershed scale: sensitivity to remotely-sensed Leaf Area Index estimates. International Journal Remote Sensing 14(13): 2519-2534

Oliver MA and Webster R (1990) Kriging: a method of interpolation for geographical information systems. International Journal of Geographical Information Systems 4(3): 31-32

Orbukhov AI and Orlov DC (1964) Spectral reflectivity of the major soil groups and possibility of using diffuse reflectance in soil investigations. Pochvovedeniye No 2. Reported in Myers VI 1983. Remote sensing applications in agriculture - Chapter 33. In: Colwell RN (ed) Manual of Remote Sensing Vol 2. American Society of Photogrammetry Falls Church Virginia USA

Pech RP and Davis AW (1987). Reflectance Modeling of Semiarid Woodlands. Remote Sensing of Environment 23: 365-377

Pech RP, Davis AW, Lamacraft RR and Graetz RD (1986) Calibration of LANDSAT data for sparsely vegetated semi-arid rangelands. Int J Remote Sensing 7(12): 1729-1750

Pech RP, Graetz RD and Davis AW (1986) Reflectance modelling and the derivation of vegetation indices for an Australian semi-arid shrubland. Int J Remote Sensing 7(3): 389-403

Peterson DL, Aber JD, Matson PA, Card DA, Swanberg N, Wessman C and Spanner M (1988) Remote sensing of forest canopy and leaf biochemical contents. Remote Sensing of Environment 24: 85-108

Peterson DL, Spanner MA, Running SW and Teuber KB (1987) Relationship of Thematic Mapper Simulator data to leaf area index of temperate coniferous forests. Remote Sens Environ. 22: 323-341

Proy C and Tanr D et al. 1989. Evaluation of topographic effects in remotely sensed data. Remote Sens of Environ 30:21-32.

Prosser IP, Hailes KJ, Melville MD, Avery RP and Slade CJ (1993) A comparison of soil acidification and aluminium under eucalytus forest and unimproved pasture. Aust J Soil Sci 31: 245-254

Richards JA, Landgrebe DA and Swain PH (1982) A means for utilizing ancillary information in multispectral classification. Remote Sensing of Environment 12: 463-477

Richardson AJ and Wiegand CL (1977) Distinguishing vegetation from soil-background information. Photogrammetric Engineering and Remote Sensing 43: 1541-1542

Rock BN and Vogelmann JE et al. (1986) Remote detection of forest damage. BioScience 36, 7: 439-445.

Ryan PJ (1993) Soil Formation on the Wallagaraugh Adamellite south eastern NSW Australia. Catena 20: 543-561

Salisbury JW and D'Aria DM (1992) Infrared (8-14 μm) remote sensing of soil particle size. Remote Sensing of Environment 42: 157-165

Siegel BS and Goetz AFH (1977) Effect of vegetation on rock and soil type discrimination. Photogrammetric Engineering and Remote Sensing 43(2): 191-196

Singh RP and Sirohi A (1994) Spectral reflectance properties of different soil types of soil surfaces. ISPRS Journal of Photogrammetry and Remote Sensing 49(4): 34-40

Singh S and Bhardwaj AK (1994) Eco-development micro plan for Bijeria village Shadol district Madhya Pradesh. WII-UNDP/FAO project report Wildlife of Institute of India Min. of Forest and Environment Chandrabani Dehra Dun 122 pp

Skidmore AK (1989) An expert system classifies eucalypt forest types using Landsat Thematic Mapper data and a digital terrain model. Photogrammetric Engineering and Remote Sensing 55(10): 1449-1464

Skidmore AK, Watford FW, Luckananurug P and Ryan P (1996) An operational expert system for mapping forest soils. Photogrammetric Engineering and Remote Sensing 62(5):501-511

Skidmore AK, Forbes GW and Carpenter DJ (1988) Non-parametric test of overlap in multispectral classification. International Journal of Remote Sensing 9(4): 777-785

Skidmore AK and Turner BJ (1988) Forest mapping accuracies are improved using a supervised nonparametric classifier with SPOT data. Photogrammetric Engineering and Remote Sensing 54(10): 1415-1421

Slater PN and Jackson RD (1982) Atmospheric effect on radiation reflected from soil and vegetation as measured by orbiting sensors using various scanning directions. Applied Optics 21: 3923-3931

Smith JA and Lin TL et al. (1980) The Lambertian assumption and Landsat data. PE&RS 46, 9: 1183-1189.

Spanner MA, Pierce LL, Peterson DL and Running SW (1990) Remote sensing of temperate coniferous forest leaf area index: the influence of canopy closure understory vegetation and background reflectance. Int J Remote Sensing 11: 95-111

Statsoft I (1994) Statistica for the Macintosh (Volume I).(Statsoft Inc: 2325 East 13th Street Tulsa OK USA)

Stoner ER and Baumgardner MF (1981) Characteristic variations in reflectance of surface soils. Soil Sci Soc Am J 45: 1161-1165

Strahler AH, Estes JE, Maynard PF, Mertz FC and Stow DA (1980) Incorporating collateral data in Landsat classification and modelling procedures. Proceedings of the 14th International Symposium on Remote Sensing of Environment San Jose Costa Rica Vol 2. ERIM: Ann Arbor Michigan pp1009-1026

Strahler AH, Logan TL and Bryant NA (1978) Improving forest cover classification accuracy from Landsat by incorporating topographic information. Proceedings of the 12th International Symposium on Remote Sensing of Environment, Volume 2, ERIM: Ann Arbor, Michigan, pp 927-942

Suzuki Y (1989) Investigation of water content from airborne MSS data. International Journal of Remote Sensing 10(1): 71-82

Thompson DR, Haas RH and Milford MH (1981) Evaluation of Landsat multispectral scanner data for mapping vegetated soil landscapes. Soil Science Society of America Journal 45: 91-95

Thompson DR and Henderson KE (1984) Detecting soils under cultural vegetation using digital Landsat Thematic Mapper data. Soil Science Society of America Journal 48: 1316-1319

Thompson DR, Henderson KE, Houston AG and Pitts DE (1984) Variation in alluvial-derived soils as measured by Landsat Thematic Mapper. Soil Science Society of America Journal 48: 137-142

Tucker CJ and Miller LD (1977) Soil spectra contributions to grass canopy spectral reflectance. Photogrammetric Engineering and Remote Sensing 43(6): 721-726

Tucker C J and Gatlin JA et al (1984) "Monitoring vegetation in the Nile Delta with NOAA-6 and NOAA-7 AVHRR Imagery." Photogrammetric Engineering and Remote Sensing 50(1): 53-61

Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. Rem Sens of Environ 8:127-150

Turner BJ and Moore DM (1987) Can SPOT help the forest manager? Fourth Australasian Remote Sensing Conference Adelaide pp 776-787

Turner BJ, Moore DM and Skidmore AK (1988) Forest management applications of SPOT data in Australia. In Symposium Proceedings: SPOT-1 Image Utilisation Assessment Results Toulouse pp 953-959, CNES: Cepadues Editions

Van Genderen JL, Lock BF and Vass PA (1978) Remote sensing: statistical testing of thematic map accuracy. Remote Sensing of Environment 7: 3-14

Varekamp C, Skidmore AK and Burrough PAB (1995) Using public domain geostatistical and GIS software for spatial interpolation. Photogrammetric Engineering and Remote Sensing (under review)

Vogelmann JE (1990) Comparison between two vegetation indices for measuring different types of forest damage in the north-eastern United States. IJRS 11, 12:2281-2297

Vogelmann JE and Rock BN (1986) Assessing forest decline in coniferous forests in Vermont using NS-001 Thematic Mapper simulator data. IJRS 7, 10:1303-1321
Wessman C, Aber JD and Peterson DL (1989) An evaluation of imaging spectrometry for estimating forest canopy chemistry. International Journal of Remote Sensing 10(8): 1293-1316
Westin FC and Frazee CJ (1976) Landsat data, its use in a soil survey program. Soil Science Society of America Journal 40: 137-142
Westin FC and Lemme GD (1978) Landsat spectral signature: studies with soil associations and vegetation. Photogrammetric Engineering and Remote Sensing 44(3): 315-325
Wilcox CH, Frazier BE and Ball ST (1994) Relationship between soil organic carbon and Landsat TM data in eastern Washington. Photogrammetric Engineering and Remote Sensing 60(6): 777-781
Williams DL (1991) A comparison of spectral reflectance properties at the needle branch and canopy level for selected conifer species. Remote Sensing of Environment 35: 79-93
Williams R J (1955) Vegetation regions: Atlas of Australian Resources.Canberra Australian Department of Natural Resources
Williamson SC and Lindauer IE (1988) Assessing Rangeland Vegetation Mapping Alternatives for Geographic Information Systems. Photogrammetric Engineering and Remote Sensing 54(5): 615-618
Williamson HD (1989) Reflectance from shrubs and under-shrub soil in a semiarid environment. Remote Sens Environ. 29:263-271
Zonneveld IS (1988) Survey approaches. In: Kuchler AW Zonneveld IS (eds) Vegetation mapping. Kluwer Academic Publishers Dordrecht

3.3 The potentials for GIS and meta-modelling for on-the-go precision farming

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Precision farming aims to optimise the use of soil resources and external inputs on a site-specific basis. Base ingredients for research in the field of precision farming are spatial data, including a characterization of the spatial variability, and simulation models for the characterization of the processes that take place. Geographical Information Systems (GIS) are systems for the storage, analysis and presentation of spatial data. A combination of GIS and simulation models is highly relevant for precision farming. At present only static one- or two-dimensional simulation models can be fully supported by commercial GIS systems. Within precision agriculture also an engineering component can be distinguished, in which the research findings are translated into operational systems to be used at farm level. GIS can support this engineering activity by providing a good platform for storage of base data, simple modelling, presentation of results, development of a user interface and in combination with a GPS control the navigation of farm vehicles. Based on GIS a decision support system (DSS) could be developed for operational application of precision agriculture at farm level. For the creation of a fast and robust system for on-the road precision agriculture, the use of meta models is recommended instead of complex dynamic simulation models.

1. Introduction

Agricultural practices are changing in response to economic, technological, environmental and social trends. Profitability and environmental impact of the farming systems are of major concern for both the farmers and the government.

Precision agriculture, which takes into account the spatial variation of the soil at field level, is being proposed as a remedy to many of these environmental problems. The concept of precision agriculture is based on matching the external inputs, such as fertilisers and herbicides, with the variation in local soil conditions, in order to reduce costs and negative environmental effects.

The last 10 years, there have been a number of publications on precision agriculture. In, for instance, the proceedings of the conference on site-specific management for agricultural systems (Robert et al., 1994) an extensive number of papers are presented on the subject. A large number of research papers deal with soil variability, yield monitoring, modelling crop growth and nutrient leaching on farm level.

The research components for precision farming are information about the site-specific soil conditions and the processes that occur in crop and soil. Information about the soil is generally presented in the form of observations at a series of sampling points and detailed soil maps. Research on the processes that occur in crop and soil is condensated in the form of simulation models. Besides a research component, precision agriculture also has a strong engineering component. One of the goals of research in precision agriculture is that it will lead to operational systems, which can be used at farm level.

The use of geographical information systems (GIS) for the storage, management, analysis and presentation of spatial data has diversified rapidly during the last ten years. GIS applications have been developed for a large variety of fields, ranging from land use planning and utility management at local scale to global warming and acid deposition on a global scale. The number of publications dealing with the use of GIS in precision agriculture are, however, limited. Han et al. (1995) describe the linking of GIS with a potato simulation model for site-specific crop management. Griffith (1995) propagates the use of GIS for economic analysis at farm level. In most papers on the use of GIS in precision agriculture the function of GIS is limited to data pre-processing to produce field management maps (Long et al., 1995) or generating (part of) the input data for simulation models.

In this paper the potentials and the problems for GIS support in research and engineering in the field of precision agriculture are discussed.

2. Research in precision agriculture and GIS support

From a research point of view precision agriculture deals with data-related and modelling-related issues and the interaction between data and modelling.

In precision farming geographical data on various aspects such as soil, crop, weather and field history are relevant.

Soil data is used in the form of point observations, describing properties of the soil in the z dimension and soil maps describing the spatial extent of the soil pattern in the x,y dimension. Crop parameters can be considered as constant at field level. Weather data can be considered as spatially constant at field level, but they are highly variable over time. Field history, e.g. the amount of fertilisers applied and crops grown vary both in space and time. In summary we see that geographical data is recorded in three dimensions in space and in time, which makes precision agriculture quite a complex system from data management and analysis point of view. Research questions are e.g.: “What data should be collected?” “Which sampling method should be used?”

Second components of research in precision agriculture are simulation models. For example, simulation models exist for the flow of water, crop growth, soil erosion, nutrient and pesticide leaching. There seems to be no general accepted classification of process models. Model types often found in literature are (e.g. France and Thornley, 1984; Burrough, 1992):

- *empirical and mechanistic* models. An empirical model describes a process based on empiricism, whereas a mechanistic model attempts to give a description with understanding.
- *static and dynamic* models. A static model does not contain time as a variable. Any time-dependent components of the behaviour of the system are ignored. Since all processes in the world involve change, a static model is always an approximation. It might be a good approximation perhaps because the phenomenon is close to equilibrium. A dynamic model, on the other hand, contains the time variable in the equations.
- *deterministic and stochastic* models. A deterministic model is one that makes definite predictions for quantities (such as crop yield, rainfall), without any associated probability distribution. A stochastic model, on the other hand, contains some random elements or probability distributions. The model can not only predict the expected value of a quantity, but also the variance. The greater the uncertainty in the behaviour of the process, the more important it is to follow a stochastic approach. Stochastic models tend to be technically difficult

to handle and can quickly become very complex. Another approach in dealing with uncertainty is to use a combination of a deterministic model and Monte Carlo simulation to obtain probability estimates.

- *spatial dimensions* models. We can distinguish between one-dimensional (1D), two-dimensional (2D) and three dimensional (3D) models.
- *qualitative and quantitative* models. A qualitative model makes predictions on a qualitative level, such as not suitable, suitable or highly suitable. The input for a qualitative model can be both qualitative and quantitative. A quantitative model, on the other hand, produces quantitative output.

Models constructed for real world processes often contain combinations of the above described model types. For example, we may have a dynamic, deterministic, quantitative, one-dimensional model for describing crop growth (Van Diepen et al., 1989) or a static, empirical, qualitative, one-dimensional model for land evaluation (Van Lanen, 1991). For the integration with GIS the characteristics, 'dimensions' and 'static-dynamic' are of major importance. Most of the models applied in precision agriculture are dynamic, one- or two-dimensional models.

Current GIS can support the research in precision agriculture in the following ways:
(i) The data collected can be stored and pre-processed in GIS in order to generate spatially differentiated input data for the simulation models. As shown by Bregt (1993) this can only be done fully for static one- or two-dimensional simulation models. The main reason for this is that the data models underlying commercial GIS are based on a two-dimensional description of the Earth's surface. For a full GIS support of the dynamic simulation models (the most relevant models used in precision agriculture) the geographical data model underlying commercial GIS must be expanded with the time dimension. Although some research prototypes have been produced, it has not yet resulted in a commercially available product. More information on the integration between GIS and simulation models can be found in Fisher et al. (1996), Goodchild et al. (1996), Maidment, (1996) and Moore, (1996).
(ii) For simple one and two-dimensional models the simulation model can be implemented fully in the GIS environment, using the analysis functions of the GIS software (tight integration). The advantage of this approach is that a more integrated system for data storage, modelling and presentation is created. A disadvantage is the limitation to relatively simple models.

For simulation models in precision agriculture the loose integration (Stuart and Stocks, 1993) is at this moment the best option. In the loose-coupled approach the simulation model and GIS are linked loosely through an interface. The interface may consist of simple manual transfer of ASCII data files or the development of programmes, which ease the data transfer. The loose coupling is flexible and a large number of models can be integrated. The choice for a particular type of integration (loose or tight) depends on the situation at hand (see Figure 1).

In the case of a complicated dynamic process model loose integration is the only practical option at this moment. Also the large investment in encoding process models combined with the limited functionality of GIS to implement process models implies that a loose coupling to GIS is the best solution for the more advanced applications. In the case of relatively simple models a tight integration with GIS is recommendable as these applications are easier to develop and maintain, and allow for easier animation of the model results.
(iii) The presentation of spatial data in the form of maps is one of the most appealing features of GIS. This function of GIS can be used to present the modelling results in a form, which can be easily communicated to others.

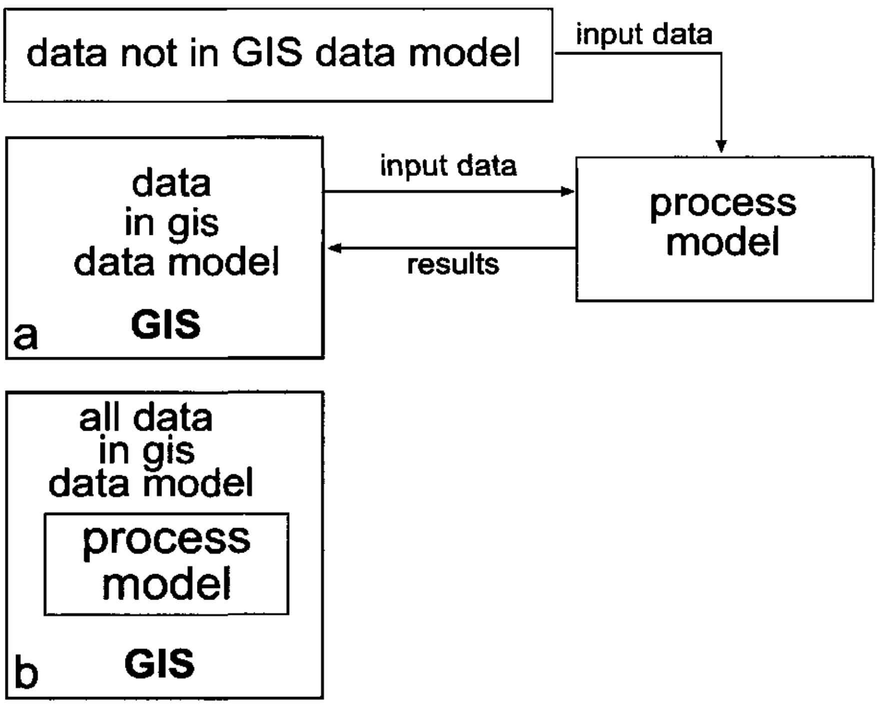

Figure 1. Different forms of GIS and simulation model integration.

3. Engineering in precision agriculture and GIS support

One of the main goals of research in precision agriculture is that it will lead to operational systems to be used at farm level. A few operational systems are described in literature. Robert (1989) describes a computerised spreader for fertilisers and chemicals as a function of local variation in soil conditions. McGrath et al. (1995) describe an expert system for combing soil test results with data of crop models, fertilisers, chemicals, weather, field history, seed characteristics and yield economics. The use of GIS in the reported systems is, however, limited. There are a number of reasons for this:

(i) Precision agriculture is a relative new research area, which has not yet received full attention of the more applied research organisations, which are more focused on the engineering side.
(ii) The data structure of data used in precision agriculture is quite complex as compared to the data models supported by current commercial GIS.
(iii) Commercial GIS-systems are still quite expensive for operational use within an integrated system for precision agriculture.
(iv) The amount of digital spatial data (soil and topography) with sufficient resolution to be used at farm level is still very limited.

Although the present use of GIS for precision agriculture is limited, the potentials in near future are high to develop a GIS-based decision support system (DSS) at farm level. What are the requirements of such a system, and how can it be constructed using GIS technology? Such a DSS for precision agriculture must be weather-proof, user-friendly, fast, interactive, simple, integrated with GPS and contain spatial data on soil and relationships between soil-crop production-nutrient and pesticide leaching as a function of the input of fertilisers and farm chemicals.

For the construction of such a DSS the keyword is simplicity. If we try to condensate all our research findings in a system we will end up with a much too complicated system to be used at farm level. What are the components of such a system, and how could it be constructed using GIS-technology?

3.1 DSS for precision agriculture

The main components of a DSS for precision agriculture are a spatial database, knowledge module, locator module and a user interface (see Figure 2).

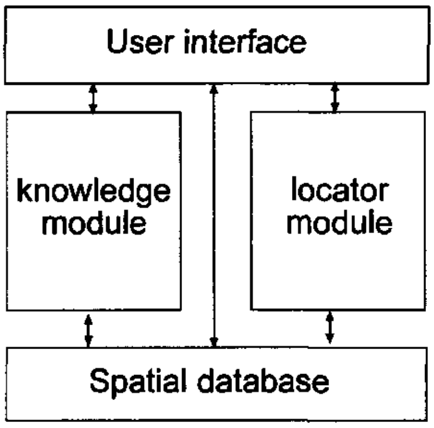

Figure 2. Components of a DSS for precision agriculture

The *spatial database* must contain a two-dimensional spatial representation of the farm. The minimum dataset to be included in such a database is a detailed topographic map of the farm and a spatial characterization of the soil in the form of a detailed soil map with representative profiles and associated attributes.

The second component is the *knowledge module*. In this module simple relationship between e.g. soil/groundwater-fertiliser application and nutrient leaching, fertiliser application and crop production, input-output relations of economic evaluation are stored. The knowledge module should not contain complex simulation models but simple relations. These relations could be derived by using:

(i) Expert knowledge which is formalised in the form of tables and expert rules.

(ii) Dynamic simulation models for modelling various scenarios of soil-water-crop relations for various input levels and summarising the modelling results in the form of meta-models.

Meta-models are proximations of the process under study. The term meta-model may be confusing, as it suggests a kind of higher level model. This is not the case, it is just a simplified description of the process in the form of e.g. a regression equation. It is obtained by analysing a large number of model-input data and associated modelling results (Figure 3).

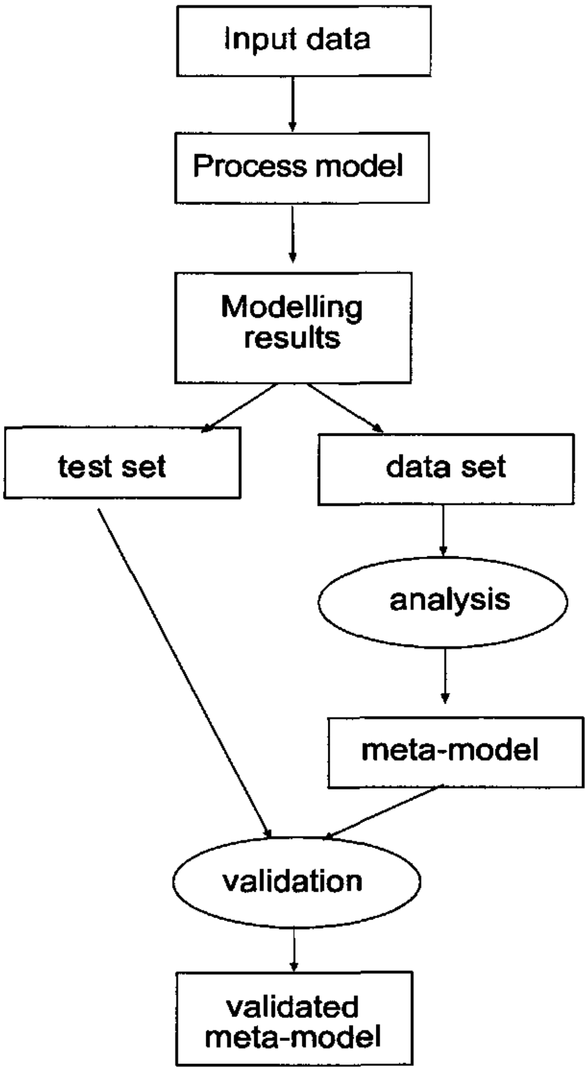

Figure 3. Schematic representation of the derivation of a meta-model.

The term proxy model is probably a better name for meta-model. For the construction of a meta-model various methods can be used:

- Regression techniques;
- Multivariate Adaptive Regression Splines (MARS) (Friedman, 1988);
- Neural Networks (Hush & Horne, 1993).

For practical application in the field of precision agriculture all three methods can be used to derive a meta-model. The differences between the methods will probably be limited. The advantages of the use of meta-models are the speed of calculation and the robustness of the software. For on-the-road use of the system there are two essential requirements. The majority of the more complex simulation models for soil-water-crop interactions are at this moment not robust and fast enough to be used in a turnkey system for precision farming. A disadvantage of the use of a meta-model is its limitation to a certain specified input domain used in the analysis, while a simulation model can be used under wider conditions.

A distinction should be made between non-spatial (e.g. economic relations) and spatial relations (e.g. nutrient leaching as a function of soil type). Most of the non-spatial relations are probably already implemented in the existing management support systems for farmers. The spatial relations must be derived for the specific physical conditions of the farm.

The third component is the locator module. In order to apply precision agriculture is essential to relate the data in the database with the position on the land. Recently a number of GIS-products (e.g. Locator GIS) have been released which provide this as standard functionality.

The fourth component is the user interface. A user-friendly interface is vital for the operational use of the system.

The above described DSS could at this moment be developed by using state of art GIS-technology in combination with user interface tools. The new generation of GIS systems is from a software point of view more open or (becoming more open) than the old systems, which means that they can be integrated with programming environments, such as Delphi or Visual Basic. The time is there to construct, based on the research findings, a GIS-based DSS for precision farming.

4. Conclusions and recommendations

The integration of GIS and process models offers interesting possibilities for enlarging the analysis for precision farming. GIS forms a good platform for the storage and management of model input data and the presentation of model results, while the process model provides the analysis capabilities which are lacking in current GIS.

If we, however, confront the current data models underlying commercial GIS with the data requirements of the process models, it appears that only simple, static one- or two-dimensional models can be integrated easily. For the dynamic process models, from an analysis point of view, the most interesting ones for precision farming, GIS can only partly play a role in storage and management of model input data.

In order to increase the integration possibilities, the geographical data model underlying commercial GIS must be expanded with the time dimension.

The prospects for creating an operational decision support system (DSS) for precision farming by using GIS-technology are good. A new generation of GIS-products is appearing on the market, with built-in GPS facilities and a more open structure, which makes the development of a DSS for precision agriculture on the basis of the existing non-spatial management support systems possible. Such a DSS should at least contain the components database, knowledge module, locator module and a user interface. As a first step the knowledge module should contain simple relations in the form of meta-models, knowledge tables and simple simulation models. It is a challenge for the research community to derive these relations from the more complex dynamic simulation models, which are used for research in the field of precision farming.

References

Bregt AK (1993) Integrating GIS and process models for global environmental assessment. In: Tateishi R (ed.) Proceedings of the international workshop on global GIS, August 24-25 Tokyo Japan

Burrough PA (1992) Development of intelligent geographical information systems.

International Journal of Geographical Information Systems 6:1-11
Fisher M, Scholten HJ and Unwin D (1996) Spatial analytical perspective on GIS. Taylor & Francis UK
France J and Thornley JHM (1984) Mathematical models in agriculture. Butterworth, London
Friedman JH (1988) Multivariate Adaptive Regression Splines, Technical Report 102, Stanford University Dept of Statistics
Goodchild et al. (1996) GIS and environmental modeling: Progress and research issues. GIS World USA
Griffith D (1995) Incorporating economic analysis into on-farm GIS. In: Robert PC, Rust RH and Larson WE (1994) Site-specific management for agricultural systems. ASA, CSSA, SSSA, Madison (Proc. 2th Conf, Minneapolis) p 723-729
Han S, Evans RG and Hodges T (1995) Linking a geographic information system with a potato simulation model for site specific crop management. J Environmental Quality 24:772-777
Hush DR and Horne BG (1995) Progress in supervised neural networks. IEEE Signal Processing Magazine 10: 8-39
Long DS, Carlson, GR and DeGloria SD (1995) Quality of field management maps. In: Robert PC, Rust RH and Larson WE (1994) Site-specific management for agricultural systems. ASA CSSA SSSA Madison (Proc 2th Conf, Minneapolis) p 51-271
Maidment DR (1996) Environmental modeling within GIS. In: Goodchild et al. GIS and environmental modeling: Progress and research issues. GIS World USA p 315-323
McGrath DE, Skotnikov AV and Bobrov VA (1995) A site-specific expert system with supporting equipment for crop management. In: Robert PC, Rust RH, Larson WE (1994) Site-specific management for agricultural systems. ASA, CSSA, SSSA, Madison (Proc 2th Conf, Minneapolis) p 619-635
Moore ID (1996) Hydrologic modeling and GIS. In: Goodchild et al. (Eds) GIS and environmental modeling: Progress and research issues. GIS World USA p 143-148
Robert PC (1989) Land evaluation at farm level using soil survey information systems In: Bouma J and Bregt AK (eds) Land qualities in space and time. Pudoc Wageningen (Proc Sym, Wageningen 1988) p 299-311
Robert PC, Rust RH and Larson WE (1994) Site-specific management for agricultural systems. American Society of Agronomy, Madison: second international conference
Stuart N and Stocks C (1993) Hydrological modelling within GIS: an integrated approach In: HydroGIS 93, Application of geographic information systems in hydrology and water resources. IAHS Publ no 211 p 333-343
Van Diepen CA, Wolf J, Van Keulen H and Rappoldt C (1989) WOFOST: a simulation model for crop production. Soil Use and Management 5:16-24
Van Lanen HAJ (1991) Qualitative and quantitative land evaluation: an operational approach. PhD Thesis, Agricultural University Wageningen.

4. Interactive decision support

The role of model-based exploration

Decisions are being taken at various scales by many decision makers: from the farmer to the policy maker and from the greenhouse through field and farm to the regional scale. The objectives of these stakeholders can be totally different, but they all need explicit information on their system(s) to base their decisions. Sound decisions require a thorough understanding of the relationships among system components and the strategic, tactical and operational options for the system that follow from these relationships. Agricultural models may play an increasingly important role in understanding these relationships and revealing consequences of decision options.

4.1 Expliciting and evaluating management strategies: a case study in dairy production

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Based on an analysis of the farmers' management problems, this paper argues in favour of a decision support approach relying on an explicit and rigorous modelling of the technical management strategy that underlies any farmer's decision making behaviour (real or hypothetical). A strategy is a set of planned tasks that incorporates provision to adapt to stochastic fluctuations of the environment (the weather in particular). A fully specified strategy enables to generate what actions to perform in any situation along the period covered by the management task and the production system under consideration. In order to compare two strategies so as to select the best one, the advocated approach makes use of a simulation tool with which the effects of applying a strategy are evaluated under different hypothetical weather conditions. The example of a dairy production system predominantly based on rotational grazing is used to illustrate the modelling of a technical management strategy covering a one-year production cycle.

1 Introduction

Internationalisation of markets, shifts in consumers' demands and requirements, rapid evolution in technologies, greater concern for environmentally friendly production are among the recently appeared factors that make competitiveness much harder to achieve and maintain in the agricultural production sector. Unlike the rather stable context of the past decades, farmers must now strive for a dynamic competitive advantage that requires a well mastered understanding of their production processes so as to control them under various constraints and towards specific objectives that both may change from one year to the other.

Consequently higher importance has been given to the ability of making the best as decisions concerning configuration choices and day-to-day technical management. It is striking to see how profitability varies from one farm to the other just because of the differences in management skills of the farmers. The most successful ones usually operate on the basis of anticipation on what situations could occur and what the appropriate reactions could be in order to ensure that their production system stays on the right track. In other words, driving profitably an agricultural production system requires a management strategy, that is, a conditional plan of actions specifying the temporally structured set of operations attached to the possible futures.

As part of a decision support project, the present paper argues in favour of a modelling and simulation approach of the management strategies elaborated to drive agricultural production systems. The systems addressed can be either a single farm enterprise (e.g. a crop on a set of fields managed in the same way), or a combination of highly interdependent or interlocking farm enterprises (e.g. a livestock enterprise that produces milk from different feedstuffs and a forage enterprise that supplies the grazing grass to the dairy cow herd). The managerial task considered in this paper deals with the making and execution of decisions concerning timing, amount and mode of use of various resources (land, labour, machinery, inputs) in the production of a commodity such as milk, cereals, fruits, etc. Hence we only deal with technical management aspects rather than marketing and financial aspects (organisation and control of capital: when to invest, where to find capital, when to replace machinery).

The following section describes the management problem and management strategies in agricultural production systems. Section 3 emphasises the need of decision support systems based on strategy simulation, and the last part of the paper illustrates these concepts on a specific agricultural management problem concerning rotational grazing in dairy production.

2 Management problem and management strategies

The management problem has a dynamic nature due to changes from one year to the other (in available resources, in economic context and legislation) and due to unpredictable fluctuations within a production cycle (climate and sometimes prices). Thus management cannot be reduced to day-to-day running of a pre-established rigid plan, and must be seen as a temporally structured cognitive process. To some extent, farm enterprise management is similar to production management in the manufacturing industry. Essentially the complexity of the problem stems from the large number of uncertain data to deal with and the numerous different decisions and alternatives to consider. A classical approach to cope with this complexity in industrial production management is to decompose the problem into different elementary functions like planning, scheduling and control of the production process (Schneeweis, 1995). In farm management, this decomposition of the decisional and technical activities has long been ignored, mainly because of the predominance of the concept of the farmer as the unique decision-maker and actor on his/her farm. Due to the nature of the processes to control and due to the level of uncertainty about the future there are, however, important differences between farm management and industrial production management. More than in industrial processes, the response of crop yield and livestock output to inputs is subject to uncontrollable variations due to weather and diseases. In agriculture the counterpart of machines is not really optimised with regard to the production objectives, since agriculture deals with biophysical systems. Moreover, the socio-economic environment is generally more multiform and less controllable by farmers. To sum up, farming systems seem to be more hazardous, more complex, and less standardised than industrial production systems.

Despite these inherent difficulties, farming system researchers (Sebillote and Soler, 1988) developed in the eighties a conceptual model of the management decision process for agricultural production systems. The framework has been studied in the setting of different production systems (e.g. sugar beet, wheat) and some implementations have been realised (see for instance Olesen, et al., 1997; Rellier, 1992; Gibon et al., 1989; Attonaty, et al., 1997), giving the concept of management strategy a more concrete content (Aubry et al., 1997). Current efforts in this line aim at further developing and formalising the notion of strategy for more difficult management problems. These include, for instance, handling the various operations in greenhouse production (Rellier et al., 1998) or controlling a production process that interacts strongly with the concomitant use of the resulting product, such as in rotational grazing systems in which herbage production highly depends on consumption through grazing (Cros et al., 1997). This last example is further developed in Section 4 of this paper.

Key assumption of this study is that farmers, consciously or not and effectively or not, decide and act on the basis of management strategies which are decision and action trajectories defined conditionally to the important situations that might occur during the management process. A strategy can be seen as a set of planned tasks that incorporates capabilities to adapt to perturbations with respect to the average course of future events. The context-dependent adaptations are means to cope with the stochastic nature of the environment. Another way to characterise this conceptual decision model is to consider the temporal and hierarchical organisations of the management task. Even if a single person (the farmer) manages the different cognitive and physical processes of an agricultural production system, it is worth considering a hierarchical decomposition of the management problem in order to better understand it and provide support for more effective and robust decisions.

The temporal structure of the management process along the decision cycle has the following features:

- one or few overall production objectives (e.g. maximising milk production, minimising herbage waste and consumed maize);
- a set of intermediate goal states which the farmer tries to achieve or trajectories which she/he tries to stick to by the day-to-day technical choices she/he makes;
- some planned *rendezvous* between the farmer and the production system, where she/he makes some observations and diagnostics;
- a set of decision rules that allows the farmer to decide how to adapt its management trajectory to unexpected events or to significant deviations caused by the weather.

The management task can also be decomposed in different enterprise, each being itself decomposable in simpler subtasks that are relatively independent from the point of view of the resources they need. Of course, the different plans of these subtasks must be co-ordinated.

As far as the hierarchical representation of the decision processes is concerned three main functions can be isolated: planning, observing/monitoring and acting. The planning function determines a temporal organisation of rather abstract subtasks on the basis of an anticipated course of future events (intermediate goals and instruction trajectories). It also constructs an initial plan and occasionally (at the *rendezvous* points) performs some adaptations when adverse trends (bad weather) or opportunities are noticed. The acting function expands the active subtasks specified in the plan by applying situation-dependent procedures (decision rules) that generate primitive actions to be performed on the controlled biophysical system. The acting function is invoked much more frequently than the planning function. Finally, the observing/monitoring function is responsible of getting relevant data about the biophysical system and external environment, in order to inform the planning and acting functions.

The level of detail in specifying a plan cannot be directly the level of primitive actions and physical variables because the plan would be too complicated to express and adapt due to the multitude of possible situations that might occur given the uncertainty about the future. Thus, the definition of a management procedure necessarily requires (essentially for planning and observing/monitoring functions) the use of abstract concepts that do not always correspond directly to tangible facts and decisions, and that are often the result of an important cognitive activity reflecting the empirical knowledge of the farmer or the community of farmers as accumulated through time.

Within this conceptual model of the management decision process, a strategy can be defined as a specification of this general model, which characterises the way of deciding and acting of a particular farm manager. The definition of a strategy requires the specification of:

- how to plan, adapt and co-ordinate long-term (with respect to the production horizon) management trajectories for the different tasks involved in the production process;
- how to generate every day the immediately executable actions expanding for each active task in a way depending on the current situation;
- how should the important events that have to be monitored be defined;
- what interpretation should be made of the data in order to feed the decision process.

Since efficiency and risk control is directly dependent on the management strategy, it is necessary to study management strategies to improve the production results. A preliminary step is to express them formally. The benefits of explicit representation of strategies are undoubtedly important. First the concept of strategy is often seen with a very restricted view as a rigid sequence (or even a set) of decisions themselves reduced to the assignment of a value to a decision variable, whereas we have seen that the truth is much more complex as has been shown by different case studies. Another reason to invest strategies is to put down the complete picture of what constitutes the decision behaviour of a farmer for the production system under consideration. It clarifies weak spots of the decision process and forces to face issues that are sometimes unconscious in the decision-maker's mind. It facilitates critics and thus improvement.

3 Simulation of management strategies

The changes in the economic, technical and legal context require innovation or at least adaptation of the way to use the resources (how to produce) and consequently the way to manage the enterprise along the production period. What was good is no longer sufficient or appropriate to new constraints and objectives. In order to support this necessary adaptation of the farm enterprise management and to cope with the difficulty of finding new solutions to new problems we suggest a modelling approach of the response of the biophysical processes to farmers' technical operations and of the articulated logic underlying the choice of these operations.

Two modelling options for the management strategies are possible depending on the kind of decision support one intends to provide. The first one, which is widespread today, amounts to consider a family of very simple strategies, classically some decision vectors, and develop an optimisation approach to search for the "best" decisions according to a well-defined numerical criteria (see for instance Mayer et al., 1996; Botes et al., 1996; Parson, 1998). The second one, that is the object of this paper, consists of modelling as thoroughly as possible the strategies and biophysical processes, and to simulate their interactions on a computer. This approach can be used to support a trial-and-error learning process by exploring rapidly, and at nearly no cost, alternative management strategies. The simulation gives basic figures of the evolution of the biophysical system which enables to analyse the economic and technical efficiency of the strategy applied (Attonaty et al., 1996) (Figure 1).

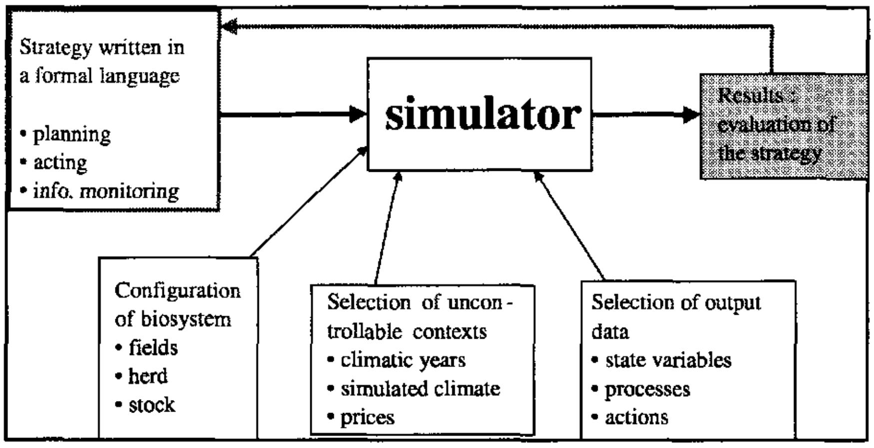

Figure 1. Simulation as a trial-and-error learning process.

The main reason why we think that this second approach is to be preferred in some cases is that usually there is no universal optimal solution to a particular management problem because the efficiency of a solution depends on the specific constraints and subjective judgement of the farmer. Furthermore the whole management problem of agricultural production systems is generally too complex to be addressed with optimisation techniques. Hence in order to stay within the realm of classical management science based on mathematical operation research techniques (e.g. linear programming or dynamic programming) it is necessary to over-simplify the strategy representation, and thus to look for solutions that most of the time do not correspond to feasible practical strategies. By contrast, the simulation approach enables the evaluation of realistic strategies, is not impeded by the complexity of the underlying decision and biophysical processes, and takes into account the essential role-played by the uncontrollable events (especially the climate). By simulating the application of a strategy for a range of hypothetical weather conditions it is possible to assess its robustness (its ability to give acceptable results in most of the situations that might be encountered). Therefore the value of a strategy can be evaluated with respect to a particular risk attitude. Finally, simulation enables to perform virtual experimentation under repeatable conditions (see Bywater and Cacho (1994) for some insights about simulation models); physical experiments over a large enough number of years would of course be impossible given the size of the sample that is required in order to take into account variability and to study the robustness of strategies.

Despite its popularity in industrial contexts, simulation is still in its infancy in the agricultural management domain. In particular, the dynamic aspect of the decisional part has not been addressed in depth so far. Most simulators deal with crop response to uncontrolled inputs (e.g. solar radiation, temperature, rain) and controlled ones generated on the basis of rather static management rules. The later usually convey pre-established sequences of technical operations and sometimes support a reactive behaviour when particular conditions occur. The farmers' management abilities are crudely modelled in such systems since no provision is given for simulating the coherent anticipatory and adaptive decision trajectory that farmers should have in order to orient the enterprise production according to their objectives and reduce as much as possible the impact of the fluctuations of the uncontrollable factors. Due to their oversimplified view of the management task and the strong hypotheses regarding the availability of information on the biophysical variables these simulation-based systems are too far from the real context of farmers' decision-making and their practical usefulness as decision support tools is questionable (arguably as limited as the current optimisation tools).

The major aim of our research is consequently to promote and develop the use of structured languages for representing management strategies in interaction with biophysical systems (similar ideas about the interaction of decision plans, natural resources and weather conditions have been investigated for management of winter wheat (Papy et al., 1988), conserved forage production (Sebillote and Solar, 1988) and greenhouse tomato production Rellier et al., 1998). In order to propose satisfying simulation-based DSS, it seems necessary to impose some design constraints on the modelling capabilities and computational framework of the simulators. These include:

- a proper level of detail and of precision of the biophysical model with respect to the intended use. The biophysical model must be able to respond dynamically to the actions determined by the decision system and it must be able to provide the kind of information used to make decisions. Although the predictive capabilities of the biophysical system need not be very high, it must exhibit a realistic behaviour of the processes it encompasses;
- openness and flexibility of the formal language used to represent the production system and more particularly the management strategies;
- usability of the simulation tool: ease of simulating the consequences of applying a strategy in different uncontrollable contexts;
- efficiency to cope with repeated simulations covering a range of hypotheses about the external (uncontrollable) environment.

The following section considers a particular management problem in dairy production and illustrates how strategies are represented in a specifically developed formal language that is interpretable by the constructed simulator.

4 A case study in dairy production

4.1 The rotational grazing management problem

The management problem in dairy production is particularly difficult for systems that rely strongly on a grassland feeding resource used through rotational grazing and completed by conserved feed (maize silage, concentrate and hay) in fall and winter times when the herbage mass is insufficient. In the late winter to early summer period the diet must switch progressively from a fully maize-concentrate feeding to a predominantly or fully herbage-based feeding and this transition phase is critical in the production process. The general objective is to keep the milk production at its optimal level despite the uncontrollable fluctuations of some important factors such as weather. Basically the decision problem consists of finding for the whole production period an appropriate combination of the following main commitments: the set of fields definitely allocated to grazing, the set of fields set aside to cope with weather deviation and grazed only if necessary, the profiles of conserved feed distribution over the whole period, the fertilisation policy, the cutting policy and the field rotation policy. A combination is appropriate if it ensures an optimal production of milk over the whole period for a sufficiently representative range of climatic conditions. The period considered in the management task covers 9 months from the beginning of

February until the end of October. The starting date corresponds to the change of the sward from the vegetative to generative stage, time at which the first fertilisation operation may have to be performed. The ending date corresponds to the calving period and the strong decrease of the herbage production, time at which it becomes necessary to turn to a conserved feed diet that is not problematic from a decision point of view (some DDS tools exist for such a feed composition task).

This problem is a complex one because it involves a multivariable optimisation: one has to decide on the above issues so that a good quantity/quality trade off of the available herbage is maintained along the considered period, given that the maize distribution profile can only be non-increasing and the grass growth rate is partially controllable by the fertilisation but also partially uncontrollable due to the climatic influence. Some agronomists' results, mainly coming from studies on continuous grazing, have shown that in order to have herbage of good quality it is necessary that the grazing intensity be high and regular on rotational periodicity. The problem of strategic management of a herd fed predominantly by rotational grazing (henceforth we simply call a rotational grazing management) has to be solved once every year because the stock of maize at the start of the period varies from one year to the other and the size and characteristics of the herd may change too. From an economic point of view, the problem is crucial because the herbage resource is much cheaper than the maize-concentrate one and it gives a better public image to the produced milk. The concern to minimise risks has led to usage of conserved forage (maize silage) and concentrate being better and grazing being worse than what can be done from a profit maximisation point of view. The conservative attitude is partly explainable by the imperfect knowledge of the farmers with respect to the mastering the complex interaction between grass growth processes and the grazing and milk production of the livestock. Another reason relates to the European Union policy that has encouraged maize production by subsidising it heavily. In France the rotational grazing management problem concerns almost 90% of the dairy producers.

4.2 The simulated production system

The next subsection shows how a rotational grazing strategy can be structured and represented in an intelligible and rigorous language. Before turning to this level of detail it is worth looking at the production system that is actually simulated so as to see where the strategy lies within this system.

The production system is constituted by three interacting subsystems represented in different shades in Figure 2: the decision system itself composed of the planning and acting systems, the information system composed of the monitoring and observing systems and, finally the biophysical system. The production system dynamics heavily depends on the external environment (weather) that is uncontrollable and only partly predictable. The objective of the production system is to optimise the milk production by a proper use of the resources given the material constraints on the biophysical system. The biophysical system (see Cros et al., 1998, for a complete description of its modelling) is the controlled system. It is modelled through a set of more or less empirical laws that express on a daily basis the dynamics of several interactive processes dealing with herbage production, cow intake and milk production. The pasture is divided into a certain number of fields having different sizes but producing the same kind of forage crop. The driving variables include, for climate, the average daily temperature, average incident solar radiation and daily rain and, for technical management interventions, the nitrogen level, grazing operation, cutting operation and amount of conserved feed in daily diet.

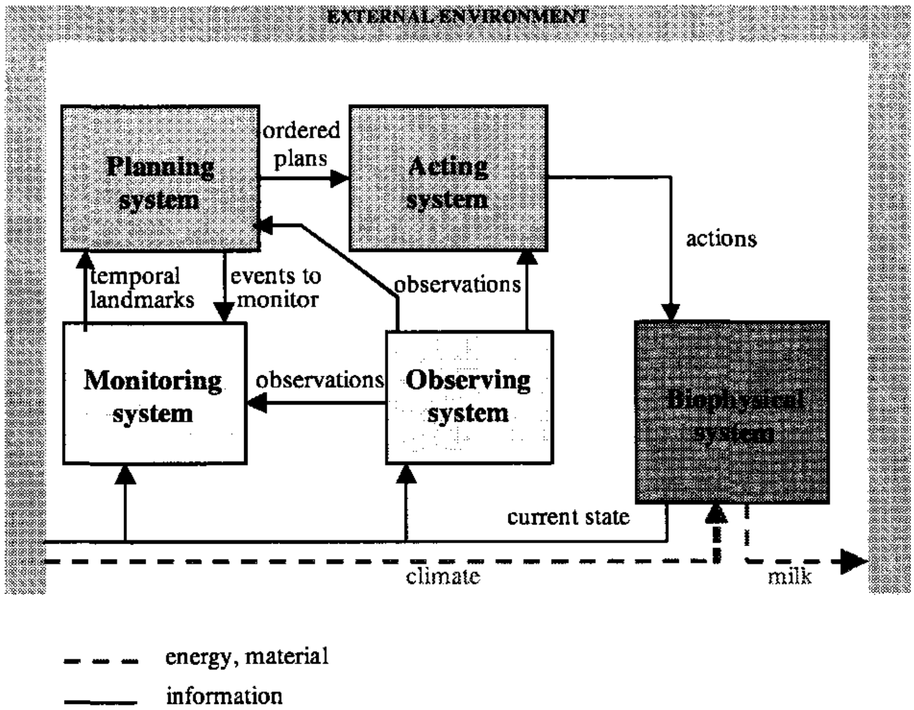

Figure 2. A systemic view of the production system.

The management actions are generated by the decision system that essentially performs the decision making task which the farmer is confronted to every day. As already mentioned, the complexity of the management task requires to decompose it into two simpler dependant modules: (i) the temporal planner of operations that produces a set of plans and operational constraints at an abstract level (i.e. instructions that are not directly executable actions) so as to ensure a consistent temporal commitment over the production horizon and (ii) the generator of executable actions that tells what to do according to the current situation at execution time and given the general instructions of the planner. An example of instructions generated by the planning system is the specification of the set of fields to be used in the first cycle of rotational grazing, this set having to be elaborated consistently with the fertilisation and feeding policy. On a given day within this cycle, the acting system is then responsible of the determination for the particular field to graze among the set fixed by the planner. The decision system must be responsive to the different situations that the production system is likely to encounter; from time to time the planning and acting systems must modify previously adopted commitments on the plans and action generator in order to adapt to weather fluctuations.

The role of the information system consists of providing access to the relevant data concerning the biophysical system and the external environment. What is relevant is highly subjective and is actually part of the decision-making behaviour adopted. Two functions must be performed by the information system: (i) monitor some expected events in the biophysical system or external environment and notify their occurrence to the decision system that uses them as decision making temporal landmarks, and (ii) interpret and store some data about the biophysical system and external environment and communicate the results to the decision system. This is respectively what the monitoring and observing systems are doing. An example of event that the decision system wants to be monitored is the earliest ending date of the first rotation. This date is defined as the first day after which the temperature sum since the beginning of February is greater than a given threshold beyond which the herbage intake decreases in relation to the quality degradation (for example, 600 degree-days for cocksfoot). The interpretation functions of the observation system are used to reproduce the real situation of a decision-maker that, first, has only partial access to information (due to lack of time and sensing devices) and, secondly, relies on aggregated pieces of data for cognitive simplicity. For instance, the decision maker may plan on the basis of qualitative appraisal of the maize stock at the beginning of February; an interpretation function computes a qualitative value (above average, average or below average) by a simple translation of the number of days of feeding that can be covered with the available maize stock.

The management strategy fully specifies the decision-making behaviour of the farmer in charge of the biophysical system control. It tells in a structured way what to do conditionally to some states and events. Therefore, in order to define a strategy one has to state:

- planning rules that define trajectories for the different tasks involved in the production process;
- acting rule expanding for each active task in the planned trajectory so as to generate situation-dependant actions;
- how the temporal landmarks involved in the planning and acting rules, and associated to monitored events have to be defined;
- what interpretation or translation functions should be defined in order to inform the condition parts stated in the planning and acting rules.

It is clear that the above items are respectively the basic components used by the planning, acting, monitoring and observing systems.

4.3 Expressing a strategy in a formal language

This subsection illustrates by giving some examples the main components of a strategy and how they are represented in the formal language created for this purpose. The reasons to develop a formal language for expressing management strategies are threefold:

- studying strategies requires a rigorous framework to support scientific experimentation and analysis;
- the writing of strategies by users of the simulator (research scientists and extension services agents) has to be facilitated by providing an easily learned and understandable environment incorporating the essential conceptual structures needed in formulating a strategy;
- the strategies have to be stated in a format lending itself to machine interpretation since they are fed into a simulator.

The basic conceptual structures that are used include the components mentioned in the previous subsection: the planning rules, the acting rules, the interpretation functions, and the indicators used in these rules. In addition to these, the rotational grazing strategies are decomposed into a set of management tasks that can be treated independently. So far five tasks have been identified as shown in Table 1. To each task a set of plan variables is associated and a set of action variables that are assigned values by the planning and acting rules respectively. For instance, the value of the *?FeedConcentrate* plan variable of the *ConservedFeed* task may be the word *no* or a numerical value indicating either that no concentrate should be given or what percentage of the maximum potential amount should be provided daily (this value depending of the stage with respect to the last calving date). The value of the *?ConcentrateAmount* action variable is the amount of concentrate given per cow.

The plan variables are typically assigned for a period, whereas the temporal scope of an action variable assignment is only one day. Note that the last task in Table 1 is of different nature than the others since it serves to specify ordering on the tasks and actions.

Table 1. The tasks and the corresponding plan and action variables.

Task	Plan variables	Action variables
ConservedFeed	?FeedConcentrate	?ConcentrateAmout
	?FeedMaize	?MaizeAmount
	?FeedHay	?HayAmount
Grazing	?GrazingFields	?FieldGrazed
	?GrazingLength	?GrazingLengthOfField
Cutting	?FieldsPlannedForSilage	?FieldsCutForSilage
	?FieldsPlannedForHayCutting	?FieldsCutForHay
Fertilisation	?FieldsToFertilize	?FieldsFertilized
	?Nrate	?Nrate
Co-ordination	?TaskOrdering	?ActionOrdering

For each task, the planning rules are responsible for assigning values to the corresponding plan variables for a given period over which these values remain constant, except if an adaptation is required (which would be realised by firing another planning rule). An example of a planning rule defining the *Grazing* task from the beginning of February until the earliest date of turnout to grass is shown in Figure 3. The decision part assigns a set of fields to the *?GrazingFields* variable. This planning rule is fired at the beginning of the simulation and defines at this initial stage the set of fields that the farmer plans to use in the first grazing rotation (knowing this set of fields is useful for other tasks such as *Fertilisation* and *ConservedFeed* and also to determine the effective turn-out date).

```
TRIGGER !beginningD
FROM Feb1
TO !earliestTurn-outD
DO ?GrazingFields = {Field1, Field2, Field4, Field5}
```

Figure 3. A planning rule specifying the set of fields allocated to grazing.

In the above rule, the term *!beginningD* is a temporal landmark that is simply set to the initial date of the management period. The term *!earliestTurn-outD* is a temporal landmark specifying a day through the conditions that the production system should satisfy at that day. Consequently the *!earliestTurn-outD* gets a numerical value only when the conditions become satisfied, the value being the current date. Before that, the value is unknown. A planning rule is fired as soon as the landmarks in its triggering part are known. Some planning rules are declared to be usable several times; every use occurs when the landmarks in their triggering parts change from an unknown value to a known one. Figure 4 shows how the *!earliestTurn-outD* landmark is defined in the strategy language. Essentially the landmark is the date of the first day such that total herbage mass over the set of grazing fields is equivalent to more than that what the herd need for 3 days, if only fed with grass.

```
LANDMARK !earliestTurn-outD
CONDITION  HerbageMassAvailability(?GrazingFields) > 3
```

Figure 4. The *!earliestTurn-outD* temporal landmark.

Besides the planning rules that set up nominal plans, a strategy normally contains planning rules that simply perform adaptation on these through modifications on plan variables or parameters involved in plans. An example of such a rule is given in Figure 5. It tells that at the end of the first grazing rotation, the set of grazing fields should be reduced (respectively enlarged) if the total herbage mass on the grazing fields initially planned is above what would correspond to 12 days of feed (respectively below 8 days). The reduction and enlargement consist in taking-out or adding as many fields (usually only one) to match as close as possible the required modification of grazing surface specified in the first parameter of the *Reduce* and *Enlarge* functions. The *HerbageMassAvailability()* function is a user-defined interpretation function.

```
TRIGGER !endFirstRotationD
IF      HerbageMassAvailability(?GrazingFields) >= 12
THEN Reduce(1, ?GrazingFields)
ELSE  IF      HerbageMassAvailability(?GrazingFields) <= 8
        THEN Enlarge(1, ?GrazingFields)
```

Figure 5. A planning rule for adapting the set of grazing fields to specific situations.

Another key component involved in the definition of a strategy is the set of acting rule that specifies completely for the current day what action to perform in the task under consideration. Figure 6 gives an example taken from the *Cutting* task. The rule specifies that if it has not rained during the past three days, then the fields to cut for silage are all those ensilable among those planned for such a use.

```
IF      NoRain3D
THEN ?FieldsCutForSilage = Ensilable(?FieldsPlannedForSilage)
```

Figure 6. An acting rule of the Cutting activity.

The *NoRain3D* term in the above rule is defined by an interpretation function, as was the term *HerbageMassAvailability* mentioned in the Figures 4 and 5. Its definition is given in Figure 7 where D stands for the date of the current day.

```
IF  Rain(D-1)=0 AND Rain(D-2)=0 AND Rain(D-3)=0
THEN true
ELSE false
```

Figure 7. The code of the interpretation function of NoRain3D.

The interpretation function is essentially used to provide past and present synthetic information about the external environment and the biophysical system. It can also be used as a predictor of future states.

4.4 Functioning and use of the simulator

The first step in using the simulator is to initialise the production system by describing, first, the various components of the biophysical system (the composition and initial state of the fields and the herd) and, secondly, the strategy as illustrated in the previous subsection. The user must also select an hypothetical climatic year in a database or construct one using a weather generator.

The simulation can then be run. For the first simulated day the planning system will try to fire all the planning rules in order to construct a nominal plan specifying the different tasks over the entire time horizon of the management problem. The planning rules also determine an ordering between the tasks. The ordered plans are then transmitted to the acting system that can start its job: consider each task in the specified order and determine the actions to execute this first day by using the acting rules. The actions are executed, causing together with the advance of time a change in the state variables of the biophysical system. The simulator considers then the next day. Similar treatments are made: detection of events corresponding to the landmarks used in the planning rules, application of planing rules to perform some plan adaptation if necessary, and generation of the actions to be executed this day according to the acting rules and the perception of the current situation (the interpretation functions), and finally updating the current state of the biophysical system. The iterations are pursued until the end of the simulated period. The user can then perform other simulations by changing only the climate hypothesis. The results of the different simulations given as time series of the most significant variables selected by the user, can then be analysed and used to define new strategies which can be submitted to the same evaluation process.

5 Conclusions

Presently the rotational grazing simulator discussed in this paper is still under development. The implementation of the first prototype is almost complete and the testing phase will start soon. A graphical user interface to specify biophysical system configuration and strategies seems necessary to make the simulator usable outside of the laboratory context.

An experimentation is planned with the intended users (research scientists and extension service advisers) so as to assess the practical value of the simulation approach advocated in this paper. Similar simulators (e.g. Rellier et al., 1998) made for other production systems than the rotational grazing dairy system presented here will be considered in this study. Depending on the result, we might consider the development of a general representation framework and of the corresponding simulation tool.

In this paper we have advocated the use of a simulation approach as a support tool for designing management strategies. The main advantage of this approach is that it enables to represent quite faithfully the types of strategies that might be encountered or conceived by farming system researchers. Nevertheless it is our belief that some optimisation approaches are worth developing in combination with the type of simulation discussed in this paper. An example of such an approach producing robust decision rules by use of machine learning techniques is presented in Attonaty et al., 1997; it applies to a strategy structure consisting in a sequence of rules *"If state then actions"*. The problem is more difficult with rotational grazing because the structure of the management strategies is more complex. Although at this stage we cannot report on the direct practical usefulness of the simulation approach, it has shown to provide a profitable basis for future development of strategic decision support systems dealing with the management of technical aspects of agricultural production. The representation framework and simulation tools of the kind discussed in this paper can enhance creativity and intuition of those willing to explore new management strategies. It can also facilitate transportation of a solution to similar production configurations, as it has already been the case in a set of similar projects dealing with seasonal crop management (winter wheat, maize and rapeseed). In this paper the management of only a part of the farm (a single component or a combination of a few interdependent ones) is considered. This excludes for instance the problem of finding the most profitable mix of crops and livestock products to produce from the available resources at the farm scale. The problem of managing a whole farm is more complex for several reasons: it requires to be addressed with a time horizon of several years, it involves many situations of concurrence on the use of resources (machinery and labour) and it is much harder to build a closed world in which to study biophysical, social, economic and managerial aspects. However, dealing successfully with the management of a combination of interdependent components gives encouraging insight in the general principles to be taken into account in order to tackle the whole farm management problem.

References

Attonaty J-M, Chatelin MH and Garcia F (1996) Interactive simulation modelling in farm decision-making. In Proc of Int Congress for Computer Technology in Agriculture, ICCTA'96, Wageningen the Netherlands

Attonaty J-M, Chatelin M-H and Garcia F (1997) Using Extended Machine Learning and Simulation Technics to Design Crop Management Strategies. First European Conf For Information Technology in Agriculture. June 15-18 Copenhagen Denmark

Attonaty J-M, Chatelin MH, Poussin JC and Soler L-G (1991) Advice and Decision Support System in Agriculture: New Issues. IFORS Conference. March 26-29, Bruges, Belgie

Aubry C, Papy F and Capillon A (1997) Modelling decision-making processes for annual crop management. Agricultural Systems, vol 56 n°1 45-65

Botes JHF, Bosch DJ and Oosthuizen LK (1996) A Simulation and Optimisation Approach for Evaluating Irrigation Information. Agricultural Systems vol 51 n°2 165-183

Bywater AC and Cacho OJ (1994) Use of simulation models in research. Proceedings of the New Zealand Society of Animals Production vol 54

Cros MJ, Duru M, Garcia F and Martin-Clouaire R (1997) Characterizing and simulating a rotational grazing strategy. First European Conf For Information Technology in Agriculture June 15-18 Copenhagen DK

Cros MJ, Duru M, Garcia F, Martin-Clouaire R and Peyraud JL (1998) Projet SÉPATOU : cadre général et composante biotechnique. Internal report of Unité de Biométrie et Intelligence Artificielle INRA Auzeville

Gibon A, Lardon S and Rellier JP (1989) The heterogeneity of grassland fields as a limiting factor in the organisation of forage systems: Development of a simulation tool of harvests management in the central Pyrenees. In: (A. Capillon, Ed.) Grassland Systems Approaches. Etudes et Recherches sur les Systèmes Agraires et le Développement 16 105-117 INRA Publication Versailles

FMayer DG, Belward JA and Burrage K (1996) Use of advanced techniques to optimise a multi-dimensional diary model. Agricultural Systems vol 50 239-253

Papy F, Attonaty JM, Laporte C and Soler LG (1988) Work Organisation Simulation as a Basis for Farm Management Advice (Equipment and Manpower, Levels Against Climatic Variability). Agricultural Systems vol 27 295-314

Olesen JE, Pedersen L, Christensen S, Secher BJM and Petersen J (1997) An integrated Decision Support System for Management of Winter Wheat. First European Conf. For Information Technology in Agriculture. June 15-18 Copenhagen Denmark

Parson DJ (1998) Optimizing Silage Harvesting Plans in a Grass and Grazing Simulation Using the Revised Simplex Method and a Genetic Algorithm. Agricultural Systems vol 56 n°1 29-44

Rellier JP (1992) Prediction and design problems in crop management. Proc 12th Int Conf on Artificial Intelligence, Expert Systems and Natural Language June 1-6 Avignon Vol 2 739-748

Rellier JP, Martin-Clouaire R, Navarrete M, Jeannequin B, Gary C, Montbroussous B, Tchamitchian M and Baille A (1998) Modelling and simulating decision making for greenhouse tomato production: the CONSERTO project. To appear in Acta Hortiulturae

Schneeweis C (1995) Hierarchical structure in organisation: A conceptual framework. European Journal of Operational Research, Special Issue on Hierarchical Planning vol 81 4-31

Sebillote M and Soler LG (1988) Le concept de modèle général et la compréhension du comportement de l'agriculteur. CR Académie d'Agriculture Française 74 59-70

4.2 Model-based explorations to support design of sustainable farming systems

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1. Introduction

In The Netherlands, as in other parts of Europe, farmers have been very successful in increasing yields per unit area during the last decades. The production techniques utilised, however, have resulted in negative side effects: emissions of pesticides and plant nutrients, (in) organic waste, high-energy consumption. It has become evident that these symptoms cannot be addressed one-by-one on ad-hoc basis. Public concern is reflected in a suite of national and international policy statements that call for more sustainable agricultural farming systems.

Sustainable systems meet a combination of socio-economic, ecological and agro-technical objectives of agricultural production (WRR, 1995). The importance attributed to each of these objectives varies among interest groups. Because the objectives are usually conflicting, at least to some extent, the development of sustainable farming systems is characterised by negotiation about acceptable compromises between objectives by various stakeholders. Actors include farmers, agro-industries, consumers and the public sector including environmental pressure groups. Agricultural research contributes to this process by developing technology packages and by offering methodologies to visualise the consequences of alternative options in a clear and quantified manner.

During the last decade, a promising empirical methodology for developing sustainable farming systems has been elaborated, coined 'prototyping' (Vereijken, 1994; Vereijken, 1997). Prototyping involves application-oriented design and testing of farming systems in collaboration with commercial farmers or at experimental farms. The approach consists of diagnostic, designing, testing, improvement, and dissemination phases, and is now being adopted in all major sectors of Dutch agriculture, including (organic) arable farming, open field horticulture, dairy farming, and flower bulb production.

Shortcomings of empirical prototyping are that, obviously, only few selected prototypes can be tested experimentally and that the approach builds on 'expert knowledge' which is, at best, summarised in the form of simple rules which unduly narrow the range of available options. Moreover, commercial farms are no suitable test grounds for evaluating 'risky' new ideas. Thus, we obtain only a partial picture of what 'fitting' agricultural systems could look like, now and in the future, and we lack a sufficient basis for quantifying the trade-offs between objectives (e.g., 'how large are income losses associated with reduction of per ha nitrate emissions, for different agro-ecological environments?').

Model-based explorations can remedy such limitations. Models combine detailed information on system components, and can thus explain the behaviour of whole farm systems based on insight in the behaviour of their components. They represent a tool to design systems that meet

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objectives of the various actors involved, and to quantify the trade-offs between these objectives. A further difference between prototyping and model-based exploration is that the latter approach is less rooted in current production practice, and thus allows to survey a broader spectrum of new (hypothetical) production technologies, with their implications.

This report highlights three case studies addressing the conflict between farmers' income and the environment. The role of models in these studies is evaluated. The sectors discussed are dairy farming, flower bulb production, and arable farming. Multiple goal linear programming was used in all cases as an integrating framework. Our contribution is based on excerpts from original works by Van de Ven and Van Keulen (1996) and Van de Ven (1996) for the dairy case; by Rossing et al. (1997a, b) for the flower bulb case; and by Habekotté and Schans (1996) and Schans (1996) for the arable farming case. Parts of Rossing et al. (1997b) were used for the introduction and methodology sections of this paper.

2. Methodology

The method represents a farm as a linear combination of so-called 'activities'. An activity is a coherent set of operations (often a 'production technology') with corresponding inputs and outputs, resulting in e.g. the delivery of a marketable product, the restoration of soil fertility, or the production of feedstuffs for on-farm use. An activity is characterised by a set of coefficients that express the activity's contribution to the realisation of user-defined goals.

The biophysical and economic rules that determine the transformation of inputs to outputs of a given activity are generally non-linear: the pesticides input required for the production of 5 t/ha of wheat grain is not equal to 50% of the amount required for 10 t/ha. The labour requirement in a stable for 1000 animals is not 10 times larger than the requirement of a stable for 100 animals. The definition of activities must therefore, ideally, be such that all non-linearities are embedded in the values of input-output coefficients. So, rearing pigs in stables for 100 animals is a different activity from rearing pigs in stables for 1000 heads. Wheat production at 5 t/ha is a different activity from production at 10 t/ha. It now becomes clear that activities are discrete 'packages of production technologies', and that the resolution by which this discretisation is performed determines to a large extent the potential outcome of the subsequent optimisation study.

Activities are the largest aggregates or 'building blocks' from which a farm design is constructed. This last step, the design of the farm system as an assembly of activities, is made with the help of multiple goal linear programming (MGLP; see, e.g., de Wit et al., 1988). The procedure consists of a number of optimisation rounds, in each of which all the goals are optimised one by one, while the constraints on the other goals are increasingly tightened. Usually only a selected set of potential activities is 'submitted' to the linear optimisation phase, to limit computation time.

In terms of software, three basic components constitute the 'toolkit' for each of the cases presented in this paper:

(i) an information system that contains data describing the attributes (properties, prices) of soils, crops and crop products, pests, animals and animal products, feeds, manures, fertilisers, pesticides, machinery, fuel, labour, etc.

(ii) algorithms to translate this data into coefficients that represent the input and output coefficients for each discrete activity; these algorithms are referred to as 'technical coefficient generators' (TCGs) and may include dynamic simulation models, static models, or simply perform summation over components of an activity (e.g. total labour input for an activity equals the sum of labour inputs of all constituent operations).

(iii) the linear farm optimisation model

3. Three cases of intensive farming

3.1. Case I. Dairy farming

Dairy farming contributes significantly to environmental pollution in The Netherlands, mainly because of imbalanced nutrient cycles. A study by Aarts and Middelkoop (1990) showed that in 1991/1992, well after the implementation of the EU quota system, only 17% (or 80 kg per ha per year) of the yearly farm nitrogen input leaves the farm in agricultural products, mostly in milk (64 kg). Inorganic fertilisers and concentrates account for 80% of the total N input of 487 kg per ha per year. The N surplus is accumulated in soil, denitrified to elemental N, leached as nitrate, or lost by ammonia volatilisation. N surplus values of 140 kg per ha were cited for ecological dairy farms, and 250 kg per ha was shown to be possible in a project referred to as MDM (Management for Sustainable Dairy Farming, cited by Ketelaars and Oenema, 1997). One of the farms developed with the explicit purpose of identifying means to reduce N surplus is the De Marke experimental farm.

De Marke represents dairy farming systems situated on drought-sensitive sandy soils in the eastern part of The Netherlands. The design of this farm was analysed with the help of the above modelling approach. The objectives quantified during the establishment of the real farm were adopted in this modelling study:

- nitrate leaching < 34 kg N per ha per year, corresponding to < 50 ppm nitrate in subsoil percolation water,
- ammonia volatilisation < 30 kg N per ha per year, corresponding to 70% reduction relative to the 1980 standard,
- phosphorus (P) surplus < 0.5 kg P per ha per year, corresponding to 'equilibrium fertilisation',
- milk production around 12 t per ha per year, representing the production on an average dairy farm on sand,
- total N surplus < 128 kg N per ha per year, an estimated acceptable surplus for De Marke based on permitted N loss terms calculated for local conditions.

Under these conditions, farm income was maximised with the help of MGLP. The first two constraints are the norms originally set for the year 2000. Just as in the real De Marke farm, these constraints were maintained as hard boundary conditions in the model runs. The other goals are rather subjective (not forced as such by government regulations), and the effects of relaxing these goals were assessed in the study.

The activities included land use activities, feeding activities, activities related to N flows in manures, animal activities, and purchase and sale activities (fertilisers, concentrates, contract labour). To characterise the various activities, the following TCGs were used:

(i) a model for grass production activities, which was used to generate coefficients for 320 'grassland activities' (= 3 cattle types x 4 grassland utilisation methods x 8 N application levels x 3 roughage-to-concentrates ratios for diets x 3 milk production levels; impossible combinations deleted *ex-post*),
(ii) a model to describe grass cutting and conservation for winter feeding, to generate 32 activities (= 4 product types x 8 N application levels),
(iii) models for maize and fodder beet production activities, to generate 384 options for producing each of these crops (= 3 yield targets x 4 fertiliser-to-slurry ratios x 3 slurry

application methods x 4 slurry allocation patterns x 2 catch crops after maize x 2 maize-derived feedstuffs; impossible combinations deleted *ex-post*).

The optimisation was subject to the following additional conditions: land area used equal to area available; nutrient inputs to crops at least equal to crop demand; all produced slurry utilised on-farm, energy supply to animals equal to energy requirement; protein supply at least equal to requirement; and total dry matter intake by animals no more than the physiological limit.

The system with maximum income, but still meeting the indicated nitrate and ammonia emission constraints, turned out to be one that has 85% of the land under grass (63% for fresh consumption, 22% for silage), with daytime grazing only, and with N input of 170 kg per ha, slurry being injected. The remaining 15% of the area are under maize, receives 150 kg N per ha, applied in rows, slurry is injected, no catch crop is grown, and maize is used as whole-plant maize silage. The number of animals in this system is 2.05 cows, 0.6 calves, and 0.5 yearlings per ha. Milk production is 8000 kg per cow per year, totalling 16350 kg per ha per year. Cows receive 2670-kg concentrates per head per year. The total N surplus is 140 kg per ha per year, for P the surplus is 8 kg. The labour income is 73% of the theoretical maximum (73% of Dfl 4380 per ha per year) that could be attained without constraints on N emission.

Relative to this optimised system, the voluntary adoption of the 12-t-milk-per-ha-limit maintained by De Marke experiment farm implies a 20% reduction of labour income, the benefit of which is only a 7% cut in N surplus. The study produced, obviously, many intermediate results that cannot be listed here. To mention only one: minimising ammonia volatilisation results in the same cropping pattern as maximising milk production: 15-20% of the land area under maize, the remainder under grass, with cows stabled continuously. But milk production is 12 t/ha in the first case with 250 kg N applied per ha per year, whereas 17.7 t milk is produced in the second case, with 350 kg N input per ha.

3.2 Case II. Flower bulb production

Current systems of flower bulb production in Netherlands use large amounts of nutrients and pesticides per unit area. Surpluses were estimated at 231 kg N, 106 kg P_2O_5, and 171 kg K_2O per ha per year (Weel et al., 1995). The level of pesticides input has been estimated at 120 kg of active ingredient (a.i.) per ha per year (Rossing et al., 1997a). High prices of bulb products and land, relatively low input prices and a defensive attitude among growers towards environmental issues are among the causes for these high input levels.

An explorative study was carried out by Rossing et al. (1997a) to support the designing - by an association of growers and environmentalists - of environmentally more acceptable production systems. The study synthesised fragmented agronomic information and employed MGLP to explore the options for flower bulb production systems with a time horizon of 10 to 15 years. The study focused on farms located on coarse sandy soils in the western part of The Netherlands.

The goals in this case were (i) maximum gross farm margin, (ii) minimum pesticide input (as kg a.i. averaged over the cropped area), and (iii) minimum N surplus, defined as input minus output leaving the farm in the form of crop produce. Important constraints were farm size, the possibility to rent additional land free of soil-borne pests and diseases, and the range of crops that could be grown.

A wide range of possible production packages ('crop activities') was defined for tulip, narcissus, hyacinth and lily. One break crop, winter wheat, was introduced because of its

favourable effect on soil structure and soil health. Each crop activity was characterised by soil type (sand/clay), soil health (3 levels), cropping frequency (7 levels), crop protection regime (5 levels) and nutrient regime (3 levels). Thus, a total of 3 x 7 x 5 x 3 = 315 hypothetical production packages for each crop-soil combination could be submitted to the optimisation phase. Obviously, many practically infeasible combinations were eliminated beforehand.
In addition to crop activities, inter-crop activities were defined, such as soil fumigation, inundation, and prevention of wind erosion with straw. The definition and technological specification of crop and inter-crop activities was not only based on current practices but also on technologies still in an experimental stage of development, and on technologies 'borrowed' from other crops. This enabled a broadening of the vista on new farming options.

The TCGs used to generate coefficients characterising the crop and inter-crop activities were based on empirical information, expert knowledge, and production ecological theory (Rabbinge, 1993; de Koning et al., 1995; van Ittersum and Rabbinge, 1997). In its final form it consisted mainly of equations to express crop-nutrient responses, and a 'shell' to transform tabulated technology specifications with corresponding yield reduction factors into the proper format for use in MGLP. The effects of crop sequence on yield were also accounted for by the TCG.

The farm systems composed from crop and inter-crop activities by multiple goal linear programming were essentially rotations, meeting the three earlier stated objectives with differing degrees of realisation. By maximising farm gross margin at increasingly tighter constraints on the two environmental objectives, the trade-off between market and environment was explored. Point A in Figure 1 represents a reference farm configuration that just meets the (anticipated) governmental targets with respect to pesticide input and nitrogen surplus for the year 2000, and has its gross margin maximised within these constraints. The constraints are nutrient surpluses of 25 kg P_2O_5, 50 kg K_2O, and 140 kg N per ha per year, averaged over the farm area; a total pesticide input of 48 kg a.i. per ha (which is -60% relative to the 1989 mean for the sector), and soil fumigation not more frequent than once per 5 years. Farm gross margin is calculated as financial returns minus allocated costs of casual (unskilled) labour, pesticides, fertilisers, contract-machine use, but not accounting for investments (farm infrastructure). Gross margin is here expressed as an index, set to 100 for maximum gross margin (Dfl 205,000) on farms that just meet the environmental constraints. The index value is zero when gross margin equals zero.

Two development paths were assessed, representing gradually reduced pesticide use and N-surplus, respectively (Figure 1). The development path for pesticide reduction showed that a substantial reduction in pesticide input may be achieved, in the first step, with farm gross margin rather stable (index = 97 at point B). This is by substituting soil fumigation by inundation, and by adopting new low-dosage fungicides in tulip. No changes in cropping sequence or area of rented land occur. Further reduction in pesticide input (B to C) is most economically accomplished by abolishing the use of mineral oil for virus control in lily. The associated yield loss in lily causes a decreased farm gross margin in point C (index = 77). Again, no changes in cropping pattern occur. The third step, zero pesticide input, causes major changes. The rotation changes from tulip-lily-wheat to narcissus-wheat and farm gross margin becomes negative (index = -4 in D). The area of rented land free of soil-borne pests and diseases remains approximately 11 ha in all steps. Tulip is grown on this rented land, with a modest pesticide input of 12 kg a.i. per ha.

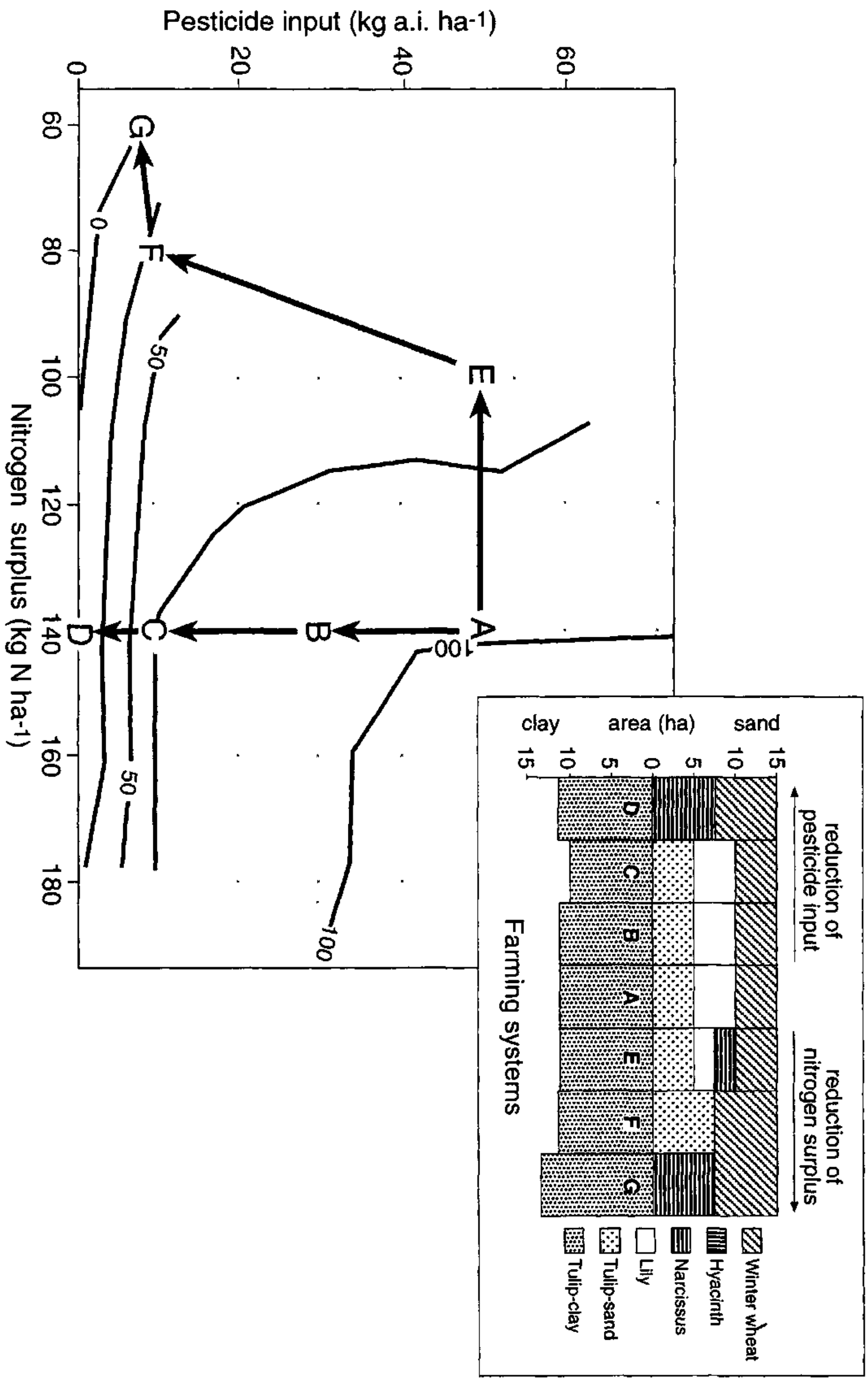

Figure 1. Iso-lines of calculated maximum farm gross margin (index) for different levels of pesticide input (kg active ingredient per ha) and nutrient surplus (kg N per ha) for a 15 ha farm with three full-time workers, situated on a sandy soil, with a possibility to rent 'fresh' (= healthy) land outside the farm property. Letters in the graph indicate the development paths for pesticide input (A-B-C-D) and nitrogen surplus (A-E-F-G). The small x-es represent calculated points, the iso-lines are interpolated. A farm gross margin index value of 100 represents the farm gross margin of the most profitable system that satisfies the governmental environmental requirements for the year 2000. Inset: Composition of the crop rotation.

The development path for N-surplus reduction shows, in contrast, that such reduction is only possible at the expense of a considerable loss of income, given the technologies as defined. A decrease in N-surplus of 30% beyond the levels anticipated for 2000 is associated with a 40% decrease in farm gross margin (point E, Figure 1). In the cropping sequence lily is replaced by narcissus, which has a much lower gross margin but higher N-efficiency. Experiences on two experimental farms and current trends in the sector support the conclusion that reducing pesticide use affects farm income less than N-surplus reduction. Remedy may be sought in developing new technologies, aiming at more precise application of nutrients in time and space, or in re-evaluating such strategic choices as growing the bulk of nutrient-inefficient flower bulb crops on sensitive alluvial sands.

3.3 Case III. Arable farming

Whereas arable cropping in The Netherlands is relatively clean compared to the sectors discussed above, it generally uses nutrient and pesticide inputs high enough to cause undesirable side effects: eutrophication of surface water, and increased purification costs in the production of drinking water (RIVM, 1996; VEWIN, 1996). The average annual surplus of 173 kg N per ha arable land may be far less than its equivalent on grassland, it is still much higher than values found in most other West European countries. The use of pesticides reduced drastically since the Multi-Year Crop Protection Plan (MJP-G) became effective in 1991, but reductions were largely confined to soil fumigants (3 kg a.i. per ha in 1995), leaving the total inputs of fungicides, herbicides and insecticides virtually unchanged: 5.6, 5.0, and 0.7 kg per ha in 1995, respectively (Lotz et al., 1997).

Integrated farming strategies were explored at several experiment farms. Integrated farming aims not only at maximum labour income, but tries to fulfil other objectives, too: moderate inputs and emissions of agrochemicals, and some level of consideration for nature and landscape values. Emphasis then moves from yield maximisation to cost reduction and improved quality of produce. Where possible, biocides are replaced by knowledge-intensive (but sometimes also labour- or capital-intensive) non-chemical methods, and nutrient management strategies aim at high efficiency.

A project was launched after the experimental stage, to introduce integrated arable farming methods with commercial arable farmers ('innovation farms'). Explorative modelling accompanied this phase. The MGLP model MGOPT-CROP which provided also the basis for the earlier discussed flower bulb case, was developed for this purpose by Schans (1996). The study focused on two regions: the central marine clay district (CZK) and the north-eastern district (NON).

The numerical characterisation of crop activities ('technology packages' approach), and the TCG used, was as described for Case II, with a few minor changes. Crops covered by the TCG and by the corresponding database are those grown at the innovation farms: ware, seed and starch potato, sugar beet, five small grains, maize, grass seed, onion, carrot, pea, bean, faba bean, rye grass, and a number of flower bulb crops. Only a selection of these was considered in the model study: ware and starch potato, sugar beet, winter wheat, maize, onion, and grass seed. Fallow was also treated as an 'activity'. Inter-crop activities such as organic manuring, catch crops and green manures were subject to a set of constraints not listed here (Habekotté and Schans, 1996).

Goal variables in the model study were: gross margin as defined for Case II, N loss per ha, and input of pesticides (active ingredients) per ha. N loss was estimated as mineral N input (in chemical and organic manures) plus net amount of N released by mineralisation (per whole year) minus N removed in crop produce, minus N transferred to the next season through green manures and crop residues.

Optimisations resulted in patterns comparable to those shown in Figure 1 for Case II, with shallow gradients around the point of maximum gross margin, both in the direction of decreasing N loss and decreasing pesticide input. Gross margin drops abruptly for N loss levels decreasing from 100 to 60 kg N per ha in the CZK district. A reduction in N surplus can be attained in both regions by (i) better matching of N supply with crop N demand, (ii) a replacement of organic by chemical fertilisers, (iii) suboptimal N supply, and (iv) changing the cropping pattern. The latter two options inevitably lead to a reduction in gross margin.
A reduction in biocide input is well possible without major losses of gross margin, especially in the NON region, by eliminating soil fumigation. Dramatic income losses with further biocide reductions occur when inputs drop below 5 kg a.i. per ha. This is associated with changes in cropping pattern. (All 'innovation farms' were below this threshold: 3.3 kg a.i. per ha.) The adoption of integrated crop protection packages is hampered in the NON region because of problems associated with mechanical weeding (surface frost; crop abrasion by windblown sand).

4. Discussion: modelling and practice

Both 'stakeholder' groups (producers and environmentalists) were directly involved in the flower bulbs case. The approach of separating objectives and bio-physical options was appreciated by both growers and environmentalists and resulted in bridging the communication gap between these two parties. The existing polarisation appeared to be caused by divergent views on objectives, rather than by disagreement on bio-technical relations. While the *a priori* outlook of growers focused on tactical decision making, the study increased awareness of the importance of strategic choices over tactical choices (introduction of winter wheat as a break crop; the renting of healthy land) to mitigate the decrease in farm gross margin under tightening environmental constraints. Participating farmers actively promoted, as a result of the study, new research on ecology of soil-borne pests at their experiment station. The lack of knowledge in this field had become apparent via the explorations. Despite uncertainty in a number of agronomic relations, the results were deemed sufficiently robust for testing and improvement on commercial farms. A major project with 'innovation farms' was formulated and is anticipated to start in 1998. All these responses made the potential role of modelling rather convincing.

The dairy study had a different character. Commercial dairy farmers were not yet involved (a project with 'innovation farms' started only recently) and it is therefore too early to assess the role models can have in adjusting dairy farm designs. For the De Marke experiment farm, results indicate that the current farm configuration is not optimal, although it satisfies all targets. Income can still be further maximised within the constraints. Such findings should normally provide a starting point for sound scientific debate, leading to either rejection or acceptance of the conclusion. This, however, did not happen. A general distrust in model outcomes on the part of the experimentalists may have been one reason. The omission of uncertainty in grassland production was mentioned as a shortcoming of the model. On the other hand, it seems that real, though experimental, farm systems have a certain 'inertia' that discourages real communication between experimentalists and modellers.

The arable farming case showed that the real innovation farms performed better, in some aspects, than the 'modelled optima'. Real cropping patterns were sometimes different, but more often crop responses at given production technologies (N input) differed from the model assumptions. Real yields were higher than modelled for seed potato, sugar beet (CZK, NON) and onion (CZK), and in starch potato (NON). These deviations are crucial, as exact yield levels of high-value crops largely determine the feasibility of a given farm configuration. Such flaws restrict the acceptance of modelling as a support for prototyping. Further, available computing power (*CPU* time) did not allow to take into account the whole array of crops grown on the project farms. The choices made here for crops to represent 'crop groups' could not ensure sufficient robustness of model outcome: crops *are* different.

Yet, the often raised issue whether farmers must shift cropping pattern or opt for suboptimal nutrient inputs was largely resolved by the model: first lower inputs per crop; only as a last resort increase the share of cereal crops.

Case III highlighted that, in order to fully realise the claims made for modelling in the introduction, it is important that 'prototypers' are constantly fed with model-based evaluations. This is only possible if the bulk of models and databases are already in existence and fully operational by the time an innovation project starts in the field. Then, model adjustments can be made 'on-the-go', and instant evaluation of proposed options becomes reality.

5. Conclusions

The claims made for modelling in the introduction remain only partially fulfilled. The usefulness of optimising models to 'roughly' assess feasible directions for development is generally acknowledged. Models can serve as rather objective instruments in the debate among polarised groups. Their potential role in the fine-tuning of farm designs in interaction with experimental 'prototypers', on the other hand, has not yet been confirmed by the cases presented.

Where scientific aspects are concerned, a limitation of the models used is the accuracy of crop response calculations. Likewise, this applies to models describing responses of animals to diet composition. This can be resolved by making better use of empirical data. Then - and especially when these data are derived from the very 'experiment farms' or 'innovation farms' themselves - a new function for these models emerges: to keep an 'evaluated overview' over the whole ensemble of farm activities.

In terms of research logistics, synchrony between modelling and field efforts must be ensured if model outcomes are to play a role of any significance in prototyping. Prerequisites for this synchrony are well-documented and flexible data systems accessible to whole research groups, and models (technical coefficient generators) simple enough to allow frequent re-use and updating. They should be built from well-documented modules by recognised experts, and should aim at a fair balance between theory and empiricism. These modules, whether dynamic or static descriptions, must be fit to serve as building blocks not only for TCGs to generate inputs for optimisation models, but also for simulation models used in the evaluation of *a priori* defined farm configurations.

References

Aarts HFM and Middelkoop N (1990) De invloed van bodemeigenschappen en bemesting op de opbrengst van mais en de emissies van ammoniak en nitraat. (The influence of soil characteristics and fertilisation on the yield of maize and the emission of ammonia and nitrate). CABO Reports 131 Wageningen 55 pp

Habekotté B and Schans J (1996) Modelmatige verkenning van mogelijkheden voor de geïntegreerde akkerbouw. AB-DLO Report 64 (In Dutch)

Ittersum MK van and Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Res 52: 197-208

Ketelaars JJMH and Oenema O (1997) Perspectieven voor een efficiënter nutrientengebruik in de Nederlandse landbouw. In: Ontwerpen voor een schone landbouw (Designs for clean agriculture), Eds JJMH Ketelaars and FJ de Ruijter. National Council for Agricultural Research (In Dutch)

Koning GHJ de, Van Keulen G, Rabbinge R and Janssen H (1995) Determination of input and output coefficients of cropping systems in the European Community. Agric Syst 48: 485-502

Lotz LAP, Van Veen JA and Kropff MJ (1997) Crop protection. In: Ontwerpen voor een schone landbouw (Designs for clean agriculture). Eds JJMH Ketelaars and FJ de Ruijter. National Council for Agricultural Research (In Dutch)

Rabbinge R (1993) The ecological background of food production. In: Crop Protection and Sustainable Agriculture. Ciba Foundation Symposium 177, John Wiley and Sons Chicester pp 2-29

RIVM (1996) Milieubalans 1996. Het Nederlandse milieu verklaard. Rijksinstituut voor Volksgezondheid en Milieu Bilthoven The Netherlands 142 pp (In Dutch)

Rossing WAH, Jansma JE, De Ruijter FJ and Schans J (1997a) Operationalizing sustainability: exploring options for environmentally friendly flower bulb production systems. Eur J Pl Prot 103: 217-234

Rossing WAH, Meynard JM and Van Ittersum MK (1997b) Model-based explorations to support development of sustainable farming systems: case studies from France and The Netherlands ESA In press

Schans J (1996) MGOPT_CROP, a multiple goal linear programming model for optimisation of crop rotations version 1/0 AB-DLO Wageningen Report 69 48 pp

Van de Ven GWJ (1996) A mathematical approach to comparing environmental and economic goals in dairy farming on sandy soils in the Netherlands. PhD Thesis Wageningen Agric Univ

Van de Ven GWJ and Van Keulen H (1996) Integrating environmental and production objectives at the experimental farm 'De Marke': a modelling approach. AB-DLO Annual report 1995 pp 43-45

Vereijken P (1994) Designing prototypes. Progress report 1. Progress reports of the research network on integrated and ecological arable farming systems for EU and associated countries. AB-DLO Wageningen 87 pp

Vereijken P (1997) A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. In: M.K. van Ittersum and S.C. van de Geijn (Editors), Proceedings of the 4th ESA Congress. Elsevier Science, in press

VEWIN (1996) De valkuilen van het bestrijdingsmiddelenbeleid. Vewin brochure Grondstoffen. Vereniging van Exploitanten Waterleidingbedrijven. Rijswijk, The Netherlands (In Dutch)

Weel, M.P.M., G.J.H. de Vries, and G.A. Pak, 1995.
[Environmental care in flower bulb cultivation] Centre for Agriculture and Environment, Utrecht (In Dutch)

Wit CT de, Van Keulen H, Seligman NG and Spharim I (1988) Application of interactive multiple goal programming techniques for analysis and planning of regional agricultural development. Agric Syst 26: 211-230

WRR [Netherlands Scientific Council for Government Policy] (1995) Sustained risks, a lasting phenomenon. Reports to the Government nr 44 The Hague The Netherlands 205 pp

4.3 Futures research and policy: paving the way with good intentions

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1. Introduction

What qualifies a future survey as 'good', measured in terms of its importance for government policy? The question seems superfluous: futures research is currently enjoying a boom, so evidently its value is undisputed. Many organisations even have the explicit task of planning or carrying out futurological studies. The public authorities commissioning these studies will surely know what they are doing in a time when every penny spent by the government is scrutinised closely?

And yet this boom can also be viewed differently, as 'merely' a reflection of a climate of increased uncertainty. In a time when the pace of life is increasing, old certainties are becoming outmoded and the letters on political signposts are fading, many pin their hopes on futures research as a means of getting their feet on firmer ground again. Of itself, however, its popularity says little about the quality of the relationship between futures research and policy.

Very little systematic study has been made of this relationship. Some research has however been carried out into whether forecasts and predictions prove correct, and the reasons for the outcome. While such evaluations are not irrelevant, they offer only a limited insight into the relationship between futures research and policy. This fact alone justifies a reflection on what constitutes good futures research. Moreover, I have the impression that the worlds of futures researchers and policymakers, while formally closely linked, are much further apart when it comes to substance. Whether or not a futures study hits its target in policy terms could then become much more a question of chance than the product of a self-evident synergy. This brings the danger of 'benign neglect', in which the two worlds - apart from mutual lip-service - fail to reinforce each adequately, or even turn away from each other. The statement once made by Dutch environment minister Margreeth de Boer that she would in future take the housing needs forecasts with 'a pinch of salt because they are always wide of the mark anyway', should provide food for thought. She was expressing her scepticism, but how many politicians and policymakers will not agree with her? Which of our surveys have genuinely influenced policy; or conversely: which policy decisions have been based at least in part on futures research?

These questions are interesting enough, but go beyond the pretentions of this article. We will stick to more modest aims and merely undertake a quest to seek out the characteristics of and conditions for 'good' futures research.

2. What is good futures research?

The most important quality of 'good' futures research - as with all applied research - is its 'usability', the ability to utilise the results of the survey in one or more phases of the process of policy formation and implementation. But can 'usability' be determined with hindsight? Simple criteria are not available. Changes in policy, in terms of either end or means, are inadequate as a criterion. From the point of view of a futures survey, they may or may not be justified, and the same applies for persisting with prevailing policy. A futures study may be very usable, without this being immediately obvious from the course of policy which results from it. Obstacles in the political and policy process can temporarily block successful implementation of what is in principle a valuable survey. Conversely, a survey which has sunk into oblivion can suddenly be brought into the spotlight, long after its publication, as changes in circumstances suddenly make it topical again. Moreover, the ongoing impact of a survey can take place in a much more indirect way than via the direct line between the party commissioning the study and the researcher - for example via the political system, via interest groups, movements, the scientific community, individuals in positions of authority or the media.

'Usable' need not be the same thing as 'used'. Some will find this regrettable, since it is tempting to regard a survey which is evidently widely used, judging from quoted indexes, as 'usable'. Examining the usability of precisely such surveys can sharpen our insight here. The study 'Scanning the Future' by the Dutch Central Planning Bureau is an example of a widely used survey (CPB, 1992). It has much been referred and it has inspired much new futures research. Apart from this successful 'inbreeding' function, however, question-marks can be placed alongside the usability of this survey as a basis for policy and political choices. What choices in respect of preservation or change has it *de facto* generated? Probably none, because the scenarios by definition generate no information about possible choices. Instead, the scenarios indicate what the possible consequences could be of imaginable circumstances which fall outside the sphere of influence of any Dutch policy. This in no way detracts from the worth of these contextual scenarios. Their significance, however, lies mainly in raising awareness about possible global changes as a result of a complex of economic and institutional factors and the pressure these exert on the Dutch economy. Furthermore, by removing the self-evident nature of a continued development along 'old' lines, the survey increases the uncertainty and thus possibly also raises the alertness for potential developments, both good and bad.

The survey remains silent, however, on which if any of the scenarios will become reality: this is simply a question of 'wait and see'. The survey also fails to make clear whether the Netherlands is condemned merely to undergo the international climate, or whether it can do anything about it through policy. The collection of variables for the international economic context can however be used for follow-up exercises aimed at testing the robustness of policy.

The broadening of perspective offered by this survey is useful as a first phase in a process of policy renewal. It creates a frame of reference and an incentive to rethink the options for the Netherlands, including policy options. The survey offers little concrete information about these options themselves, however; this requires different types of survey. This example illustrates that opinions about usability cannot be separated from the envisaged function of a survey. Two parties are involved in defining this function: the futures researcher and the users of his survey. Mutual expectations are extremely important for the usability of futures research. The next sections look first at the characteristics and needs of the target group for policy-specific futures research, before examining what futures research has to offer.

3. Characteristics of the target groups

The frequently documented frictions between applied research and policy also hold for futures research and government policy, though the latter relationship has a few additional singularities. Futures research is concerned with an as yet unknown reality. In whatever form the results are presented, they are always theoretical constructs rather than representations of an observable reality. This makes the position of futures research weaker than that of empirical applied research.

According to Rip (1992), science is expected to produce 'hard facts'. In reality, the 'hardness' of even the scientifically processed present-day reality is sometimes questionable, but the information offered by futures research lacks almost by definition any 'hard' basis: this information almost always concerns imaginary realities.

The policymaker, by contrast, stands firmly in the midst of reality, and this is often not an easy position. There are few policy domains where policy is purely routine. A more accurate picture is that of a policymaker whose appointments diary is overfull with problems of the here and now, and where short-term issues dominate his attention. He has to take account of often conflicting demands: from fellow politicians, his minister, other policy sectors, and from interest groups, from the media. The free scope for variation of policy ends and means is often stongly reduced by this contextual framework.

A further singularity in the relationship between futures research and government policy is that the government is not an arbitrary actor. All policy implies interventions in the lives of citizens, this even when intervention consists merely of information provided by the government on possible future situations. As a consequence, higher standards are set for statements by the government than by other organisations. It is no coincidence that the basic human right of freedom of expression does not apply to governments. The standards naturally become even higher where intervention involves compulsion or prohibition or, through subsidies or otherwise, changes price relationships. It is therefore not surprising that, to use the words of Van Gunsteren (1985), a certain conservatism and resistance to follow every fashion is inherent in government. 'The government has authority and is charged with sustaining a meaningful present which offers the prospect of a common future'. As a result of earlier acts of authority by government, citizens have acquired rights and had duties imposed upon them, and institutions and individuals have geared their conduct to this. Governments wishing to change this situation must be in a very solid position.

Van Gunsteren's formulation also indicates that the special position of the government implies responsibility for the longer term too. Politics is not focused purely on sustaining 'a meaningful present', or - in baser parlance - acquired rights. Even the most conservative politics is not restricted purely to the present, but will wish to place the nature of the protection of the values concerned in the context of possible future events. Whatever normative preferences are held, those concerned will always try to gain support for analysis of problems foreseen in the future and for their preferred solution path for tackling those problems. They will thus seek to offer the prospect of a common future. Ideally, the purpose of actions in the present - of tactical policy in other words - is also a derivative of the future that strategic policy aims for.

The consequence of its special position is that information on which the gouvernment should base its (strategic) policy must meet high standards, on penalty of loss of legitimacy. Seen in this way, futures research is not in an easy position as a policy resource. It is unable to offer hard facts, but it can seek to achieve maximum persuasiveness. The information and insights provided must give rise to new arguments for policy formation. It is therefore of great importance that futurologists acquaint themselves with the policy situation and thus with the nature of the information requirement. This is not a formality, but an object of research, but this will often not be clear even to the policymakers themselves. The primary interest of this policymaker will be in information which enables him to hold on to the policy theory to which he has succeeded in committing the cacophony of participants. He is of course not blind to the dynamics of the circumstances which are relevant for the package of ends and means he is applying. He therefore needs information which enables him to perform the right operational actions.

Seen in this way, it is no wonder that futures research is primarily used where it can help in the further development of his policy, whilst also confirming his problem analysis and solution path. In the latter case, the survey constitutes a welcome additional source to legitimise existing intentions. Explanatory memoranda often bear this out. All will recognise the standard response: 'We are already doing that which is unlikely to produce political difficulties, and will intensify our efforts here; the rest we will ignore'. Even when an exploration offers more, when there is a heavy political and/or policy investment in a consensus achieved on the ends/means structure, it will still be viewed in this way. This also explains the strong preference for policy-legitimising statements with a high degree of 'probability' or 'plausibility'. Researchers can accordingly expect little consideration for their scrupulous tying of such outcomes to the assumptions used.

This also lifts the veil on the reverse of the coin. If surveys offer perspectives which point in a totally different direction from what has just been achieved through laborious negotiation, a predisposition to 'reluctance' with respect to this information is not surprising. Alternative policy schemes, conceptions or perspectives will only receive attention if it is made clear in a convincing way that the prevailing scheme is running out of steam and that the objectives are totally unattainable: in short, if the policymaker himself is in a 'crisis'. In policy schemes in which a great deal has been invested, therefore, information about the future can only 'break in' if it is less arbitrary, if the 'story' told possesses a great deal of attraction or persuasive power.

The receptiveness to information from futures studies thus depends on the policy situation of the recipient. The contents of these studies will not simply be taken note of in an impartial way: policy production is tied up too much with internal and external factors for this. The information requirement depends greatly on the relative certainty concerning - and the loyalties invested in - prevailing policy schemes. Where these are high, recipients will be mainly interested in information which makes it easier to implement these schemes (predictive research into relevant circumstances). If on the other hand a policy domain is hedged in by great uncertainty or, worse still, if there is a crisis - to which futures research can also contribute - then there will be greater receptiveness to surveys from the broader field (boundary surveys, etc.).

Receptiveness to the offerred information, therefore, depends a great deal on whether the interest is limited to instrumental questions or whether the nature of the objectives and their prioritisation, are also important. The futurologist for his part should gear the research to the information requirement. If a study has the pretension of providing policy-relevant insights, but in reality merely sketches possible futures without examining how the policy can contribute to their realisation, then policymakers - however enlightened their view may be to alternative futures - are left empty-handed. Futures research commonly offer divergent scenarios, but illustrate variation of variables other than those which are relevant for policy (means or end). High-medium-low variants of this type can be useful as contextual scenarios, but offer little concrete assistance in terms of suggesting perspectives to be aimed for or avoided.

The worst option is to trivialise the uncertainties inherent in futures research in a response to the ever-present temptation to produce facts. In many cases the news value of our studies lies precisely in providing a sharper definition of those uncertainties. The special position of the government forces us to treat these uncertainties with the greatest care. The dismissal of housing needs forecasts by Minister De Boer cited earlier cannot be overcome by offering her the prospect that correct forecasts will one day be produced, but only by making the inherent uncertainties as clearly visible as possible, and thus usable in creating the most robust policy possible.

Achieving the best possible match between the information needs of the recipient of futures research and what the researcher can offer with his arsenal of information sources is a crucial condition. Usability thus also demands organisation. This is of course an open door, but still one which is worth going through. If, for example, the seeker of information is mainly interested in the shorter term, this demands a different approach from long-term information requirements. The nature of the policy problem, tactical or strategic interest, policy freedom, target variables, steering variables, etc., are all important variables for structuring the research. And not only for the problem definition and survey design: clarity on these aspects also gives the futurologist an opportunity to show what he has to offer. Unrealistic expectations can then be discarded. These interactive requirements for usability of the research naturally do not go so far as to suggest that both paradigms have to coincide. If this were the case, the research would not produce anything 'new' at all. It will be argued later that an important function of futures research is precisely to introduce dynamics to the policymaker's frame. Mutual knowledge does however set limits on the scope for this.

4. The information sources

Futurologists do not stand empty-handed before their task of producing 'persuasive accounts'; there are four sources of information on which they can call:

the past;
examples from elsewhere;
intentions for the future;
their own imagination.

All four ingredients can be of use in futures research. What is the persuasive power of our theoretical constructs based on these ingredients?

4.1 The past

The past is a widely used source, though one which offers less certainty now than used to be the case, at least in retrospect. In days gone by traditions always seemed to remain nicely in place, whereas today change has become the norm. We therefore put much into regaining a grip on the uncertainty this brings. Traditions have thus found their successor in trends (Van der Loo, 1993). Regularity in change again offers a degree of certainty, and much futures research therefore excels in trend analysis, sometimes with bandwidths to allow for theoretical or statistical uncertainties. Highly complex predictive model approaches are also often based in essence on dynamics and relationships which are assumed to be constant. Forecasts on this basis are in great demand by policymakers: as stated earlier, policymakers are all too keen to assume that the 'most probable outcome is the same as the expected future'. The need of policymakers for such fixed points is understandable and explains the wide use of middle variants, or the ignoring of the inherent variation in the variables studied, as if the middle variant were indeed the hardest expectation.

The interest of policymakers in fact often goes even further than pure information about trends: above all, there is a desire to know the net outcome of trends which work on each other. How much farmland will prove to be superfluous on balance in the coming decades?

How much employment will there ultimately be in the agricultural sector? These balances are the most interesting aspect for policymakers, because they indicate the size of the problems which policy seeks to anticipate. Given the margins of uncertainty of the individual trends themselves, as well as lack of knowledge regarding future feedback mechanisms, this is also the most difficult task for futures research. This is exacerbated by the fact that the assumed trend-based continuation of current developments is not self-evident. There are innumerable other phase theories, with different change patterns than those based on an assumption of continuity.

The hardness or persuasiveness of trends lies in the dependency of developments on a particular path, in the slowness or inertia of institutions - both of which (not least within the government itself) can be widely observed. Some of this slowness, for example in the demographic field, is unavoidable. But how realistic is it that the past, either as a constant (system of relationships) or as a given dynamic system, should continue to dictate the course of future events in many domains? In a sector such as agriculture this is at least doubtful, because one of the most decisive environmental factors, namely the Common Agricultural Policy, is itself frequently undergoing major changes.

The future is partly determined by the past, but this is a selective process. Many institutions are undeniably intent on preservation, but their grip on their surrounding environment is limited. Moreover, there is no such thing as complete consensus: the precise aspects of situations or dynamic paths which one wishes to preserve can vary from actor to actor, with as a result that the existing status quo is always a provisional one, even endogenously. Consequently, a pattern of change which appears to form a trend can always be broken. The persuasive power of predictions based on the past must therefore be seen as declining in proportion to the length of the period considered. This source of information is consequently most appropriate for short-term questions, but even then it remains necessary to take account of the ever-present variation.

The use of predictive models for long-term policy is more problematic, not only because this approach fails to do justice to possible dynamics, but also because possible alternative policy options are not considered. For example, if the models comprise fixed behavioural relationships, this strips the government of the ability to develop policy geared explicitly to changing those relationships.

Predictive models often suggest a greater degree of certainty for the longer term than exists in fact when the piled-up uncertainties are considered more closely. Basing policy on such knowledge becomes even more problematic as the weight of the interests at stake increases. Funtowicz and Ravetz (1991) point out that the combination of great uncertainty and major interests means that the interested parties are likely to refuse to accept a (provisional) scientific opinion if the outcome is negative for their interests, and may for example call in a second opinion to expose the unreliability of that outcome. This phenomenon, which becomes more important as the complexity of many phenomena increases, moves these authors to a plea for the development of a 'post-normal' science, focusing on entirely new forms of interaction between science, policy and interests.

4.2 Examples from elsewhere

Examples from elsewhere are the next important source of knowledge for futures research. Exploiting this source as an empirically underpinned argument for a subsequent phase in the development also demands (theoretically inspired) selection, in the form of an opinion about who leads the field or lags behind, or about the direction of diffusion of all manner of innovations. There has been an unmistakeable increase in the tendency to copy situations elsewhere. The increasing policy competition, based on the argument that 'this country can no longer afford to lag behind in ...' also encourages receptiveness to such catching-up exercises. Futures research which calculates the importance of adopting an open stance to experiences and solutions in other countries can produce surprising insights and give an important shot in the arm to policy domains. And yet the persuasiveness of the argument of the need to keep up is not always total. Today's leader can be yesterday's also-ran. Many Dutch delegations visited Sweden in the past, a country where the welfare state was considered by many to have achieved perfection. The flow of travellers has virtually dried up in recent years, however, as the welfare state in Sweden too has now entered a serious crisis. And who leads the field now in this area? The Netherlands? Blair? Clinton?

It is just as difficult to define the leaders and those lagging behind on the agricultural front. Not only does the Netherlands consider that it occupies a front position in some respects, and that it therefore has little to learn from others, but supporters of ecological farming also define 'front' differently from supporters of farming aimed at efficiency. Opinions about who leads and who lags behind are thus determined partly by normative assessments of good and bad. Examples from elsewhere can thus offer *normative* inspiration.

4.3 Intentions for the future

Although normative uncertainty about the future (which paths should we take?) is often just as big a problem as actual uncertainty (which paths are we taking?), and often leads to setting up of futures research as a basis for strategic policy, there are also most definitely intentions which in a certain sense reduce the uncertainty. The expansion plans for the European Union, for example, are serious enough and are supported by sufficient power to offer some certainty regarding the area of farmland, etc. in the future. This relative certainty introduces many new uncertainties, however: what quality, which products, which markets, what consequences for the farming industry in the present member states, what implications for the Common Agricultural Policy?

The discussion in recent years has sown confusion concerning the importance of intentions with regard to the future, and even led to cynicism concerning the makability of society. Yet this discussion should not be misunderstood. Negative experiences with what in hindsight often turn out to have been naive pretensions regarding desired changes have sharpened awareness of the complexity of society and of unintended consequences of goal-oriented actions. Despite the rhetoric, however, the pretension of makability has not disappeared: many institutions in fact use it to legitimise their existence. One difference is that the question will now be asked earlier than in the past as to who the making subject should be: the government or others. As a result of this learning process, the planning has changed in nature, though not everywhere. Blueprints are still envisaged goals of environmental policy, for example.

Attention for unintended consequences of policy intentions, however, irrespective of the actor by which they are to be realised is not always great in futures research. Once again the earlier statements about uncertainties apply: it is precisely its ability to shed light on unintended consequences that gives futures research its news value, even where the contribution intends to create new conceptions or perspectives. Although such insights may be hard for the recipient to digest, it has become sufficiently clear that intentional action can have not only unexpected but also totally undesirable consequences, to justify focusing the research sharply on these matters.

In the area of farming it can safely be said that the aimed-for objectives (productivity increases, employment, reasonable living standard, market stabilisation, safe food supply, reasonable prices, the environment and nature) will all continue to apply in the future. The normative uncertainty lies not in the objectives as such, but in the degree to which we should aim to achieve these, particularly in the longer term. The relative emphasis after all determines the mutual trade-offs. This is one lesson which we have learned from the past. Futures research can help here by making the consequences of normative choices visible and thus clarifying the trade-offs for different prioritisations. This does not reduce the normative uncertainty as such, but does make it easier to assess and thus facilitate the making of choices.

4.4 Imagination

No researcher will deny making wide use of his imagination when thinking about the future. This is the least hard source. The past and examples from elsewhere can convince thanks to their (quasi-)empirical underpinning (slowness/diffusion patterns) and political and policy intentions derive credence from the powers behind them. Fantasy, however, can only convince through argumentation. This is sufficient reason for examining this source a little more closely.

Imagination plays a role in all phases of the research: when choosing the assumptions, when determining the design of the study, and when processing or manipulating the findings. Moreover, it plays a role both in predictive and exploratory futures research. The unflagging extrapolation of trend-based changes often confronts the researcher with extreme results. Where one researcher will see these as absurd, another may see them as the most important characteristic of the society of the future. Many examples can be given, such as the virtualisation, networking and making classless, of society. With every extrapolation, therefore, the researcher faces the question of how far he should allow the trend to continue, when he should assume saturation and when the limits of toleration of society (or the government) should be deemed to have been exceeded. If he is inclined not to allow himself to be carried along by the trend in question, he will also be aware of how much the future in twenty or thirty years' time can differ from today. After all, he knows how far the situation of today differs from that in around 1960, and also from the predictions made then. Predictions starting from this basis probably demand more imagination that he dares to apply. If predictions in our exploratory research already demand a good deal of imagination, this pales into insignificance compared with what is needed if we wish to chart possible futures through exploratory surveys. Given the uncertainty about and complexity of the future, we have seen a recent rise in scenarios which seek to map out the 'corner flags' of our scope for development. But which situations can genuinely be regarded as 'corner flags'? In other words: how can the 'possible' be limited? This is a very thorny problem for futurologists, and determines the credibility of their work. After all, it is our pretension to produce something other than science fiction!

There are four important notions for keeping the imagination in check, and thus increasing the power of persuasion: probability, plausibility, feasibility and - of a slightly different order - consistency.

Probability and Plausibility

Plausibility is sometimes interpreted as a weak form of probability. The two notions derive from different disciplines, however, and must be kept well apart. What is considered plausible need not by definition be probable. Probability is a scientific category which indicates the chance that a phenomenon will occur given certain assumptions. It is thus linked to theories about selected empiricism and employed methodology. Whether the effect actually does occur given the assumptions thus depends up on the exactness of earlier observations and the 'noise' which the analysis techniques introduce. However, the theory tells us nothing about whether the assumptions are correct; for this we must fall back on their plausibility.

Plausibility, however, relates to a pre-scientific or non-scientific frame of reference. We refer to something as plausible if we have seen it earlier or elsewhere: this makes it credible. As a result, our opinions on plausibility are strongly embedded in our culture. How discriminatory or limitative is this opinion? Probably not very. The container of historical and contemporary experiences from which the plausibility criterion draws its information allows many surprising variants: 'history has many forms'. At the same time it has to be acknowledged how much the cultural dynamics implies a process of compaction when constructing what is perceived as the plausible future. Many of our opinions about the future, our future expectations, have a self-evident character. They are rarely if ever questioned, but have nevertheless come to play a major part in directing our behaviour (and often also our futures research). This compaction can even block our vision of other possibilities than those contained in the whole of our collective expectations.

The dynamics of the whole of these expectations, our image of the future, is fairly complex. History undoubtedly plays a role here, but above all our own more contemporary experiences. Selection of perceived possibilities also takes place through what Downs (1967) refers to as our automatic search information and opinion of which we take note in order to 'keep up to date', without making any extra effort to do so. Scientific information also seeps in here, but without the conditionality which is inherent in theory formation. Fora are active in every domain in determining the agenda. The media, too, are important in the transmission and, particularly, preselection process.

What we consider plausible, then, is of course subject to dynamics. What we consider normal or abnormal, possible or an illusion, often evolves gradually without us being aware of this. Looking back, we then often discover to our amazement that we now hold totally different views from in the past. An example is the transformation in social security from thinking in terms of income-before-work to work-before-income. The fact that such change can also be saltatorial can be illustrated by the reversal in thinking about the future of the European Union.

At the same time, however, existing opinions constitute a substantial filter. It has often been pointed out that during the income-before-work era, information about abuse of the social security system was trivialised or even ridiculed. Ten years ago a 'duties' scenario would consequently have found little support. Equally, a scenario highlighting the aberrations of a society based purely on 'rights' would have had difficulty in penetrating to the core of the political and policy system, even though empirical indications were available. The spectre of the 1930s, with highly trained people willing to take unskilled jobs, is something we now find quite normal, however. If we wish to keep our study firmly on the ground by using plausibility as a criterion, therefore, we must realise that there is an easy tendency to portray futures which fit in with what is now considered normal. Herein lie both the strength and the weakness of this argument. Such surveys accordingly sometimes lead to the reaction that the futures described 'resemble the present so closely'. This does not of course mean that the results may not be interesting - after all, the future might closely resemble the present. Neither does it mean that attention for those results will always be limited. The commotion caused by a publication by the Social and Cultural Planning Bureau, which made the hardly surprising prediction that the secularisation of society would continue in the next decade, was completely unexpected (including by the researchers) (Becker and Vink, 1994).

At the same time it has to be acknowledged that the plausibility criterion, while limiting the spectrum of possible outcomes, is not necessarily bound to reproduce the dominant thinking of the present. The present can always be interpreted in a variety of ways, as movements never take place consistently in a single direction. Exploring the spectrum of possibilities can therefore have a positive function in creating greater openness towards the future. This liberating function can result in structuring of policy, increasing the allowance for the possibility of changing circumstances. As more direct pointers, however, these futures fail because the plausibility criterion cannot discriminate between choices within the area delimited by it. Whichever survey of plausible futures is considered, the spectrum of variants offered can easily be expanded by innumerable other, equally plausible snapshots of the future.

Feasibility

What appears plausible needs not necessarily be feasible. Conversely, the culturally determined estimation of what are considered plausible developments draws a veil over totally different options. Surveys focusing on such possibilities are not primarily interested in probability or plausibility. Instead, they explore the limits of the system, and for this purpose tendencies and expectations which can be observed now are irrelevant. In doing this, they identify the area within which trend breaks, desired or otherwise, *could* occur.

If it was made apparent above that common or garden knowledge can suddenly appear more interesting, at least as interesting is whether and when information about quite different possibilities from those contained in prevailing ideas of the future can break through the existing consensus. The shifts which future expectations undergo admittedly also discipline the thoughts of the futurologist, but precisely the awareness of this process also gives him the scope to place question-marks alongside what is considered plausible, to raise a genuine discussion about countervailing ideas. After all, futures research aims to be slightly ahead of the spirit of the times, and to point out possibilities or perspectives before these have been generally accepted.

It appears a difficult dilemma: in the case of accepted future projections, the research may well be listened to, but the ability of the future to change or be changed may receive only lip-service. Where bolder statements are made, there is a strong chance that the futurologist will 'price himself out of the market'. The examples given earlier indicate that, where doubts about the policy theory have not yet become widely ensconced, the ground for widely deviating conceptions will not yet be sufficiently fertile. In this situation plausibility arguments can still prove persuasive. But if the arsenal of conventional insights comes to be seen as no longer adequate to solve the prevailing problems, mental scope arises for new possibilities. Crisis situations are ideal breeding grounds for accelerations in thinking.

This broadening of the mental scope by futures research raises the question of the limits of the possibilities. When talking about possibilities there is after all a great temptation to allow the imagination a free rein. Can such limits be identified? Where this is possible, this is of great importance, both if it enables the boundaries to be drawn in further than would seem possible on the basis of plausibility, and also where the area surrounded by these boundaries proves to be greater. The degrees of freedom for society are then different from what is assumed in the collective ideas about what should and should not be considered plausible. Both forms of information can then rightly be termed convincing information, and thus add a new argument to the political and policy debate. Such a system limit can be identified in the area of agriculture. The question of the maximum realisable production in the area of the European Union can be answered because the relationship between the determinant factors (characteristics of soil, water, solar radiation, photosynthesis, crop characteristics) is theoretically known and the value of each of these factors for the various regions of Europe can be determined. A large gulf between the potential and the (trends in) realisation is in itself interesting for policy (degrees of freedom). The importance of this insight increases further for locations where the potential and the realisation lie close together There is then support for the argument that a cherished prospect of continuous increases in productivity is only realisable to a limited extent, and this in turn can force changes in that prospect (SCGP, 1992).

This example may come across as somewhat suggestive, because agronomic research happens to make it possible to draw a boundary to the possibilities. This may be impossible elsewhere. Whatever the case may be, this can be used to advantage in the field of agriculture and rural policy. Moreover, the possibility cannot be ruled out that the search for system limits and the relative hardness of potential limits is undertaken far too little in futures research. If this search were undertaken more, it would lead to surprising answers. Providing those answers would however require an integration of scientific disciplines which is by no means always achieved in the practice of research.

Boundary explorations are not the only form of feasibility study with persuasive power. Studies in which the conditions for and consequences of a given objective or combination of objectives are sharply analyzed can also convince. Taking full account of existing uncertainties, this mirror function of futures research can make clearer which transformations are needed if a given imaginable or envisaged development is to be achieved. The more or less radical nature of this then offers society an insight into the feasibility or otherwise of a possible future development.

Consistency

Finally, an attempt can be made to keep the imagination in check by using consistency as a guideline for the research. This aspect is particularly relevant in the practice of scenario research. Many scenarios are characterised by their comprehensiveness, in a bid to take full account of the complexity. To be able to create order in that complexity without a relevant empirical and theoretical basis, the rule of consistency is often used. The resultant stylisations are deemed to contribute to an insight into the possible choices with regard to the future. In doing so they evoke a picture of a society in which there is a strong relationship between all the various factors and domains identified. All assumptions are positively correlated with each other.

In such stylisations, citizens adapt their behaviour to the postulated nature of the scenario, institutions place themselves in the envisaged order and government policy displays unity (sic!) and is obeyed (ditto!). In short, everything and everyone works together in harmony (SCP, 1994, pp. 413-414). Let us briefly recall the policymaker from the start of this article. Will he easily recognise these stylised scenarios as options for choice? In what respect does such a survey provide the required convincing account; does it really offer a new insight or perspective for a current political or policy debate? Where such portrayals lack controllability - leaving aside their substantive merits - the choice boils down to an integral acceptance or rejection of the integral scenarios presented; in reality, however, a society is never capable of making such choices.

Good science is moreover something which should provide a lesson, but this possibility is lacking if the output of a scenario has become largely identical to its input. For example, is it not almost tautological when an ecocentric scenario, in which all actors without exception work in support of environmental values, turns out to be good for the environment? Or when a market scenario, in which all actors are able to strive for their preferred prosperity goals, unfettered by any regulations, turns out to be bad for the environment? The information content would be greater if the findings were contrary to the starting principles. The rule of consistency, however, is unlikely to lead to such a result. These conflictless portrayals, in which there is virtually no place for the unintended consequences referred to earlier, offer little help to a policymaker who has to make his choices in a world governed by inconsistencies. The range of choices facing him does not lend itself for maximisation, but rather for optimisation.

Naturally, a futures study has to simplify reality. The consistency approach can be of some use in doing so, but should not become too far removed from its connection with the real world. The futurologist must realise that consistency accords more uniform rationality to a society and government than can reasonably be expected from those quarters.

5. Conclusions

Futures research is not a non-committal activity; the aim should be to provide usable insights. As a form of applied research, it is not carried out purely and simply to provide insight into the future. By charting developments, identifying possible trend-breaks, exploring margins within which developments could occur, and offering new perspectives for policy, the aim is to enable the information offered to play a role in the formation of opinions and decisions in the present day.

Our future projections are always constructs and thus manipulable. This brings responsibility: the nature of the manipulation must be as transparent as possible, must be based on the available policy options, and must have the greatest possible power of conviction for the party requiring the information.

This is the *leitmotif* running through the foregoing argument, which is also indicative of the pitfalls facing futures research. Many examples have been given in the foregoing and can still be given, exploring options for the distant future without any realisation of the problems of today. Or precisely the reverse: predictive research where an evident crisis calls for explorations, offering of views of the distant future without any concrete pointers for policy; consistent scenarios which have become removed from social reality.

The needs identified at the start of this article on the part of politicians and policymakers for futures research to provide information with a high degree of certainty, is understandable. Precisely in a period of great uncertainty, people look for new certainties outside themselves. However, this research can produce few if any hard facts. What it often can do is to provide a better delineation of the uncertainties, and that alone is no small contribution. An exploration can after all be extremely usable if it can show precisely where a solid basis for choice, dictated by circumstances, is lacking, where politicians take on more the role of risk-taking entrepreneurs.

The usability, and thus the persuasive power, of the contributions cannot be separated from the nature of the information required and the context in which the party requiring it operates. These determine the mix of information sources to be addressed and the technical apparatus to be used. For this reason futures research is usually not a routine affair, but each study demands a new and careful judgement of the problem definition and most appropriate method. This, incidentally, is a comforting thought for futurologists: this constant adaptation to changing circumstances would appear to secure their future.

References

Becker JW and Vink R (1994) Secularisatie in Nederland 1966-1991; de verandering van opvattingen en enkele gedragingen (Secularisation in The Netherlands 1966-1991; Changes in Attitudes and Behaviour) SCP, Rijswijk

CPB (1992) Scanning the Future; a long term study of the world economy 1990-2015 Control Planning Bureau The Hague

Downs A (1967) Inside Bureaucracy

Funtowicz SO and Ravetz JR (1967) A new scientific methodology for global environmental issues; in: R. Constanza (ed) Ecological economics: the science and management of sustainability, New York

Rip A (1992) Expert advice and pragmatic rationality; in: N Stehr and RV Ericson (eds) The Culture and Power of Knowledge, Berlin/New York

SCGP (1992) Scientific Council for Government Policy, Grond voor keuzen, Vier perspectieven voor de landelijke gebieden in de Europese Gemeenschap (Ground for Choices. Four Perspectives for the Rural Areas in the European Community) sdu uitgeverij The Hague

SCP (1994) Social and Cultural Planning Bureau, Sociaal en Cultureel Rapport 1994 (Social and Cultural Report 1994) Rijswijk

Van Gunsteren H (1985) Het leervermogen van de overheid (The Learning Capacity of the Government); in: MAP Bovens en WJ Witteveen (eds) Het schip van staat; beschouwingen over recht, staat en sturing (The State, reflections about Justice, State and Governing) Zwolle

Van der Loo H (1993) Land van individuen; individualisering en vermaatschappelijking in het fin-de-siècle (Land of Individuals; Individualisation and New Sociations in the Fin-de-Siècle) RPD