IT Applications in Agriculture: Some Developments and Perspectives

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The paradise lost of decision-making under certainty

Animals secure their survival and well-being through instinctive actions. Man, however, was driven out of this paradise. Man must consciously establish alternatives of action, predict the consequences of these alternatives, and eventually choose the best course of action for his survival and well-being.

Formally considered, this process is nothing more than the transformation of data into information. Thus, in order to predict consequences of possible actions, we basically need three things, namely

(i) data on environmental variables, relevant to our decision space;
(ii) data on cause and effect relationships within the systems to be employed for our survival and well-being;
(iii) prediction aids as decision support models, which contain the cause and effect relationships and process the data into information.

The expulsion from paradise, however, has had an additional consequence: Whereas animals by means of their instinctive actions always seem to decide under complete certainty, man had to realize that he must decide under uncertainty with incomplete knowledge. He cannot see into the future and only partially grasp the complexity and dynamics of the environment influencing his pondered actions. Hence, the consequences of actions can only be predicted imperfectly and with probabilities. So we need

(iv) knowledge about the "stochastics" connected to the data, as well as to the generated information.

How and where does IT help?

We are convinced that IT helps us in mastering our very existence. Otherwise, we would not tackle corresponding research problems. There are basically three areas of investigation – analogous to production systems for real goods – in which substantial progress has already been made by IT applications, and may certainly be expected in the future.

First, IT supports the production process, i. e. by generating information output from data input by means of models.

For instance, the calculus of differential equations and their particular suitability for the design of dynamic prediction models has been well known for centuries, i. e. since the works of LEIBNIZ, NEWTON, LAGRANGE and EULER, to name just a few. Nevertheless, these systems have only been used to a very limited extent, because (i) analytical solutions can be calculated only for rather simple systems and (ii) manually derived numerical solutions, although possible, are prohibitively time consuming. Hence, alternative calculations with various data sets, in order to explore the decision space, and to conduct sensitivity analysis, were beyond the scope of decision makers. Not before the advent of the computer, could the enormous utility of differential equations for dynamic simulation models unfold.

Also, the basics of (statistical) decision theory have been well-known for centuries, i. e. since BERNOULLI and BAYES. Nevertheless, the theory has – except for simple classroom examples – hardly been used for practical decision support, because analytical solutions were limited to simple problems and manual numerical calculations were too time consuming in this case as well. Again, the usefulness of this quantitative methodology could only unfold when powerful computers became available.

Of course, the ability of computers to perform fast calculations has also triggered the development of new classes of quantitative models. Numerical mathematics, statistical inference, BOOLEan algebra, iterative optimization, and solving of general equilibrium models, may be mentioned in this context.

Second, IT supports the procurement, i. e. the gathering of data as necessary model input.

The tedious counting, measuring and weighing “by hand” or by analog devices has been replaced to a large extent by electronic sensors and digital data collection systems, such that the data may be fed directly into digital decision support models without additional data handling. Automated on-line management of production processes, employing feedback loops, are feasible, as well as the use of geographical information systems for the analysis and simulation of spatially explicit consequences of agricultural and environmental policy measures.

Third, IT supports the logistics, i. e. the transformation of data and information over space and time.

Telecommunication and data warehousing are the preconditions for distributed data processing, involving many agents, logging into the systems at different locations and at different times. An efficient overall management of complete supply chains becomes feasible, as well as data and information exchange for E-Commerce. Not every dream seems to come true, however: Only a few years ago electronic commerce for agribusiness was greeted very enthusiastically. Today, disillusionment can be detected. Even for agricultural commodities, face to face trading seems to be indispensable.

Trends in model development

I will not go into any details concerning the fields of data procurement and logistics. I do not know enough about these problems. Instead, I will concentrate on models as decision-support systems. What developments took place and what developments can and should be expected in the future? I see the following – of course subjectively identified – five trends:

(1) The path of development changes from the construction of predominantly retrospective to mainly anticipative models.

According to the general phase theorem of decision making, planning should pre-empt control to further subsequent pre-post comparison as an information source for corrective actions and for efficiency improvements. However, real life shows a different picture. All empirical investigations with respect to the use of computer models by farmers reveal that most farmers employ only retrospective models to generate descriptive and – at most – diagnostic information. Anticipative models for generating predictive and prescriptive information are used to a much smaller extent.

The recent demand for a complete documentation of activities within entire supply chains has induced an additional impulse for the development of rather sophisticated retrospective models. Traceability and quality assurance are the relevant catch words here, as well as efficient consumer response and just in time delivery.

Nevertheless, in the future, planning models supporting strategic, as well as tactical management tasks – although somewhat more user friendly than at present – should be developed more intensively. Because (as a reminder): Control without planning is impossible, and planning without control is useless.

(2) The path of development changes from the construction of skeleton models to (domain) knowledge-based models.

Up to now, by far the greatest number of models for firm-related as well as for region-related decision support are designed as so-called skeleton models. Not only data for factor inputs but also those for product outputs must be provided by the model user as exogenous entities. The models do not contain any substantial knowledge-based relationships, be it production functions, production rules or behavioural functions, which would be necessary for endogenous predictions of model outputs, based on exogenous model inputs. The prediction of most of the outputs is left to the user.

Reasons for this less than satisfying situation seem to be that agricultural production systems differ in at least two major phenomena from industrial production systems. Contrary to most industrial production systems, where production devices almost completely consist of man-made systems, biotic systems, such as plants and animals are used in agriculture. In industrial branches complex production systems are combinations of simple elements, whose inner structures are well known as a precondition for the determination of production functions. In agriculture it is just the opposite: First one has to break down the complex biotic systems into their basic elements by means of research, to learn more about their inner structures as a precondition for viable predictions of their behavior in response to exogenous input variables. Applied biologists are becoming more and more successful in this area but not so successful that detailed input-output-relationships may be used for concrete predictive calculations. And, for that matter, employing (statistical) black-box-models for the estimation of production functions, does not help very much. These production functions are only valid for the particular experimental plots and vegetation periods from which the data originate. This way, generalized production functions cannot be derived.

In addition, especially the production system “land plus crop” (in rain-fed agriculture) is – with respect to output quantities and qualities – very substantially determined by non-controllable variables like e. g. solar energy and plant usable water. This, however, means that the decision maker cannot control the production system completely. He can only try to optimally adapt the quantities and qualities of the controllable variables (e. g. nutrient supply, plant protection) to the expected values of the non-controllable variables. This is no trivial task, since the values of the non-controllable variables vary over space and time, without the decision maker being able to allocate and predict their values exactly.

In the past, the construction of proper decision aids for this problem area showed only limited progress. But it may certainly be expected to accelerate in the future, if one considers e. g. the efforts concerning precision agriculture or spatially explicit land-use modelling for entire regions.

(3) The path of development changes from open-loop control models to closed-loop control models.

Facing the uncertainty of expectations connected to the risk of false decisions, model designers – whenever this is feasible – replace open-loop control models with models which make use of feedback loops and operate as closed-loop control models. Through more or less continuous monitoring, the decision maker detects deviations between reference values of outputs and their actual values. He then uses these deviations as a base for corrective decisions during process time, i. e. during the growth period of plants or the growth and lactation periods of animals. The on-line approach in the field of precision agriculture (e. g. nutrient supply according to actual crop state), as well as the efficient coordination of complete supply chains, may be mentioned here as examples.

(4) The path of development changes from the construction of models, which assume perfect information about relevant data during the planning period, to models which take into account incomplete knowledge. In other words: Models which abstract from the complexity and dynamics of the relevant environment are more and more replaced by models which explicitly incorporate these phenomena.

Initially, the “number crunching” capacity of computers was used in batch mode. Later on, this mode was replaced by the interactive approach with repeated runs under different data sets, in order to explore the decision space more comprehensively and to identify sensitive input variables.

Meanwhile though, more and more models incorporate the complexity and dynamics of the relevant environment, on the base of sound decision theory, by means of probability distributions for the non-controllable variables. Investment models for strategic decision making, as well as models for operations control of production processes, may be mentioned here.

(5) The path of development changes from the construction of "point in time" and "point in space" models to models which explicitly incorporate time and space.

The characterization of time and space variant non-controllable variables by means of probability distributions is certainly a substantial progress in the model building area. However, it would be even better, if one were e. g. able to directly allocate the values of the non-controllable variables to particular sites within a land parcel and to particular time spans within a vegetation period. If one knew exactly in advance, which values of the non-controllable variables prevail at which sites and in which time spans, one could control e. g. crops with almost perfect information and thus without any substantial efficiency losses. The estimation of probability distributions would not be necessary anymore. However, for the time being, this will no doubt remain a most desirable but hardly realizable state of the model building art.

Nevertheless, we should try to develop such bio-economic models, which explicitly incorporate the relevant time and space variant non-controllable variables, because of their obvious advantages for agricultural production and – for that matter – for the natural environment. They would, at the same time, help to increase production per land unit and decrease the amount of waste, e. g. by not applying more nutrients than needed by the crops.

By means of a very simple example, I would like to show which challenges and opportunities lie before us in this area of model based decision support.

An example: Determining the optimal nutrient supply for a crop

The following example refers to the task of determining the proper nutrient supply (e. g. nitrogen) for a crop (e. g. wheat) on a parcel of land. In order to predict the optimal nutrient supply, we need a production function (as a yield response function), describing the quantitative relationship between the nutrient supply(1) and the attainable yield. Suppose, this relationship can be described by a linear response and plateau function, which is a special case of the LIEBIG yield response function (and, for that matter, a special case of the LEONTIEF function). Such a function is depicted in *fig. 1*. If A is the attainable maximal yield per ha, limited by a given supply of a non-

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(1) In this paper the term „nutrient supply” is meant to include fertilization, as well as plant usable soil deposits of the nutrient.

controllable yield factor on a specific site (e. g. plant usable water), then the attainable yield (y) increases with increasing supplies of the controllable yield factor (x), (e. g. the nutrient nitrogen) until the yield plateau (A) is reached. The plant usable water may in this example simply be the sum of the field capacity (nfk), assumed to be completely saturated at the beginning of the vegetation period, and the precipitation (ns) during the vegetation period.

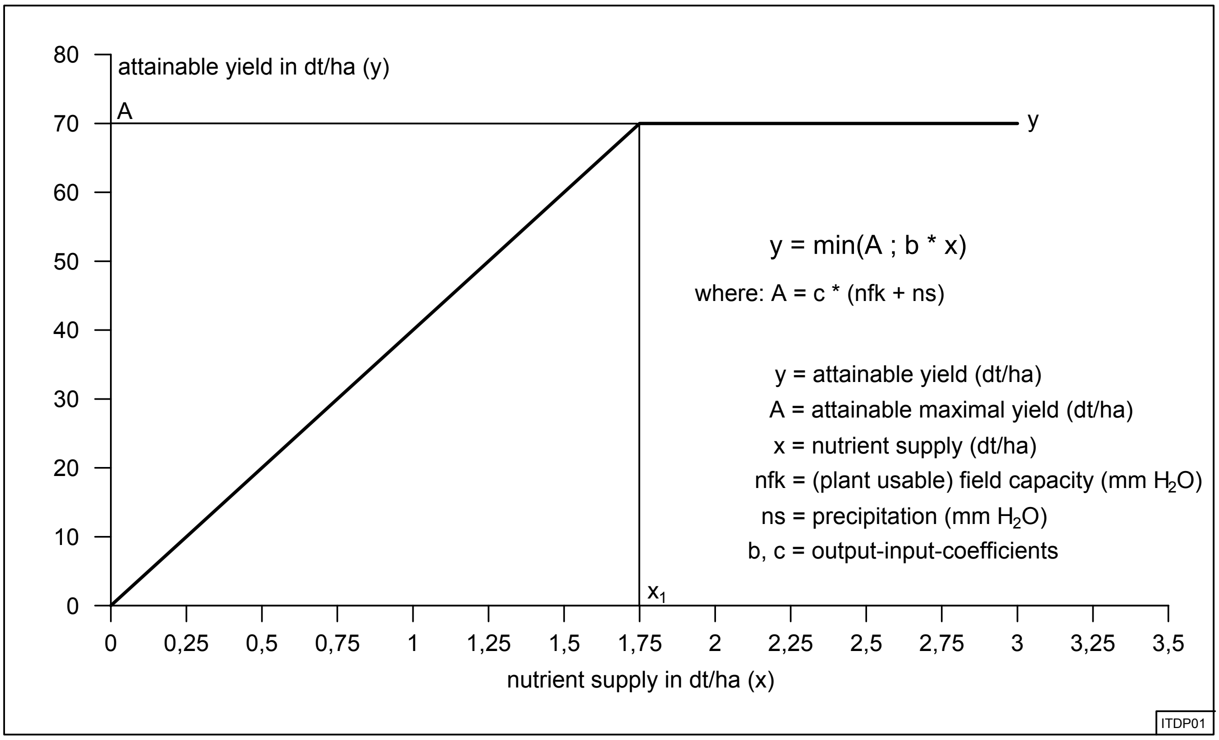

Fig. 1. Linear response and plateau function (Liebig yield response function - simplified case -)

In order to secure the maximal efficiency, the decision maker would obviously take care of the nutrient supply level x_1. If he supplies less than x_1, the maximal yield would not be attained, thus wasting yield potential. If he supplies more than x_1, nutrients would be wasted, since the yield level is limited by the plant usable water. Thus, we have the yield response function

$$y = \min (A; b \cdot x)$$

where b is the output-input-coefficient for the nutrient (x). Obviously in this example b = 40.

In reality, however, the supplies of the non-controllable yield factor plant usable water are variable over space and time. The field capacities may vary from site to site within a land parcel. The precipitation levels vary from vegetation period to vegetation period. Thus, in the simplest case, we may have the situation as depicted in *fig. 2*. On some sites of the land parcel and in some vegetation periods the attainable maximal yield may only be A_1, on other sites and in other years, however, it may be A_2. If the decision maker does not know where and when the attainable maximal yield is either A_1 or A_2, he faces a decision problem under uncertainty: If he supplies only x_1 = 1,25 dt/ha of the nutrient, assuming the proper yield response function is y_{A1}, he would on some sites and in some vegetation periods forgo the yield Dy = 40 dt/ha. If, on the other hand, he chooses the nutrient supply level x_2 = 2,25 dt/ha, assuming the proper yield function is actually y_{A1}, he would on some sites and in some vegetation periods waste a nutrient supply of Dx = 1,00 dt/ha. So, what strategy for the nutrient supply should the decision maker choose?

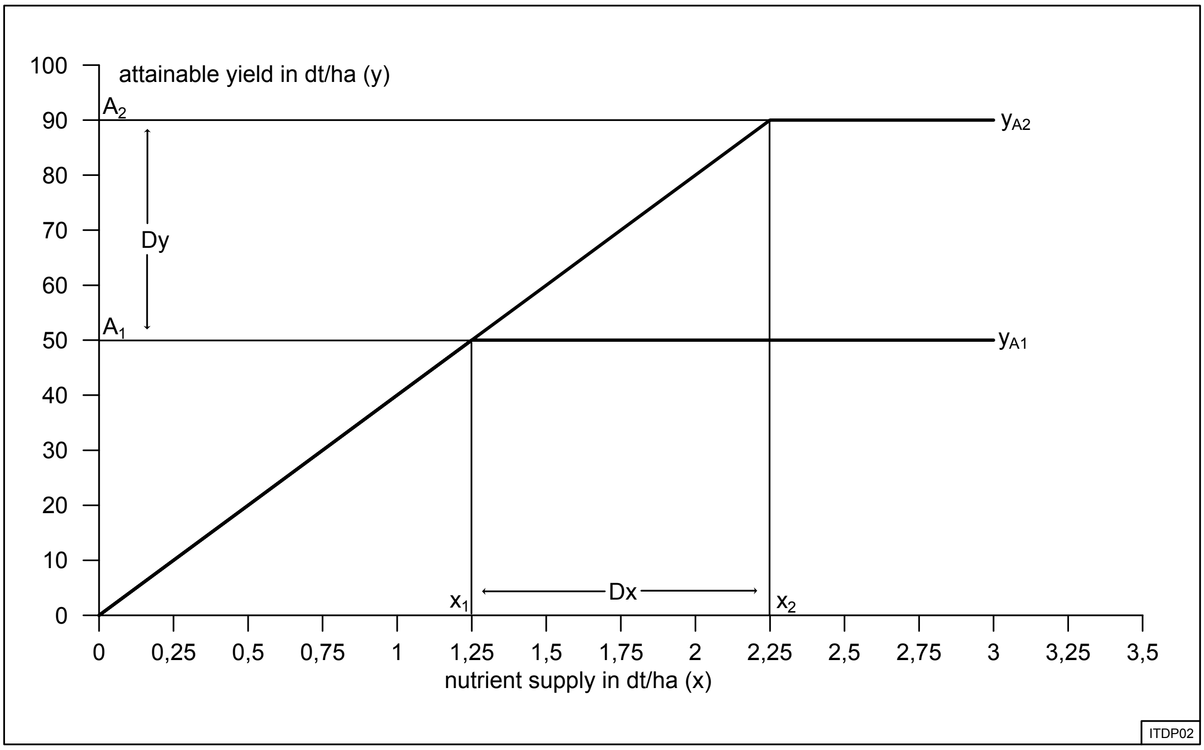

Fig. 2. Linear response and plateau functions with variable attainable maximal yields

Due to progresses in farming technology, there are now two basic strategic alternatives available: Either a “parcel specific” or a “site specific” strategy. In a parcel specific strategy certain amounts of nutrients are uniformly distributed over the entire land parcel. Of course, the amounts may vary from parcel to parcel and from vegetation period to vegetation period. In a site specific strategy the farmer employs precision agriculture equipment, and may fertilize with variable rates at different sites within a land parcel, e. g. according to site specific nutrient requirements of the crops.

Parcel specific nutrient supply strategies

Table 1 shows the decision situation for the simplest case one can think of: One distribution for field capacities on the land parcel and one for precipitation levels per vegetation period with two classes each. If we assume, for further simplification, high and low precipitation respectively in 50% of the years and high and low field capacities respectively on 50% of the land parcels, the maximal attainable yields will fall into four classes with probabilities of 25% each. For the example it is assumed (see head of *table 1*) that the attainable maximal yields are 40, 60, 80 and 100 dt/ha, respectively.

Table 1. Parcel specific nutrient supply: Expected values of yields and nutrient consumption, as dependent on increasing nutrient supplies, under the conditions of space and time variability for the plant usable water, due to spatial variability of field capacities within a land parcel and to variable precipitation levels from vegetation period to vegatation period

	Precipitation:	"Low"		"High"				
	Probability:	0,50		0,50				
	Field capacity:	"Low"	"High"	"Low"	"High"		Input-output-coefficient for nutrient [b]:	40,00
	Probability:	0,50	0,50	0,50	0,50			
	Attainable maximal yield [A_j]:	40,00	80,00	60,00	100,00		Expected value of attainable maximal yield:	70,00
	Probability of yield class [f_j]:	0,25	0,25	0,25	0,25			
Action alternatives: Nutrient supplies [x_i] in dt/ha		Yield matrix: Yields [y] in dt/ha				Expected values of yields dt/ha	Expected values of nutrient consumption dt/ha	Expected values of wasted nutrients dt/ha
x_1	0,50	20,00	20,00	20,00	20,00	20,00	0,50	0,00
x_2	0,75	30,00	30,00	30,00	30,00	30,00	0,75	0,00
x_3	1,00	40,00	40,00	40,00	40,00	40,00	1,00	0,00
x_4	1,25	40,00	50,00	50,00	50,00	47,50	1,19	0,06
x_5	1,50	40,00	60,00	60,00	60,00	55,00	1,38	0,13
x_6	1,75	40,00	70,00	60,00	70,00	60,00	1,50	0,25
x_7	2,00	40,00	80,00	60,00	80,00	65,00	1,63	0,38
x_8	2,25	40,00	80,00	60,00	90,00	67,50	1,69	0,56
x_9	2,50	40,00	80,00	60,00	100,00	70,00	1,75	0,75
x_{10}	2,75	40,00	80,00	60,00	100,00	70,00	1,75	1,00
								ITDP00

Assuming a value of b = 40 for the output-input coefficient of the nutrient, and by increasing nutrient supplies (x_j), uniformly distributed over the entire parcel, we get the yield matrix for the four yield classes shown in the lower left part of *table 1*. For each of the four yield classes the attainable yields increase linearily until the yield plateaus put a limit to further increases. The column to the right of the yield matrix shows the expected values for the attainable yield per ha of the parcel. The expected values of the yield, as dependent on increasing nutrient supplies, increase initially with constant and then with diminishing rates, until the expected value of the attainable maximal yield level for the land parcel of 70 dt/ha is attained.

The two far right columns of *table 1* show the expected values of the nutrient consumption, and of the wasted nutrients. Starting at supply level x_4, the nutrient consumption is less than the supply, because already in yield classes with relatively low maximal yields more nutrients are supplied than can be consumed by the plants due to water shortage. The differences between supply and demand (consumption) are wasted.

Fig. 3 depicts the expected values of the yields as dependent on increasing nutrient supplies. Averaged over the entire land parcel and a sufficient number of vegetation periods, we would get a yield function, which behaves according to the law of diminishing returns. In addition, *fig. 3* also shows the expected values of the wasted nutrients. As dependent on increasing nutrient supplies, the amounts of wasted nutrients are progressively increasing.

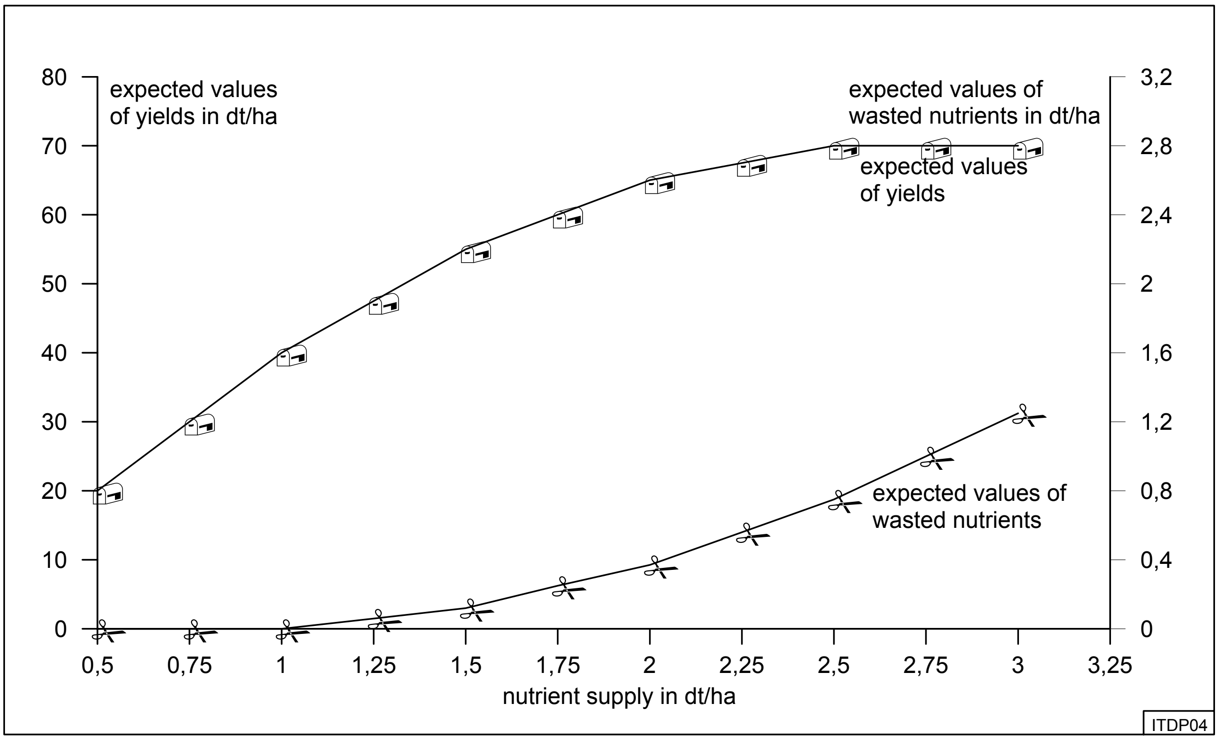

Fig. 3. Expected values of yields and wasted nutrients as dependent on parcel wide uniform nutrient supplies

Facing the yield situation outlined in *table 1*, and assuming that the decision maker knows the probability distributions of the field capacities and the precipitation levels, what action alternative, i. e. which nutrient supply level should he choose? Obviously, the question can only be answered by calculating the expected values of the gross margins (revenues from the crop over nutrient costs), as dependent on increasing nutrient supplies. Assuming prices for the product and the nutrient of 12,00 and 60,00 €/dt, respectively, *table 2*, in addition to the yields, shows the expected values of the revenues, the nutrient costs and the expected values of the gross margins.
Under these circumstances, and taking into account the above mentioned information, a risk neutral decision maker would probably choose the action alternative with the maximal expected value of the gross margin. Thus, given the situation outlined in *table 2*, he would choose the nutrient supply x_9. Although in this case the nutrient supply of 2,50 dt/ha would surpass the nutrient consumption of 1,75 dt/ha by 0,75 dt/ha (see *table 1*), the decision maker will expect the highest value of the gross margin, in this example amounting to 690,00 €/ha.

Usually, however, decision makers do not have knowledge on the probability distributions of the field capacities and the annual precipitations, or, for that matter, do not bother to acquire this knowledge from standard soil maps and long-term precipitation data. Instead, they use some average yields of the past, which may in fact be the expected value of the attainable maximal yield, as a base for the determination of the parcel-wide uniform nutrient supply. Using this yield, however, also implicates that the decision maker assumes an average level of precipitation and an average level of the field capacity for the entire land parcel.

Table 2. Parcel specific nutrient supply: Decision framework and expected value of attainable maximal gross margin, by taking into account the probability distributions of the field capacities and the precipitation levels per vegetation period

	Precipitation:	"Low"		"High"						
	Probability:	0,50		0,50					Product price [€/dt]:	12,00
	Field capacity:	"Low"	"High"	"Low"	"High"				Nutrient price [€/dt]:	60,00
	Probability:	0,50	0,50	0,50	0,50				Output-input-coefficient for nutrient [b]:	40,00
	Attainable maximal yield [A_j]:	40,00	80,00	60,00	100,00					
	Probability of yield class [f_j]:	0,25	0,25	0,25	0,25				Expected value of attainable maximal yield:	70,00
Action alternatives: Nutrient supplies [x_i] in dt/ha		Yield matrix: Yields [y] in dt/ha				Expected values of yields dt/ha	Expected values of revenues €/ha	Nutrient costs €/ha	Expected values of gross margins €/ha	Optimal action alter-native
x_1	0,50	20,00	20,00	20,00	20,00	20,00	240,00	30,00	210,00	
x_2	0,75	30,00	30,00	30,00	30,00	30,00	360,00	45,00	315,00	
x_3	1,00	40,00	40,00	40,00	40,00	40,00	480,00	60,00	420,00	
x_4	1,25	40,00	50,00	50,00	50,00	47,50	570,00	75,00	495,00	
x_5	1,50	40,00	60,00	60,00	60,00	55,00	660,00	90,00	570,00	
x_6	1,75	40,00	70,00	60,00	70,00	60,00	720,00	105,00	615,00	
x_7	2,00	40,00	80,00	60,00	80,00	65,00	780,00	120,00	660,00	
x_8	2,25	40,00	80,00	60,00	90,00	67,50	810,00	135,00	675,00	
x_9	2,50	40,00	80,00	60,00	100,00	70,00	840,00	150,00	690,00	x9
x_{10}	2,75	40,00	80,00	60,00	100,00	70,00	840,00	165,00	675,00	
										ITDP03

In our example, the decision maker would take the expected value of the attainable maximum yield of 70,00 dt/ha (see *table 1*) and then principally decide upon the relevant nutrient supply according to the input-output-relationship depicted in *fig. 1*. In order to attain the maximal efficiency, the decision maker would secure a nutrient supply level of 1,75 dt/ha. Taking into account the afore mentioned product and nutrient prices of 12,00 €/dt and 60,00 €/dt, respectively, he would predict revenues of 70,00 dt/ha · 12,00 dt/ha = 840,00 €/ha, nutrient costs of 1,75 dt/ha · 60,00 €/dt = 105,00 €/ha, and thus, a maximal gross margin of 735,00 €/ha.

Table 2, however, shows that because of the probability distributions for the field capacities and the precipitations, a nutrient supply of x_6 = 1,75 dt/ha would only result in an expected value of the gross margin, amounting to 615,00 €/ha which is 120,00 €/ha less than the predicted 735,00 €/ha.

Thus, proper knowledge on the probability distributions of non-controllable yield factors, as well as on suitable decision support aids clearly leads to economic advantages, in this case to an increase of the expected value for the gross margin from 615,00 €/ha to 690,00 €/ha.

Besides, the above described facts may also explain why many farmers fertilize more than the strict calculation of the crop's consumption would suggest. They may have learned from past experience.

For the above described strategies it is assumed that the decision maker has fertilized the land parcel, in order to provide for the envisioned nutrient supply, before he knows about the actual precipitation level of a particular vegetation period. Furthermore, it was assumed that he provides an invariable nutrient supply from vegetation period to vegetation period.

Actually, one can at least think of one more parcel specific strategy which makes use of available additional information. Instead of securing constant nutrient supply levels over the years, in this case the decision maker would apply variable amounts of fertilizers from vegetation period to vegetation period. Moreover, he would apply the fertilizer in several split doses during the vegetation periods, monitoring the growth states of his crop and employing a closed-loop approach as the vegetation period proceeds. Since the growth states of the crop very much depend on the supply levels of the non-controllable yield factors, in vegetation periods with relatively high total precipitation, the decision maker will apply a relatively high total amount of fertilizers, in order to attain the relatively high maximum yields of those vegetation periods. The opposite would be true for vegetation periods with relatively low total precipitation.

Such a strategy is outlined in *table 3*. In this table the yield matrix is divided in two parts. The (upper) left part shows the yields, as dependent on increasing nutrient supply levels for the vegetation periods with low total precipitation, the (lower) right part those for the vegetation periods with high total precipitation.

The columns to the right of the yield matrices show the expected values of the yields for both precipitation levels, as well as the nutrient costs and the expected values of the revenues and gross margins. In vegetation periods with low total precipitation, the decision maker should obviously secure a nutrient supply level of x_7 = 2,00 dt/ha which translates into a maximal gross margin of 600,00 €/ha. In vegetation periods with high total precipitation, he should secure the nutrient supply level of x_9 = 2,50 dt/ha translating into a maximal gross margin of 810,00 €/ha. Since it was assumed earlier that the probabilities for vegetation periods with low and high precipitation are 50% each, the decision maker will on average accomplish a maximal gross margin of 705,00 €/ha (calculated in the last line of *table 3*).

Table 3. Parcel specific nutrient supply: Decision framework and expected value of attainable maximal gross margin, by taking into account the probability distribution of field capacities and fertilizing in a closed-loop-approach according to precipitation conditions during the vegetation period

Precipitation:		"Low"		"High"						
Probability:		1,00		1,00					Product price [€/dt]:	12,00
Field capacity:		"Low"	"High"	"Low"	"High"				Nutrient price [€/dt]:	60,00
Probability:		0,50	0,50	0,50	0,50				Output-input-coefficient for nutrient [b]:	40,00
Attainable maximal yield [A_j]:		40,00	80,00	60,00	100,00					
Probability of yield class [f_j]:		0,50	0,50	0,50	0,50					
Action alternatives: Nutrient supplies [x_j] in dt/ha		Yield matrices: Yields [y] in dt/ha				Expected values of yields dt/ha	Expected values of revenues €/ha	Nutrient costs €/ha	Expected values of gross margins €/ha	Optimal action alter-native
x_1	0,50	20,00	20,00			20,00	240,00	30,00	210,00	
x_2	0,75	30,00	30,00			30,00	360,00	45,00	315,00	
x_3	1,00	40,00	40,00			40,00	480,00	60,00	420,00	
x_4	1,25	40,00	50,00			45,00	540,00	75,00	465,00	
x_5	1,50	40,00	60,00			50,00	600,00	90,00	510,00	
x_6	1,75	40,00	70,00			55,00	660,00	105,00	555,00	
x_7	2,00	40,00	80,00			60,00	720,00	120,00	600,00	x7
x_8	2,25	40,00	80,00			60,00	720,00	135,00	585,00	
x_9	2,50	40,00	80,00			60,00	720,00	150,00	570,00	
x_{10}	2,75	40,00	80,00			60,00	720,00	165,00	555,00	
x_1	0,50			20,00	20,00	20,00	240,00	30,00	210,00	
x_2	0,75			30,00	30,00	30,00	360,00	45,00	315,00	
x_3	1,00			40,00	40,00	40,00	480,00	60,00	420,00	
x_4	1,25			50,00	50,00	50,00	600,00	75,00	525,00	
x_5	1,50			60,00	60,00	60,00	720,00	90,00	630,00	
x_6	1,75			60,00	70,00	65,00	780,00	105,00	675,00	
x_7	2,00			60,00	80,00	70,00	840,00	120,00	720,00	
x_8	2,25			60,00	90,00	75,00	900,00	135,00	765,00	
x_9	2,50			60,00	100,00	80,00	960,00	150,00	810,00	x9
x_{10}	2,75			60,00	100,00	80,00	960,00	165,00	795,00	
Expected value of maximal attainable gross margin, given the probability distribution of field capacities and probabilities of precipitation levels:						600,00 * 0,5 + 810,00 * 0,5 =			705,00	
										ITDP05

As a result, acquiring additional knowledge on the values of non-controllable yield factors, by means of their continuous monitoring, may lead to additional economic advantages, in our example to a further increase of the expected values of the gross margin from 690,00 to 705,00 €/ha.

Site specific nutrient supply strategies

Until now, it was assumed that the decision maker uses parcel specific nutrient supply strategies, which in any case lead to uniform levels of fertilization for the entire parcel, although – as in the last case – they may vary from vegetation period to vegetation period. The whole idea of precision agriculture, however, is site specific fertilization according to expected yield potentials on the various sites of a land parcel.

First we shall look into the case where the decision maker does not only know the probability distribution of the field capacities of his land parcel, but has properly located the actual field capacities of the sites within the parcel. On the other hand, the decision maker does not employ the above described closed-loop approach for the nutrient application. Instead, he assumes average precipitation levels to be relevant. In reality, this is often the actual information base.

In this case, the decision maker would actually assume that on sites with low field capacities the attainable maximal yield will be 50 dt/ha as the weighted average of the attainable maximal yields of 40 and 60 dt/ha for “dry” and “wet” vegetation periods, respectively (refer to head of *table 1*). On sites with high field capacities he would assume an attainable maximal yield of 90 dt/ha as the weighted average for the attainable maximal yields of 80 and 100 dt/ha for “dry” and “wet” years, respectively.

The decision situation which the decision maker actually assumes to be relevant, is outlined in the upper part of *table 4*. The output-input-coefficient for the nutrient still being b = 40, the decision maker computes the necessary nutrient supply for the sites, having low and high field capacities, with 1,25 dt/ha and 2,25 dt/ha, respectively. According to the assumption that the sites with low and high field capacities each prevail on 50% of the parcel surface, the weighted average of the nutrient supply level is 1,75 dt/ha. The same reasoning applies to the weighted average of the attainable yields, with an expected value of 70,00 dt/ha. Assuming again the product and factor prices of 12,00 and 60,00 €/dt, respectively, the decision maker computes the expected value of the attainable gross margin to amount to 735,00 €/ha (see upper right part of *table 4*).

Table 4. Site specific nutrient supply: Expected and actually attainable results under the assumption of average precipitation, given site specific perfect information on locations and values of field capacities

Site specific nutrient supply: Expected results, assuming average precipitation, and taking into account site specific perfect information on locations and values of field capacities:								
Precipitation:	"average"							
Probability:	1,00						Product price [€/dt]:	12,00
Field capacity:	"Low"	"High"					Nutrient price [€/dt]:	60,00
Probability:	0,50	0,50					Output-input-coefficient for nutrient [b]:	40,00
Attainable maximal yields $[A_j]$:	50,00	90,00						
Probability of yield class $[f_j]$:	0,50	0,50						
	Yield matrix: Yields [y] in dt/ha				Expected values of yields dt/ha	Expected values of revenues €/ha	Nutrient costs €/ha	Expected values of gross margins €/ha
	50,00	90,00			70,00	840,00	105,00	735,00
Chosen action alternative: Nutrient supplies on parcel shares [dt/ha]:	1,25	2,25						
Site specific nutrient supply: Actually attainable results, given the probability distributions for the precipitation, and taking into account site specific perfect information on locations and values of field capacities:								
Attainable maximal yields $[A_j]$:	40,00	80,00	60,00	100,00				
Probability of yield class $[f_j]$:	0,25	0,25	0,25	0,25				
Chosen action alternative: Nutrient supplies on parcel shares [dt/ha]:	1,25	2,25	1,25	2,25				
Actually attainable yields [y] in dt/ha:	40,00	80,00	50,00	90,00	65,00	780,00	105,00	675,00
								ITDP06

However, contrary to the decision makers assumption, there is no constant average precipitation level over time. Given the probability distribution for the precipitation, the decision maker will only gain an expected value of the gross margin of 675,00 €/ha. The relevant computation is shown in the lower part of *table 4*. In applying the calculated nutrient supply strategy, the decision maker will only obtain an expected value for the attainable maximal yield of 65,00 instead of 70,00 dt/ha. This is mainly due to the less than sufficient nutrient supply for the sites with high field capacities in vegetation periods with high total precipitation. With a nutrient supply of 2,25 dt/ha he will only produce a yield of 90,00 dt/ha, although the amount of plant usable water would be sufficient for a yield level of 100,00 dt/ha.

As a result, the expected value of the gross margin for this site specific nutrient supply strategy is less than it would be, if the decision maker would only make use of the probability distributions of the field capacities instead of taking them directly into account (675,00 €/ha compared to 690,00 €/ha). The negative difference is even higher when the parcel specific nutrient supply strategy is employed with the closed-loop approach for fertilization (675,00 €/ha compared to 705,00 €/ha).

In other words: Ascertaining only the levels of the field capacities of the different sites of the parcel and not taking into account the variability of the precipitation levels does not lead to economic advantages over parcel specific nutrient supply strategies, taking into account probability distributions for non-controllable yield factors.

Site specific nutrient supply, however, is becoming economically superior, if the decision maker uses site specific knowledge of the field capacities and employs the closed-loop approach for fertilization. Formally, this would be decision making with perfect information. The relevant decision situation is outlined in *table 5*.

Table 5. Site and time specific nutrient supply: A-priori expected and a-posteriori attained results (the case of perfect information): Taking into account given site specific information on locations and values of field capacities, and fertilizing in a closed-loop-approach according to precipitation conditions during the vegetation periods

Precipitation:	"Low"		"High"					
Probability:	0,50		0,50				Product price [€/dt]:	12,00
Field capacity:	"Low"	"High"	"Low"	"High"			Nutrient price [€/dt]:	60,00
Probability:	0,50	0,50	0,50	0,50			Output-input-coefficient for nutrient [b]:	40,00
Attainable maximal yields [A_j]:	40,00	80,00	60,00	100,00				
Share of yield class [f_j]:	0,25	0,25	0,25	0,25				
	Yield matrix: Yields [y] in dt/ha				Expected value of yields dt/ha	Expected value of revenues €/ha	Nutrient costs €/ha	Expected value of gross margin €/ha
	40,00	80,00	60,00	100,00	70,00	840,00	105,00	735,00
Chosen action alternative: Nutrient supplies on parcel shares [dt/ha]:	1,00	2,00	1,50	2,50				
								ITDP07

Relying on the data about the precipitation level, gathered by the monitoring process during the vegetation period, and knowing the field capacities of the different sites of his parcel, the decision maker calculates the relevant nutrient supply levels to be 1,00, 2,00, 1,50, and 2,00 dt/ha for the four possible supply levels of the non-controllable yield factor plant usable water. Under these conditions he will attain an average gross margin of 735,00 €/ha for the parcel. Since, in this case, the a-priori known values for the field capacities and the total precipitation per vegetation period are identical to their a-posteriori values, the decision maker employs a strategy for which expectations and results are identical.

Of course, the attainable value of the gross margin will change from vegetation period to vegetation period, due to the time variant precipitation levels. But in the long run, the decision maker can expect an average gross margin of 735,00 €/ha, provided – of course – the a priori-assumed probabilities for the precipitation levels are identical to their future values, i. e. do not change over time.

In our example, using site as well as time specific information as a base for the derivation of proper nutrient supply strategies, leads to an economic advantage of 45,00 €/ha over the parcel specific strategy, taking into account only the probability distributions for the field capacities and the precipitation levels (735,00 €/ha compared to 690,00 €/ha). The site and time specific nutrient supply strategy has the additional advantage of wasting less nutrients leading to environmental improvements (e. g. lower nitrate concentrations in the ground water).

Beware, however, of jumping on conclusions too soon. In order to apply the site specific supply strategy, the farmer needs to make additional investments to determine the site specific field capacities and in the equipment for site specific fertilization. Only if the additional costs for these investments amount to less than 45,00 €/ha, the site specific nutrient supply strategy is – in strictly economic terms – comparatively advantageous.

Table 6 sums up the different described nutrient supply strategies and shows the connected expected values for the gross margins.

Table 6 . Nutrient supply strategies for crops, taking into account different levels of information on non-controllable yield factors

1	**Parcel specific nutrient supply strategies**	Expected value of gross margin €/ha
1.1	Provision of parcel specific nutrient supplies, determined by known parcel average yields of the past	**615**
1.2	Provision of parcel specific nutrient supplies, determined by known probability distributions of the field capacities and vegetation levels for the parcel	**690**
1.3	Provision of parcel specific nutrient supply, determined by known probability distribution of field capacities and known actual precipitation level for the vegetation period (on-line fertilization in split doses as the vegetation period proceeds	**705**
2	**Site specific nutrient supply strategies**	
2.1	Provision of site specific nutrient supplies, determined by known site specific field capacities and by known average precipitation level per vegetation period	**675**
2.2	Provision of site specific nutrient supplies, determined by known site specific field capacities and by known precipitation level for the vegetation period (the case of perfect information)	**735**

ITDP08

Conclusions

In conclusion, the simple example suggests that we should develop decision support systems which properly take into account the complexity and dynamics of the systems environment which comprise subject matter, as well as economic components. In other words: One major application of IT in agriculture will certainly be the development of knowledge-based, bio-economic models which

(i) will contain appropriate input-output-relationships as generalized production functions,
(ii) will take into account space and time variability by incorporating the relevant, non-controllable yield factors, preferably with their direct values or at least with their probability distributions, and
(iii) will contain biological and technological, as well as economic components, in order to provide effective decision support for the agricultural land users.

Obviously, such models will have to be developed by multi-disciplinary teams, comprising subject matter experts from the fields of agriculture and business management, as well as computer scientists and statisticians. In order to guarantee practical relevance and user friendliness, extension specialists and selected professional farmers should be involved in the model building process as early as possible.

As a rule, the development of a decision support model may be designed as a stepwise and iterative process. A thorough systems analysis and the establishment of a theoretical concept should lead to the prototyping of a first model version. These steps will be followed by tests on research farms and by extension specialists and farmers, as a base for model enlargements and refinements. After several model adaptations and improvements the final product will eventually be ready for the farming community.

While the marketing will typically be conducted by public or private service providers, subject matter research and model development will typically lie in the hands of university groups or specialized institutions for applied research. Since the agricultural sector, being composed of many small business entities is not able to finance these research and development efforts, funds will have to be provided through governmental agencies and research foundations, of course, based on competitive bidding and peer group reviewing of proposals.

With such models we will certainly not regain the paradise lost of decision making under certainty by way of instinctive actions, but we will eventually be able to support decisions which yield results being technically and economically less inefficient than they are usually now.

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