MODELLING AGRICULTURAL PRODUCTION

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Descriptive and explanatory models

In modelling in general and biological modelling in particular two approaches may be distinguished: a descriptive and an explanatory approach. In descriptive models the system and its behaviour are described at the same level at which the observations about it are made.

A good example are the chilling unit models that were discussed in this symposium and are used to calculate at what time the temperature demand is met to break the dormancy of buds. Another example is the statistical analysis of crop-weather relations. In the process of eliminating non-significant terms, the latter may lead to the well known regression equations that relate yield to for instance radiation, temperature and rainfall in certain months or decades of the year in linear, quadratic and cubic terms. The use of this statistical blunderbuss-approach, to borrow a term of Monteith (1981), is facilitated by the widespread availability of computers and software for the purpose. However, it remains not only clumsy, but also to a large extent uninstructive because it ignores the underlying mechanisms and their interactions and builds hardly on existing knowledge. At best the results describe observed situations, but they hardly help to organize thoughts about the possible.

The other approach is the construction of explanatory models in which the processes that occur in the system form the basis of the model. It is then not the behaviour of the system as a whole, but the underlying processes that are analysed and described. Explanatory models suggest themselves in biology because various levels of organisation are distinguished in this science. These levels may be classified according to the size of the elements that are distinguished as those of molecules, cell structures, cells, tissues, organs, individuals, populations and ecosystems. Models that are made with the objective to explain are bridges between such levels of organisation: they allow the understanding of larger systems on the basis of knowledge gained by experimentation on smaller systems. In this way the properties of membranes may be understood better by studying molecules and the properties of ecosystems by studying species.

The "blunderbuss models" are both static and descriptive, but there are also static models of the explanatory type. An example is the model of Penning de Vries et al. (1974) that contains all the necessary information to calculate the relation between respiration and growth on basis of the underlying biochemical processes. Another example are light-models that calculate the transmission, reflection and internal distribution of light by crop canopies, based on architecture, leaf properties, amount of direct and diffuse light, solar position and so on. By now, this latter family of static, explanatory models is mature in the sense that any situation ranging from a homogeneous grass cover to a planted orchard and from remote sensing to crop growth applications may be covered (Chen, 1984; Goudriaan, 1977).

Dynamic models

Such static models are often a part of dynamic, explanatory models that simulate the accumulation of biomass by a crop by considering the processes of CO_2-assimilation, respiration, assimilate partitioning and leaf formation. For each of these their dependency on environmental factors such as temperature and light and on the internal status of the crop is quantified. The internal status of the crop is then characterized by state variables such as the biomass of leaves and roots, their surface and architecture and for instance their turgidity and nitrogen content. With the model then, the rates of these processes are calculated, given the current external conditions and the internal status. The biomass that is formed during a short time interval is computed as a rate multiplied by the length of the time interval and this is added to the biomass already present. Other relevant state variables are updated at the same time and the calculations are repeated again and again until the whole growth period has been covered by this process of numerical integration.

Crop growth expressed in this way is thus explained on basis of a broad knowledge of the underlying physiological, physical and chemical processes involved and the effect of environmental factors on them. It is typical that the behaviour explained on the higher integration level and the explanatory processes are characterized by different relaxation times and often studied in different disciplines. Their use leads therefore to an integration of different fields of knowledge. One must be modest, however: only by comparing simulated results with the results of field experiments sufficient confidence may be built up to use the models for exploration of the possible.

Modelling crop production

Given the long-standing continuing interest and research on soil-water relations, potential transpiration and, later, potential assimilation, it is not surprizing that the most sophisticated, comprehensive models are available for situations where nutrients are in optimal supply and the crop is assumed to be free of pests and diseases. If in that case water is also optimally supplied, crop yield is only determined by the type of crop, the radiation and temperature. The amount of rainfall and its distribution and the soil physical and chemical conditions are then of no concern.

The intensity of radiation throughout the day, the degree of interception and utilisation of light and the efficiency of the use of energy are then key factors in the understanding of the growth rate in this situation, which is diagramitically presented in Figure 1.

Irradiation is a driving variable and its intensity is obviously not modified by the crop. The efficiency of the utilisation of light by a crop is, however, a characteristic of the plant species and canopy density and architecture. The assimilated carbohydrates, stored only temporarily in an easily accessible form like starch, are utilized for maintenance and growth. In growth processes this reserve is converted into structural biomass with a certain efficiency.

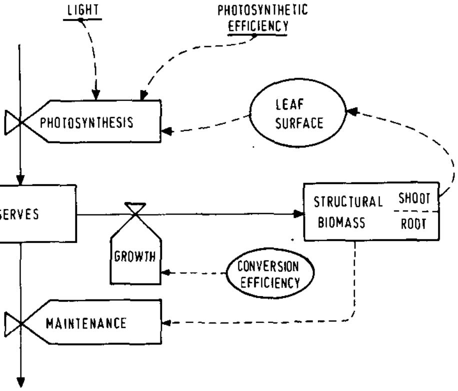

Figure 1 - A simplified relational diagram of the production situation where light is the main limiting factor. The diagram is drawn according to Forrester (1961): rectangles represent state variables, valve symbols flows, circles auxillary variables and underlined names external variables; drawn lines represent flows of materials, and broken lines flow of information (Penning de Vries, 1982).

Structural biomass in contrast with reserves consists of those components that are not easily mobilized for growth and maintenance elsewhere in the plant. The calculation of the transpiration of such closed, green crop surfaces well supplied with water is practically always done according to methods that can be traced back to the classical approach of Penman. Typically, the comprehensive explanatory models that simulate this situation operate with time steps of an hour or less. The modelling results are not only evaluated in field experiments but also with the use of special equipment that enables the continuous determination of CO_2-assimilation and transpiration under field conditions. The growth rate of the crop in terms of dry matter amounts to 150-350 kg/ha/day when the canopy fully covers the soil. In practice this situation may be reached on well drained, irrigated fields, but in general it sets a standard for the upper limit of production that can be reached, in the climate under consideration.

More often than not it appears that growth is limited by water for at least part of the time. The degree of exploitation of soil water and the efficiency of its use are then key factors, as is diagramitically illustrated in Figure 2.

Water shortage then leads to stomatal closure and to simultaneous reduction of CO_2-assimilation and transpiration. The rates of both processes are therefore closely linked and the calculation of water limited canopy transpiration is a direct route to the calculation of crop assimilation. Use is then made of a simulated water use efficiency coefficient under optimal water supply. The buffering capacity of the soil for water and the simultaneous loss of water by transpiration and by non-productive processes cause the growth rate to depend only indirectly on the rainfall. This situation may be approached in practice on non-irrigated, but properly drained and fertilized fields and the model has been extensively evaluated for this situation.

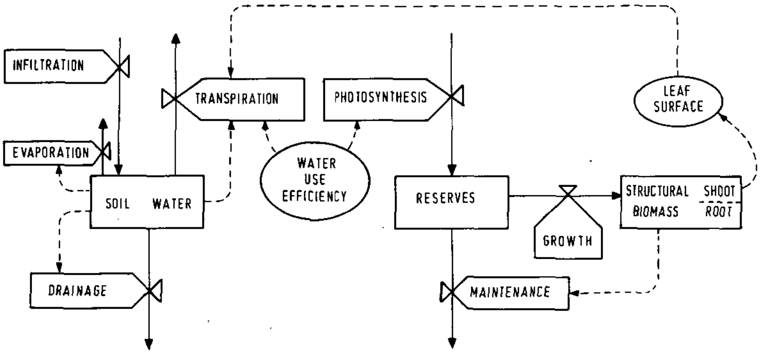

Figure 2 - A simplified relation diagram of the situation where water shortage is the main limiting factor. For use of symbols see Figure 1 (Penning de Vries, 1982).

Both production models are in summarized form used to evaluate the production possibilities of regions and to set in this way standards for development (Van Keulen and Wolf, 1985). Such models for these two production situations have also been used to estimate food production potentials on a world scale to contribute to the continuing discussion of the possibilities of food production (de Wit, 1967; Buringh et al., 1975).

There are also many production situations where the main limiting factor on growth is the supply of nutrients and then especially nitrogen, phosphate and potassium. Rather than the photosynthetic properties of the crop, the chemical properties of the soil come then to the foreground, whereas also the organic matter and nitrogen balance are emphasized. This situation is common in situations where few, if any, external inputs are used as in many forms of subsistence farming. Typical crop growth rates are then around 25 kg/ha/day.

By far the weakest feature of these production models is the simulation of assimilate partitioning among organs and the response of the plants in terms of function and morphology to their growing conditions. A breakthrough is badly needed but can only be expected if there is a renewed interest in morphonenetic problems in the biological sciences (de Wit and Penning de Vries, 1983).

The only morphogenetic aspects that are modelled by our group in explanatory fashion are the functional balance between shoot and root growth and the organogenesis of especially grasses and grain crops. The functional balance between roots and shoots is modelled according to the principle that the roots provide necessities as water, nitrogen and minerals for the shoot and the shoot carbohydrates for the roots, so that one cannot grow without the other (Brouwer and de Wit, 1968). Only in cases where there is a lack of growing organs above the ground, as with deflowered trees, the root growth may be considerable larger than is needed to maintain the above-ground growth.

In simulating organogenesis the general principle is adopted that the formation of new organs depends on the current supply of carbohydrates (van Keulen, 1982; de Wit and Penning de Vries, 1983). For instance, to simulate the vegetative growth of wheat, the average carbohydrate production during the last two to three days is divided by the number of sprouts. If the resulting figure is larger than some threshold value, new sprouts are formed, whereas sprouts are aborted when this figure is lower than this threshold. Subsequently, it is assumed that the rate of formation of ears depends on the carboxylate supply per tiller, that the spikelet formation depends on this supply per and the number of seeds per spikelet on this supply per spikelet. This continuous morphological adaptation to the current supply makes that, barring special circumstances like severe water shortage during the seedfilling stage, the simulated wheat crop ends up with the number of seeds it needs to store the carbohydrates it produces during ripening.

It may very well be that this approach is fruitful in simulating effects of fruitset and thinning in orchards. In a season without fruits to grow, the supply of carbohydrate per branch is so large that many fruit buds develop. Then next year plenty of fruits are initiated. A part of this fruit is then aborted in an early stage, because the carbohydate supply per fruit is too small. However, this abortion is too less or too late or both, since the remaining fruits appear to monopolize so much of the carbohydrate supply that too little is left for the fruit buds of the next year. Consequently no fruit buds are formed and no reserves are built up. The next year is then an off-year again, unless so much of the "parasitic" fruits are removed at an early stage that the threshold values for the fruit buds are met. Apart from this, regular thinning is needed to maintain the tree open enough to ensure a sufficient carbohydrate flow per branch.

Maintaining soil fertility: an early example of dynamic modelling

The first dynamic model in agriculture directed itself to the situation of structural nutrient shortage and then especially to the problem of maintaining and increasing the fertility of the farm. This model may be traced back to a pupil of Thaer: Carl von Wulffen. He started out to show that the problem of farm management could at that time be understood much better by leaving primitive chemistry alone and by studying in detail the dynamics of input and output of whole farms.

It is the first example of a careful system analysis in agriculture, which was made long before the term was invented. Von Wulffen's first articles were written during the many idle hours spent in the Prussian army that fought Napoleon and the end of his Russian adventure. They are difficult to read because he formulated then all relations in the clumsy terminology of Thaer. Much better is his article "Ideeen zur Grundlage einer Statik des Landbaues", which appeared in 1823 in the Mogliner Annalen and his book "Die Vorschule der Statik des Landbaues" that appeared in 1830.

For each field, Von Wulffen started out with distinguishing two quantity parameters: the yield and the "Reichtum" of the soil and one intensity parameter: the "Thätigkeit" of the soil, which he joined by the equation:

Yield = Thätigkeit x Reichtum

The Reichtum is obviously a measure of the total yielding capacity of the soil and the Thätigkeit the fraction of this Reichtum that is each year removed by the harvest. The Reichtum is therefore expressed in the same unit as the yield. The relation between yield, Reichtum and Thätigkeit in course of time is graphically presented in Figure 3 where the Reichtum in the (n+1)th year is given as a function of the Reichtum in the n-th year.

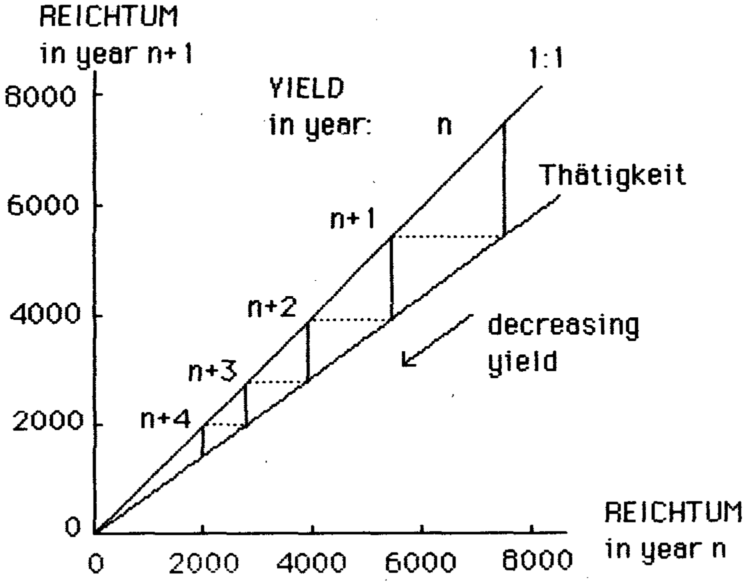

Figure 3 - A graphical presentation of the exponential decay of yield and Reichtum by cropping, according to Von Wulffen (de Wit, 1974).

In situations of zero Thätigkeit the activity line coincides with the 45 degree line, the yield is zero and the Reichtum does not change. To characterize a Thätigkeit of 0.275, a line is also drawn with a slope of 0.725. The successive yields, here starting at a Reichtum of 7 500 kg/ha may now be read by following the broke line to the origin. Obviously the yield of a field decreases exponentially to zero in situations where nothing is added to the Reichtum of the soil.

Von Wulffen showed that the Reichtum and Thätigkeit of any soil could be calculated by considering successive harvests, although the analysis was complicated by what we call now random errors. To compare crop species Von Wulffen advised to grow them together with rye and express the Reichtum then in standard rye units. In the same way the effect of species, soil type and soil cultivation on Thätigkeit could be evaluated.

The Reichtum could be increased by adding manures, by fallowing and by growing fodder crops. The amounts of these manures were not expressed in cartloads, but very sensibly as the weight of the various products that were fed to the animals that produced the manure. To cope with the problem that one soil needed more fertilizer than the other he introduced the Gattung of the soil. This Gattung was said to be one when it was possible to return to the original Reichtum of the soil by applying the manure obtained by feeding the harvest to the soil.

What are now the successive yields in the simple situation where the Thätigkeit is 0.275 and the Gattung 0.5 and when every year an amount of manure equivalent to 4 000 kg rye per hectare is given? The answer is given in Figure 4, with again the Reichtum in two successive years along the axis.

The slope of line 3 characterizes again the Thätigkeit. The yearly change of Reichtum is equal to the vertical distance between the lines 1 and 2. This distance is 2 000 kg/ha because 4 000 kg/ha manure is given and the Gattung is 0.5. The yield is then equal to the vertical distance between the lines 1 and 3 and the yearly net change in Reichtum, equal to the distance between the lines 2 and 3. Starting from a low Reichtum, there is a net increase and starting from a high Reichtum there is a net decrease. Hence from both sides an equilibrium point is approached in which the yield stabilizes at 2 000 kg/ha and the Reichtum at 5 700 kg/ha.

In Von Wulffen's view farm management had to be directed to the maintenance of this "Beharrungspunkt" on such a level that the grain yield is as high as possible without too much straw production and without running the risk of lodging. On basis of this optimization criterium, he was able to calculate for every farm the amount of grassland that was needed to provide the necessary manure to compensate for the amounts of products taken from the farm. Within this framework it was still possible to adapt to current needs or prices by managing the Thätigkeit and with this the Reichtum of the soil and the current yield level.

Von Wulffen's model is fully descriptive because the behaviour of the farm system is solely described at the same level at which the observations are being made. The merit of his approach is that he analysed the system in such a way that the necessary data base could be built by some experimentation an by careful bookkeeping of all inputs and outputs of each field and the farm as a whole. Von Wulffen's system analysis was lucid and reflected considerable common sense and this explains the existence of the many excellent farm accounts that were made in Germany up to the end of the 19th century with the main purpose to evaluate the year to year operations according to Von Wulffen's concept.

In 1956 it was already convincingly proven by Wolff in his small brochure "Die Erschöpfung des Bodens durch die Kultur" on basis of fertilizer experiments and crop analyses that under normal agricultural practice the exhaustion of the soil was in the first place due to lack of nitrogen compounds suitable for plant use. Hence, even at that time Von Wulffen's model could have been interpreted as a nitrogen model, in which the Reichtum stands for the organic nitrogen in the soil. As far as I know, this was not done. This may very well be due to the overriding influence of Von Liebig who assumed erroneously that nitrogen was obtained from the air and therefore never limiting.

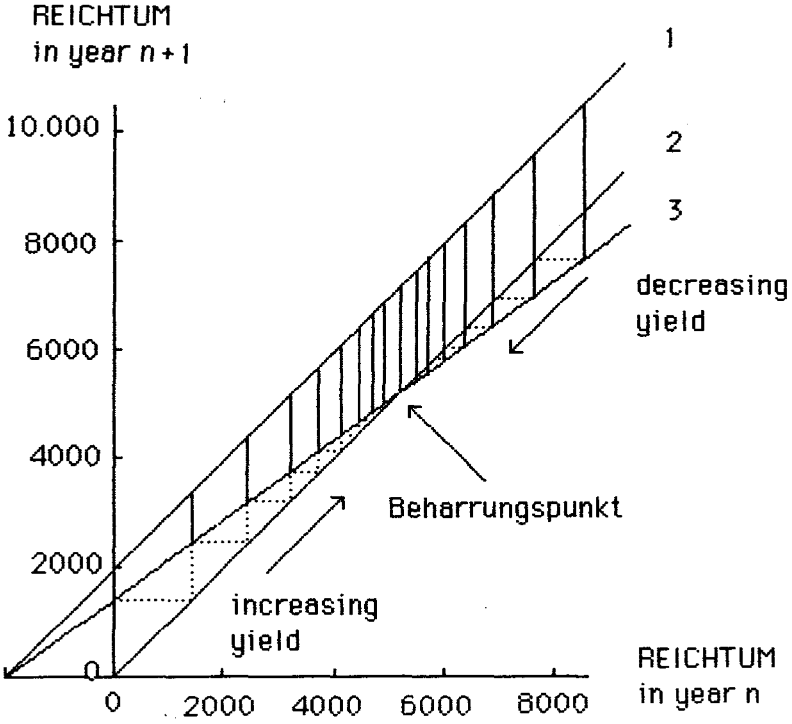

Figure 4 - A presentation of the approach to an equilibrium situation in the simple case where each year the same amount of manure is given and the same crop is grown (de Wit, 1974).

A comprehensive model of soil nitrogen

By now, the important role of nitrogen in maintaining and improving soil fertility is fully recognized and this reflects itself in an abundancy of nitrogen models which differ widely in concept and detail, depending on the ultimate goal. In a workshop on the subject in 1981 (Frissel and Van Veen) on the state of the art of he soil-physical, micro-biological, and plant physiological aspect of the fate of nitrogen in the soil-plant system, already 29 models were discussed. Some of these are of the bookkeeping type, but there are also dynamic, explanatory models in which it is tried to cover all aspects. These could be distinguished again in models with emphasis on transport processes and on the organic matter transformations.

A scheme of a model of the latter type and which concerns therefore only one layer in the soil, is presented in the relational diagram of Figure 5.

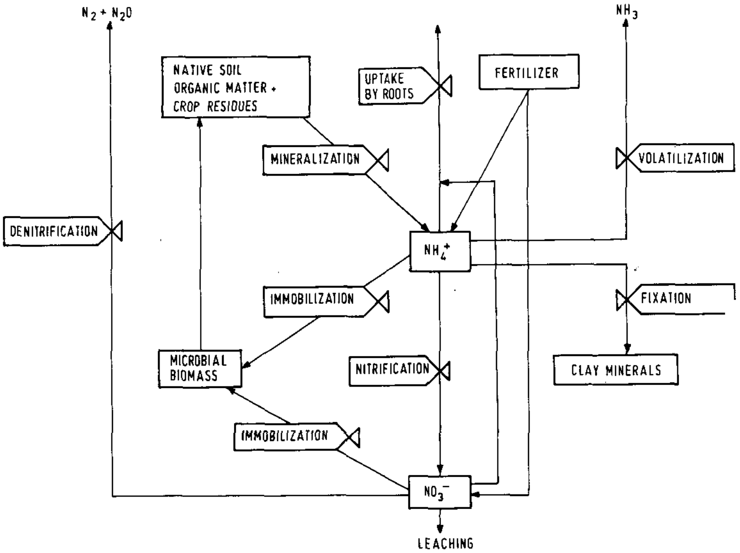

Figure 5 - A simplified relational diagram of the nitrogen model (van Veen and Frissel, 1982).

Each of the transformation processes that are presented here by the usual valve symbols are described in separate submodels, which are each of considerable complexity in case attempts are made to be explanatory and comprehensive.

For instance mineralisation and immobilization are controlled by the growth and activity of the total microbiological mass in the soil, carbon and nitrogen being growth limiting substrates. To account for the differences in availability of the organic matter compounds as substrate for micro-organisms, both plant residues and soil organic matter are divided into several components: sugars and other well decomposable carbohydrates, hemicelluloses, proteins and amino-acids, lignins and slowly decomposable microbiological debris. The microbes that live on easily available components have a fast turnover rate, whereas the microbes that grow on resistant fractions turnover slowly. The magnitudes of the growth and decay processes that are distinguished determine whether nitrogen is mineralized or immobilized and then at what rate. These processes are not only determined by the availability of the substrates, but also by factors as temperature and moisture content. The turnover rates are so large and the environmental conditions change so rapidly that submodels that go in this detail have to operate with time steps of an hour or sometimes even less.

A summary model of soil nitrogen

Comprehensive models of this kind contain a wealth of information, but are unwieldy. The use of them is mainly restricted to making simulations runs for evaluating and identifying gaps in our knowledge, for sensitivity analyses and for guiding experimentation. Although some of them are well documented and elements out of them widely used, their use as such is mainly restricted to the group that developed them and their efforts are in the longer run only fruitful if parallel-wise summary models are developed. These models retain much of the scientific base and quality of the original but are much easier to apply, especially by those who did not develop them. The simplification practically always starts with a reduction and much better specification of the aims of the model, so that depending on these, a number of summary models may evolve from one comprehensive model. For nitrogen summary models are especially developed for two purposes. The first is the management of nitrogen fertilizer throughout the season to promote its efficient use and the other is the long term management of nitrogen fertilization to maintain and improve soil fertility.

The latter summary models are operated over a number of years, so that they are often set up in such a way that they can operate with time intervals of a year. It appears then that they have much in common with the model of Von Wulffen. Instead of Thätigkeit and Gattung, coefficients of nitrogen transfer and nitrogen loss are considered, whereas instead of one Reichtum, two organic pools of nitrogen are distinguished: one in labile and young organic matter and the other in a more stable form of organic matter. Even the simplest of these models require still close to ten parameters. These are the transfer coefficients between the labile and stable pool, the rate of mineralisation of the labile pool, the relative uptake of mineralized nitrogen by the crop and the relative losses by leading, volatisation and denitrification of this nitrogen. And then of course estimates of the amounts of nitrogen in both pools to begin with.

A part of these coefficients are derived from operating the appropriate comprehensive submodel fur the situation at hand. To this extent the summary model is of the explanatory type. However, there remain at present always some coefficients that have to be estimated by adapting the modelling results to the field data that are to be understood and to this extent the model is still descriptive.

The nitrogen models can be linked with the production models that were discussed before. These production models allow to set reasonable target yields and from these the crop need for nitrogen is calculated. This amount of nitrogen has to be taken up from soil and fertilizer. The amount that is taken up from the soil is then derived from the size of the labile pool and this amount is substracted from the total. By dividing the remaining amount with the recovery of nitrogen, the fertilizer rate which is needed to reach the target yield is calculated. The recovery percentage is typically 50 percent, but experimental evidence or simulations with comprehensive models may lead to larger or lower percentages. The soil water content and the rate of water leaching as obtained from the production models is also used as an input. It is then simulated how much of the applied fertilizer may be lost in the year of application by volatisation, denitrification and leaching and how much ends up in the labile organic nitrogen pool. This latter nitrogen leads to a higher availability in the next year and hence to a lower need for fertilizer. This goes on until the dynamic equilibrium situation, the Beharrungspunkt, is reached.

The dynamic behaviour of these summary models with the purpose of strategic management is to such an extent similar to the dynamic behaviour of Von Wulffen's model, that, albeit with some adaptations, the latter is still useful in situations where one has to operate with a minimum of information.

Weeds, pests and diseases

Weeds, pests and diseases may occur in any production situation. Well verified comprehensive models have been developed in Wageningen for epidemics of pests (aphids), diseases (rusts) and weed (annuals) (Rijsdijk, 1985; Rabbinge, 1982; Rabbinge and Carter, 1983). These have drawn attention to the fact that damage depends very much on the production situation. As a result of an increased competitive ability of the crop, damage by weeds may decrease relatively with increasing yields. For aphids the reverse is, however, true because the value of the host plant as a source of foods to the aphids increases with increasing yields.

Upon the initiative of Prof. Zadoks models have been developed for damage-control management on a field by field basis. For each field basic data are stored in a data bank. Farmers send in their own field observations from which the basic field data are updated by means of the models. Expected damage and loss are calculated and used in a decision system that leads to one of the three decisions: "treat", "do not treat" or "make another round of field observations at some later, specified date".

This system of integrated control ("Epipre") has been adopted for the management of wheat by the extension service in the Netherlands and is used by the farmers to a satisfactory extent. It leads to a much more conscious application and therefore less use of biocides at the same low damage level as is obtained with spraying according to the calendar. All evidence suggests that such supervised disease, pests and weed management systems are gaining in importance.

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