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MAKING PREDICTIONS ABOUT FARMING

The theory of production ecology, applied in computer models, traces interactions between crops and their environments.

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▲ Thaer and von Wulffen
German pioneers of agricultural science, Albrecht Thaer and his pupil Carl von Wulffen, are commemorated in Hugo Hagen's bas-relief from a war-damaged statue of Thaer, now conserved at East Berlin's Humboldt University. According to Hans-Heinrich Stamer (Bad Freienwalde) Thaer is towards the right; von Wulffen is left of centre holding a lupin, a crop that he introduced from Grenoble in France for improving light soils.

Good harvests are rare in the famine belt of Africa but commonplace in Europe, where the main problem is now overproduction, due to the European Community's farming policy and the successes of agricultural science. Yet even in Europe in the 1980s, the farmer who wants to earn a reasonable living is just as preoccupied as his grandfather was, with the productivity of his land. A host of factors can reduce yields or increase costs, as compared with the optimum he is driving at. For example, too little fertilizer results in loss of production, while applying too much wastes money and effort, and causes pollution.

Production ecologists analyse the interactions of factors in complex living systems, in order to advise the farmers how to achieve high production with moderate inputs. Their chief tool is systems dynamics, whereby crops and the factors affecting their performance are simulated in computer models which are rich in mathematical relationships and feedback loops that reflect fundamental growth processes. During the past 20 years, the Wageningen Agricultural University has developed this technique with some success. The idea of dynamic modelling in agriculture is, though, far older than the electronic computer.

Early Concepts

After Napoleon's retreat from Moscow in 1812, his Prussian allies defected and joined with the Russians in fighting the *Grande Armée*. Faced with more tedium than action, a Prussian officer named Carl von Wulffen passed his idle hours in thinking about the dynamics of farming on his estate. He was a pupil of the famous Albrecht Thaer, one of the pioneers of scientific approaches to agriculture. Von Wulffen's dynamic approach became very popular among German land owners, who kept their books and evaluated their operations, field by field and year by year, according to his concepts.

Von Wulffen addressed the question of how to optimize soil fertility by distinguishing three parameters for quantity, intensity and efficiency. In his analyses, the yield from a field is a certain fraction of its total fertility (*Reichtum*) and this fraction (*Thätigkeit*) is a measure of the intensity of the agricultural operation. Unless manure is applied, a succession of crops will exhaust the soil (*ill. 3*). One of his insights was that manure should not be reckoned in cartloads of dung, but in terms of the amount of food consumed by the herd of animals that produced it. This made it possible to characterize each combination of soil and manure by an index, *Gattung*, according to the efficiency of the use of manure. This *Gattung* is set at 1 if the fertility of a field is maintained at its original level when the whole of its yield is fed to a herd and the manure that is then produced is returned to the field. The parameters were derived by recording the inputs and outputs of each field, and then used to calculate how much pasture was needed to produce the necessary manure to reach and sustain the yield at the desired *Beharrungspunkt* (*ill. 4*).

Von Wulffen's model still works today. His *Reichtum* translates into reserves of nitrogen in the soil, and his *Thätigkeit* and *Gattung* into coefficients for the uptake of nitrogen by the crop and the loss of nitrogen from the soil by other processes; the manure may be complemented by industrial nitrogen fertilizers. Comprehensive models are being constructed in which the organic matter, the processes of nitrogen transfer, the roles of microbes and the effects of water are taken into account, but for field use these are condensed into 'summary' models that are very much like von Wulffen's, and give answers to the same old questions.

Explanatory Models

Although nitrogen looms large in contemporary analyses, many other factors affect crop production. They range through all levels of description and explanation in biology: molecules, cell components, cells, tissues, organs, individual plants, populations of plants, and ecosystems. The last of these embrace factors such as weather, soil-water relations and soil chemistry. Computers sometimes encourage what has been called 'the statistical blunderbuss approach' (Monteith), where crop yields are numerically related to various factors, without any explanatory insight. However, to organize one's thoughts about the possible, and to make predictions, with some confidence, models have to explain and not merely describe what occurs.

Explanatory models do not need to be dynamic. There are static models that describe, for example, the flow of light through a crop, taking account of the transmission and reflection of leaves, and the architecture of the crop canopy. Giving light-response curves for single leaves, these models are widely used to calculate the potential photosynthesis of crop surfaces, whether of wheat or of natural forests. They also find application in remote sensing.

Explanatory dynamic models of crop growth simulate the accumulation of biomass on the farmer's field, by computing the interplay of carbon-dioxide uptake, respiration, partitioning of carbohydrates, and leaf formation. Each of these varies with environmental factors such as temperature and light, and with internal factors such as the biomass, the architecture of leaves and roots, and their nitrogen content. The biomass that forms during a short interval of time is computed and added to the biomass already present; other variables are updated in a similar way. These calculations are repeated again and again for the whole season's growth. Expressing crop growth in this way integrates our knowledge of physiological, physical and chemical processes, and the effects of environmental factors. By comparing simulations with field

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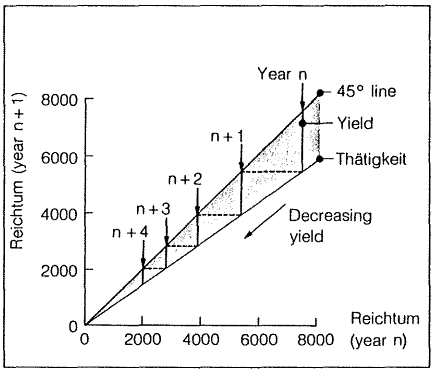
1, 2. **African contrasts**
While plant breeders in Mali (1) seek higher yields of millet, some traditional farming methods can be counterproductive. Burning the forest (2) clears the ground for sowing or grazing, but valuable nitrogen is lost from the system. Even in drought-prone areas, lack of nitrogen or other nutrients may be the main factor limiting crop yields.



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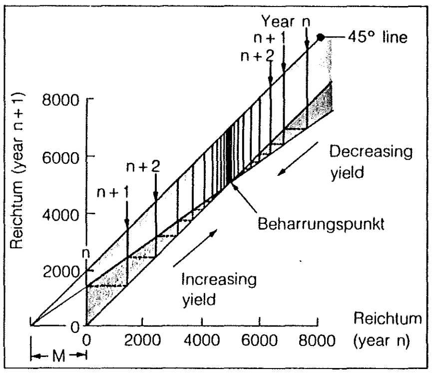

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3, 4. **Yields on a staircase**
Carl von Wulffen assumed that the soil contains a certain amount of *Reichtum* which, without manure, diminishes from year to year (3) by an amount equal to the yield. The yields decrease rapidly in successive years, as shown by the vertical distances between a 45-degree slope and another line that characterizes the *Thätigkeit* or coefficient of utilization. With manure (4) the lines are shifted to the left by a distance M, which reflects the quantity of manure added each year. The 45-degree line is shifted upwards by the same distance M, representing the increase in *Reichtum* due to manuring. If the initial yield is larger than M, it decreases until equilibrium is achieved at the *Beharrungspunkt*. Applied to a soil with little *Reichtum* and low yields, manuring carries them both up the staircase to the same *Beharrungspunkt*. These nineteenth-century concepts are still valid today.

experiments, confidence grows in the use of the models for exploring and predicting what would happen in novel situations.

Modelling Crop Production

The analyses distinguish between three groups of factors that affect production: climatic factors, which are beyond control of the farmer and determine potential production; factors like water and nutrients, by which the growth of a crop can be modified; and factors like weeds, pests and diseases, which reduce the yields.

At the level where nutrients and water are in optimal supply and crop yields are not reduced, the key factors for understanding the crop growth rate are the temperature, the intensity of solar radiation, the development pattern of the crop, and its efficiency in capturing and using the light to make carbohydrates. These are temporarily stored in forms such as starch, but subsequently they are used both in maintaining life and for growth. In the latter case, carbohydrates are converted into structural biomass.

In ideal conditions, the light-limited growth rate amounts to 150-350 kilograms of dry matter per hectare per day. The crop yields depend on the length of time for which the crop maintains its full growth rate. A top scorer is sugar cane, which may yield over 100,000 kg of dry biomass per hectare by combining growth rates of over 300 kg/ha/day with a growing period of a full year. A good maize crop may grow for 4 months at the ideal growth rate, and yield 20,000 kg/ha of shelled maize and the same amount of straw. The seed produced is sufficient to meet the calorie needs of more than 60 persons for a whole year. Wheat and rice may have a period of full growth of 100 days, but their potential growth rate is less, so that their maximum yield is only a little over 10,000 kg/ha of grain. This is still very high, compared with 1000-2000 kg/ha typical in von Wulffen's time.

In the 1960s, these calculated light-limited yields met with considerable scepticism, but they have been confirmed for the main crops by means of field experiments and photosynthesis measurements in the open (*ill. 7*). Of course, in less suitable conditions the light-limited production is lower, but the purpose of these calculations is precisely to identify the other limiting factors, as a first step towards guiding development planning.

Yields are often lower than the crops' potential because the crops are short of water for at least part of the season. Access to soil water and the efficiency of its use then become important factors. A plant short of water closes the stomata (pores) in its leaves. This reduces loss of water by transpiration but also cuts the supply of carbon dioxide. Calculations of photosynthesis and growth can therefore be based on calculations of transpiration as developed 40 years ago in the United Kingdom (Penman at Rothamsted). Water-limited models developed on these principles have been validated in various situations. It appears that animal husbandry prevails over crop-raising where water-limited biomass yields are less than one-fifth of the light-limited yields; in these situations, the risk that crops will fail to set seed is too great.

Since 1945, yields have been increasing by a few per cent per year in Western Europe and the United States, but there still appears to be a considerable margin for further gains. In developing countries yields are typically only one-tenth of the potential, and these yields cannot be improved unless the shortage of plant nutrients is made good. This appears to hold also in semi-arid regions like the Sahel, at the southern edge of the Sahara. Here, lack of water reduces the period of growth to about three months in the year (as does lack of heat in high latitudes). During the wet season in the Sahel, however, the growth of the crop and the pastures is limited by low soil fertility rather than by water. The nomadic forms of animal husbandry can be understood only if this salient fact is recognized (*ill. 8*).

The global lack of soil fertility favours a strategy for feeding the growing number of people in the world by better fertilizing of existing agricultural land, rather than by reclaiming more and more land at the expense of humid rain forests and other fragile ecosystems. Mathematical modelling appears indispensable for developing such strategies, because it reduces the need for lengthy and costly field experiments.

Pests, Diseases and Weeds

Comprehensive models of the interaction between the growth of crops and the activities of pests, diseases and weeds are also being developed from basic principles and verified under field conditions. These reveal the extent to which a vigorous crop competes better with weeds on the one hand, but on the other hand encourages aphids to thrive better. The models also show that ripening diseases like rust are less harmful in low-yielding situations, where the leaves of the crop die prematurely in any case, for lack of nutrients.


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5, 6. **Limits to growth**
Lack of light or low temperatures curtail crop production in Europe in winter, and Irish sugar-beet farmers sow early (5) to benefit from long summer days. In Mali in tropical Africa, light and warmth are plentiful throughout the year, but rainfall often limits the growing season (6).


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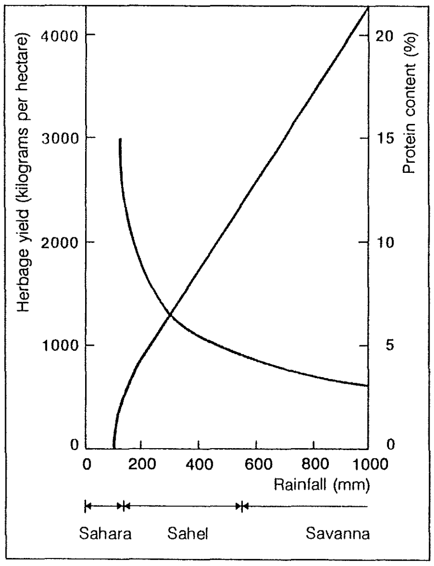
7. **Measuring growth**
A Dutch agricultural scientist uses temporary plastic enclosures to measure a crop's rates of photosynthesis (carbon-dioxide assimilation) and transpiration (water vapour leaving the crop). Data logged in the van show how these rates vary with light, temperature, and the available carbon dioxide.

8. **Paradox of the Sahel**
Analysis by Dutch scientists sheds light on the problems at the edge of the Sahara. Desert vegetation is sparse (green curve) but rich in protein (blue curve). In the rainy season, cattle of the Sahel graze a very wide area at the 200-millimetre rainfall line, and gain in weight and numbers. Damage occurs in the dry season, when the cattle crowd at the better-watered 500-millimetre line, where soil fertility limits the quantity and quality of the pasture.



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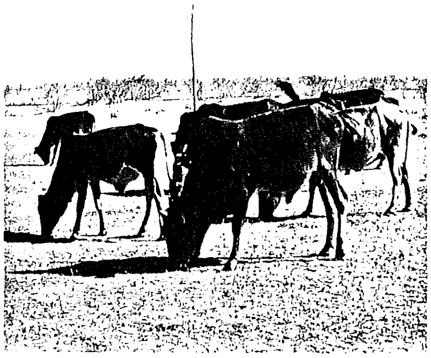

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9. **Vanishing vegetation**
The southward migration of cattle in the dry season, in the African Sahel, is halted at the edge of farmed land. Much low-quality vegetation has to be burnt to produce a little food of higher quality for maintaining the herds. Recommended remedies aim at increasing soil fertility with legumes and locally-mined phosphates, and the integration of arable farming and animal husbandry.

Summary versions of these models serve in developing methods for integrated damage control. For this purpose, information on farmers' fields is stored in a data bank, and when the farmers send in current observations, the models update the situation in each field and calculate expected damage and loss. The results lead to one of the three possible decisions: treat, do not treat, or make another round of field observations later. The extension service in The Netherlands has adopted this system (Epipre) for the management of wheat. The farmers served by it make more considered and therefore more moderate use of biocidal sprays. Such management systems for pests, diseases, and weeds are gaining in importance, not least for minimizing harm to farmers, crops and environments by agricultural chemicals.

Limits Of Knowledge

Ultimately the modeller reaches the limits set by ignorance of basic biological processes. This is most conspicuous in the case of the development and morphogenesis of growing plants. So far two morphogenetic aspects are modelled in a rudimentary explanatory fashion. One, the balance between shoots and roots, is modelled on the general principle that shoots need water and nutrients provided by the roots, while the roots need carbohydrates from the shoots; the one cannot grow without the other.

Sprouting in wheat and rice is simulated on the assumption of 'apical dominance'. For this purpose, the average carbohydrate production during the previous two or three days is divided by the number of existing sprouts: new sprouts are formed if this quotient is larger than a threshold value, whereas sprouts are aborted if it is smaller. Subsequently the rate of formation of ears is assumed to depend on the carbohydrate supply per surviving sprout, spikelet formation on the supply per ear, and seed formation on the supply per spikelet. By this continuous adaptation to circumstances, the simulated wheat crop ends up with about the number of seeds it needs to store the carbohydrates during ripening. This simple scheme works reasonably well, provided that enough data on the crop variety are available to estimate the threshold values.

The formation of leaf area is calculated simply by multiplying weight growth by the 'specific leaf area', which is derived from field experiments. It is well known, however, that the growth of weight and area in leaves are, within certain limits, independent of each other, so that specific leaf area should be an outcome of the simulation rather than a driving input. To do better, a breakthrough in the knowledge of morphogenesis is badly needed, but up to now neither whole-plant physiology nor molecular biology has been of much help.

This illustrates once again the eclectic nature of systems analysis. Von Wulffen, nearly two centuries ago, could help farmers to deal with questions of soil fertility long before nitrogen came to be recognized as the key agent. Similarly, we do what we can within the limits of knowledge of the biological sciences. As this knowledge grows, we can look forward to models of increasing power and sophistication, that will weave a web of explanation reaching down from the intricate ecosystems of the world's fields and forests, to the actions of individual genes.

ILLUSTRATION CREDITS

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