1.4 Coordination of models

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1.4.1 Necessity of coordination

The main processes and phenomena that are considered in this textbook are schematically presented in Figure 8. They all centre around the plant, but they are nevertheless related to various fields of knowledge that have been developed rather independently of each other, for example plant physiology, biochemistry, meteorology, population dynamics, soil science and soil biology. Crop models that attempt to simulate crop growth under field conditions contain important elements of these fields of knowledge. These disciplines are thus interrelated in one way or another and they should be considered together at some stage of the modelling effort.

The existence of these interrelations poses problems of coordination between and within disciplines, certainly at the present stage of knowledge and modelling. Those coordination problems cannot be treated in any way exhaustively, so that a more pragmatic introduction must suffice here.

1.4.2 Linkage of submodels

A model may be built out of submodels that originate in different disciplines. Each may describe different parts of the system, which are often connected on only a few characteristic points. The connections may often be severed without affecting the integrity of the submodels. Such models may be developed and used on their own. The only thing that has to be done is to replace the effect of the eliminated submodel by some forcing functions.

A model of an insect that feeds on plants, and makes in the process holes in the leaves, is an examоle. The insect and the plant model may be developed independently of each other by supplying the model-insect with varying amounts of food and damaging the leaves of the model-plant with varying numbers of holes. Linkage may then be achieved at any time by transposing the consumption rate of insects into a rate of increase of the number of holes in the leaves and equalizing the mass of food available for the insect to the leaf-mass of the plant. Section 6.1 provides an example. Models of the uptake of water by plants from soil are another example. The effect of the soil model on the plant model may be replaced by a forcing function of the soil water tension around the roots and the effect of the plant model on the soil model by a forcing function of the uptake of water.

Since submodels out of various disciplines operate to a large extent independently of each other there is no reason at all to elaborate them to what is con-

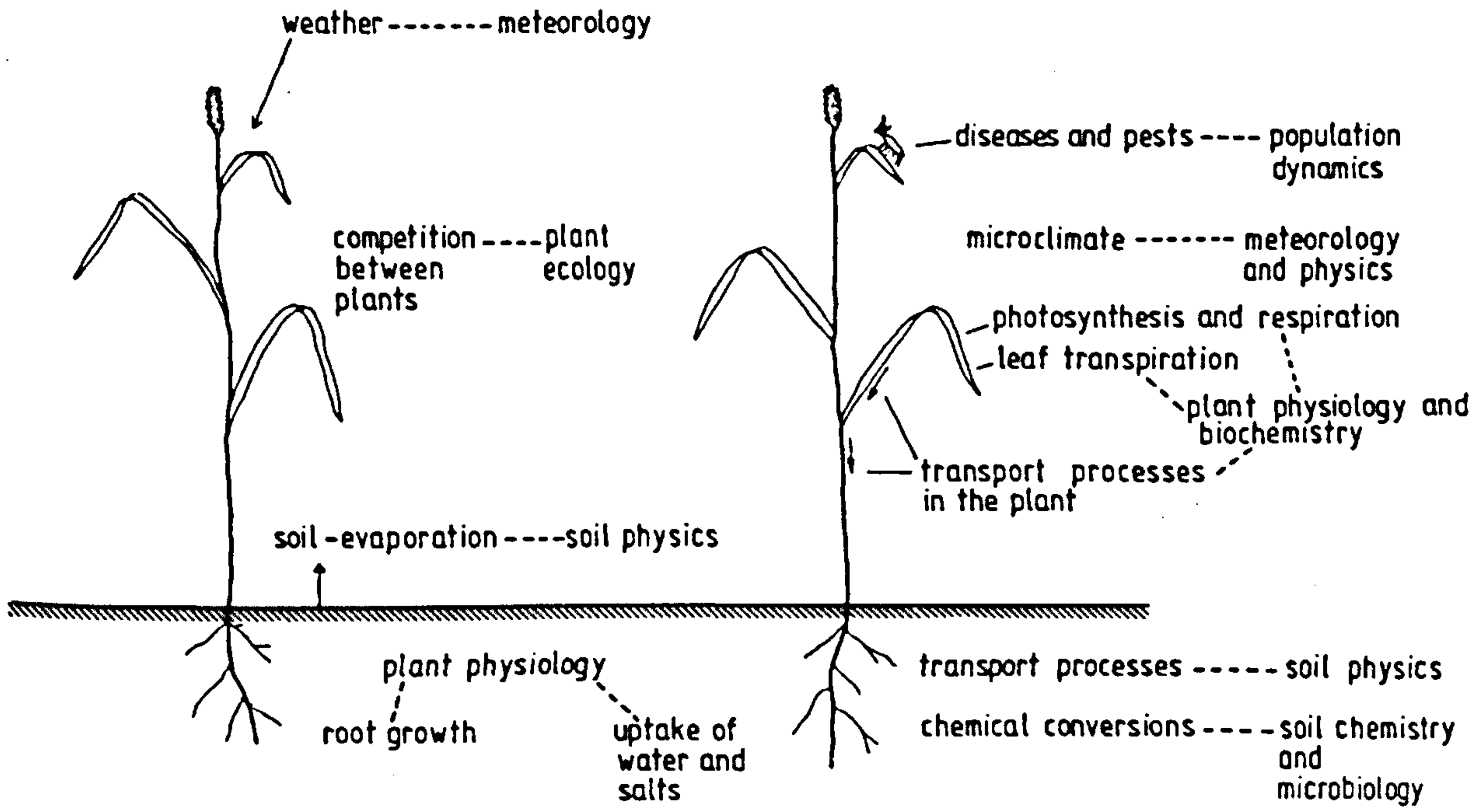

Figure 8. Fields of knowledge that need consideration in a study of plant growth.

sidered a comparative level of detail. Depending on the focus of interest, the insect model or the soil model may be worked out and the plant model may be treated elementary, or vica versa.

Preliminary, comprehensive and summary submodels may be intertwined. With respect to each other, submodels are ordered in a parallel or serial fashion. The main problem is often the maintenance of lucidity. This is facilitated by the use of higher order programming languages that allow a conceptual presentation of the model, since the language itself takes care of the construction of a proper algorithm. A well known example of such a language is Continuous Systems Modeling Program (CSMP), which will be discussed in Sections 2.2 and 2.3.

The simplest form of linkage occurs when one submodel provides an output that is used as input for another submodel, there being no effect of the latter on the former. The models can then be executed independently of each other, the first model generates data that are used as parameters or tabulated functions in the second model. The advantage is obvious. Once correct, the first model does not have to be executed again during simulation with the second model.

An example of such a uni-directional linkage between models was presented previously in Subsection 1.2.3. There the model for the first production level – optimal water and nutrients – provides the input data for the model of the second production level – optimal nutrients, but at times water shortage. Likewise, the results of a macrometeorological model may be used directly as an input for a micrometeorological model.

In the latter case there is obviously a weak feedback of the micrometeorological situation in the field under consideration to the macrometeorological situation, but the complexity of the interrelations is greatly reduced by neglecting this. Such a neglect of weak feedbacks is especially justified in situations where there is a lack of knowledge or little interest in details. The ease of handling and operation of the whole then often outweighs whatever may be gained by purism. Unfortunately, rules of thumb for this type of simplification cannot be given – it is a question of common sense and experience.

1.4.3 Hierarchical nesting

As has been said in Subsection 1.1.2, an inherent feature of biological sciences is the conceptualization of complex systems in organizational levels: molecules, organellas, cells, organs, plants, populations and communities. This conceptualization is the starting point for the distinction of explanatory and descriptive models. In the explanatory approach, the processes that are recognized at the lower organizational level are incorporated in a model that aims at understanding the phenomena at a higher level. Here again submodels may be used, for instance to represent leaves, cells, stomatal behaviour or the photosynthesis process. These submodels are then, however, not so much ordered with respect to each other in parallel or serial fashion, but are what may be called hierarchically nested: models on the higher organizational level envelop those on the lower level, like a leaf envelops its cells.

The lower and the more hierarchically nested an organizational level is, the more numerous and smaller its elements are. A crop may consist out of a hundred thousand plants, which have together millions of leaves and billions of cells. This problem of excessive numbers may be overcome by lumping plants in size classes, leaves in position classes and cells according to their function. But this lumping does not overcome the problem of size: cells remain small and respond therefore rapidly to changing conditions.

As has been said in Section 1.1, small time coefficients or response times of processes lead to small time intervals of integration and these may lead to serious problems in growth models. For instance a growing plant may recover within a week or so from pruning part of the root system, whereas stomatal cells that govern the water loss of the leaves may open or close in minutes. Hence, a crop physiologist who develops a simulation program is likely to work with time intervals of integration in the order of days, whereas a stomatologist works with time intervals of less than a minute. As long as both work separately, there is no problem. The time interval of integration for the stomatologist is large enough to execute his program for an hour and the time interval of integration for the crop physiologist is large enough to execute his program for a month.

The problem starts when the crop physiologist discovers that the program of the stomatologist is useful to him and he incorporates it as a submodel in his simulation program. He creates then a situation where he has to integrate with time intervals of a minute over a period of a month. Hence all his rates, also those who change rather slowly, have to be calculated every minute or so and this leads to excessive number crunching. A stomatologist trying to incorporate molecular submodels in his simulation program would meet the same difficulty and the crop physiologist who would then try to incorporate this stomatal model in his crop growth program would have to face the problem squared.

Any simulation program that spans response times that are orders of magnitude different contains this so-called stiff-equation problem. At least when it is executed on a digital computer. With analog computers the problem does not exist because in them all integrations are physically executed in truly parallel fashion, as in real life. Obviously the problem has to be avoided in simulation programs that are executed on digital computers by restricting the number of hierarchical levels that are incorporated into one simulation program or, what amounts to the same, by limiting the range of response times within the same simulation program.

1.4.4 The time interval of integration in crop growth models

One of the key variables in any crop model is the relative growth rate. This rate may amount to 0.25 kg kg^{-1} d^{-1} or to formulate it otherwise, the time coefficient of growth is about 1/0.25 = 4 d. It appears in practice (see Section 2.1) that a time interval of integration of about 1/4 of the time coefficient, in this case 1 day, is often small enough to justify the assumption that the rate of growth does not change materially over this time interval. Hence in this case 150 integration steps would be sufficient to cover a crop growth period of 150 days.

Indeed, quite a number of crop simulators that emphasize growth use daily time intervals of integration. But one fundamental problem with all these is that the diurnal course of the meteorological forcing functions, especially irradiation and temperature cannot be handled satisfactorily. This course is, however, accounted for in sufficient detail with time intervals of an hour; their use leads to $24 \times 150 = 3600$ time intervals of integration. As will be shown later, computers are fast and their use is generally cheap enough to make this a manageable number. But is this time interval acceptable for the crop physiologist who aims at the construction of a process-oriented model that explains at least in part the phenomena at the crop level? This appears to depend to a large extent on the possibility to simulate the water status of the crop with this time interval of integration, because this status determines many important physiological processes of growth, transpiration and water-uptake.

The water content of a crop may be 5 kg m^{-2}; a 10 percent difference in relative water content being the difference between full turgidity and permanent wilting. The transpiration of this crop in the full sun may amount to 0.5 kg m^{-2} h^{-1} and this leads to a first estimate of the time coefficient of the process of dessication of (0.5 kg m^{-2})/(0.5 kg m^{-2} h^{-1}) = 1 h. A time interval of integration of this length could therefore violate severely the assumption of constancy of the relative water content over this period. In practice it appears that the time interval of integration should not exceed 0.1 h, because growth and stomatal opening respond to difference in relative water content of a few percent. The resulting number of integration steps is then 240 per day. This appears acceptable for simulation programs that cover a few days and that are centered around the analyses of the diurnal course of growth. However the number appears to be prohibitive for simulation programs that cover the whole period of growth, especially when these are used for routine purposes.

Sacrificing the simulation of the relative water content in a reasonable way means sacrificing a process-oriented description of many of the growth processes and therefore it is worthwhile to investigate possibilities of tracking dynamically this water content, without using small time intervals of integration. One possibility is to compute the water content every hour in an interactive fashion. This is done by assuming that the relative water content is the same as in the previous hour and to calculate on the basis of this assumption the stomatal opening, the rate of transpiration by the leaves and the rate of water uptake by the roots. When these calculated rates differ the water content is adjusted by iteration until both are sufficiently equal. This equilibrium water content is then also used for all other rate calculations and serves again as the first estimate for the next interval of integration. Examples are given in the Subsections 2.3.4 and 3.3.7.

It may be feasable to handle a few other phenomena in similar fashion, but by and large it must be concluded that the inclusion of processes that require shorter time intervals of integration than considered here is practically impossible.

This holds also for such a central process as leaf CO_2 assimilation. Much is known about the biochemistry of the process, but incorporating this knowledge into crop simulation programs would require time intervals of integration that are an order of magnitude smaller than feasable because the concentration of intermediates and mediating enzymes may respond very rapidly to changing conditions. These small time intervals are then avoided by using strictly descriptive functions of the relation between CO_2 assimilation and light intensity on the leaf level. Of course it becomes then very difficult to incorporate adaptive phenomena into the simulation program, like for instance the transition of sun into shade leaves. These descriptive functions on the leaf level are either obtained by experiment or generated in their turn by a leaf CO_2-assimilation model on a biochemical basis. This model provides then basic parameters for the simulation program and in this respect the treatment does not distinguish itself from those other uni-directional linked submodels.

One other remark should be made. When a modeller reduces the time interval of integration of his model to improve on the simulation of a process, with a short time coefficient he should realize that this does not imply that the simulation of the time course of other processes improves automatically. For instance, by adding a submodel that simulates properly the behaviour of stomates with time intervals of minutes to a crop growth model, based on 1 h time steps, the simulation of growth and respiration processes has not been refined: although the computation of such rates occurs then more frequently, the model still implies a direct link of the carbohydrate reserve level to the rate of growth (Subsection 3.3.4), whereas it is in fact an indirect link that takes some time to establish. Obviously the degree of accuracy of simulation of a process does not increase by decreasing the time interval of integration to below about one-quarter of the corresponding time coefficient.