Root, shoot and soil parameters required for process-oriented models of crop growth limited by water or nutrients

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Abstract

A review is given of the prospects for using process-oriented models of water and nutrient uptake in improving ‘integrated agriculture’. Government-imposed restrictions on the use of external inputs will increase the likelihood of (temporary) nutrient or water stress in crop production in NW Europe and thus a better understanding is required of shoot-root-soil interactions than presently available. In modelling nutrient and water uptake, three approaches are possible: 1) models-without-roots, based on empirically derived efficiency ratios for uptake of available resources, 2) models evaluating the uptake potential of root systems as actually found in the field and 3) models which also aim at a prediction of root development as influenced by interactions with environmental factors. For the second type of models the major underlying processes are known and research can concentrate on model refinement on the one hand and practical application on the other. The main parameters required for such models are discussed and examples are given of practical applications. For the third type of models quantification of processes known only qualitatively is urgently needed.

Introduction

The tradition of root ecological research in the Netherlands dates back to the beginning of the 20th Century (Maschhaupt, 1915). Although concepts (Greenwood et al., 1985; Schuurman, 1983; Van Noordwijk and De Willigen, 1987; Wiersum, 1962) as well as methods (Schuurman and Goedewaagen, 1971; Van Noordwijk, 1987) of root research have shown considerable development since then, knowledge of root growth and function is not often applied directly to farm management. Farm operations such as choice of crops and cultivars, type and amount of fertilizer applied at a specific time and place, soil tillage, drainage and irrigation are still largely guided by empirical evidence of yield effects or by management models in which empirically derived water or nutrient uptake efficiencies (output/input ratios) are used. This category of models can be designated as ‘models-without-roots’. Research aimed at avoiding nutrient and water limitations to crop production could progress without detailed description of the plant response to such limitations, as long as the environmental effects of excess applications were disregarded. Presently, a much sharper identification of the transition zone between insufficient and surplus is required as environmental problems are not restricted to situations of a real excess, but start within the range of soil nutrient levels required for near-maximum crop production (Neeteson et al., 1989; Van Noordwijk et al., 1990). This is certainly the case when the spatial heterogeneity of agricultural fields is taken into account (Van Noordwijk and Wadman, 1992). Instead of aiming at a complete avoidance of ‘stress’ conditions, farm management in ‘integrated’ agricultural systems will be directed at minimizing losses of yield and crop quality while keeping environmental side-effects at acceptable levels. The increasing concern
for environmental consequences of farm management operations thus requires a more complete understanding of crop performance. Periods with restricted availability of nutrients or water, competition between crop plants and weeds, incomplete elimination of pests and diseases will be difficult to avoid in ‘integrated’ agricultural systems. If we are to take full advantage of the plasticity of the crop’s developmental and physiological processes, improved understanding is needed of plants and crops as self-regulatory systems. Until now much effort has been put into the study of single factors, a logical choice as all single factors should be at a nonrestrictive level in order to reach maximum yields. In a multiplicative model, maximum yield is only achieved if all reduction factors (defined to be in the range 0 to 1.0) are 1.0. If final yields of, say, 90% of the maximum are acceptable, a large number of solutions exist (e.g. 1.0 × 0.95 × 0.95, 1.0 × 0.9 × 1.0 or 0.965 × 0.965) when a multiplicative model with more factors is involved. To optimize crop productions systems operating well below the maximum yield, a more complete understanding of interactions and trade-off’s between production factors is required. Future management systems, based on simplified versions of process-oriented models, will require crop- and site-specific information, either from easily operated monitoring equipment, or from accurate databases. Apart from the need for accurate input data, however, a bottleneck is formed by a lack of sufficiently validated, process-oriented models of uptake processes, based on operationally defined parameters.

In this paper, we will review recent achievements in modelling crop performance aimed at improving decisions on farm operations. The knowledge required, as well as experimental data for parametrization of models of root growth and function, will be discussed. The complexity of the models required in relation to the actual problem to be solved will be dealt with, giving some examples of using knowledge on root systems in recommendations on soil fertility, irrigation, soil tillage and plant breeding.

**Crop growth and demand for water and nutrients**

**Models of shoot growth of different complexity**

To describe crop growth and yield formation as influenced by environmental conditions, three types of factors can be distinguished (Rabbinge and De Wit, 1989): a) factors determining potential yield (such as light, temperature, and CO₂), b) factors limiting growth (such as nutrients and water), c) factors reducing growth (such as pests and diseases). The distinction between a and b is mainly based on the degree to which the factors can be controlled by the farmer. Crop growth models have been developed for, and applied to, widely varying crop types and growing conditions. All models have to take factors of type a into account. In a stepwise fashion factors of type b and c can be added. Models for shoot growth range in complexity from a simple, direct conversion of the amount of light energy intercepted into an amount of biomass, to models including such details as stomatal response and light interception per leaf layer in a closed crop canopy (Goudriaan, 1977; Penning de Vries and Van Laar, 1982; Spitters, 1987, 1990; Spitters et al., 1989b; Van Keulen and Seligman, 1987; Van Wijk and Feddes, 1986; Weir et al., 1984; Williams et al., 1989).

As a first estimate, the potential rate of dry matter production of a closed crop canopy in the Netherlands is about 200 kg ha⁻¹ day⁻¹. This figure applies to situations with complete interception of photosynthetically active radiation (PAR) and absence of factors of type b or c that limit or reduce crop growth. By multiplying this daily production rate by the crop-specific duration of the linear growth period, a first estimate of the biomass production potential of crops can be obtained. Based on knowledge of the development of the light interception capacity from plant emergence to full ground cover, the total biomass production by a crop can be predicted from \( \Sigma \text{PAR}_i \times \text{LUE} \) (Monteith, 1977), where \( \text{PAR}_i \) is the amount of PAR intercepted and \( \text{LUE} \) is the ‘light use efficiency’, or biomass per unit PAR intercepted, (g MJ⁻¹). Such a direct conversion of intercepted light to biomass produced is only valid in conditions where LUE does not change. A constant LUE can only be expected if losses by, for instance, respiration processes and conversion costs for structural material and metabolites (such as oils and proteins) do not change substantially during the growing period (Penning de Vries, 1972, 1975; Vertregt and Penning de Vries, 1987). In Figure 1 the conversion steps between assimilation rate and growth rate are