

Plant growth models for precision agriculture

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During the last few decades technology used in crop production has developed noticeably. The work needed to be done by humans becomes easier and finally decreases by means of technology and automation. However, the benefits of new technology also depend on the efficiency of their use, i.e. decisions and timing of field operations during growth season. Information from field is essential when trying to achieve higher level of accuracy in decision making. Increasing number of measurements and information from fields create a need for system supporting the farmer with the vast amount of information and in decision making. The models used for this purpose have to be simple but complex enough. For example to be useful in decision making the plant growth model should give the present status of the plant and be simple enough for utilizing in precision farming, i.e. to be used site-specifically within fields. In order to make the simulation feasible, crop growth and water transport models were kept as simple as possible taking into account the objectives of the simulation. Therefore the number of parameters was also held low and each has a clear physico-chemico-physiological meaning. In this paper the simplest model is preliminary tested against site specific field data.

Key words: plant growth model, measuring, forecasting, decision making, precision agriculture

Introduction

During the last few decades technology used in crop production has developed noticeably. The work needed to be done by humans becomes easier and finally decreases by means of technology and automation. Developments in the machinery, technology and automation have eased the work done by farmers and finally decreased the workload. Farming methods must be developed further and new machines have to be developed to make it possible. Despite of the developments done by today the farming methods and the used machinery must be developed even further. This will inevitably lead to increase in the amount of automation used in machines and gradually to the use of automated machines which are able to work autonomously without humans. However, to get all the available benefits of efficient and automated machines, they have to be used in a way that the growth conditions for the plant are optimal during the whole growing season. For this to be possible, information for decision making from the field has to be collected from sowing to harvest, so there is a need for automated information gathering from fields. One opportunity for this are wireless sensors embedded in fields [1-3] that give real time information of the status of the field. Further this information is an aid for decision making, e.g., in choosing machines and timing cultivation operations, but on its own it is not enough, as one has to be able to forecast the future demand of plants, e.g., need of water and nutrients, from the present status of the plant and field. Decision making and online measurement from the field creates the need for a plant growth model, that gives the present status and near future needs of the plant and is simple enough to be utilized in precision farming, i.e., to be used site-specifically within fields.

Within a field, the properties of soil, movement of water and nutrients in the soil, radiation, and wind circumstances can all vary in space and time [4].

Simulation results and observations may hence disagree significantly when average values for parameters are used in the simulation of a whole field as a single homogenous area. Instead, considering the field as a heterogeneous area, as is the idea of precision farming, it is possible to study the genuine growth of the crop instead of its averaged values. This spatial information can be used as a decision aid, with the help of a model that is capable of processing site-specific information. In this way it is possible to achieve information for supporting decisions of site-specific field operations. In order to utilize the whole capacity of most advanced crop models on a field scale, a huge amount of information would need to be collected from fields. The difference between simulating mean yield and spatial variation of yield is considerable and often leads to changes in the model structure due to expansion from a one-dimensional model to a spatially coupled model [5]. By including only the most essential processes, when compared to the use of simulation results [6]), it is possible to reduce the amount of information that needs to be collected from the fields. This also includes the spatial resolution that should combine the spatial variability of field properties for crop growth and working widths of farming machines. Simplifying the model does not have to mean losing the essential accuracy and dynamics in the model results, but reducing the amount of information required from field.

In our simulation model the aim is not to simulate crop growth and water transport from the first principles. Instead we try to include the essential points and to get the potential yield of correct magnitude with as few parameters as possible. Traditionally water transport is treated by solving the Richard's equation which combines the Darcy flow and water conserving equation. The solution is straightforward, it automatically contains all aspects of water transport like infiltration and capillary rise. However, hydraulic conductivity and water potential as a function of water content at any level and place of the field are needed. This is never the case in field conditions due to heterogeneous and layered structure of soil. Further, solving the Richard's equation requires dividing the soil to layers which are thin enough, typically 5-10 cm. Transport of water to and from each layer must be calculated by using so small time increments that water content does not essentially change in one time step. Typically the maximum allowed change may be $0.01 \text{ (m}^3/\text{m}^3)$ and during rainy days this results in time steps with length of 0.01-0.001 days. Because of these unavoidable facts the calculation is slow and simulations are usually restricted to horizontally homogenous soils. Therefore calculation in only depth direction is needed and existing weather data is used to compare the simulated growth with experiment. However, this is not enough for predicting purposes, strategic planning and risk analysis. We need a model that may be used in the whole field with varying slopes and shadows and using many options for the weather. We clearly need a different strategy for simulating the water transport in soil.

In addition to simulation models [7,8] we have also developed a simple and transparent analytical model for C3-crop biomass accumulation [9]. The model is aimed to be the basic module in simulation of automated crop farming, when 3D simulation is essential due to slope-dependent solar

radiation, water transport or other site irregularities. At the early stage of growth, when radiation interception is limited by leaf area, the growth is exponential due to the expanding leaf area of the crop. The growth turns to linear when the leaf area is adequate to utilize all radiation. When water is limiting, the root-growth model becomes critical, because the daily root growth determines directly the crop's growth. Despite the simplicity of the model, it fits the essential dynamics in crop biomass accumulation before anthesis, when growth is limited by only radiation or water. In this paper the model is tested against field data.

Model

The basic ideas behind the models are sketched in Fig.2. Here we only describe the simplest model, the analytical model [9]. The simulation models have been described earlier in [7,8].

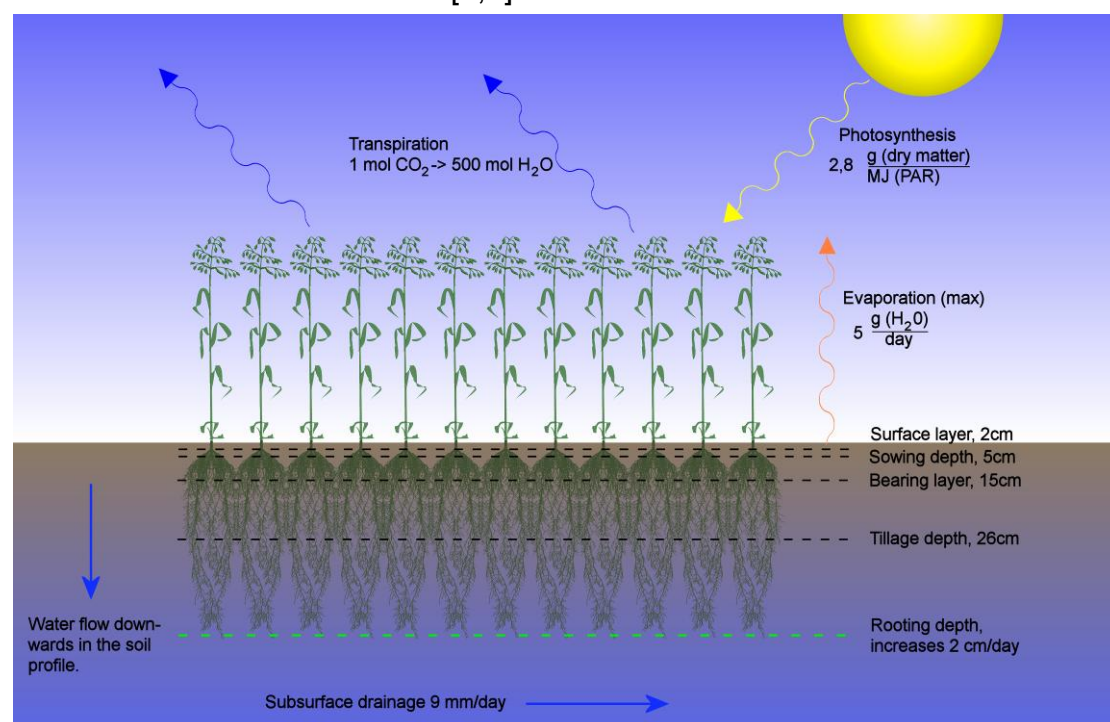


Figure 1. Main features of the model.

Growth conditions

It is first assumed that only radiation and water limit the crop growth, there are enough nutrients for optimal growth and competition, there are no pests or diseases, and temperature is within the optimum range for the crop. The key assumptions in the model (see Fig. 1) are the constant parameters: radiation use efficiency (RUE), water use efficiency (WUE) and leaf weight ratio (LWR). Furthermore, it is assumed that a leaf can utilize photosynthetically active radiation (PAR) up to a maximum intensity (I_{sat}). Further it is assumed that utilization of the whole PAR at intensity (I) needs an optimum leaf area index (LAI). The close relationship between biomass increase and the radiation received by single leaf was reported by Monteith [10]. The model assumes constant WUE, that is, the ratio of the amount of CO_2 obtained by the plant to the amount of water transpired during photosynthesis. To obtain CO_2 , the crop has to open the stomata, which leads to loss of water, because the relative humidity inside the stomata is almost

100%. An average C3 plant transpires 500 moles of H₂O per 1 mole of CO₂ [11]. When there is enough water available for the crop, the growth is limited by radiation rather than by water, so WUE has no effect on the growth.

Leaf area and radiation limited crop growth

The six parameters for leaf area and the radiation-limited case are: initial biomass (mass of seedling (m_s) × emerged plants/m² (seedling density, SD)), specific leaf area (SLA, in m²/kg), leaf weight ratio (LWR) of the mass of leaves (m_l) to the total biomass (BM, in kg/m²), daily PAR (radiation intensity I × hours of sunshine, n), radiation use efficiency (RUE), and the maximum (saturating) intensity of PAR that the leaf may utilize (I_{sat}). Seedling mass is equivalent to the biomass of a single plant, when seed reserves are totally used. The growth of the crop starts from this stage. A rather simple derivation [9] yields an equation

$$\begin{aligned}
 BM(t) &= BM(0) \cdot e^{Kt} = m_s \cdot e^{Kt}, \text{ when } LAI < \frac{I}{I_{sat}} \text{ and } t < t_o \\
 LAI(t) &= BM(t) \cdot LWR \cdot SLA \\
 K &= RUE \cdot I_{sat} \cdot LWR \cdot SLA \\
 t_o &= \ln\left(\frac{I/I_{sat}}{LAI(0)}\right) / K
 \end{aligned} \tag{1}$$

After time t_o (Eq. 1) all PAR is absorbed and the growth becomes linearly dependent on time, giving for the total biomass

$$BM(t) = BM(t_o) + RUE \cdot I \cdot (t - t_o), \text{ when } LAI > \frac{I}{I_{sat}} \text{ and } t > t_o. \tag{2}$$

During this period, the growth depends solely on the total radiation energy $I \cdot t$. It is not effective for a crop to increase leaf area any more because of increasingly overlapping leaves. Instead, the crop starts to grow stem, which in our model does not make a difference since in any case BM is the total biomass and $LWR \cdot BM$ the above ground biomass of the crop, respectively. Eqs. 1 and 2 give the total biomass (kg/m²) at any time t (s) and multiplying this value by 10 gives it in units of t/ha.

Water limited crop growth

In optimal conditions, Eqs. 1 and 2 give the biomass growth until grain filling. As already mentioned, in optimal conditions, water is not assumed to be a limiting factor. When growth is limited by water, the model needs five additional parameters: water use efficiency of the crop (WUE), permanent wilting point (PWP) and field capacity (FC) of soil, maximum rooting depth, and rooting depth increase per day (m/day). When water is a limiting factor, it determines the accumulation of biomass. Rain (R) and evaporation (E) describe the water movement at the soil surface, which greatly effects to the plant available water and plant growth. Then the biomass is limited by the depth of the roots:

$$BM(t) = [(FC - PWP) \cdot r_{depth}(t) + t \cdot (R - E)] \cdot \rho_{water} \cdot WUE \cdot \frac{M_{glc}}{M_{CO_2}} \quad (3)$$

$$BM \left[\frac{\text{kg}}{\text{m}^2} \right] = \text{water available [m]} \cdot \text{water density} \left[\frac{\text{kg}}{\text{m}^3} \right] \cdot WUE \left[\frac{\text{g}_{CO_2}}{\text{g}_{H_2O}} \right] \cdot \text{molar mass} \left[\frac{\text{g}_{glc}}{\text{g}_{CO_2}} \right]$$

In Eq. 3, the formula in parenthesis gives the water available for plants (in meters) and $r_{depth}(t)$ is the depth of roots at time t (in days). M_{GLC} and M_{CO_2} are molar masses (g/mol) for unit of glucose and carbon dioxide, respectively. In the soil, water is available for the plant between PWP and FC, when roots do not reach ground water level or capillary rise is not effective in soil. The values of all parameters are listed in Table. Notice that none of them is fitting parameter, all are measured or taken from literature.

Table 1. Values for parameters in crop growth, both radiation and water limited cases.

Parameter	Abbreviation	Value	Unit
Radiation and leaf area limited crop growth			
Radiation Use Efficiency	RUE	2.8×10^{-9}	kg/J
Incoming solar PAR	I	250	W/m ²
Maximum PAR for leaf	I _{sat}	100	W/m ²
Seedling density	SD	500	plants/m ²
Specific leaf area	SLA	20	m ² /kg
Mass of the seedling	m _s	40	mg
Leaf weight ratio	LWR	0.5	
Duration of daily sunshine	n	10	h
Water limited crop growth			
Water Use Efficiency	WUE	0.0008	g _{CO2} /g _{H2O}
Field capacity	FC	0,37	m ³ /m ³
Permanent wilting point	PWP	0,14	m ³ /m ³
Daily root growth		0,02	m/d
Maximum rooting depth		1,0	m

In practice, the equations for biomass accumulation contain only three independent terms: the cultivar specific term SLA, the agronomic term the initial biomass per square meter (m_s·SD), and the site-specific term total radiation energy per day (I·n). Effectively we have 6 parameters for radiation limited growth and 4 additional parameters for water-limited growth since only FC-PWP is an independent variable.

Experimental

We have made site specific measurement at two sites, one spring wheat and the other winter wheat. We have tried to measure the relevant characteristic as reliably as possible using many kinds of sensors. Leaf area index, specific leaf area, soil moisture content and temperature, soil water potential, solar radiation, PAR radiation, air humidity and temperature and canopy radiation temperature were measured during the growing season.

Results

In fig. 2 we give the sensor data for some of the moisture sensors. Notice the linear decrease in moisture at depth 30 cm indicating the extension of roots at that depth at that time. At lower depth the more exponential decrease is also due to evaporation. The moisture saturates at approximately 37% (field capacity) and never decreases lower than approximately 14 % (permanent wilting point) at depth 20 cm. Spring was dry as seen from the moisture levels at depths 5 and 10 cm. Therefore the initial growth was water limited.

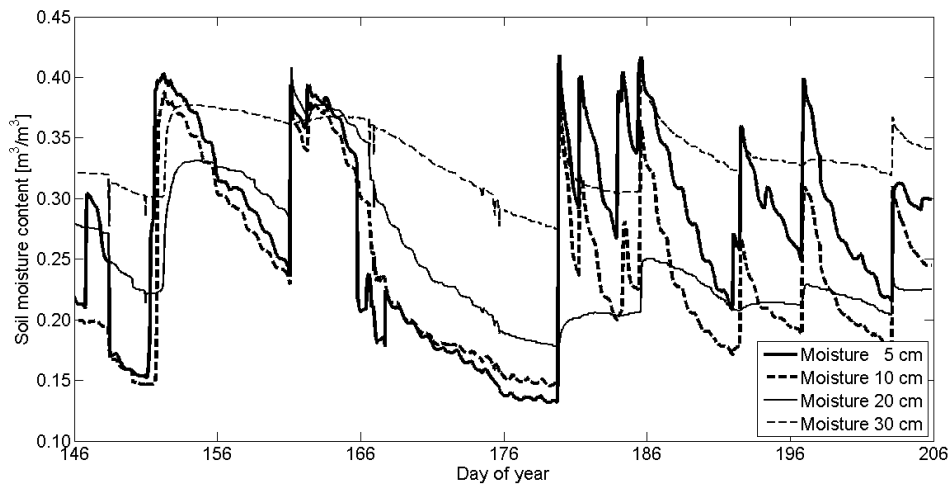


Figure 2. Measured soil moisture content from different depths of the soil.

In fig. 3 we compare the measured leaf area with the leaf area LAI(t) received from Eq 1.

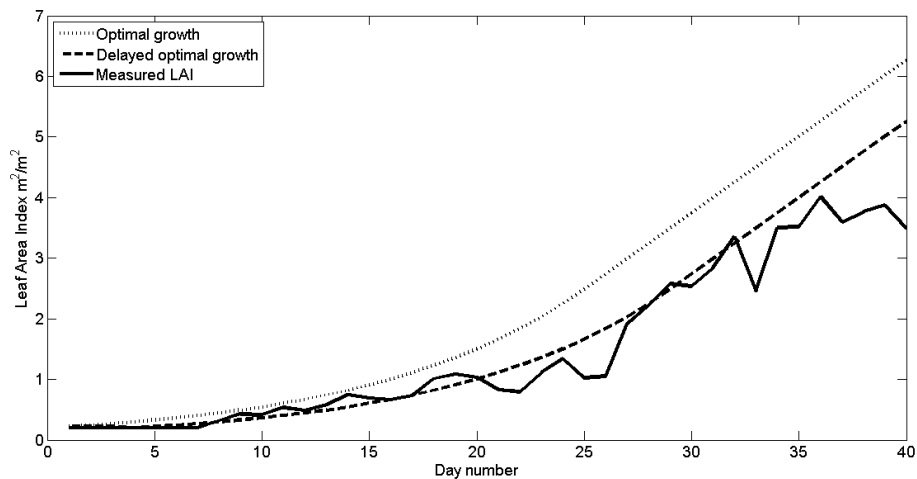


Figure 3. Simulated and measured leaf area development during the early growth.

It is clearly seen that growth is delayed in spring due to water lacking conditions (see fig. 3). Measured LAI ceases to increase at LAI=3. Further biomass increase goes mainly to stem and grains. In Eq. 1 all biomass goes to LAI. Further comparison of total biomasses indicates good agreement. Thus this preliminary comparison indicates that the present analytical model is adequate.

Further information of what is happening below soil (water and roots) may be obtained from more detailed simulations of water movement and root growth. The comparison of simulated moisture profiles with measured (Fig.2) gives useful information of water evaporation and root profiles as well as on how complex a model needs to be for precision agriculture and decision purposes.

Discussion and conclusions

The strength of the present model is that all its parameters are known to a first degree of approximation and when additional accuracy is desired, they can be easily measured. Possible differences between measured values and model results reflect the variability or uncertainty of model parameter values on the field scale where nutrient deficiency and diseases incidence have been eliminated from contention. On the other hand, the present model is flexible and it is easy to utilize data measured during the season, in order to improve the accuracy of the model and its ability as a decision support. The model is essential in order to make the simulation reliable and to reduce the number of parameters needed. Using the model, it is easy to include the essential factors in yield variation such as slopes and soil heterogeneity. Soil heterogeneity is planned to be included in the whole simulation iteratively. Spatial and yearly information of water status and biomass accumulation, as well as pulling resistance during tilling operations should give enough information for site-specific soil property determination without detailed measurement in field. While it is not feasible to determine hydraulic conductivity on a detailed spatial scale, a future possibility is to use in situ sensors that reveal the water status [1-3]. Nutrients were not included in the model, but the need for nitrogen can easily be calculated. A scenario is that in spring, only the nitrogen required for the exponential growth period is applied, and thereafter the need for extra nitrogen can be decided with help of the model. This is essential since the total amount of rain varies a widely during the initial period of growth, e.g., in Finland from 20 mm to 200 mm between 1 April and 15 June during the last 20 years. When water is limiting, there is no value in increased nutrient provision. The goal is thus optimal harvest using minimal input in the existing weather and at the same minimizing the leaching of nutrients. The model requires no calibration, it uses minimal amounts of experimental data from the soil and the plant. The preliminary test against field data represented in this paper is very encouraging.

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