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Optimization of Subirrigation Water Level in Humid and Arid Conditions

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Abstract: In Finland crop yield varies considerably yearly due to unsuitable rainfall distribution. During the same growing period soil may be both too dry and too wet. Therefore it is interesting to study what is the optimal ground water level as a function of the amount of rain in order to maximize the yield while field operations being possible in due time. A simulation code was established with this aim in mind. The code should reasonably simulate real water dynamics. The rain is obtained by Monte Carlo calculation using experimental distributions of rain event duration, dry spell duration and precipitation in a rain event. By varying total yearly rain in a stochastic manner as well as ground water level, it is possible to find optimal conditions for ground water level for different plants in any soil. 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 crop growth has only two crop specific parameters; mass of seeded grain and seeding density and soil has four; SWC, FC, PWC and saturated hydraulic conductivity. Seed mass is divided into leaves and roots. Further dry mass growth comes from the experimental fact that C3-plants produce 1.4 g HCO_2/MJ solar energy when radiation is above 100 W/m^2 and there is no lack of water and nutrients. An experimental (and physical) fact is that about 500 moles of water is transpirated when 1 mole of CO_2 is used in photosynthesis. This water is taken from the root volume if available. If there is no water available for the crop, the growth ceases. If water shortage takes place a certain time or soil is wetted a certain time, plants die. Further demand is that at harvesting time soil must have a bearing capacity. Soil is divided into four layers and water moves only when water content is above FC. Preliminary results of the simulations are presented in this paper. The benefits and drawbacks of the method are also discussed.
Key words: Monte Carlo, crop growth, subirrigation

INTRODUCTION

Water is an essential part of plant growth. It is needed in photosynthesis and for transporting nutrients from soil to plant. Water for plant growth is stored in soil and the amount of plant available water is mainly increased by rains. Also capillary rise from groundwater can increase the water available for the plant if the distance between roots and groundwater is not too long.

Seeds need heat and moisture for germination after sowing. To avoid destroying the structure of soil by compaction it is necessary to decrease the moisture content of soil before cultivation operations. Bearing capacity increases as soil moisture content decreases which is feasible for field machines and soil structure. Unfortunately at the same time as the soil dries with the help of the drainage, the amount of the water available for the plant decreases. Therefore lack of rain after sowing may become the biggest growth limiting factor, and it would be beneficial to increase plant available water with irrigation.

Changes in the amount of rain and the effects to crops growth can be estimated via simulations using a model which includes soil, plant and rain. A model with reasonably short simulation time but which includes the main effects of water interactions in plant and soil is needed. With short simulation time the model can be used for simulating several scenarios and the overall effects of the changes can be estimated in a stochastic manner.

The present status of crop growth models was reviewed by Porter and Hay (2006). Also Larcher (1993) gave an overview of relevant plant ecology. The number of parameters typically used in models is huge and their influence almost intractable. For example in the STICKS-model there are 132 parameters and tens of thousands of simulations were performed in the sensitivity analysis (Ruget et al. 2002).

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. This enables statistical simulation of growth as a function of various parameters when yearly weather is statistically changed by Monte Carlo techniques. Typically one hundred simulated rains are used for each combination of parameters in order to obtain distributions of biomass growth as a function of a selected parameter. Main justification is that potential production is rather unsensitive to parameters compared to actual cases when growth is constrained by limited availability of resources (Aggarwal, 1995). In this paper we outline a framework how this can be handled. The model is at present rough but even though it is able to present interesting results. From weather only rain statistics is properly included. Temperature, cloudness and moisture are neglected. The motivation for the negletion is their marginal average role in the yield variations compared to water. Their effects are still included in input parameters e.g. radiation intensity and evaporation. To achieve realistic rains the experimental statistics were used.

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 heterogenous 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 (m^3/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 code that may simulate 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 principle we use the same ideas that e.g. van Laar et al. (1997) have used. The soil is divided into 3-4 layers and each day the water is transported from one layer to another as a whole. The enormous problem here is making the simulation accurate enough. The disadvantage of this approach is very complicated logic compared to solving Richard's equation.

THE RAIN MODEL

In a recent study, the statistics of 50 year summer precipitation in one location in Finland was presented by Kilpeläinen et al. (2008). The cumulative distributions of rain event duration, dry spell duration and precipitation in a rain event were given as a sum of two exponentials which we use to create the rain. The yearly rain is obtained by Monte-Carlo method. If F(x) represents one of these distributions, then a random number $0<R<1$ gives a single event x: $F(x)=R$. The weather of one summer is then obtained by random numbers; consecutively rain event duration, dry spell duration, precipitation in a rain event, rain event duration, and so on. The total amount of one growth period is achieved from daily rains.

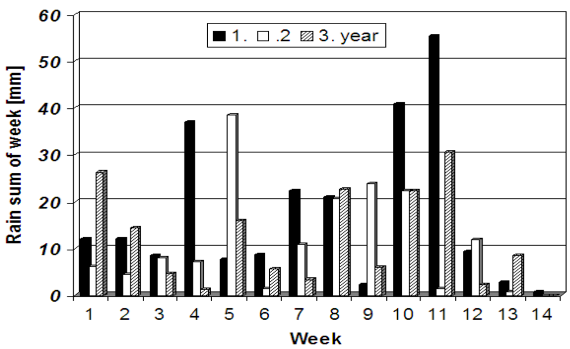

Figure 1. Examples of rain distributions, simulated rains for three sequential years.

Three simulated rain distributions are given in figure 1. An average rain sum during 14 weeks period was 181 mm, when rains were simulated for 1000 years. Within the same simulation the highest rain sum for the same period was 328 mm and the lowest 86 mm. Daily maximum rainfall was 67.6 mm. It is to be noted that any type of rain is easily created in this model.

THE PLANT GROWTH MODEL

The overview of the plant growth model is presented in figure 2. The model contains fixed parameters, and the size of each may be altered by a multiplication factor in order to find out its influence on the plant growth. The model and its parameters are: the mass of a seed, biomass partitioning between shoot and root, sowing density, leaf biomass density and thickness of leaf.

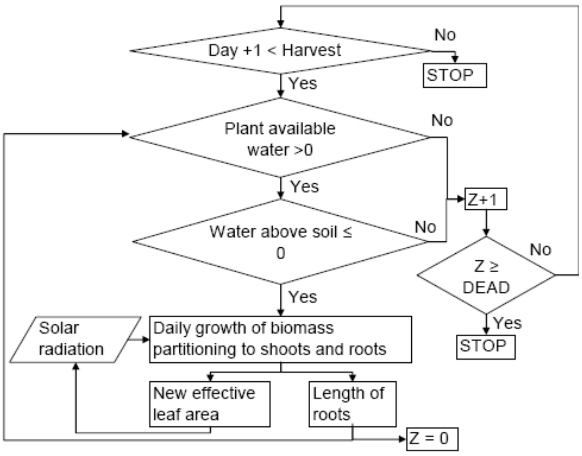

Figure 2. Flowchart of calculations in the plant growth model. The plant dies, when Z is greater than DEAD. Z gives the number of consecutive days when soil is either too dry or too wet.

The normal values of parameters were: Mass of the seed was 50 mg and root to shoot ratio 0.3. Density of leaf was 500 kg/m^3 and the thickness 50 µm. Thus the area of the seed leaf was 2.5 cm^2. The sowing density is 500 seeds/m^2, i.e. the ratio of the assimilative leaf area to the ground area (later LAI) in start is 0.125 m^2/m^2.

Biomass growth comes from the experimental facts that C3-plants produce 1.4 g CH_2O/MJ solar energy when radiation is above 100 W/m^2 leaf area and there is no lack of water and nutrients (Monteith 1977). Radiation (500 W/m^2) is effective 14 hours/day in each simulation. For LAI>1 we use Lambert's law with attenuation factor 0.5. Root growth is 8 mm/day in depth and the maximum root depth is limited to 0.8 m. This determines the available water for plant in soil. At the start of each simulation seeds are expected to be germinated and root length is set to be 5 cm downwards.

WATER TRANSPORT MODEL

An overview of the water transport in soil is presented in figure 3. Soil is divided into four layers. The first layer is limited between soil surface and depth of 2 cm. Water content of the first layer is not limited due to possible ponding of water. The second layer is limited to depth of 15 cm and bearing capacity is calculated from this layer. The third layer begins from the bottom of the second layer and continues to the depth of 25 cm which is assumed to be the depth of ploughing. The fourth layer (if it exists) includes the distance between tillaged soil and ground water.

Water percolation from layer to layer is possible only for the amount of water between saturated water content (SWC) and field capacity (FC). For heavy rains this is rather unrealistic limitation. Further, the water flow is limited by saturated hydraulic conductivity (K). The values for different soil types are presented in table 1. Bearing capacity is 0.9 x FC. Ground water level is set to be 2 m unless altered. Ground water flow may always be limited by covered drain capacity and has the maximum value of 9 mm/day which corresponds the covered drain sizing value in Finland. Maximum water evaporation is 5 mm/day and is reduced by plant leaf area and moisture content of the first layer. This is a conservative estimate of evaporation. During rainy days evaporation is not assumed to occur.

Table 1. Values for soil properties (Karvonen and Varis 1992).

	PWP m^3/m^3	FC m^3/m^3	SWC, m^3/m^3	K, m/d
Fine sand	0.024	0.198	0.364	0.500
Heavy clay	0.364	0.494	0.540	0.002
Silty clay	0.276	0.442	0.507	0.013
Peat	0.302	0.681	0.863	0.053

Seeds are sown into 5 cm depth and water for plant is gained beneath the first soil layer. During the growing period the depth of the plants root system determines the region of available water in the fouth soil layer. The water content of the root zone is treated separately, when it is below FC.

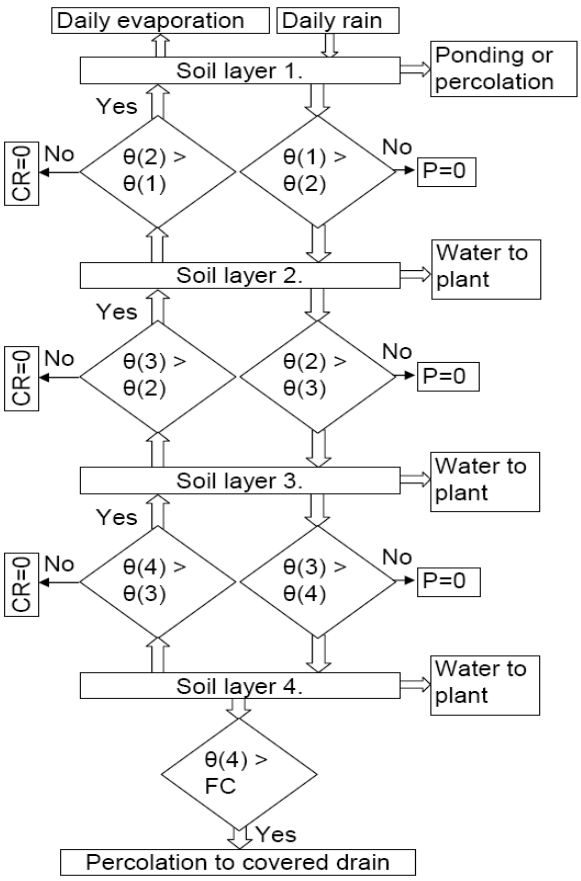

Figure 3. Principle of water movements in soil. CR is capillary rise, P is percolation from layer to layer and θ(i) is the water contnet in layer i.

At the beginning of the simulation the soil water content is assumed to be in FC and water is available for plant to PWP. It is to be noted that only water between FC and PWP is relevant for growth in the simulation. An experimental (and physical) fact is that about 500 moles of water becomes transpirated when 1 mole of CO_2 is used in photosynthesis (Taiz and Zeiger 1991). This water is taken from the root volume if available.

It is assumed that plants die if there are five sequential days with unsuitable growing conditions, i.e. the water content in the root layer is less than PWP or more than SWC. Also pond above the soil surface can cause the plants death if water doesn't run off, infiltrate into the soil or evaporate during five sequential days.

RESULTS

The basic parameters define the maximum yield. The total biomass including roots when water is not lacking is 10.8 tons/ha. The maximum yield can be easily tuned to any number by changing e.g. solar radiation. One should thus not look the exact numbers but instead pay attention to the changes in the yield. However, the chosen parameters are realistic and therefore also the maximum yield can be achieved in field conditions. The results presented are preliminary and their aim is just to indicate the potential of the method we have used. The details of the results depend on the logic of the code. The logic is partly preliminary.

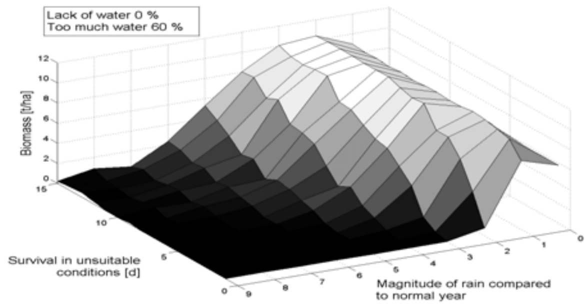

Figure 4. Effect of plant survival (=DEAD in Fig.2) on different moisture conditions on silty clay.

The effect of crop survival in unsuitable conditions to the yield is presented in figure 4. Survival time seems not to be a critical parameter which is encouraging since it is difficult to determine exactly for a specific plant. The figure is an example how one can easily check whether any uncertain parameter is relevant and needs further experimentation.

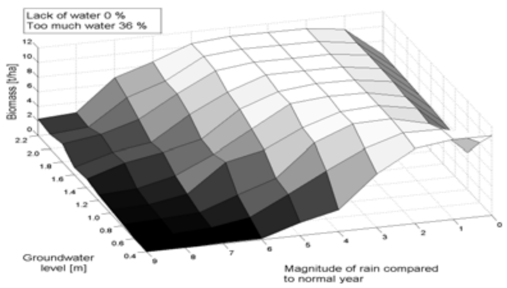

Figure 5. Final biomass yield as a function of ground water level and amount of rain for fine sand.

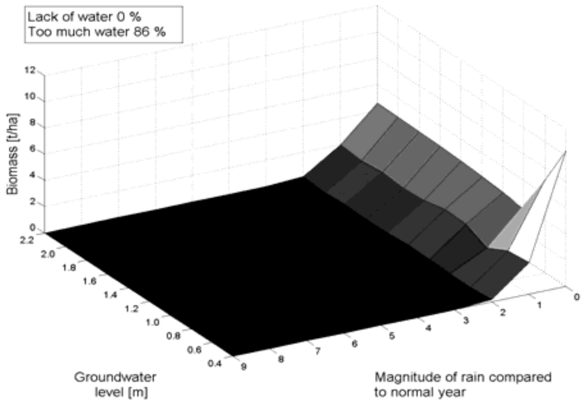

Figure 6. Final biomass yield as a function of ground water level and amount of rain for heavy clay without granular structure.

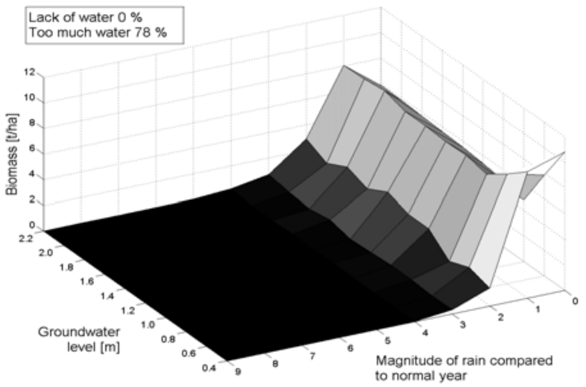

Figure 7. Final biomass yield as a function of ground water level and amount of rain for heavy clay with granular structure.

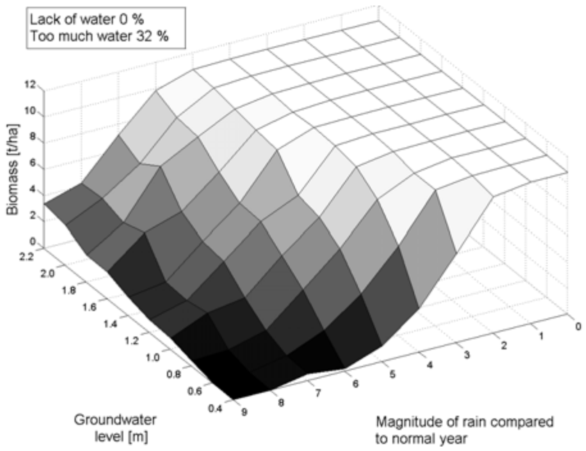

Figure 8. Final biomass yield as a function of ground water level and amount of rain for peat.

Total biomass yields for different soil types are presented in figures 5-8. In figures the growth for each rain and ground water level is an average of 100 simulations. Although the results are probably only indicative they show the potential of the present approach. Compacted heavy clay without granular structure transmits water in relatively slow rate and the plant lacks always water and the biomass remains low. With too much rain the water remains on the surface and causes plant death. With small rain levels it is beneficial to have ground water in so low level that roots can reach it. With higher levels of rain it is beneficial to have ground water level lower than the rooting depth to avoid plants suffering from too moist soil.

In Finland a major problem is rainy autumns due to short harvesting time and the lack of bearing capability during harvesting. Fig. 8 gives an example of when the harvest may be harvested or not. This kind of information is very valuable when possible risks of subirrigation procedures are estimated.

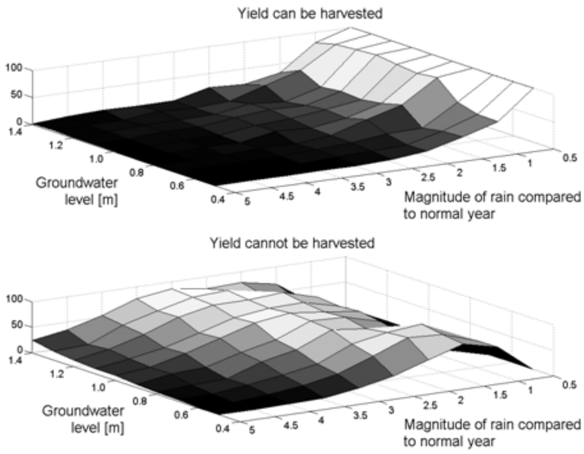

Figure 9. Soil bearing capacity at harvesting time on fine sand soil. Cases when plants have died before harvesting time are neglected.

DISCUSSION

The structure of the created model is attempted to make such that the simulation is rapid and the results are still realistic. With very simple structure the accuracy of simulations is of course not as good as with the finest existing growth models. However, the purpose of the present model is not to mimic the growth of plant as accurately as is possible with existing knowledge. With simple structure of model it is possible to achieve short simulation times for one growing season, to simulate several seasons in reasonable time and to explore the effect of the parameters. With yearly and separately simulated realistic rains it is possible to see the effect of normal rain variation without measured data from a long period of time. This property of the model enables the estimation of a risk to have considerable yield losses.

The basic idea in the crop growth simulations is to look the changes in the yield when the value of only one parameter is changed. For our purpose this is a great and welcome improvement/advantage when compared to those models which include hundreds of parameters which are correlated with each other. Sensitivity analysis naturally helps but it is not an easy task with such a huge amount of affecting parameters as e.g. Ruget et al. (2002) indicates.

Solving Richard's equation needs at least ten layers and the time step may be only 0.001 days when rain occurs. We have four layers and time step is one day. This results to reduction in computing time in maximum by a factor of 2000. Our simulation of 10000 years takes less than half a minute in laptop computer. The same calculation solving Richard's equation would take then some 15 hours with the same computer. This is actually not the case since time step in drying soil might be around 0.1 days and the water transport in layers may be mostly treated using vectorized code. In optimum case one might need one hour. This would be true for one location in the field. However, the field must be divided horizontally to lets say 10 m x 10 m areas. One hectare would have then 10000 simulation locations. Solving Richard's equation clearly needs substantial increase in the speed of computers. At the moment the presented strategy is the only way for shorter simulation time.

Our strategy has its own problems. The logic becomes extremely complicated when all possibilities are included. Especially altering the ground water level and capillarity have turned out to be challenges. At the moment we do not have a satisfactory model for capillary rise and it is therefore left out from the presented model. The present code is basic Matlab but we are making the same simulation by using Simulink. This will hopefully guarantee the correctness of the codes in their logic. Preliminary tests with Simulink have indicated big increase in computing time which presumably is due to the memory use. For each simulated year the memory had to be reorganized. There fortunately seems to be a way to treat this problem.

Even in its present form the code yields interesting results and seems to be a good aid for estimating risks of various ground water levels or irrigation strategies in varying weather conditions in any type of soil. This seems a promising aid for strategic planning in future changing climate. The examples indicate that with this model it is easy to calculate risks of environmental factors. The code seems adequate for the purpose it was planned. With this kind of a model the boundaries of growing conditions are clearly discovered.

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