

Environment simulator for studying automatic crop farming

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Abstract: Agricultural machines capable of utilizing variable rate application technology are tackling spatial variability in agricultural fields. Agricultural field robots are the next step in technology, robots which are capable of utilizing sensor and actuating technologies without human contact and operate only areas of interest. However, agricultural field robots are still under research. Robots are just one part of the next generation of crop farming having more advanced tools to do the work which currently requires humans. The next generation of crop farming, in the vision of the authors, is based on automation, which incorporates stationary and moving sensors systems, robots, model based decision making, automated operation planning which adapts to spatial variability according to the measurements as well as to weather conditions. This article presents a top-down approach of automated crop farming using simulation, trying to cover all the component parts on a fully automated farm. In the article, the developed simulation platform is presented as well as sample simulation results. The environment simulator is based on crop growth models, weed growth models, soil models, spatial variation generation and weather statistics. Models for the environment were found in literature and were tailored and tuned to fit the simulation purposes, to form a collection of models. The collection of models was evaluated by using sensitivity analysis. Furthermore, a full scale scenario was simulated over one season, incorporating 9000 spatial cells in five fields of a farm.

Keywords: robots, crop growth models, soil water models, decision making, operation planning

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1 Introduction

Developments in automation, information and communication technologies have enabled highly automated production at factories and plants. At many factories humans only supervise automated processes and perform the maintenance. The driving forces for automation have been both the requirement of efficiency as well as technological advances. The same kind of trend can be seen in agricultural development, where an increasing amount of information from fields and crops is available to assist in decision making and to regulate operations in fields (Stafford, 2000). When compared to

industry, the working environment of farms is far more complex due to the inability to limit the impacts of the environment, for instance, like the weather. Therefore, the most advanced solutions can be found in the most restricted environments, such as automatic milking, feeding and cleaning in cowsheds. Many agricultural field machines incorporate assistive automation technology, but purely autonomous field machines do not yet exist.

On the other hand, variable rate application (VRA) technology has been a way to tackle the spatial variability using position stamped measurements and apply position specific actions (Stafford, 2000). Nowadays the positioning technology is not a problem and mechatronic solutions to apply the desired rate are commercially available. The challenges in utilizing VRA for precision farming are related to the question: “if I have this and that

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measurement, what should be the application rate". If formulated as an optimization problem over uncertainties, giving a precise answer is very challenging. Rough answers can be given based on common sense, but generally, a *model* is needed to formulate control law.

The goal of study was to develop a simulator for the farm environment and test a robot farm concept to automatize crop farming operations. The main method of the research was simulation and the goal was to utilize literature models, if available, for modeling the environment. The developed AutoCrop simulator is a complete simulation model for a robot farm. The purpose of simulator is to provide a platform with realistic noises to study algorithms and methods for robotic farming. The literature models are used to create proper dynamics and noises including spatial variability. This paper describes the structure of the simulator as well as sample results of environment simulation. The location of simulation was set to southern Finland.

2 Literature models

2.1 Simulators

Crop farming simulation has been studied in the past. The development of crop growth models started in the 1960s (de Wit, 1965, Monteith, 1969), and in the 1980s the first models which could be utilized in farm planning were developed (Yin and Laar, 2005; Stöckle et al., 2003). The first simulation models concentrated on a specific sub process of crop farming and they were not complete simulators in that aspect. Some advanced simulators have been developed, which predict a yield and try to optimize fertilizer usage. The common structure in the simulators includes similar low-level models (Eckersten et al., 2004; Eckersten et al., 2006; Eriksson et al., 2005; Hill, 2006; Jones et al., 2003; Larsbo and Jarvis, 2003; Stöckle et al., 2003; Yin and Laar, 2005 and Wang et al., 2002). The most advanced simulators incorporate also sub models for pests, diseases and microclimate (Stöckle et al., 2003; Eriksson et al., 2005 and Jones et al., 2003).

CropSyst is a collection, which includes sub models describing changes in soil water, soil nitrogen, environment, crop growth, development and management. Therefore, this simulation model includes all necessary

elements required for a realistic crop farm simulation, with crop rotations, lasting several years (Stöckle et al., 2003). The program also includes a weather generator, which can be used for prediction and scenarios. CropSyst is made for research purposes and, therefore, the user interface is not as easy to use as it could be; the input files have to be manipulated by hand if the customizations of crop rotations or management operations are needed, for instance.

SALSA (Systems Analysis for Sustainable Agriculture) combines the crop production and pig management from the environmental point of view (Eriksson et al., 2005). It provides a tool for studying the environmental impacts of a single farm including both crop farming and a piggery. With SALSA, a user can simulate the changes in environmental effects with a different feeding strategy or manure management strategy (Eriksson et al., 2005).

DSSAT (Decision Support System for Agrotechnology Transfer) is a cropping system model with modular structure and can be used as a decision support tool as the name of it stands for. A modular structure makes it easier to change a single part of the simulator and management of the model collection is simpler. DSSAT contains models for 16 different crops (Jones et al., 2003).

DAISY is a simulator for dynamics of soil water and nitrogen in crop production (Hansen et al., 1991). Originally it was developed for management purposes, but it is nowadays used for many purposes. The model concentrates especially on nitrogen and water modelling in soil. The simulator is split into components or submodels that allow extensions.

STICS is another model that can be used to simulate water and nitrogen balances with crop growth. This simulator is also divided into modules: development, shoot growth, yield components, root growth, water balance, thermal environment and nitrogen balance. The simulation is based on weather data input and computes yield and balances (Brisson et al., 1998).

GECROS (Genotype-by-Environment interaction on CROP growth Simulator) is a crop growth model, which incorporates the current knowledge of individual

physiological processes and their interactions and feedback mechanisms. The model is developed on the basis of physiological models, for photosynthesis-transpiration, carbon-nitrogen interaction, functional balance between shoot and root activities. The GECROS model also contains a simple soil model, but this is claimed to be just an example. The crop growth model simulates one plant, or a homogenous field area – no spatial variability is considered. The weather inputs to the model are taken from real measurement data. Fortunately, the GECROS model is available as FORTRAN code, but unfortunately, it requires a special runtime environment called FST or FSTWin, and it requires a special Fortran compiler, which is unfortunately not available for new computers (Yin and Laar, 2005).

Eckersten et al. (2004) developed a simulator for model grass and red clover growth. The model is based on radiation use, regrowth from stored biomass after cutting and winter, allocation and loss of biomass. The model contains a separate model for soil water dynamics. Later, the same modeling principle was applied to willow forest farming (Eckersten et al., 2006), to study the effect of nitrogen conditions on growth. The model was used to predict a biomass harvest. However, this simulator simulates only a homogenous area and no spatial variation is taken into account.

Berntsen et al. (2003) developed the FASSET simulator to study nitrogen related issues like environmental impact and economical consequences including taxation. The simulator utilizes linear programming models but also dynamic elements. The simulator incorporates up to seven crops. The simulator was developed with C++ programming language.

2.2 Crop growth models

The modeling of crop growth started as early as the 1960s, when de Witt (1965), Monteith (1969) and others established the basic phenomena in crop growth. They described crop biomass accumulation in varying amounts of detail. They included factors such as radiation interception, assimilation, CO₂ intake, root water take up, physiological age, leaf growth and senescence, for instance. Some of the models included a separate

calculation for a microclimate for the crop, where solar radiation, air humidity and air movements in the canopy are considered in the canopy level, which should improve the accuracy of simulation for real life situations (Bouman et al., 1996). Because of their long development and the historical aim to improve the knowledge of plant growth, the models can consider various processes, with great detail, related to crop growth and, therefore, be very detailed and complicated (Bouman et al., 1996). These same plant growth models have been used not only for researching the plant itself but also for investigating yield variation, as they provide a versatile tool for analyzing the effect of different processes related to the growth of the plant. However, the great number of details in some cases makes the use of the developed model difficult partly due to the number of parameters and partly because of experiment specific information included in the parameters (Hautala and Hakojärvi, 2010). If a certain parameter is to have an effect on the crop growth, it is necessary to know the site-specific value of the parameter within a field or simulated area.

2.3 Soil models

In this context soil models are established to simulate changes in soil properties, like moisture, nutrients and temperature, which are relevant to crop growth (Stöckle et al., 2003; Eriksson et al., 2005; Larsbo and Jarvis, 2003; Jones et al., 2003; Eckersten et al., 2004 and Eckersten et al., 2006). Simulation of soil nutrients and soil water are usually in connection, because most of the nutrients are soluble; or move in the soil with water flow. Layered structure, where these layers interact with each other, is typical and common for these kind of models (Stöckle et al., 2003; Eriksson et al., 2005; Larsbo and Jarvis, 2003 and Jones et al., 2003). Most of the models are one-dimensional and consider changes within this one dimension (Jones et al., 2003 and Ferreyra et al., 2006), but exceptions exist, where layers are divided into separate cells which are spatially coupled (Ferreyra et al., 2006) or phenomena in soil are considered in 3 dimensions (Basso, 2000; Warsta, 2007 and Warsta, 2011). The most accurate way to calculate changes in soil moisture is trying to solve Richard's equation. The

major disadvantage with this approach is a high computational cost, which leads to a long simulation time. This had led to attempts to find faster but accurate enough ways to calculate changes in soil moisture over larger areas.

3 Simulator structure

The aim of an underlying research project was to study a vision of automatic crop farming. The main method of the research was simulation and the goal was to utilize literature models as much as possible for modelling the environment. The structure of the developed AutoCrop simulator consists of three layers. The bottom layer contains models for soils, the weather, solar radiation, crop growth, pests, and weeds. In the simulator, the fields are in a horizontal direction split into small regular pieces. The interaction of these models is modelled in the middle layer as well as operations and actions made in the field. The top layer models decision making processes, operation planning and the effects on the environment. This article concentrates mainly on the two bottom layers.

Fields, field properties, roads, shadowing forests, sheds and storages form *scenarios* in the AutoCrop simulator. The purpose is to study different kinds of scenarios, later in the project. The fields, roads, forests and locations of sheds and storages are determined by the user. The spatial properties of the field are generated automatically based on expectation values and variances for each soil property. Landscape height is generated in the same way.

In the simulator, both the spatial space and time space are discretized. Both parameters can be changed but in this article the values for the discretization were: 5×5 meters (*cell size* in the *grid*) in spatial space and 1 hour (*time step*) in time space. The denser grid gives results that are more accurate but, on the other hand, takes more time to compute, and the selected default values are considered a good compromise with current computer processors.

As in the simulator both spatial and time space are simulated and models apply to both, a hybrid approach simulator is required. This means that the

time-dependent effects are modeled separately from the spatial effects and in the simulator, they are computed one by one. In other words, in every step in the simulator, in the first phase all the cells (in the fields) are computed separately one time step further and, in the second phase, the interaction between cells is computed. These two phases are repeated in turn.

In the other simulators, the weather is either generated or measured weather station data is directly applied in the simulator. For the AutoCrop simulator, the generated weather was selected due to the requirements of different scenarios requiring, for example, dry and moist seasons. Hourly simulated variables are the temperature, rainfall, humidity and solar radiation. The temperature, rainfall and humidity are generated using statistical data from the Helsinki weather station from 1971-2000, monthly expectation values and variance, and daily trends. In the weather generator, solar radiation is computed using an available solar simulator (ArcGIS Solar Analyst). This solar radiation tool automatically computes shadows from landscape, forests and buildings. In shadow areas, the decrease in solar radiation was considered but the effect on temperature, humidity and rainfall was not taken into account.

The time range in the simulator was selected to be one cultivating season, and in Finland, this was set to start from the beginning of April and last until the end of October. In the beginning, the fields are very moist and the weather is cold and when the simulator is started, the temperature rises and fields start to dry and decision making starts to analyze when the field is ready for sowing.

4 Simulator implementation

4.1 Simulation tools and software integration

In the implementation of the simulator, several software tools and technologies were used and integrated. The main tools used were ESRI ArcGIS/ArcInfo 9.2, Visual Studio .NET 2005, SQL Server Express 2005, Matlab R2007a, Simulink 7.0. All the used tools are found powerful in certain areas, but none of them, if used alone would be good enough for developing a crop farming simulator, and software integration is required.

The crop farming simulator contains both spatial space and time space; Matlab/Simulink is a powerful tool for time space simulation with dynamic systems, but very poor with spatial simulation purposes. On the other hand, GIS tools are powerful in spatial simulation, but time space is not considered much. These tools allow several ways of integration with other tools and, therefore, two different integration and implementation approaches were studied. In both approaches, ArcInfo was used as a user interface and the main differences were found in the computational speed and extensibility of the simulator.

The workflow of the AutoCrop simulator is presented in Figure 1. In the first phase, a scenario is created. In this phase, fields are created and it is possible to import map and road data from external resources. The field properties are generated also in this phase. The field properties are generated in two stages: at first, a certain number of coordinates per hectare are randomly put inside the field and value properties for the coordinates are generated using the expectation values and variances. During the second stage, to get a smooth spatial variation, a 3D surface is fit to the generated points to represent the property of the field. Spline surfaces were used in AutoCrop simulator as it gives a smooth and continuous surface. Field height variation is created in the same way.

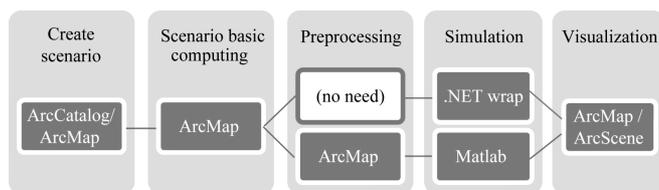


Figure 1 Work flow of AutoCrop simulator

In the basic computing phase (Figure 1) the scenario is converted to a format applicable to the simulator. This includes rasterizing 3D surfaces created in the scenario using the grid size parameter. In the basic computing phase, also cloudless solar radiation is generated for the whole season beforehand (using ArcGIS Solar Analyst). In addition, other static properties of the fields are computed at this time, like the inclination rate and direction in each cell, and cell neighborhood arrays.

The pre-processing phase in simulator workflow is required only if environment simulation is done outside the GIS system. This transforms GIS data to an SQL

database as tables; and creates empty tables where simulation results are to be put.

The crop growth models were developed using Simulink and the modeling level is a small homogenous spatial area. Two different approaches were used in computing the simulation phase (Figure 1): Simulink C++ code generation together with .NET wrapping and direct simulation using Matlab. In the first approach, the Simulink model is compiled to C++ code, wrapped with custom C++ code in a .NET component and then wrapped in ESRI compatible .NET component using C# code. In the second approach, Matlab is used in the simulation phase and it runs Simulink in a normal way, by utilizing command line operations to run the Simulink model. The simulator runs the crop growth model every hour, in both cases. Inside the model, some parts run only once a day. One hour was considered small enough for all model dynamics from the point of view of farming simulation.

Finally, the last step in the AutoCrop simulator is visualization, where GIS tools are used to interpret the simulation results. The selected states from the crop growth model and other models are stored as raster to the SQL database in the simulation phase and these can be examined over time. The goal is also to show decision making indices in the same way, in future developments of the simulator.

4.2 Crop growth model

The main structure of the crop growth model used here is similar by structure to a grain sorghum model called SORGF (Arkin et al., 1976). Here it is modified to represent a typical Finnish grain crop, barley, against the official variety trial yields and growth times (Kangas et al., 2006). The crop growth model starts from the sowing and emergence of a crop. After the crop has emerged, the development of leaves begins. Each one of the leaves appear according to a rate which is calculated from mean daily temperature. After all the leaves are fully expanded, the total leaf area starts to decline at a certain rate. To make the crop growth model more realistic, root depth growth was included in the model to determine plant available water and to place plant water consumption, which was calculated from

daily biomass growth as well as nutrient consumption (Figure 2).

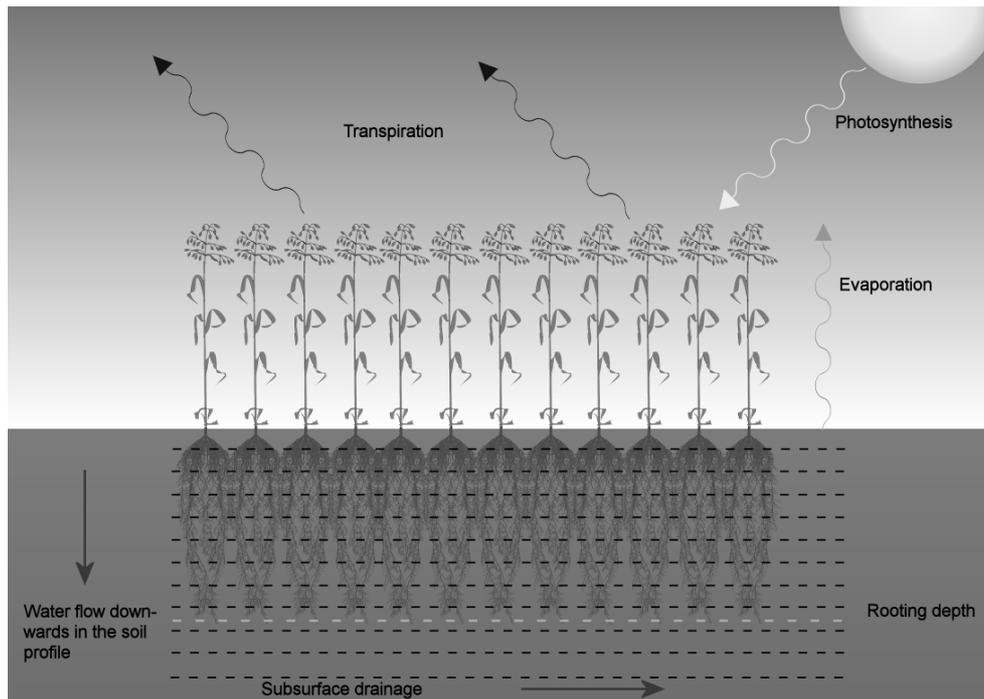


Figure 2 Phenomena considered in the crop growth and soil models

There are also separate models for weeds and diseases, which weaken the plant growth by shading and violating assimilating leaf surface. The disease model structure (Equation (1)) is similar to powdery mildew-wheat, where the growth of disease is affected by relative growth rate (R_c) and temperature that further effects on the reproductivity of the disease (latency period (A_{d-p}) and infectious time (A_{d-p-i})) (Rabbinge et al., 1989). Further the infected leaf area (A_d) can not grow larger than the leaf area of the crop (A_c). The beginning of disease growth is enabled after the leaf area of the crop has begun to expand. The effect on the crop growth is via reduced leaf area used for assimilation.

$$\frac{dA_d}{dt} = R_c \cdot (A_{d-p} - A_{d-p-i}) \cdot \left(1 - \frac{A_d}{A_c}\right) \quad (1)$$

The growth of weeds is enabled at the time of sowing, when the seed bed for cultivated crop is prepared and possibly existing weeds are destroyed by sowing machine. There are separate models for 3 weeds: *Chenopodium album*, *Galeopsis ssp.* and *Viola Arvensis*, which also belong to the most frequent weeds in Finnish spring cereal fields (Hyvönen and Salonen, 2005). The growth of the weeds (Equation (2)) was calculated with the approach presented by Spitters (1989), where several

different weed species are allowed in the same vegetation and they compete for resources with each other as well with the crop. The weed growth rate (dBM_{weed}/dt) is limited by its leaf area (A_w), total canopy leaf area (crop + weed, $A_w + A_c$), incoming solar radiation (R_{solar}) and weeds efficiency to convert radiation to biomass (RUE_{weed}). The seed bank in soil is separately specified for each weed before the start of the simulation and the effect on crop growth is considered as shading the leaves of the crop.

$$\frac{dBM_{weed}}{dt} = \frac{A_w}{A_w + A_c} \cdot (1 - \exp(-0.7(A_w + A_c))) \cdot R_{solar} \cdot RUE_{weed} \quad (2)$$

4.3 Soil model

The soil is separated into 11 equally thick layers (10 cm) as a function of depth (z), which enables setting the initial values separately for each layer. The water flux q ($\text{cm}^3/\text{cm}^2 \text{d}$) is calculated using Darcy's law.

$$q = -K(\phi) \frac{d\phi}{dz} \quad (3)$$

where water potential (ϕ) and hydraulic conductivity ($K(\phi)$) are expressed by

$$\begin{aligned} K(\phi) &= K_s e^{\alpha_K \phi}, & \phi &\geq \phi_{\max} \\ K(\phi) &= a_K (-\phi)^{-1.4}, & \phi &< \phi_{\max} \end{aligned} \quad (4)$$

where, K_s is saturated hydraulic conductivity; ϕ_{max} is a soil water potential limit, α_k and a_k are soil specific parameters (Driesen, 1986; Karvonen and Varis, 1992). The water potential as a function of water content θ (m^3/m^3) is

$$\phi(\theta) = -e^{\sqrt{-\left(\frac{1}{\mu}\right)\ln\left(\frac{\theta}{\theta_s}\right)}} \quad (5)$$

where, θ_s is soil saturated water content and μ is soil specific parameter (Driesen, 1986; Karvonen and Varis, 1992). The parameter values for various types of soils are presented in Table 1.

The water potential and soil hydraulic conductivity are calculated for each layer using Equations (2) and (3). By splitting the soil into thin layers, changes in soil type and properties with depth can be considered and more

realistically evaluated. Vertical water movements are calculated separately for each cell ten times during an hour. The calculation for each layer is rather intensive, but it enables including soil types where water movement is relatively fast. Changes in moisture content in one location and at various depths for loess loam are shown in Figure 3.

Table 1 Parameter values for Equations (4) and (5) (Driesen, 1986; Karvonen and Varis, 1992)

Soil texture class	ϕ_{max} , cm	K_s , cm/d	α_K	a_K	θ_s	μ
Fine sandy loam	-290	12.0	26.5	0.025	0.504	0.0207
Loam	-300	5.0	14.4	0.023	0.503	0.0180
Loess loam	-130	14.5	22.6	0.049	0.455	0.0169
Sandy clay loam	-200	23.5	33.6	0.035	0.432	0.0096
Silty clay loam	-170	1.5	36.0	0.024	0.475	0.0105
Clay loam	-300	0.98	1.7	0.025	0.444	0.0058

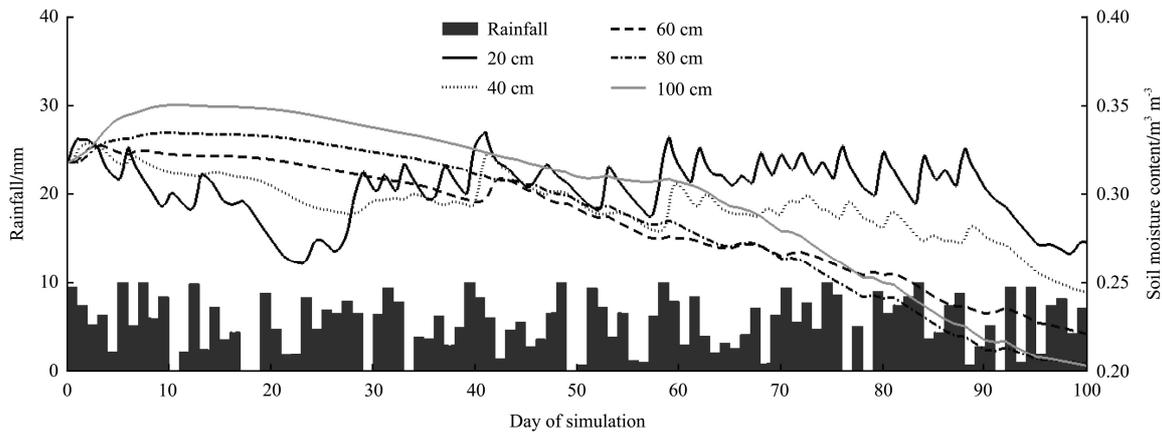


Figure 3 Development of moisture content in one location and at different depths during growth season. The graph begins from the germinated seeds

5 Results

5.1 Sensitivity analysis of for the collection of models

The described models for soil, cultivated crop, disease and three different weeds were put together with Simulink. This collection of models was used in the simulator to describe the events occurring in the fields in site-specific manner. Therefore environment model was implemented in each cell that was defined as a field in the simulator. Because existing models were used they were not evaluated separately but the collection of models in Simulink was evaluated with sensitivity analysis. In the sensitivity analysis the model parameter and input values were increased and decreased by 10% one by one and the model output (crop biomass) was compared to the

output value with original parameter values (Table 2). The crop yield was decreased if parameters effecting on water or radiation availability were decreased (Table 2).

5.2 Full-scale scenario

To test the simulator with a fictitious robotic farm, a farm with five fields was created. The geographical location of the farm was southern Finland and the location of fields and bounding roads and forests is based on a real map. In Figure 4, five fields are presented with solid black boundary lines and the yield at the harvest time is presented. Forests are located on the south east side of two fields, on the right, and in the middle of fields. The forests overshadow the field located on south east, which can be seen as a highly decreased biomass yield. Also minor variations in the yield are mainly due to the

variation in altitude, which leads to variation in solar radiation accumulation.

Table 2 Effects of the most essential parameters and inputs to the model collection for environment simulation. Relative changes (%) in simulated biomass yield in sensitivity analysis

Parameter	Decreased (-10%)	Increased (+10%)
Crop model parameters		
Plant density	-2.4	2.4
Maximum leaf area	-1.9	1.9
Leaf light interception	-1.8	1.9
Radiation use efficiency (RUE)	-2.9	3.0
Soil model parameters		
Soil a_k	-0.6	0.7
Soil α_k	1.6	-1.5
Soil μ	3.4	-2.8
Soil K_s	-1.9	2.2
Inputs		
Rainfall	-1.6	0.0
Solar radiation intensity	-2.9	3.0

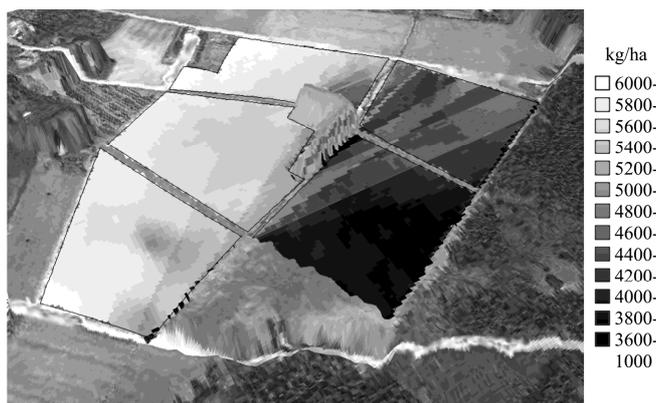


Figure 4 Simulation results for field area of five field plots

The soil properties were generated as described earlier and soil type parameters were generated using Table 1. The initial nitrogen level was 30 kg/ha \pm 25% and the phosphorus level was 14.6 kg/ha \pm 25%. The initial moisture level was set to correspond to the field capacity of the selected soil type.

Sowing with fertilizer placing was done when the soil moisture had decreased below 94% of water content in field capacity for the whole field. For seeding and fertilizing a constant application rate was used. During the growth season fields were operated based on good farming practices i.e. weeds and diseases were controlled site specifically in the locations where they existed. In the next phase, the amounts of herbicides and pesticides

are to be controlled site specifically according to the amount of weeds and diseases, and more advanced operation planning algorithms are to be developed.

In Figure 4, most of the variation for the yield rate is explained by variation in solar radiation, which is caused by the shading of forests during the day. The forests are modelled as non-transparent objects, and the effect on decreasing the solar radiation was computed using ArcGIS Solar Analyst. The solar radiation depends on the date and time as well as cell location in the field. In Figure 4, it can be seen that the yield is remarkably smaller in the areas where forests are located in the south. Due to the non-transparent modelling of forests, the effects of shadows are not smooth.

5.3 Implementation

In the developed AutoCrop simulator, software integration was used to combine the beneficial features of specific simulation and software tools. Two different approaches were attempted for the simulation phase, the first way was to compile a Simulink model to C++ and further to a .NET component and run the simulation using ArcGIS; and the other way was to use Matlab as a simulation engine. It was found that the first one is better even if it takes more time to develop. Simulink is a tool for analyzing and developing time dynamic systems, and it is poorly suited for combined time and spatial simulation. The only way to do this in the case of thousands of spatial cells was to simulate the Simulink model for one cell one step further at time, then change the state data from the other cell and so on. Changing the state data in Matlab seems to take plenty of overhead computing time and besides it was impossible to capture all the state data. The computing efficiency comparison showed that the first approach took only 2% of the computing time required with the Matlab approach.

For the presented scenario with 9000 cells of 5 \times 5 meters, the time step of one hour from the beginning of April to the end of September and with data being stored in the database every other day, it took about 10 hours to compute with a P4@3.2GHz processor. The total computing time depends on grid and time step parameters; by using these parameters the spatial and temporal grid contains about 39 millions of cells and therefore the total

computational time depends heavily on how long it takes to compute one step for each cell. This limits the complexity of models. Based on profiling the computation process, most of the time (over 90%) is spent in soil water model computation, which is done iteratively every hour. However, spatial interactions between cells are calculated at the end of each simulated day.

6 Discussion

The developed AutoCrop simulator is a complete simulation model for a robot farm. The main objective was to support realistic, but not real, spatial variation. This was done by auto generating the field properties for scenarios, by using realistic spatial and value variations; and by counting the shadow areas that are usual in the fields near forest areas. The collection of models describing the environment in the simulator was constructed with Simulink and evaluated with sensitivity analysis. The sensitivity analysis results did not indicate any problems in the realization as the changes in the crop yield were logical to the changes in parameters.

This simulator does not only represent one homogenous field, but several fields with internal variation, which is necessary to study precision farming methods in a farm. This simulation platform combines literature models and creates realistic variations and outputs, ready for studying operational planning and decision making algorithms for field operations. The presented scenario was made only for one growth season. Focusing only on a single season was reasoned by the fact that in southern Finland the winter causes a long time pause for farming and for changes in soil properties it would not be essential to model snowfalls, snow melting etc. Therefore, the start of the season is set to the state where snow has melted and the soil starts to dry. However, this does not limit usage for multiyear simulation, as the initial values for each growth season could be derived from the past season.

The simulator has all necessary parts to study robotic farm operations based on the environment given impulses, measurements and forecasts and the infrastructure of the farm. The weather generation model produces

temperature, rainfall, humidity and solar radiation, and it is based on the hourly data of real weather in southern Finland. Therefore, it is necessary to re-model the weather generation if using in another location. In addition, growth related environment properties in the canopy, like humidity, CO₂ and temperature, may need to be included in the environment as they have a great impact on both transpiration and photosynthesis. On the other hand, every additional sub-model slows the simulation and hinders the usability of the simulator especially when studying farms cultivating large field areas. Still, the purpose of this simulator is to provide a platform for studying robotic farming rather than a simulator capable of handling all details effecting on the crop growth.

The presented results were based on a scenario of a fictitious robotic farm in southern Finland. In this study, the models used are found in the literature and the parameters used in the scenario were chosen to represent the conditions of southern Finland in average, not in any specific location. The literature review and experiences in implementation revealed that there is a need to develop more generic models, as several models were developed to describe the crop growth in a single location (Batchelor et al., 2002; Sadler et al., 2000). Since the spatial variation in crop growth is due the variation in the growth resources the need for spatial processes in crop model is minor but notable e.g. in models describing soil moisture, canopy microclimate, pest and disease growth in spatial dimension. The challenge in case of a crop model is the validity of the crop model parameters since site specific growth simulation is notably different from simulating the mean yield (Sadler et al., 2000). Another issue is the selection of a crop model since different models were found to give different results when used to simulate similar growing seasons (Palosuo et al., 2011; Rötter et al., 2012).

7 Conclusions

The objective was to develop a simulator for the farm environment and to test a robot farm concept to automatize crop farming operations. The created simulator provides a versatile tool for researching

precision farming with an ability to consider the spatial variation in the weather and soil, but also the spatial processes in both the soil and the canopy. In spite of the fictitious farm and randomly generated parameters for soil and altitude variation, the results show that the simulator is capable of handling variations. If measured information about e.g. site and depth specific soil properties exist, those can be placed in the simulator to simulate a real farm.

When compared to the earlier simulators, the ability to combine variation within field, seasonal variation in

weather and capability of GIS program, is notable. These advances create a new aspect for the simulation of management practices and decision making when their effect can be studied more precisely.

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