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MIKKO HAKOJÄRVI

Challenges in Real-Time Precision Farming: A Case Study of Modelling Biomass Accumulation

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Challenges in real-time precision farming: a case study of modelling biomass accumulation

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MIKKO HAKOJÄRVI

University of Helsinki
Department of Agricultural Sciences

ACADEMIC DISSERTATION

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Supervisors: **Docent Mikko Hautala**
Department of Agricultural Sciences
FI-00014 University of Helsinki

Professor Laura Alakukku
Department of Agricultural Sciences
FI-00014 University of Helsinki

Professor Emeritus Jukka Ahokas
Department of Agricultural Sciences
FI-00014 University of Helsinki

Reviewers: **Docent Jouko Kleemola**
Boreal Plant Breeding Ltd.
FI-31600 Jokioinen, Finland

Professor Hans W. Griepentrog
University of Hohenheim
DE-70953 Stuttgart, Germany

Opponent: **Docent Tapio Salo**
Natural Resources Institute Finland (LUKE)
FI-31600 Jokioinen, Finland

Language revision: **B.Sc. Michael Bailey**
Maininkitie 9
FI-02320 Espoo, Finland

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Contents

List of original publications **5**

The author's contribution in the original publications **5**

Abstract **6**

List of symbols and abbreviations **8**

1 Introduction **10**
1.1 Crop growth . . . 11
1.1.1 Resources for crop growth . . . 11
1.1.2 Spatial and temporal yield variation . . . 12
1.2 Crop models . . . 13
1.2.1 Content and the operating environment of the crop models . . . 14
1.2.2 Applicability of the crop models . . . 15
1.3 Precision farming . . . 16
1.3.1 Tools for collecting site-specific information from the fields . . . 16
1.3.2 Possible actions in the fields . . . 21
1.3.3 Crop modelling for precision farming purposes . . . 23
1.3.4 Decision making and future conditions . . . 24

2 Objectives **26**

3 Materials and methods **27**
3.1 C3-biomass accumulation model . . . 27
3.1.1 Photosynthesis and radiation interception . . . 27
3.1.2 The role of water in photosynthesis . . . 31
3.1.3 Soil water and crop water uptake . . . 33
3.2 Field experiments for establishing and evaluating the model . . . 35
3.3 Testing devices for soil moisture content measurements . . . 36
3.4 Evaluation of yield variation using site- and depth-specific soil properties and a crop model . . . 37
3.4.1 Field properties . . . 37
3.4.2 Yield information . . . 39
3.4.3 Yield variation due to the observed soil properties . . . 39
3.5 A simulator for fully automated crop farming . . . 40

4 Results **42**
4.1 Model establishment . . . 42
4.2 Model evaluation in varying radiation, fertilization and precipitation conditions . . . 43
4.2.1 Growing conditions and soil moisture conditions . . . 43
4.2.2 Leaf area development and radiation measurements . . . 47
4.2.3 Simulated and observed biomass accumulation . . . 49
4.3 Devices for soil moisture content measurements . . . 51
4.4 Application of the model in the study of yield variation using site- and depth-specific soil properties . . . 53
4.4.1 Soil properties, observed yields and simulated yields . . . 53
4.4.2 Exceptional yield variation in the fields Jokioinen 1 and 2 . . . 54
4.4.3 Exceptional yield variation in Vihti . . . 56

4.4.4 Temporal standard deviation of the observed yield 57
4.5 Application of the model in a fully automatic crop farm simulator . . 58

5 Discussion 59
5.1 The basis of the model: vegetative growth period and constant parameters 59
5.1.1 Intercepting the radiation, parameters I, n and RUE 60
5.1.2 Crop specific parameters: m_s, SD, LWR and SLA 61
5.1.3 Water-limited biomass accumulation, parameter WUE and soil properties 62
5.2 Measuring the soil moisture content 63
5.2.1 Aspects of soil moisture for cultivation practices 64
5.2.2 Soil moisture and modelling 64
5.3 Reasons for yield variation 65
5.3.1 Field specific variation in Jokioinen 1 and 2 65
5.3.2 Field specific variation in Vihti 66
5.3.3 Temporal standard deviation of yields 66
5.4 Automated crop farm simulator 67
5.5 Further use of the model in enhancing fertilization practices 67

6 Concluding remarks 70

Acknowledgements 71

References 72

List of original publications

This thesis is based on the following publications:

I Hautala, M. and Hakojärvi, M., 2011. An analytical C3-crop growth model for precision farming. Precision Agriculture, 12: 266–279.

II Hakojärvi, M., Hautala, M. and Alakukku, L., 2014. Testing the use of an analytical and mechanistic C3 -biomass accumulation model for precision fertilization. Agricultural and Food Science, 23: 89–105.

III Hakojärvi, M., Hautala, M., Ristolainen, A. and Alakukku, L., 2013. Yield variation of spring cereals in relation to selected soil physical properties on three clay soil fields. European Journal of Agronomy, 49: 1–11.

IV Hakojärvi, M., Hautala, M., Ristolainen, A. and Alakukku, L., 2013. Spatial and temporal yield variation in three different clay soil fields. Agricontrol, 4(1): 196–201.

V Oksanen, T., Hakojärvi M., Maksimow, T., Aspiala, A., Hautala, M., Visala, A. and Ahokas, J., 2014. Environment simulator for studying automatic crop farming. Agric Eng Int: CIGR Journal, 16(1): 217–227.

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The author's contribution in the original publications

Task	Article				
	I	**II**	**III**	**IV**	**V**
Initial idea	Hak, MH	Hak, MH	Hak, LA	Hak	Hak, TO
Planning the experiment	Hak, MH	Hak, MH, LA	LA, AR	LA, AR	-
Conducting the experiment	Hak	Hak	AR	AR	-
Planning the simulation	Hak, MH	Hak, MH	Hak	Hak	Hak, TO, TM, AA, MH, AV, JA
Conducting the simulation	Hak	Hak	Hak, Hau	Hak	Hak, TM, AA
Data analysis	Hak, MH	Hak, MH, LA	Hak, LA, AR	Hak, MH	Hak, TO
The original manuscript	Hak, MH	Hak, MH	Hak, LA	Hak	Hak, TO
Revision of the manuscript	Hak	Hak	Hak	Hak	Hak, TO

AA = Antti Aspiala; AR = Antti Ristolainen; AV = Arto Visala; JA = Jukka Ahokas; LA = Laura Alakukku; Hak = Mikko Hakojärvi; MH = Mikko Hautala; TO = Timo Oksanen; TM = Thomas Maksimow

Abstract

Precision farming is a set of advanced technologies and cultivation practices that aim to enhance crop growing conditions in a site-specific manner. Current machinery offers many technical tools for such actions, but information about when and where it is necessary to use the developed machinery effectively is lacking. Yield maps and different canopy measurements have been used for this purpose but due to changing growing conditions in different years the results have not been as good as expected. The use of crop models has been proposed to combine the effects of growing season conditions and field spatial properties. However, in a timely and spatially variable environment, which a field often is, much information about site-specific growing conditions should be available in order for an advanced crop model to reproduce the site-specific growth in a detailed manner. Unfortunately the information from fields has often been very limited, and insufficient for such purposes. Furthermore the set of precision farming tools and the number of growth factors that can be managed is limited. For these reasons, the knowledge of crop growth limitation by the unmanageable factors could be useful in the decision making for precision farming purposes.

For describing maximal biomass accumulation, a simple crop model was introduced (**I**) and evaluated in this thesis (**II**). The model is mechanistic, and it uses a minimal number of parameters that all are based on physics, chemistry or physiology. The model can be used for calculating the radiation or radiation and water limited biomass accumulation of a C3-crop. A field experiment equipped with continuous measurements was used for model establishment (**I**) and after model establishment the model was evaluated with a field experiment with various radiation, nitrogen fertilization and precipitation conditions (**II**). In both the studies the crop model was found to produce the maximal biomass accumulation when parameter values measured in the experiment were used.

The model was applied in a study evaluating the effects of selected site- and depth-specific soil properties on yield variation on three different clay soil fields located in southern Finland (**III**). The used soil properties (PAWC and K_{sat}) were found to affect maximal biomass accumulation, but only to certain extent. In order to evaluate the effects of selected soil properties under various weather conditions a Monte Carlo method was used with the biomass accumulation model and generated precipitations **(IV)**. The yield variation was evaluated according to temporal mean biomass yield and temporal standard deviation of the biomass yield. The temporal mean yield varied according to the precipitation during the growing season. During growing seasons with low precipitation (<80 mm) the simulated temporal mean yield was on average more than 3.5 Mg ha^{-1} lower than during growing seasons with high precipitation (>180 mm), and was in both cases at the same level as the observed temporal mean yield. By contrast, the temporal standard deviation of the simulated biomass yield was very similar despite changes in the precipitation in each field, and in all cases was lower than the observed deviation.

For studying the use of the model in a spatial environment, the introduced biomass accumulation model was applied in a simulator built for simulating a fully automated crop farm (**V**). The software capable of conducting simulations in a spatial dimension was combined with software capable of simulating the time dimension in order to achieve a simulator capable of handling both dimensions. The biomass accumulation model was an option for a more detailed crop model. The simple structure was found to be feasible for the time consumed for simulations, but the time consumed in crop growth simulation was minor in comparison to the time used in soil moisture simulation.

In addition, the use of continuous soil moisture measurements for measuring the crop water use and further for biomass accumulation was tested. The different results of the two types of sensors used led to wider tests of various soil moisture sensors in laboratory and field conditions. The difference between the sensor reading and observed soil moisture (gravimetric method) was found to be high, which further causes challenges for measuring the soil moisture sufficiently accurately enough for modelling purposes.

According to the results, the crop model was capable of simulating the highest biomass accumulation of the crops used in the experiments. This was the case for all radiation-limited simulations and for most of the water-limited simulations. In a few cases the values of the observed soil properties were found to cause too low biomass accumulation in simulations but in such cases the problem was also present in the comparisons of observed soil properties and observed soil water content during the growing season. For future research with the model, the next phase will be to test the model use in precision farming-related decision making. The structure of the model enables its use with other C3-crops than small grain cereals. Therefore testing of the model with other C3-crops could be performed in future research.

Keywords: Crop model, mechanistic, maximal biomass accumulation, water-limited biomass accumulation, radiation-limited biomass accumulation, physical soil properties, yield variation, precision farming, decision making.

List of symbols and abbreviations

Symbol	Unit	Description
ε_a		Dielectric permitivity (relative)
ψ_m	Pa	Water potential of soil, matric potential
σ_i^2	Mg ha^{-1}	Temporal variance of the yield
θ	m^3 m^{-3}	Volumetric water content
ρ_{H_2O}	kg m^{-3}	Density of water
A	m^{2}plant^{-1}	Leaf area
BM	kg ha^{-1}, Mg ha^{-1}	Biomass
C	1 s^{-1}	Constant, see equation 3
C3-crop		Plants that acquire carbon dioxide through the stomata and first fix the carbon dioxide into a compound containing three carbon atoms before entering the Calvin cycle of photosynthesis.
$C_6H_{12}O_6$		Glucose
CO_2		Carbon dioxide
CV		Coefficient of variation
DOY		Day of year
E	mm d^{-1}	Evaporation
FC	m^3 m^{-3}	Field capacity (ψ_m = -10 kPa)
GNSS		Global navigation satellite system
GPS		Global positioning system
HI		Harvest index
I	W m^{-2}	Intensity of incoming photosynthetically active radiation
I_{sat}	W m^{-2}	The maximum intensity of photosynthetically active radiation that a leaf can use
K_{sat}	cm d^{-1}	Saturated hydraulic conductivity of soil
LAI	m^2 m^{-2}	Leaf area index, crop leaf area divided by land area
LWR		Leaf weight ratio
m_s	mg plant^{-1}	Mass of seedling
M_x	g mol^{-1}	Molar mass of chemical compound x
N		Nitrogen
NUE		Nitrogen use efficiency
PAR		Photosynthetically active radiation, any light that has wavelengths 400–700 nm because it contains photons of blue (400 nm) and red (680 nm) light (Hay and Porter 2006)
PAWC	m^3 m^{-3}	Plant available water capacity
p_{CO_2a}	Pa	Partial pressure of carbon dioxide in the ambient air
p_{CO_2i}	Pa	Partial pressure of carbon dioxide in the leaf
p_{H_2Oa}	Pa	Partial pressure of water in the ambient air
p_{H_2Oi}	Pa	Partial pressure of water in the leaf
PWP	m^3 m^{-3}	Permanent wilting point (ψ_m = -1500 kPa)
R	mm	Precipitation
r_{depth}	m	Rooting depth
r_{growth}	m d^{-1}	Root growth rate
RUE	kg J^{-1}	Radiation use efficiency
S.E.		Standard error
SD	plants m^{-2}	Seedling density
s		Standard deviation

SLA	m^2 kg^{-1}	Specific leaf area
SWC	m^3 m^{-3}	Saturated water capacity ($\psi_m = 0$ kPa)
t	s, h, d	Time
t_0	s, h, d	Time when the crop growth turns from exponential to linear in the crop model
UAV		Unmanned aerial vehicle
WUE	g g^{-1}	Water use efficiency, the ratio of the amount of CO_2 (in g) obtained and of H_2O (in g) transpired by the crop during the gas exchange
Y_i	kg ha^{-1}, Mg ha^{-1}	The yield in year t at site i
$\overline{Y}_t$	kg ha^{-1}, Mg ha^{-1}	The mean yield for the whole field in year t

1 Introduction

The technology used in crop cultivation, as well as in other areas of agriculture, has been under intensive development during the past half century. During their early years tractors were purely mechanical work tools for the farmers (Renius 1999). Today, tractors have evolved from coarse power sources and pulling machines to highly advanced and versatile vehicles, in which the cabin offers the farmer a comfortable working environment. Thanks to the increased size of tractors their workability has increased considerably and less and less people need to be involved with primary production. For example, in Europe 5.3% of the active workforce was employed in agriculture in 2013, whereas the corresponding share was 7.6% in 2003 and 10.9% in 1993 (FAOSTAT 2014). The recent technological development does not concern only the machinery size but also its ease of use, thanks to the increasing amount of electronics for controlling the machinery (Scarlett 2001).

The driver work load has been decreased by using mechatronics in controlling the tractor and its various implements (Freimann 2007). By means of mechatronics it is possible to automate certain prodecures (Auernhammer 2002) while maintaining high field efficiency and precision (Suomi et al. 2006). In the development of tractor and implement cooperation the standard ISO 11783 (market name ISOBUS) has had a significant role. With this standard the tractor-mounted implements are controlled by a single terminal and independently on the implement manufacturer (Freimann 2007; Oksanen 2010). In addition the standard provides a possibility to control the tractor from auxiliary equipment (Oksanen 2010). This function provides additional benefits when it is possible to e.g. optimize the tractor loading according to the power need of the implement (Auernhammer 2001; Freimann 2007; Oksanen 2010), or the implement may use the tractor's facilities (e.g. positioning and auxiliary hydraulic valves) for site-specific operations on the fields (Oksanen 2010; Suomi et al. 2006).

The machinery currently used in crop production can assist the driver by performing a certain portion of the work. During a field operation automated steering can steer the tractor along parallel tracks running through the field with working width spacing (Keicher and Seufert 2000; Reid et al. 2000), or the tractor can perform predefined sequences automatically (also known as headland management) instead of the driver (Suomi et al. 2006). The state of the art in crop production machinery is highly advanced. However, the technological solutions available today make it possible to build even autonomous machines that can perform crop cultivation tasks on the fields autonomously (Blackmore et al. 2004; Grift et al. 2008; Pedersen et al. 2006). Such solutions have already existed for some time (Alakukku et al. 2002; Nieminen et al. 1994) but until today, autonomous field machines or field robots have mainly been used in research (Grift et al. 2008; Oksanen 2010; Tamaki et al. 2013) and currently the most similar commercial solution to a field robot is a semi-autonomous slave tractor that can follow and mimic the work of a human-operated tractor (Zhang et al. 2010).

Automation in agricultural machinery offers many indisputable benefits. However, the use of advanced machinery is a challenge, i.e. how we can use the new properties of farming machinery or autonomous machinery effectively. For overcoming this challenge we must be able to intensify the crop production in a sustainable (ecologically, environmentally, socially and economically) manner. This means that we must be able to increase the crop yield with current input application rates or decrease the amount of applied inputs while maintaining the current yield level, leading to increased profitability and environmental benefits (Auernhammer 2001; Corwin and Lesch 2003; McBratney et al. 2005). Therefore we must be able to allocate the cultivation inputs such as fertilizer or pesticide more efficiently (Asseng et al. 2001; Basso et al. 2011, 2012; Hakojärvi and Hautala 2010; Walsh et al. 2013). For this task the application of new and advanced farming machinery capable of performing site-specific tasks is in a key position when old practices including uniform applications and treatments are to be enhanced (McBratney et al. 2005; Pierce and Nowak 1999; Suomi et al. 2006). Under current practices the outcome is greatly dependent on the farmer; how the crop cultivation is managed or decisions regarding the input or machinery use are made (Adamchuk et al. 2004; Basso et al. 2011; McBratney et al. 2005; Pierce and Nowak 1999). In addition to the new properties in farming machinery, for successful management and effective use of farming machinery, real-time or at least recent information on the crop status and soil conditions are needed in order to be able to estimate the crop's need for growth resources in the near future (Basso et al. 2011, 2012; Hakojärvi and Hautala 2010).

1.1 Crop growth

1.1.1 Resources for crop growth

The three most important growth resources for crop growth are solar radiation, water (H_2O) and carbon dioxide (CO_2), as stated in the chemical equation of photosynthesis:

$$6CO_2 + 6H_2O \xrightarrow{Light} C_6H_{12}O_6 + 6O_2 \qquad (1)$$

The energy used in photosynthesis is photosynthetically active radiation (PAR), the portion of solar radiation with wavelength between 400 and 700 nm which is intercepted by the crop green tissues, in which the leaves play a major role (Hay and Porter 2006; Taiz and Zeiger 1991). The CO_2 for photosynthesis comes from air surrounding the canopy via stomata in the leaves (Hay and Porter 2006; Taiz and Zeiger 1991). The amount of crop available CO_2 can be assumed to be uniform over large areas, but during the past century the CO_2 concentration of air has notably and rapidly increased due to burning of fossil fuels (Porter and Semenov 2005; Taiz and Zeiger 1991). The crop takes water for photosynthesis from the soil with its roots and therefore the soil properties have a major effect on the water availability in addition to the size and density of the root system (Taiz and Zeiger 1991). A smaller portion of water is also needed to construct the plant itself, but the highest portion of water is lost through the stomata while gaining CO_2 from surrounding air through diffusion (Hay and Porter 2006; Taiz and Zeiger 1991). The water is consumed via transpiration during the whole vegetative growth period, i.e. during the time when there is green tissue in the crop conducting photosynthesis (Hay and Porter 2006; Taiz and Zeiger 1991). In addition to the resources for photosynthesis (Eq. 1), temperature and different nutrients also have effects on the crop growth.

The photosynthesis rate of a crop is a parabola-shaped function of the temperature and has an optimum value at which the rate is the highest; when moving away from the optimum temperature the rate is decreased (Hay and Porter 2006; Taiz and Zeiger 1991). Also the availability of different nutrients effects on the growth. The nutrients are divided into micro- and macronutrients according to the quantities they are consumed by the crop (Fageria 2010; Mengel et al. 2001). Nitrogen belongs to the group of macronutrients and is one of the most yield limiting nutrients in crop production worldwide (Fageria 2010; Mengel et al. 2001). Nitrogen can affect the crop growth and yield in three different ways. First, a lack of nitrogen decreases the leaf area and the content of light absorbing green tissue (chlorophyll), which further diminishes the light interception capacity of the leaves and leads to decreased photosynthesis rate

(Hay and Porter 2006; Taiz and Zeiger 1991). Secondly, nitrogen availability during early growth affects the grain number of the coming yield in addition to the photosynthesis (Jenner et al. 1991). Thirdly, before and during the grain filling stage nitrogen availability affects the size and the protein content of the grains (Finney et al. 1957; Jenner et al. 1991; Kraybill 1932; Parameswaran et al. 1981; Spiertz and De Vos 1983).

The crop growth rate in relation to the growth resource availability or crop yield in relation to the resource availability over the growing season can approximately be outlined with Liebig's law, i.e. a wooden barrel filled with liquid (Figure 1). The crop growth rate is defined by the growth resource availability (Figure 1, water level) and in a large scale the lack of one growth resource cannot be compensated by increasing the availability of other resources (although e.g. sodium can replace potassium up to a certain extent (Mengel et al. 2001)). In addition to the resources, there may be other limitations for crop growth, such as weeds that compete for growth resources and pests or diseases that decrease the crop growth by violating the crop itself.

1.1.2 Spatial and temporal yield variation

The availability of growth resources may cause variation in the crop yield in two different ways: yield may vary within a field when the yield is different from one location to another (spatial variation) or the yield in a single location of a field may be different from year to year (temporal variation).

The field specific properties are such features that can be assumed to be static properties of a field that do not essentially change between the years but only in the

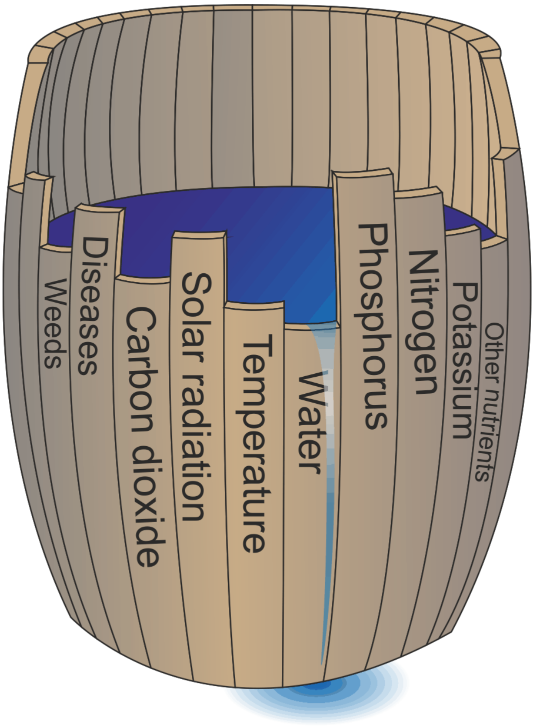


Figure 1: Outline of the crop growth rate or yield in relation to different resources. The planks describe different growth resources and the water in the barrel describes the crop growth rate or ultimately the crop yield.

long run (Kersebaum et al. 2002). Because the fields are not necessarily homogenous areas the field specific properties can be site-specific causing spatial variation in growing conditions within the field. Spatial variation in crop growth or in crop yield can be found from the fields with spatial changes in e.g. soil properties (Basso et al. 2009; Cox et al. 2003; Derby et al. 2005; James and Godwin 2003; Keller et al. 2012; Timlin et al. 2001) or topography (Basso et al. 2009; Godwin and Miller 2003; Hanna et al. 1982; Kaspar et al. 2003; Kravchenko et al. 2005). The crop adapts to the prevailing and site-specific growing conditions, which further leads to spatial variation in the crop appearance, use and need of the growth resources and eventually to the crop yield (Diacono et al. 2012; Wood et al. 2003).

The effect of season specific factors such as growth resources caused by changing weather can be assumed to be homogenous over relatively small areas like single fields but variable in time e.g. during a single growing season or between the seasons. Weather is a challenging source of temporal variation because it cannot be known for the coming growing season and can be predicted reliably only over limited periods. The weather also includes extreme events that may have tremendous effect on the crop growth even up to total crop failure, but such cases can be assumed to be very unlikely although they may be more frequent in the future due to the climate change (Porter and Semenov 2005).

The joint effect of precipitation amount and precipitation timing has been found to be the greatest reason for the temporal yield variation in rainfed production (Basso et al. 2013, 2012; Sadras et al. 2012; Taylor et al. 2003). Although the precipitation sum of two separate growing seasons may be the same, their effect on crop growth and yield may be quite different due to the timing of precipitation. In the case of water, the precipitation effect on crop growth is also dependent on the soil's capability to store water for the crop's use (soil water holding capacity). In limited conditions where precipitation is repeatedly low and water is the most frequent reason for limited growth, the patterns of yield maps from several years can be similar and correlate well with the site-specific soil water holding capacity (Cox et al. 2003; Diacono et al. 2012). However, in many studies on spatial variation the yield pattern has been unstable due to temporal variation due to the weather (Basso et al. 2009, 2013; Blackmore et al. 2003; Cox et al. 2003; Marques da Silva 2006; Taylor et al. 2003; Wood et al. 2003). Therefore the following conclusion in these studies has been that it is necessary to consider also the changes in the growing conditions during the growing season in addition to site-specific soil properties. When the site-specific soil properties are know their effect on the crop growth can be estimated by using crop models and historic weather data (Basso et al. 2011; Timlin et al. 2001), for instance.

1.2 Crop models

Crop growth modelling was initiated before the 1960s when the first mathematical descriptions of photosynthesis were established (see review by Hirose 2005). During the 1960s the photosynthesis models evolved to crop models (de Wit 1965; Monteith 1969) that were used to increase understanding and knowledge of plant growth and the phenomena occuring inside a plant. Later on the focus in modelling studies turned to more practical and operational use of models when they were to be used as tactical or strategic decision support tools or were involved in evaluating different explorative scenarios (Bouman et al. 1996; Hirose 2005). Due to the long history of using crop models in research the most advanced ones are very detailed in the description of crop growth and phenomena inside a crop (Bouman et al. 1996; van Ittersum et al. 2003). Therefore the most advanced crop models provide a versatile and important research tool for studies on understanding the crop behaviour and responses to changes in growing conditions e.g. during climate change (Nendel et al. 2014; Porter and Semenov 2005; Rötter et al. 2011) or different management practices (Miao et al. 2006; Nendel 2009; van Ittersum et al. 2003). However, crop growth is a complex issue and the models are always simplifications of reality which limits their use (Boote et al. 1996; Penning de Vries et al. 1989).

1.2.1 Content and the operating environment of the crop models

The processes involved in the crop model and the way the processes have been presented in the models determine the capabilities and applicability of a model (Boote et al. 1996; Penning de Vries et al. 1989). The crop models, as well as other mathematical models in general, consist of equations that describe certain processes inside the crop in a numerical way (Ahuja et al. 2002; Thornley and Johnson 1990; Wallach 2006b). Such processes include e.g. leaf area development or radiation interception. It is challenging to define the essential processes to be included in the crop model because the crop growth is highly dependent on the soil properties and the processes above and below the ground. The structure of a model varies from one to another because different processes are included in the models and the same process may have been included with different equations depending on the model purpose (Boote et al. 1996; Brisson et al. 2006; Hanks and Ritchie 1991; Jamieson et al. 1998; Mukhtar et al. 2013; Porter et al. 1993; Thornley and Johnson 1990; van Ittersum et al. 2003). This also works *vice versa* and the model structure determines which processes do have an effect on the simulated crop growth when a specific crop model is used. Further this is one of the reasons why different simulation results may be obtained when simulating the same case or scenario with several crop models (Jamieson et al. 1998; Palosuo et al. 2011; Porter et al. 1993; Rötter et al. 2012).

In the equations, parameters and inputs are used in calculating the value for a state variable that is the wanted quantity (e.g. daily biomass accumulation) or a necessary step before calculating the wanted crop quantity (e.g. daily radiation interception) (Penning de Vries et al. 1989; Thornley and Johnson 1990; Wallach 2006b). By definition, a parameter has a constant value over the limited conditions and in the case of crop models a parameter value can depend on the cultivated crop (e.g. harvest index (HI)) or soil type (e.g. water content at field capacity (FC)), for example (Makowski et al. 2006; Wallach 2006b). The crop model inputs, however, have a value that can be updated during the simulation (Thornley and Johnson 1990; Wallach 2006b). The value of the input must be updated at the same rate as the calculation and the rate can be daily (e.g. daily amount of precipitation), hourly (e.g. hourly solar PAR intensity) or even more often if necessary. If a description of a single phenomenon is wanted with the very last detail it is necessary to shorten the time step of calculation in order to increase the accuracy of a discrete model or a section of a model (Penning de Vries et al. 1989). This problem is faced if stomatal closure and opening is to be considered in the photosynthesis model or if rapid flows of water in soil are to be considered in a soil moisture model (Penning de Vries et al. 1989). However, for practical applications of a crop model a daily time step (24 hours) has been found adequate (Penning de Vries et al. 1989). Further, such a property of a model may cause problems in model application for larger areas (e.g. fields), since input values are needed with corresponding frequency and in a site-specific manner (Adams et al. 2000; Boote et al. 1996; Sadler et al. 2002; van Ittersum et al. 2003).

The level of detail in the description of a certain process affects the equation selection. More complex equations are often required for very detailed description of a process, which also often increases the number of parameters involved in the model. When applying the model in other conditions the large number of parameters is disadvantageous since all parameter values must describe the new conditions instead of the ones at the time of model establishment (Boote et al. 1996; Brooks et al. 2001; Thornley and Johnson 1990; van Ittersum et al. 2003; Wallach 2006a). However, for balanced model operation and efficient structure, the level of detail in the description of each phenomenon included in the model has been found essential (Boote et al. 1996; Hay and Porter 2006). Therefore, from the point of view of the crop model output, it is not beneficial to have very detailed description of a single process if all other processes are described with less detail. Further, although complex models include explicit descriptions of various processes in the crop they have not always performed better than the more simple models (Brooks et al. 2001; Jamieson et al. 1998).

1.2.2 Applicability of the crop models

The processes involved in the crop model and the way the processes have been presented in the models determine the capabilities and the applicability of a model (Boote et al. 1996; Penning de Vries et al. 1989). Several different ways have been presented for classifying the models according to their content and structure. One of the most advantageous ways of classifying the models is a division between descriptive and explanatory models. Descriptive models or empirical models have simple structure and the phenomena are described with a few equations (Penning de Vries et al. 1989; Thornley and Johnson 1990). The descriptive crop models are often based on empirical relationships (e.g. regression equations) and are easy to derive for observed cases but are challenging to take into other conditions in which e.g. weather or soil are different from the observed case (Boote et al. 1996; Penning de Vries et al. 1989; Whisler et al. 1986). The explanatory or mechanistic models describe the system with the mechanisms and the processes included in the system (Penning de Vries et al. 1989; Thornley and Johnson 1990; Whisler et al. 1986). Therefore the crop growth in the explanatory models is a consequence of the underlying processes and mechanisms that need to be quantified separately before the model can be established (Penning de Vries et al. 1989). The strength of an explanatory crop model is the model applicability in other growing conditions (than where the model was established), but only as far as the assumptions for the selected equations are valid for the new conditions (Penning de Vries et al. 1989; Thornley and Johnson 1990). Regardless of the classification, explanatory models often also include aspects of descriptive models because it is not beneficial to include a very detailed description of a phenomenon if the effect on the model output is minor (Penning de Vries et al. 1989).

Generally crop models can be used in varying conditions by changing the values of the parameters and inputs for others corresponding to the environmental conditions in the studied situation (Hay and Porter 2006; Penning de Vries et al. 1989; Thornley and Johnson 1990; Wallach 2006a). This procedure is called evaluation where model performance in new conditions is evaluated (Thornley and Johnson 1990; Wallach 2006a). When the model is taken to new conditions the values of parameter and inputs must be changed to represent the new conditions. In some cases the word calibration is used to describe the process of searching correct values of the model parameters (Penning de Vries et al. 1989; Thornley and Johnson 1990). After the right values for parameters in new conditions have been found the model performance is investigated that is a procedure that can be called validation (Penning de Vries et al. 1989; Wallach 2006a). In detail, the validation refers to a check if the model is suitable for attended purposes or not and is therefore also dependent on the study where the model is going to be used (Penning de Vries et al. 1989; Wallach 2006a). The model performance is rated according to the comparison of the model output (and values of possible state variables) and corresponding observed values (Penning de Vries et al. 1989; Thornley and Johnson 1990; Wallach 2006a). The result of this whole process (evaluation) is an estimate of the model performance in new environment or conditions (Thornley and Johnson 1990; Wallach 2006a). Therefore model evaluation is something that should follow the model over its lifetime rather than a procedure that is done only once at the time of model establishment (Thornley and Johnson 1990; Wallach 2006a). All together, the model must include the essential processes and the parameters involved must have appropriate values corresponding to the crop and growing conditions under investigation.

1.3 Precision farming

The yield variation, whether spatial or temporal, is a challenge in crop cultivation when uniform and predefined applications are often-used cultivation practices on the farms. The new farming machinery with capabilities for site-specific actions is one suggested solution to focus the use of farming inputs (Auernhammer 2001; Earl et al. 2003; McBratney et al. 2005; Pierce and Nowak 1999; Suomi et al. 2006). Precision farming or precision agriculture are titles that in the case of crop cultivation combine the use of the most advanced available technologies with the aim to develop more crop oriented cultivation practices. Definitions for these terms vary but McBratney et al. (2005) defined precision agriculture as agricultural production in which the quantity or quality of production is increased and environmental impact is lowered along with the same or decreased inputs. Precision farming has been defined as a concept that uses all available methods for improving the growing conditions of the crop, focusing on the site-specific issues of farming (Blackmore 2003; Pierce and Nowak 1999). The definition of McBratney et al. (2005) highlighted the importance of decision making in both space and time but the major message of both definitions has been the cultivation targeting to more crop oriented farming in comparison to existing cultivation methods (Blackmore 2003; McBratney et al. 2005; Pierce and Nowak 1999). Later in this thesis the term precision farming is used and is defined as a concept of different methods aiming towards crop cultivation based on the plant needs and acknowledging the importance of both space and time dimensions.

The precision farming problemacy is outlined in Figure 2. The first and essential issue is the site-specific information, about the crop current state and growing conditions. After receiving this information the necessity of available actions can be evaluated. However, there are only a few possible actions that can be made during the growing season in rainfed crop production. In addition, there may be other restrictions such as profitability of the action or regional regulations (e.g. environmental regulations) concerning the application level or timing of the application.

1.3.1 Tools for collecting site-specific information from the fields

The early development of precision farming was strictly bound with the development of global navigation satellite systems (GNSSs), mainly the global positioning system (GPS), as it provided a practical tool for recording site-specific crop yields for the first time in history (Auernhammer 2001; Blackmore 2003). For precision farming purposes the development of positioning techniques was not the only key solution but progress in other fields of electronics such as sensors and computers has also provided the keys for conducting the measurements and processing the collected data to site-specific infor-

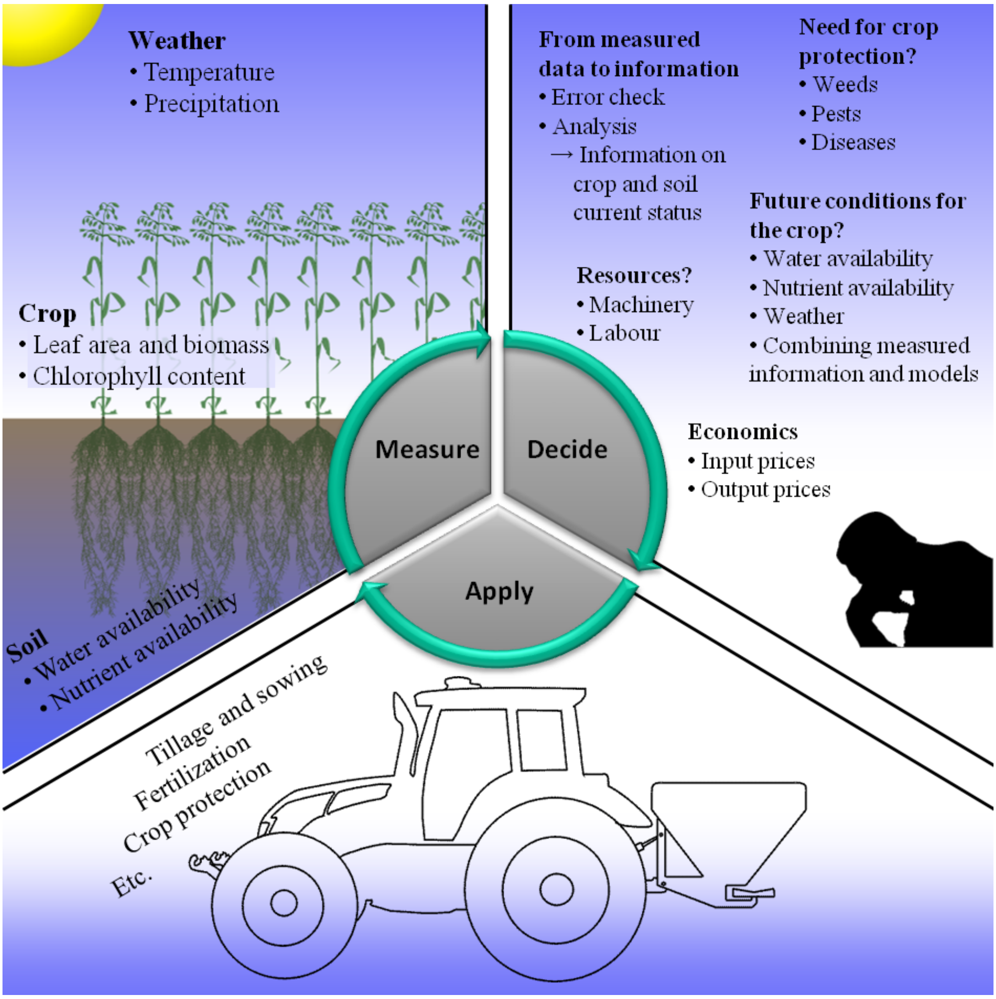


Figure 2: The basis of precision farming; measuring the crop current state, evaluating the necessary action and possible site-specific applications according to the decision made.

mation (Auernhammer 2002; Pierce and Nowak 1999). Site-specific yield measurement in combine harvesters (also called a yield monitor) is a good example of using advanced techniques (at that time) for precision farming purposes (Auernhammer 2001; Pierce and Nowak 1999). The yield monitor was a state of the art technology in the beginning of the 2000s (Auernhammer 2001) and the first practical tool to provide numeric information about spatial yield variation within a field (Blackmore 2003). The yield monitoring devices provide valuable information from the site-specific yield but even today the use of yield maps to fulfill the aim of precision farming is hindered by the fact that the spatial yield pattern has been found to vary from year to year (Blackmore 2000; Blackmore et al. 2003; Godwin et al. 2003). Therefore it was concluded that the yield maps cannot be directly used as application maps (e.g. for fertilization) during the following growing season. Later attempts to use GPS in precision farming have focused on various measurements of the crop growth, soil properties and growing conditions during the growing season.

On-the-go-measurements The soil and crop properties indicate the current growth conditions and their effect on the crop, respectively. The most practical way of obtaining information on these factors is different measurements that are conducted during some of the mandatory field practices (on-the-go measurements) (Adamchuk et al. 2004; Schmidhalter et al. 2008). When the on-the-go measurement is conducted in this way, the amount of additional work required is very low but the information availability is limited to the time of application.

In most cases measuring the soil on-the-go requires a contact between the soil and the instrument or sensor and has therefore been conducted during soil tillage practices (Adamchuk et al. 2004; Schmidhalter et al. 2008). The measurement of soil mechanical resistance has been one of the few direct measurements on the soil. Soil mechanical resistance can be measured with load cells or strain gauges that provide a robust and cost effective solution as they can easily be connected to data acquisition equipment systems and the measurement can be made in real-time, e.g. during tillage operation (Adamchuk et al. 2004). The measurement result is dependent on several factors such as the soil type, bulk density and moisture content, which makes the use of measurement results challenging (Adamchuk et al. 2004). However, if the information on soil compaction can be extracted from the measured mechanical resistance the information can be used to estimate the crop root growth, soil porosity and water conductivity in the measured field (Adamchuk et al. 2004; Keller et al. 2012).

In most on-the-go soil measurements the soil has been measured with indirect measurements e.g. by measuring mechanical, electrical and spectral properties (Adamchuk et al. 2004; Corwin and Lesch 2003; Mueller et al. 2003). In these studies the disadvantage of the indirect soil measurements has been the need for calibration that in many cases is at least soil specific. The soil electrical inductance, capacitance and resistivity or conductivity are dependent on soil physical (e.g. texture, structure, strength and moisture) and chemical characteristics (e.g. pH, salinity and nutrients) (Adamchuk et al. 2004; Mueller et al. 2003; Schmidhalter et al. 2008). These measurements have been used to determine the water and nutrient availability of nutrients for the crop roots but because the measurement results are simultaneously dependent on several soil properties (e.g. moisture and ion content), the use of measurement results has been challenging (Adamchuk et al. 2004). In addition to the soil electrical measures, the reflectance of visible and infrared wavelengths from soil has been used in several studies. Soil properties including moisture (Kaleita et al. 2005; Sudduth and Hummel 1996), organic matter content (Ehsani et al. 1999; Schmidhalter et al. 2008; Selige et al. 2006; Sudduth and Hummel 1993), clay content (Selige et al. 2006; Sørensen and Dalsgaard 2005) and nitrate content (Ehsani et al. 1999) have been measured by using a single wavelength or combination of several selected wavelengths (Adamchuk et al. 2004).

Common to all these on-the-go measurements is that the results are dependent on several soil properties (Adamchuk et al. 2004; Corwin and Lesch 2003). Because several factors affect a single measured quantity the results are often field specific or at least soil type specific. A solution for this problem has been searched from combining several measurements (e.g. using conductivity and capacity measurements for measuring the soil moisture content) for retrieving information on several soil characteristics, when it may be possible to exclude some factor that is also affecting the quantity under interest (Adamchuk et al. 2004; Corwin and Lesch 2003). Soil moisture is very often present in the results and one way to avoid the effect of water on the measurement results is to conduct the measurement at the time when moisture content is equal within the measured area (Earl et al. 2003). More information about various possible on-the-go measurement techniques for gathering site-specific information on soil is available e.g.

in Adamchuk et al. (2004), Corwin and Lesch (2003), and Schmidhalter et al. (2008).

Many approaches and devices for on-the-go measurements on canopy have been suggested and presented in previous studies. The crop leaf area, biomass and nutrient status were among the first approaches in on-the-go canopy sensing (Reyniers et al. 2004; Schmidhalter et al. 2008). The crop biomass has been measured with a mechanical pendulum sensor (angle measurement of a pendulum that is guided through the crop canopy at constant height from the ground) (Ehlert et al. 2004; Schmidhalter et al. 2008), or it has been estimated from the canopy height and density measured with an ultrasonic sensor (Portz et al. 2013; Scotford and Miller 2004a,b). The canopy cover has been measured with digital image analysis that usually produces canopy area in relation to the ground area (Reyniers et al. 2004). The recent crop measurement solutions have been based on spectral reflectance measurements that have been further converted to e.g. crop leaf area, crop density, biomass and nitrogen concentration (Portz et al. 2013; Schmidhalter et al. 2008; Scotford and Miller 2005). In the spectral measurement the reflection of wavelengths 400–500 nm (blue) and 600–700 nm (red) is decreased with increasing amount of biomass or concentration of absorbing constituents, whereas the reflection in the spectral region of 500–600 nm (green) and >700 nm (near-infrared) is increased with increasing biomass (Schmidhalter et al. 2008; Taiz and Zeiger 1991). The spatial variation in these properties indicates variation in the current crop growth that may further lead to yield variation but gives a possibility for site-specific actions if the measurement is conducted early enough. The canopy temperature measurement has also been used for the early detection of lacking water because the lack of water forces the crop to decrease the transpiration, leading to an increase in canopy temperature (e.g. Blum et al. 1982; Huband and Monteith 1986; Tilling et al. 2007). More information about different possible on-the-go measurement techniques for gathering site-specific information on crop canopy is available in Reyniers et al. (2004) and Schmidhalter et al. (2008).

Remote sensing One solution for measuring large areas with relatively low effort is a technique called remote sensing. In remote sensing, the spectral properties of soil surface or crop canopy are retrieved via aerial or satellite imagery (Adamchuk et al. 2004; Moran et al. 1997; Pierce and Nowak 1999; Reyniers et al. 2004; Schmidhalter et al. 2008). Crop properties such as crop biomass, nitrogen content and nitrogen uptake can be observed through reflectance-based measurements in the same manner as in on-the-go measurements (Adamchuk et al. 2004; Laurila et al. 2009; Schmidhalter et al. 2008). Remote sensed visible and near-infrared wavebands can be used to measure the soil moisture content (Kaleita et al. 2005) but also to determine the organic matter and clay contents of the soil, respectively (Schmidhalter et al. 2008; Selige et al. 2006; Wetterlind et al. 2008).

The challenge in remote sensing through aerial or satellite imagery is the varying weather that limits the time when the measurement can be conducted because clear sky and even radiation conditions are required for successful operation (Moran et al. 1997). This is a clear limitation in northern latitudes where the cloudiness is intensive during growing seasons although information on microwave wavelengths can be acquired despite the clouds (Laurila et al. 2009). Atmospheric correction is also often required e.g. for aerial or satellite imagery before the gathered data can be actually used (Moran et al. 1997). For measuring the soil properties, the remote sensing with aerial or satellite imagery is even more limited because only the top soil layer can be measured and the measurement must be conducted when the soil is bare (no vegetation or crop residue covering the soil surface) (Adamchuk et al. 2004; Moran et al. 1997).

In addition to the challenges caused by weather, the cost is another issue in remote sensing. Technically, sensing can be conducted in several different ways (e.g. with satellites, aeroplanes or unmanned aerial vehicles (UAVs)), but the cost is dependent on the treated area and on the used sensing technique. For example, in the case of aeroplane sensing the cost is high if the area for survey is sparse and scattered over a wide area. Recent developments in UAVs, especially in multi rotor copters, provide a cost-effective solution for obtaining information with high spatial and temporal resolution for research purposes (Berni et al. 2009; Everaerts 2008; Honkavaara et al. 2012). With multi rotor copters, or other UAVs, it is technically possible to arrange the sensing (in a scouting manner) with an autopilot, as a result of which less human labour is needed for completing the task and expenses are reduced (Berni et al. 2009). However, there is always some human labour involved in the task and it remains to be seen whether the relative cost of covering large areas (e.g. all the fields of a single farm) is low enough to make this technique widely applicable by the farmers.

Sampling, manual and continuous measurement in the fields Sampling and conducting manual measurements are versatile approaches because almost all possible quantities can be measured from the soil or the crop. However, acquiring spatial information requires several measurements made or samples collected from a single field. Therefore the amount of work required in this approach is considerable and the approach is inappropriate when high spatial resolution is required.

Despite the high labour demand and cost of sampling or manual measurement, for some quantities they can be the only options. For this reason, ways to reduce the necessary number of samples from a specified area have been developed in order to limit the economic and labour cost while maintaining the necessary resolution in spatial dimension. Solutions for optimizing the number of samples have been searched from measurements of such quantities that correlate strongly with the wanted quantity but are easy to measure over large areas. In the case of soil sampling the measurement of soil electrical properties has been widely studied (Earl et al. 2003; Godwin and Miller 2003; Lesch 2005). For other important quantities that requiring sampling, the necessary spatial information for optimizing the sampling can be obtained e.g. via remote sensing (Fitzgerald et al. 2006; Lesch 2005) or different on-the-go-measurements (Adamchuk et al. 2011). Various algorithms can be used to further process the spatially observed data in order to place the samples to a field in the most effective way (Adamchuk et al. 2011; Brus and Heuvelink 2007; Fitzgerald et al. 2006; Lesch 2005; Minasny et al. 2007) i.e. to gain maximal representativity with minimal number of samples. In addition to the spatial representativity, with the algorithms the range and variation in the spatially observed data can be considered (Adamchuk et al. 2011; Brus and Heuvelink 2007; Fitzgerald et al. 2006; Lesch 2005; Minasny et al. 2007). However, an essential requirement for using the approach is the correlation between the quantity to be sampled (or manualy measured) and the spatially observed data (Fitzgerald et al. 2006; Brus and Heuvelink 2007; Lesch 2005).

A single sample or measurement includes only the information about the crop or soil current state but in many cases information about the development of the specific quantity is needed for making a conclusion about the state, direction or speed of a phenomenon for decision making purposes. To be able to capture some of the above-mentioned properties of a phenomenon, several measurements during a specific time are required and the amount of work necessary becomes inappropriately high.

Some of the manual measurements can also be conducted in a continuous manner. In continuous measurement systems the sensor is installed permanently to a desired location and usually connected by wire to a datalogger that collects the data from the connected sensors at a specified time interval. Because the measurement is conducted unattended, only sensors that do not require human assistance or operation can be used. Although the quantities that can be measured continuously are limited, many properties of soil (e.g. moisture, temperature and electrical conductivity) and crop canopy (e.g. air temperature, humidity, carbon dioxide concentration and canopy temperature) have been measured in field conditions (e.g. Irmak 2010; Knuutila et al. 2011). Spatial resolution of continuous systems is limited according to the location and the number of the sensors used and measurements take place only at certain locations to keep the cost of the system on a reasonable level. However, the autonomous measurement systems provide valuable information when placed on sites describing the most extreme conditions in the field (high and low yielding or high and low altitudes, for instance).

In addition to wired systems, wireless solutions also exist. In the wireless systems independent devices (called nodes) are conducting the measurement. The nodes are part of a sensor network in which the information is sent directly (single-hop) (Tiusanen 2013) or through other nodes in the network (multi-hop) to the device that saves the information or sends it further to be saved (Pierce and Elliott 2008). In most solutions the nodes include an aerial part for transmitting and receiving the signal but in one solution (Soil Scout$^{\mathrm{TM}}$) the nodes can operate totally below the ground (Tiusanen 2013). The challenges with the wireless measurement systems concern the working range of the nodes and the power delivery. In order to operate over a specified time period each node needs a certain amount of energy that is dependent on the transmission power required for operating over the required distance, taking into account the fact that vegetation also increases the power consumption to some extent (Tiusanen 2009). Pierce and Elliott (2008) used solar panels to power the sensor network nodes but faced problems during the times with low solar radiation. The energy consumption can also be decreased with aerial antenna (Tiusanen 2009), but this is disadvantageous in field conditions because the nodes must be avoided during the field practices. Fortunately the energy consumption and the range can be regarded as solvable technical challenges. Completely buried nodes have a life cycle at least up to a decade (theoretically 42 years) with a 2500 mAh battery, with a range of up to 300 m depending on the soil type (Tiusanen 2013). With this kind of solution it is possible to increase the spatial density of the devices measuring soil properties with reasonable effort, although the challenges in the canopy measurements remain.

1.3.2 Possible actions in the fields

Depending on the cultivated crop, a limited set of actions is available for enhancing the growing conditions or to enhance the use of cultivation inputs. Spatial dimension sets limits for crop growth at two different levels. In large spatial scale the geographical location (climate region, radiation conditions, soil properties) determines the growing conditions for crops cultivated on the fields and limits the set of suitable crops for field production. Furthermore the conditions may vary in a small scale, such as between different fields or within a single field, according to the site-specific properties of that field (soil properties (Asseng et al. 2001; James and Godwin 2003; Keller et al. 2012; Kravchenko et al. 2005; Timlin et al. 2001), topography (Basso et al. 2009; Godwin and Miller 2003; Hanna et al. 1982; Kaspar et al. 2003; Kravchenko et al. 2005) and the changes in radiation intensity and micro-climate due to the topography (Godwin and Miller 2003; Kravchenko et al. 2005)). In the reasons for temporal variation, the weather has been found to be one of the major determinants of the growing conditions, especially the combined effect of amount and timing of the precipitation (Basso et al. 2012, 2013; Sadras et al. 2012; Taylor et al. 2003). These all are factors that are technically or economically challenging factors to be adjusted over fields. Therefore technical solutions such as irrigation (e.g. basin, furrow, border, sprinkler and drip irrigations) and mulch are used mostly when the crop water supply through precipitation and soil storage capacity is insufficient or when the yield value is high enough to cover the costs of providing the lacking water through irrigation (Brouwer et al. 1988). In the case of water, for example, the availability for the crop is dependent on the amount and timing of the precipitation, the crop root system, soil storage capacity and soil hydraulic conductivity. Therefore it is possible that the need of the crop for additional water is varying spatially and in such conditions site-specific irrigation has been found to be a feasible action during years with low precipitation (Bronson et al. 2006). This causes a need for site-specific irrigation that is technically possible but challenging and expensive to arrange (Bronson et al. 2006). Fortunately water availability can be affected with drainage and cultivation practices upto certain limits.

Excluding the organic crop cultivation practices where two or more crops are often cultivated at the same time, most often the crops are cultivated one crop at a time. In such production all other plants existing on the fields are considered as weeds that are competing for the growth resources above and below the ground (e.g. water, nutrients, PAR, CO_2) and may further lead to diminished growth of the cultivated crop and inefficiently used cultivation inputs. Site-specific weed control has already been conducted in research in which weed detection and herbicide application control (site and amount) have been combined, and notable savings in the herbicide amount have been achieved without decreasing the control application effect (Gerhards 2013; Slaughter et al. 2008; Weis et al. 2008). The site-specific resolution has been developed down to a level of cropping systems that enable individual plant care (Griepentrog et al. 2003). In some studies the herbicide application has been replaced with mechanical weeding or thermal weed control methods, when no herbicide is needed and herbicide resistant weeds are also destroyed (Slaughter et al. 2008; Weis et al. 2008). Sprayers capable of site-specific application for controlling weeds have been developed and used (Tian et al. 1999) but the use of such machinery is not straightforward due to challenges in the site-specific identification of the diseases and pests. Because the tools for enhancing crop control with site-specific actions do exist the topic is not further considered in this thesis.

The studies conducted in the area of precision farming have concerned the possible site-specific actions on the fields including tasks suc as soil tillage (Heege 2013c), sowing (depth and seeding density) (Heege 2013d), fertilization (nutrients and lime) (Heege 2013b) and crop control (Gerhards 2013; Thiessen and Heege 2013). However, most often the research has been focused on the use of fertilizer (Auernhammer 2001). The interest is consistent because the fertilization is not only a notable economical input for the farmer (Basso et al. 2011; Godwin et al. 2003; Welsh et al. 2003a,b) but also a potential source of environmental loading (Barbieri et al. 2008; Basso et al. 2011; Walsh et al. 2013). In addition the nutrients must be provided for the cultivated crop during every growing season. Enhancing the fertilizer use is challenging because the crop nutrient demand is dependent on the growing conditions, which vary according to the weather (Diacono et al. 2012; Ferguson et al. 2002; Godwin et al. 2003; Pierce and Nowak 1999; Walsh et al. 2013), especially precipitation timing and amount (Basso et al. 2012, 2013; Sadras et al. 2012; Taylor et al. 2003). The nitrogen use efficiency (NUE, the yield per amount of applied fertilizer) has been increased with so called split application in which the fertilizer dosage is divided into two or more applications (e.g. Alcoz et al. 1993; Basso et al. 2011; Esala 1991; Fischer et al. 1993; Hakojärvi and Hautala 2010; López-Bellido et al. 2006; Peltonen 1995; Peltonen et al. 1995).

With this kind of application the crop growth until the time of application and the weather over the predictable time can be considered in the sizing of the applied dosage that further can be site-specific if necessary (Basso et al. 2011; Hyytiäinen et al. 2011; Olesen et al. 2000; Raun et al. 2002; Shanahan et al. 2008). Although split application is a good step forwards the information about the crop current state is required for evaluating the current growth, and the uncertainty of upcoming weather is inevitably a challenge in dosage sizing (Lobell et al. 2004; Shanahan et al. 2008).

1.3.3 Crop modelling for precision farming purposes

The adaptation of cultivation practices according to the crop growth variation in time and space are the general challenge in precision farming (Pierce and Nowak 1999). The majority of crop models were created to increase the understanding of the crop itself and therefore they describe the crop growth in a point-based manner considering only the variations in a vertical direction and assuming the crop to stand in a spatially homogenous area (Batchelor et al. 2002; Sadler et al. 2000, 2002). Therefore the crop models face a new kind of challenge in fields where the growing conditions for some reason are not equal in each location on the field and there is variation in the crop appearance and yield (Diacono et al. 2012; Lark et al. 1998; Wood et al. 2003). In previous studies, yield variation has been found to include various factors differing with their effect from site to site (Kersebaum et al. 2002; Sadler et al. 1999; Blackmore et al. 2003). In many cases the reason for spatial yield variation has been searched from soil properties, such as soil type (Earl et al. 2003; Godwin et al. 2003; Godwin and Miller 2003; James and Godwin 2003; Lark et al. 1998; Taylor et al. 2003), water holding capacity (Blackmore et al. 2003; Cox et al. 2003; Godwin et al. 2003; Timlin et al. 2001) and saturated soil hydraulic conductivity (Keller et al. 2012). Especially surface flow and lateral subsurface flow have been speculated to have a great effect on the soil moisture conditions and on crop growth (Sadler et al. 2002). The significance of dimensionality is presumably field dependent, as e.g. the topography impact on crop yield has been found to vary from field to field (Basso et al. 2009; Godwin and Miller 2003; Kersebaum et al. 2002; Kravchenko et al. 2005). Further the relevant spatial processes can be limited to only a few specific processes such as water redistribution in a spatial dimension (Basso et al. 2009; Green and Erskine 2004; Hanna et al. 1982; Kravchenko et al. 2005).

Despite the limitations in modelling the processes in the horizontal dimension, the results have been improved in some cases by increasing the spatial density of the input data (Karlen et al. 1990; Sadler et al. 1999; Steinwand et al. 1996), which is a result that commonly can be expected when using the mechanistic (or deterministic) models (Kersebaum et al. 2002). The spatial information about the field properties is often limited, which may be a limitation for obtaining the necessary information for defining the site-specific values for model parameters. The limited availability of parameter values causes challenges in utilizing the full capacity of the most advanced crop models and generating the spatial yield variation in the very last detail, that necessarily requires site-specific values for several inputs and parameters (Sadler et al. 2002). On the one hand, the spatial resolution of field information must be high enough to cover the spatial changes in the field properties (e.g. soil type) (Batchelor et al. 2002; Pierce and Nowak 1999; Sadler et al. 2002; van Ittersum et al. 2003) and therefore the lower limit for spatial resolution is dependent on the field. On the other hand, there is basically no need for data with higher resolution than can be managed (e.g. the part of the working width that is not adjustable) and therefore the highest theoretical upper limit for spatial resolution is dependent on the machinery used for crop cultivation. Fortunately, some of the parameters (e.g. soil texture or field topography) have been found to be sustainable in time when their measurement is required only once (Godwin and Miller 2003; Kersebaum et al. 2002; Heege 2013a), although unavoidably there are some parameters or input values that require more frequent measurements (e.g. soil nutrient status).

For site-specific growth modelling it is essential that the crop model is sensitive to its parameters and inputs (Kersebaum et al. 2002). However, in some cases the number of significant parameters has been found to be far less than the total number of parameters involved in the models (Brooks et al. 2001; Ruget et al. 2002; Sadler et al. 2002; Wallach et al. 2001). Some studies have even shown that the description of a phenomenon can be better with a model including a low number of the parameters (Boote et al. 1996; Brooks et al. 2001; Sinclair and Seligman 1996). The high number of parameters in crop models has been discussed critically (Baker 1996; Monteith 1996; Passioura 1996; Sinclair and Seligman 1996) and a common outcome is that the level of detail depends on the intended use of the model. Basically, it has been found possible to reduce the number of the crop model parameters without losing the essential sensitivity of the model (Brooks et al. 2001). In this way the number of the necessary site-specific measurements is decreased, which would be advantageous for the model use in research and in practical farming applications (Sadler et al. 2002).

1.3.4 Decision making and future conditions

Many different tasks, routines and actions have been suggested to be used in precision farming with the common purpose of enhancing the growing conditions of the cultivated crop in a site-specific manner. In past studies various approaches to consider the spatial variation in growing conditions have been evaluated. Several attempts have been made to divide the field into smaller homogenous areas, called management zones, based on e.g. site-specific soil properties (Ferguson et al. 2002; Fleming et al. 2000; Fridgen et al. 2004; Miao et al. 2006; Shanahan et al. 2008) or yield maps from previous years (Basso et al. 2013; Blackmore et al. 2003; Welsh et al. 2003a,b). Furthermore, the management zones have been the basis for several suggested site-specific crop management strategies (Basso et al. 2011; Batchelor et al. 2002; Blackmore et al. 2003; Godwin et al. 2003; Shanahan et al. 2008; Welsh et al. 2003a,b). However, in the studies on management zones it was found that the areas delineated according to the yield level may not necessarily be temporally stable (Basso et al. 2009, 2013; Blackmore et al. 2003; Cox et al. 2003; Marques da Silva 2006; Wood et al. 2003). This result has led to a search for factors causing yield variation in addition to existing and known spatial variation in the field properties.

A specific action has a beneficial effect on a crop growth only if the growing conditions are enhanced with the action. This has been found in fertilization experiments in which the effect of nitrogen fertilizer has decreased with decreasing amount of crop available water (e.g. Adams et al. 2000; Angus and Fischer 1991; Asseng et al. 2001; Basso et al. 2012; Hancock et al. 2011; Olesen et al. 2000; Sadler et al. 2000). Therefore, the first challenge is to determine the minimum growth resource that is limiting the growth (Auernhammer 2001; Basso et al. 2011; Pierce and Nowak 1999). In order to identify the limiting growth resource in a certain field and at a certain time, information and preferably real-time information about the current crop growth is required. The task is challenging because the growth is dependent on many factors (Figure 1) and the information is needed in a site-specific manner (Basso et al. 2011; Pierce and Nowak 1999). Only after determining the minimum growth resource is it possible to evaluate the effect of a specific resource. The set of available actions is often limited;

for example in the case of rainfed production if the growth limiting factor is water the growth conditions cannot be enhanced by fertilizer application (Auernhammer 2001; Basso et al. 2011, 2013; Hancock et al. 2011) but only by irrigation (which may not be available in all cases). Lawless et al. (2008) highlighted this problem well in their simulation study on nitrogen fertilization and soil moisture, in which they concluded that it is impossible to simulate the effects of different nitrogen fertilization levels without knowledge of soil moisture characteristics.

A further issue after resolving the necessary action is the decision on conducting the action. In the decision making there are practical things to consider, such as that the field must be trafficable with the required machines and the wind must be low enough for spraying tasks, for example. Another common challenge for all solutions concerning precision farming actions is the economical feasibility of the action, for example in crop protection the cost of an action must be lower than the possible economical loss due to decreased yield (Godwin et al. 2003; Miao et al. 2006; Pierce and Nowak 1999). Perhaps the most challenging factor in the decision making process is the future conditions, that are not known at the time of decision making but can be predicted over a certain time. The future conditions can affect the time when the action must be taken and whether it is needed. For example decreasing soil water content may indicate a need for irrigation but an upcoming rainfall in the near future may cancel the need for irrigation. In particular, the temporal variation, including the future conditions, is the unknown and unpredictable variable that makes the use of spatially stable field properties (Ferguson et al. 2002; Fridgen et al. 2004; Kravchenko et al. 2005), yield history (Basso et al. 2012; Blackmore et al. 2003; Welsh et al. 2003a) or both (Godwin et al. 2003; Miao et al. 2006) as a basis for site-specific field actions very challenging and is the major challenge in developing current precision farming practices. Therefore current precision farming practices should be reinforced with real-time components that means including more tools related to achieving information on current crop conditions and growth. The measurements should be conducted preferably in real-time or at least close to real-time in order to produce the most recent information for adjusting the necessary action made to enhance the growing conditions of the cultivated crop. In addition to the real-time measurements the crop models could be used as a decision support tool in order to e.g. estimate the current crop state or near future growing conditions based on the measurement results.

2 Objectives

In previous studies it has been shown that the spatial pattern of a yield varies between years (Blackmore et al. 2003; Godwin et al. 2003), indicating that the best and worst yielding areas of a field are not necessary located in permanent positions. Although the yield maps produce valuable information about the spatial yield variation during different growing conditions, it has been found impossible to use them directly, e.g. as fertilizer application maps during the next growing season (Basso et al. 2012; Blackmore et al. 2003; Welsh et al. 2003a,b). This has been due to the temporal yield variation that also causes challenges in using the spatially stable field properties (Ferguson et al. 2002; Fridgen et al. 2004; Kravchenko et al. 2005). Therefore decision making during the growing season should not be made solely according to the yield history but the present growing conditions and the recent crop growth should also be considered. In the decision making the growth of the crop should be evaluated according to the maximal growth in the prevailing growth conditions. Only in this way can the lack of growth resources be evaluated and supplementary nutrients provided in additional fertilizer treatment if necessary. However, the spatial information about the maximal growth should be obtained somehow and a model that requires a minimal amount of measured information is proposed to fulfill this task.

The main aim of the thesis was to study the use of crop modelling for improving the current crop cultivation practices towards more crop oriented and automated cultivation. The specific objectives of the thesis were:

1. To introduce a C3 crop biomass accumulation model based on the principles of physics, chemistry and physiology and containing a minimal number of parameters and excluding any fitting parameters (**I**).
2. To evaluate the model in different radiation and nitrogen conditions (**II**).
3. To apply the model in a study on yield variation using site- and depth-specific soil physical properties from three different fields with clay soil (**III**; **IV**).
4. To apply the model in a simulator for studying the challenges on the way towards fully automated crop production (**V**).

3 Materials and methods

The theoretical basis of the used model and different phenomena included in the model are described in this section. The model description is continued with a description of two field experiments for model development (**I**) and evaluation (**II**). After the model evaluation, the studies on application of the model to investigation of yield variation in three different clay soil fields (**III**; **IV**) and as a part of a simulator for fully automated crop production (**V**) are described. Detailed descriptions of field experiments and model applications in studies of yield variation and an automated crop farming simulator are available in the original publications' **I**–**V**.

3.1 C3-biomass accumulation model

The crop model used in this thesis was a mechanistic biomass accumulation model for C3-crops (**I**; **II**). The model was published in the original publication **I** but is described here with a wider scientific background. Physics, chemistry and crop phenology were the basis of the model as far as possible and the model structure was kept as simple as possible (**I**; **II**). The model was developed for precision farming actions, namely to be used in site-specific fertilizer application. The application time for fertilizer split application is limited by the crop nutrient uptake taking place in the very beginning of the growth and later before the yield formation (**II**). Therefore the applicability of the model was limited to the vegetative growth of C3 crops and the model did not include calculation routines for time-dependent changes in the crop growth due to phenology. The model was aimed to calculate the maximal biomass accumulation when only solar radiation or water availability were limiting the growth. Therefore the effects of weeds, diseases, extreme temperatures, lack of nutrients or excess moisture were neglected in the model.

3.1.1 Photosynthesis and radiation interception

Basically the crop biomass accumulation is dependent on photosynthesis (Eq. 1) which occurs in the crop canopy, mainly in the leaves but also in other green tissues in the canopy (Hay and Porter 2006). The photosynthesis is initiated by photosynthetically active radiation (PAR), the part of solar radiation between 400 and 700 nm. During the initiation, the energy absorbed from PAR is used in raising the electrons in the thylakoids to a higher energy level initiating the photochemical events of splitting water (H_2O) and driving the chemical reactions in the Calvin cycle (e.g. Hay and Porter 2006; Taiz and Zeiger 1991). The end products of the Calvin cycle will be converted to glucose ($C_6H_{12}O_6$) and finally to sucrose ($C_{12}H_{22}O_{11}$) and starch ($(C_{12}H_{22}O_{11})_n$) in the subsequent reactions (Hay and Porter 2006; Taiz and Zeiger 1991). The overall efficiency of the various processes involved in photosynthesis is described with radiation use efficiency (RUE) (Hay and Porter 2006). RUE is the ratio of the dry matter amount produced per unit of radiation intercepted and was used as a parameter in the model to describe the accumulation of biomass as a function of PAR (**I**). The C3 crops grown in temperate climate have been measured to gain 2.8 g dry biomass when 1 MJ of PAR is acquired (Monteith and Moss 1977). As various processes are included in the photosynthesis, it is to be noted that the parameter RUE defined in this way includes the effect of all the processes starting from radiation interception and ending up with formation of the biomass. Another way to calculate the biomass gain from photosynthesis would be to consider the efficiencies of all the involved processes. This would be essential if the aim was to simulate the growth from the first principles in prevailing growing conditions. However, as the purpose was to calculate the maximal biomass accumulation in the prevailing growing conditions, there was no benefit gained if all the processes of photosynthesis were regarded in the model as they decreased the biomass accumulation.

The PAR for photosynthesis is intercepted mainly in the crop leaves (e.g. Hay and Porter 2006; Taiz and Zeiger 1991). Regarding only the radiation interception, if there would be no constraints in the radiation interception of the leaves, the crop would need only a leaf area large enough to cover the available land area. This leaf area would be equal to 1 if expressed with a common unit, leaf area index (LAI), that is leaf area (m^2) divided by land area (m^2). However, the net photosynthesis of a typical C3 crop leaf has been found to saturate at around 100 W m^{-2} PAR (e.g. Hay and Porter 2006). In southern Finland (Helsinki-Vantaa airport, 60° 18' 52" N, 24° 58' 13" E) the highest solar PAR intensities observed were 270, 320, 320 W m^{-2} in the years 2006, 2007 and 2008 (FMI 2006, 2007, 2008). Although at high latitudes the highest diurnal radiation intensities are low or only moderate, a single leaf is saturated over long time periods during the day and is thereby incapable of utilizing all the available radiation. Therefore, to be theoretically capable of utilizing all incoming PAR the crops LAI should be: $\frac{Incoming\,PAR}{100}\frac{W\,m^{-2}}{W\,m^{-2}}$ which in the case of the years 2006–2008 in southern Finland would be 2.7, 3.2 and 3.2 m^2 m^{-2}, respectively. However, only higher amount of leaf area does not alone remove the saturation problem. The leaves are not allowed to overlap excessively and the incoming PAR must be distributed to the crop leaves in such a way that the uppermost leaves do not become saturated and that there is still enough radiation for the leaves located lower in the canopy. This involves distribution of the leaves along the height of the canopy and inclination of the leaves (Hay and Porter 2006). These attributes describe the structure of the canopy and also for their part determine how the radiation is distributed along the height of the canopy.

Radiation limited growth, the exponential growth phase The starting point of the model is the seedling stage of the crop. Two parameters describe the initial biomass (BM(0)): mass of seedling (m_s) × seedling density (SD, number of emerged plants m^{-2}) (Eq. 2) (**I**). Leaf area at the beginning of the growth (seedling leaf area, A(0)) is calculated from mass of seedling (m_s) with two more parameters: leaf weight ratio (LWR, leaf biomass divided by total seedling biomass) and specific leaf area (SLA, the ratio of the leaf area and leaf dry mass, in m^2 kg^{-1}) (Eq. 2). In the model the biomass accumulation per square meter is calculated instead of the biomass of a single plant (**I**). The leaf area is calculated for individual seedlings and therefore it has to be multiplied with SD in order to produce a value equal to LAI.

$$\begin{cases} A(0) & = m_s \times LWR \times SLA \\ BM(0) & = m_s \times SD \end{cases} \tag{2}$$

In a study with barley (*Hordeum vulgare*), the biomass allocation inside a crop was measured and the fraction of the biomass allocated to leaves was found to be constant during the vegetative growth (Poorter and Nagel 2000). Because the model is applicable only during the vegetative growth, parameter LWR is constant during the simulations (**I**). For simplicity, the same constant LWR value is used for the initial leaf area calculation (Eq. 2). The seedling leaf area is small and insufficient to intercept all the incoming radiation and the increase in total biomass is calculated with the seedling density, the maximum PAR that a leaf can use (I_{sat}), the leaf area (A) and RUE as follows:

$$\begin{cases} \frac{d(BM)}{dt} & = RUE \times I_{sat} \times A \times SD = RUE \times I_{sat} \times SLA \times LWR \times BM \equiv C \times BM \\ C & = RUE \times I_{sat} \times SLA \times LWR \end{cases} \tag{3}$$

The time (t) is expressed in seconds, but it represents only the actual growing time (Eq. 3). Therefore, when BM(t) is expressed on a daily basis, the length of a day is not 24 hours but $t_{sun} \times 3600$ s h^{-1}, where t_{sun} is the daily sunshine duration in hours. The Eq. 3 is based on the assumption that the crop leaf area has not expanded sufficiently to capture all incoming radiation (i.e. is less than $\frac{I}{I_{sat}}$). The assumption relies on the ability of the leaves of a C3 crop to use PAR that further is limited to a certain intensity I_{sat}. The limitation comes from the ratio of photosynthetic pigments (that absorb the light to power the photosynthesis) and reaction centers (that use the energy from photosynthetic pigments and actually conduct the photosynthesis) (e.g. Nobel 1999; Taiz and Zeiger 1991). The approximation is rather crude and more accurate equations are available (Hay and Porter 2006). However, because the purpose of the model is to describe the maximal biomass accumulation, it should be reasonable to calculate the biomass accumulation according to the I_{sat} and crop leaf area (A(t) until the leaf area has expanded enough to intercept all incoming PAR.

Usually the Monsi and Saeki equation has been used in the calculation of radiation interception (Hay and Porter 2006). The equation is based on Beer's law (e^{-kx}), that introduces the declining radiation intensity in vegetation to the calculation of intercepted radiation. In the Beer's law equation x is the depth of vegetation measured from the top of the canopy to the ground and k is the radiation extinction coefficient that is crop related and includes the effect of plant and canopy characteristics. However, the use of Beer's law has made the equations more complex (see Goudriaan and Monteith (1990)), which is unnecessary regarding the aim of the biomass accumulation model. Another challenge in the Beer's law application has been the value of k, which has been found to be dependent on many factors such as crop canopy structure, row spacing and solar elevation (Sinclair 2006). Sinclair (2006) concluded that a realistic value for k requires a measurement over the time interval of interest or a measurement at a certain and limited time of the day. Further, these dependencies have led to widely varying values of k when Beer's law has been observed experimentally (Irmak and Mutiibwa 2008). Therefore the plant physiological values for the absorption of PAR (parameter I_{sat}) are used in the model. Another reason is that the variation in azimuth angle is included in $\frac{I}{I_{sat}}$ because LAI determines the absorption (**I**). Further on, the total biomass (per square meter) as a function of time is solved from Eq. 3 by

$$\begin{cases} BM(t) = BM(0) \times e^{Ct} = m_s \times SD \times e^{Ct} \\ LAI \leq \frac{I}{I_{sat}} \wedge t \leq t_0 \end{cases} \tag{4}$$

At the beginning of the growth, the biomass accumulation is exponential due to expanding leaf area. The exponential growth period ends at time t_0, when the crop leaf area has expanded enough to intercept all incoming PAR (i.e. $t=t_0$, $A = \frac{I}{I_{sat}}$). The biomass at the end of the exponential growth is calculated as follows

$$BM(t_0) = \frac{\frac{I}{I_{sat}}}{SLA \times LWR} = BM(0) \times e^{Ct}. \tag{5}$$

Further on, t_0 is solved from Eq. 5:

$$t_0 = ln\left(\frac{I/I_{sat}}{BM(0) \times SLA \times LWR}\right)/C \tag{6}$$

From Eq. 6 it is concluded that t_0 is mainly affected by C, which further on comprises of SLA, RUE, LWR and I_{sat} according to Eq. 3.

Radiation limited growth, the linear growth phase After the time t_0 the leaf area has expanded sufficiently to capture all incoming radiation. The growth cannot be enhanced anymore by increasing the leaf area. Therefore the biomass increase becomes linearly dependent on time and incoming radiation:

$$\frac{d(BM)}{dt} = RUE[kg\,J^{-1}] \times I[J s\,m^{-2}] \tag{7}$$

and for the crop total biomass:

$$\begin{cases} BM(t) = BM(t_0) + RUE \times I \times (t - t_0) \\ LAI > \frac{I}{I_{sat}} \wedge t > t_0 \end{cases} \tag{8}$$

During the linear period, the biomass accumulation in the model depends on the total radiation energy $(I \times t)$ (**I**). Instead of growing more leaves, the crop starts to grow the stem (Hay and Porter 2006), which makes no difference in this model because it calculates the total biomass (BM) including all parts of the crop (**I**). Eqs. 4 and 8 are used to calculate the total biomass (kg m^{-2}) at any time t (s) and to convert the biomass to a more common unit (Mg ha^{-1}) it is multiplied by 10.

During the exponential growth phase, the radiation measurement can be used to determine total biomass above the ground. By measuring PAR both above (I_{above}) and below the crop canopy (I_{below}), LAI is approximately $\frac{I_{above} - I_{below}}{I_{sat}}$ and the total biomass $BM(t) = \frac{LAI}{SLA \times LWR}$ (**I**). This equation is valid when photosynthesis is maximal, i.e. when solar radiation is at least as high as the leaves can intercept and the water availability does not limit the photosynthesis. Therefore the LAI measured in this way is sensitive to radiation conditions during the measurement and to the crop water status (**I**). In addition the results are dependent on the crop properties, e.g. leaf absorptivity and leaf angle distribution in the canopy (Garrigues et al. 2008). There are also other methods for measuring the crop leaf area, such as gap fraction analysis using transmittance measurement of appropriate wavelengths through the canopy (Weiss et al. 2004) or digital hemispherical photography (Garrigues et al. 2008), but all the techniques have their “specific problems and limitations” as Jonckheere et al. (2004) noted in their review on methods for in situ leaf area index determination.

In the transmittance measurement the leaves in the canopy have been regarded as a “black body” that absorbs certain wavelengths (Weiss et al. 2004). With the same assumption concerning the PAR, the radiation intensity measurements above and below the canopy should give a reasonable estimate of biomass amount and canopy radiation interception (**I**). In addition it should give a reasonable estimate of canopy radiation interception (**I**) if the reflection of PAR from canopy can be assumed to be negligible. Therefore a continuous measurement of radiation interception could be used for calculation of biomass accumulation. Combining Eq. 7 and intercepted PAR measurement we obtain:

$$BM(t) = \int_0^t RUE \cdot (I_{above} - I_{below}) \tag{9}$$

The highest radiation intensity varies from day to day and therefore high and low radiation intensities will be observed during long term measurements. However, as long as the previously mentioned assumptions are valid, under both conditions the measurement devices placed above and below the canopy measure the intercepted radiation. Therefore the biomass accumulation calculated according to the measurement results should be realistic (**I**).

3.1.2 The role of water in photosynthesis

To receive CO_2 for the photosynthesis (Eq. 1), the crop leaves have small openings called stomatal pores that provide entrance to the leaf and finally to the carboxylation site of Rubisco (e.g. Hay and Porter 2006; Taiz and Zeiger 1991). The CO_2 concentration inside the leaf is low due to the use of CO_2 in photosynthesis but by contrast the air humidity inside the leaf is high (the relative humidity can be assumed to be 100%) due to the moist cell walls (Taiz and Zeiger 1991). The low CO_2 concentration in the stomata and higher CO_2 concentration in the air surrounding the leaf cause a diffusion process to occur. The diffusion of CO_2 is a purely physical process in which the CO_2 moves through the boundary layer, stomata and the intercellular spaces of the leaf according to Fick's Law (Taiz and Zeiger 1991). The same diffusion process occurs for water but the direction is reversed because of the high air humidity in the stomata (e.g. Steduto et al. 2007; Taiz and Zeiger 1991). The crop water loss through the gas exchange is called transpiration. However, up to a certain extent the crops have a possibility to regulate the gas exchange with the guard cells which regulate the opening of the stomatal pores (e.g. Steduto et al. 2007; Taiz and Zeiger 1991). Despite the crop's ability to regulate the water loss in this way the pores must be held open for CO_2 intake to continue and photosynthesis to occur (Taiz and Zeiger 1991).

The diffusion pathways for the water vapour and CO_2 are the same but there are some other differences that lead to different diffusion rates. In the case of both gases the driving force is the concentration difference but the difference for water vapour is greater, which was found to lead to an approximately 50 times higher gradient (Taiz and Zeiger 1991). Furthermore the H_2O molecule is smaller than CO_2, which leads to a greater diffusion coefficient for water (Taiz and Zeiger 1991), which experimentally has been found to be 1.6 (Jarvis 1971). These two differences lead to a higher loss of water than CO_2 acquisition during the gas exchange. The ratio of water loss and CO_2 intake has been described as water use efficiency (WUE), which can be calculated as follows:

$$WUE = \frac{CO_2\, assimilation}{H_2O\, transpiration} = \frac{p_{CO_2a} - p_{CO_2i}}{1.6(p_{H_2Oi} - p_{H_2Oa})} \tag{10}$$

where p_{CO_2a} is partial pressure of CO_2 in the ambient air, p_{CO_2i} is partial pressure of CO_2 in the leaf, $p_{H_2Oi}$is partial pressure of water in the leaf and p_{H_2Oa} is partial pressure of water in the ambient air (Taiz and Zeiger 1991). The $p_{CO_2i}$is technically a challenging variable to be measured but because of the same pathway with water it can be calculated from evaporation rate and resistance (Taiz and Zeiger 1991). Furthermore it is not necessary to measure p_{H_2Oi} because the relative humidity in the stomata can be assumed to be 100% when the water vapour pressure is a function of the leaf temperature (Taiz and Zeiger 1991). In practice the $p_{CO_2a} - p_{CO_2i}$ is 1×10^{-5} MPa for a C3 crop (Taiz and Zeiger 1991). With a leaf temperature of 23 °C and a relative humidity of 45% this would lead to a WUE of 0.0040 mol of CO_2 mol^{-1} of H_2O. For comparison, an increase of relative humidity to 70% would decrease the transpiration ratio to 0.0074 mol of CO_2 mol^{-1} of H_2O.

Although the boundary layer is the same for both CO_2 and water it affects the rate of leaf gas exchange (Hay and Porter 2006; Taiz and Zeiger 1991). The thickness of the laminar air layer between the canopy air and stomata therefore has a considerable effect on transpiration and the thicker the laminar air layer is, the slower is the transpiration. The laminar air layer thickness is dependent on the wind when the increasing wind speed decreases the laminar air layer thickness and unavoidably affects the air humidity in the crop canopy micro climate. (Hay and Porter 2006; Steduto et al. 2007; Taiz and Zeiger 1991) For the reasons above the transpiration is dependent on the microclimate in the crop canopy, which further makes the phenomenon dependent on weather, in particular on air humidity and wind speed in the canopy. These attributes change along with the diurnal rhythm, but may also change even more rapidly.

To overcome the complex problem with crop water use, the transpiration in the model was considered over longer time intervals (**I**). This was found to make it possible to calculate the biomass accumulation on a realistic level although the diurnal changes cannot be included in the model capabilities (**I**). In the model the water loss in transpiration over a specific time interval is described with the parameter WUE (Eq. 12) that has a constant value over the time interval. Because all the factors affecting the transpiration are included in the WUE, there is no need for any other climatic factors except for radiation in this model (**I**). For the reasons above, the constant WUE is a significant simplification and can be assumed to be valid only over long time intervals, i.e. several days or longer periods. Regarding the biomass accumulation, however, the total water consumption is a more essential factor for crop growth than the daily water use (**I**).

A proper value for WUE is another important question. The crop water use is underestimated if the WUE value is higher than the weather conditions indicate. In this case the biomass accumulation is overestimated (Eq. 12). If the WUE value is lower, the crop water use is overestimated and the biomass given by the model is less than actually observed (Eq. 12). In this sense the model can be used as a best-worst-scenario tool. Then the model output would be the highest biomass yield in the most demanding evaporative conditions. Further, the effect of WUE on the simulation result is dependent on the crop water status and appears only in cases when water is limiting the growth, which has also been seen in field experiments (Ewert et al. 2002).

Water limited growth In the case of radiation limited growth (when water availability is not limiting the growth) the biomass accumulation is calculated with Eqs. 4 and 8 until the beginning of grain filling. When growth is limited by water, five more parameters are needed to calculate the water limited biomass accumulation. The parameter WUE describes the magnitude of water loss through stomata during the gas exchange. Two more parameters describe the crop water uptake ability: rooting depth increase per day ($\mathrm{r}_{\mathrm{growth}}$, m d^{-1}) and maximum rooting depth ($\mathrm{r}_{\mathrm{max}}$, m). The rooting depth is calculated as follows:

$$\begin{cases} r_{depth}(t) = r_{depth}(t-1) + r_{growth} & |\, r_{depth}(t-1) < r_{max} \\ r_{depth}(t) = r_{max} & |\, r_{depth}(t-1) \geq r_{max} \end{cases} \tag{11}$$

The two last parameters in water limited growth calculation (Eq. 12) describe the soil's ability to hold water for crop growth: field capacity (FC) and permanent wilting point (PWP). The simplest case is when there is constant precipitation, (R, in m d^{-1}), and constant evaporation (E, in m d^{-1}), and roots do not reach the ground water level or gain supplemental water through capillary rise (**I**). In this case the biomass accumulation is limited by the depth of the roots.

$$\begin{cases} \Delta BM[kg\,m^{-2}] & = available\,water\,[m] \times water\,density\,[kg\,m^{-3}] \times ... \\ & WUE\,[g_{CO_2}\,g_{H_2O}^{-1}] \times molar\,mass\,ratio\,[g_{C_6H_{12}O_6}] \\ \Delta BM(t) & = [(FC - PWP) \times r_{depth}(t) + t(R-E)] \times \rho_{H_2O} \times ... \\ & WUE \times \frac{M_{C_6H_{12}O_6}}{M_{CO_2}} \end{cases} \tag{12}$$

When water-limited biomass accumulation is calculated the growth may not exceed the growth given by Eqs. 4, 8 or 12, i.e. radiation and water limitations are both considered. The calculation is closely related to the soil properties, in particular to plant available water capacity (FC-PWP), which is mainly determined by soil texture (Table 1). Precipitation varies considerably during the growing season and from one season to another. Evaporation is also dependent on weather and time. Therefore constant evaporation or precipitation are rather unrealistic assumptions and are applicable only in a few cases. Measured precipitation and evaporation could be used instead of constant values but especially the continuous measurement of evaporation has been found to be a demanding task (Hautala et al. 2012). In addition, the precipitation and evaporation are expressed here as constants (Eq. 12) to bring the model to analytic form, but this does not prevent using the model with other kind of inputs such as measured or simulated precipitations and evaporations.

Table 1: Soil water contents at saturated water capacity (SWC), field capacity (FC) and approximately permanent wilting point (PWP, (ψ_m= -1600 kPa) and saturated hydraulic conductivity (K_{sat}) for different soil texture classes (Driessen 1986).

Soil texture class	SWC (m^3 m^{-3})	FC (m^3 m^{-3})	PWP (m^3 m^{-3})	K_{sat} (cm d^{-1})
Coarse sand	0.395	0.047	0.000	1120.0
Fine sand	0.364	0.198	0.024	50.0
Loamy sand	0.439	0.218	0.020	26.5
Fine sandy loam	0.504	0.325	0.072	12.0
Silt loam	0.509	0.344	0.090	6.5
Loam	0.503	0.343	0.093	5.0
Loess loam	0.455	0.318	0.093	14.5
Sandy clay loam	0.432	0.352	0.176	23.5
Silty clay loam	0.475	0.380	0.178	1.5
Clay loam	0.444	0.393	0.258	1.0
Light clay loam	0.453	0.378	0.204	3.5
Silty clay loam	0.507	0.442	0.276	1.3
Heavy clay	0.540	0.494	0.364	0.2
Peat	0.863	0.681	0.302	5.3

3.1.3 Soil water and crop water uptake

Because the time dependence of precipitation has been found to cause considerable variation in the crop yield (Sadras et al. 2012; Taylor et al. 2003), it is appropriate to simulate soil water content together with crop growth in many cases. The soil is a porous medium where the water may stay or move according to the laws of physics (e.g. Driessen 1986; Hillel 1998; Kutílek and Nielsen 1994; Thornley and Johnson 1990). The two most important quantities describing the soil moisture status are soil water potential (ψ_m) and soil volumetric water content, that describe how high suction

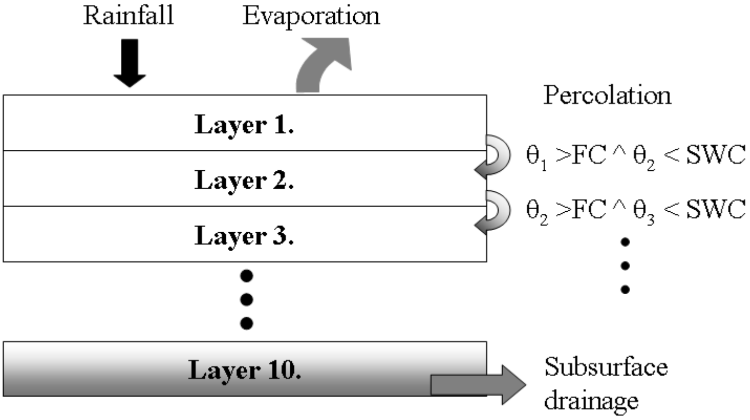


Figure 3: Schematics of the soil water model. FC is an abbreviation for field capacity, SWC for saturated water capacity and θ_n for volumetric water content of layer n.

is needed to extract the water from soil and how much water does a certain volume of soil contain, respectively (Hillel 1998; Kutílek and Nielsen 1994). The volumetric water content is a relatively easy soil property to measure and can be directly used to calculate the water amount in the soil but it does not contain information about how much water can be used by the crop (Dirksen 1999; Kutílek and Nielsen 1994). The information about the soil water availability for the crop is included in the soil water potential that can also be measured but the measurement requires more time and is more demanding to conduct in practice (Dirksen 1999; Kutílek and Nielsen 1994).

For soil water content simulations a separate model was established, the structure of which is outlined in Figure 3. The structure of the model is a bucket type that is similar to many approaches found in the studies of other models (Guswa et al. 2002; van Ittersum et al. 2003). In the model the soil is divided into layers (Δx) with 0.1 m thickness down to the depth of 1.0 m that is assumed to be the depth of the water table (Figure 3). Each layer has three parameters that are related to the water content: saturated water content (SWC), field capacity (FC) and permanent wilting point (PWP). These parameters correspond to the volumetric soil water contents at potentials (ψ_m) 0, -10 and -1500 kPa, respectively (e.g. Larcher 2003; Miller and Donahue 1995). SWC is the maximal soil water content that may not be exceeded (air pore space is filled with water), except in the uppermost layer where the maximal soil water content is not limited to allow ponding of water above the soil surface. FC is the soil water content when the large pores have released their water and no more water can be lost via gravimetric flow through the drainage and PWP is the limit below which the crop is not able to extract water from the soil (Driessen 1986; Karvonen and Varis 1992). Further the soil water content between FC and PWP is the capacity of plant available water (PAWC) in soil.

Pores, their size, distribution and continuity have been found to be important properties for water movement in the soil (Alakukku 1997; Hillel 1998; Kutílek and Nielsen 1994). Consideration of the pores in the water movement calculation in a very detailed manned has necessitated a tremendous number of calculations for even relatively small volumes of soil (Kutílek and Nielsen 1994). Therefore in many cases it has been reasonable to use simplification of the soil pore system to a reasonable level (Kutílek and Nielsen 1994).

In the used soil model the water is assumed to percolate (to flow only downwards in the soil profile) and the flow rate is limited by saturated hydraulic conductivity (K_{sat}). This assumption makes the model unsuitable for soils which the particle size distribution is suitable for effective capillary rise, i.e. both rise height and flow rate via capillary rise are high. On the other hand the assumption is very well suitable for soils where the clay fraction (the smallest particles, diameter <0.002 mm) of the soil texture is the highest and is very feasible for the calculation time (**III**, **V**). For this type of soils, the capillary rise can reach levels up to several meters due to the great portion of small particles in the soil medium (Driessen 1986; Hillel 1998; Kutílek and Nielsen 1994). However, for the same reason the water flow rate in capillary rise becomes smaller as the particle size decreases and makes the effect of capillary rise negligible for the cultivated crop (Hillel 1998). Furthermore, the water flow in the model may always be limited by the SWC and FC. SWC cannot be exceeded in the layers below the first one and the water content of any layer cannot decrease below the FC in any layer due to water flow between the layers.

The water available for the crop is limited by the water content of each layer (volumetric, θ_i) and the depth of the roots ($\frac{r_{depth}}{\Delta x}$). The daily amount of water available for crop growth (m^3 m^{-2}) can be calculated as follows:

$$PAWC = \sum_{i=1}^{r_{depth}/\triangle x} \begin{cases} \triangle x \times \theta_i - PWP_i & , \theta_i > PWP_i \\ \triangle x \times 0 & , \theta_i \leq PWP_i \end{cases} \tag{13}$$

Furthermore the water limited growth becomes:

$$\triangle BM(t) = PAWC \times \rho_{H_2O} \times WUE \times \frac{M_{C_6H_{12}O_6}}{M_{CO_2}} \tag{14}$$

3.2 Field experiments for establishing and evaluating the model

The field experiments were performed in Helsinki, southern Finland (60° 13' 19.357" N, 25° 0' 36.881" E). The soil was classified as clay loam and according to the Soil Taxonomy system as Sulfic Cryaquept, and the topsoil (0–0.31 m) composition of textural fractions was 40% clay (<0.02 mm), 30% silt (0.02–0.06 mm) and 30% sand (0.06–2 mm) (Mokma et al. 2000). The area of the field where the experiments were conducted was flat and characterized by a high ground water level. The weather during both experiments was observed with a Vaisala WXT510 (Vaisala Oy, Finland) weather station with close proximity (~350 m) to the experiment area (**II**).

The cultivated crops in the experiment for model establishment were spring and winter wheat (*Triticum aestivum* L.). The most relevant characteristics of growing conditions from above and below the ground were monitored in the field continuously (half-hour basis) (Table 2). To observe the crop growth, measurements of leaf area index (AccuPAR LP-80, Decagon Devices) and specific leaf area (from samples) were conducted during the growing season. The total biomass at the end of the growth was obtained from the weighing results of grains, stem, leaves and roots. More information about the experiment is available in article **I**.

Spring wheat was cultivated in the experiment for model evaluation. The experiment included four different nutrient treatments (0, 15, 50 and 150 kg N ha^{-1}) created with N-P-K fertilizer (28-3-5) and three different levels of precipitation (0, 1 and 2 times the natural precipitation) and two radiation levels (natural solar radiation and 79% of natural of solar radiation) (**II**). The soil and canopy conditions as well as crop development were monitored continuously in one plot of the experiment (Table 2). The other treatments of the experiment and ground water level were measured

Table 2: The devices and sensors used for continuous soil and canopy measurements in the field experiments for model establishment (**I**) and evaluation (**II**).

Measured quantity	**Manufacturer**	**Sensor or device**	**Model establ.**	**Model eval.**
Soil volumetric water content	ICT International	MP406	x	x
	Decagon	5TE	x	x
Soil water potential	Decagon	MPS-1	x	x
Soil temperature	-	PT100	x	
Solar radiation	Decagon	QSO-S[1]	x	x
	Decagon	PYR[2]	x	
Crop leaf temperature	Calex Electronics Limited	EL101LTO	x	x
Canopy air temperature	Decagon	RHT	x	
	Gemini dataloggers	Tinytag Ultra 2 TGU-4500		x
Canopy air humidity	Decagon	RHT	x	
	Honeywell	HIH-4000-001	x	x
	Gemini dataloggers	Tinytag Ultra 2 TGU-4500		x

[1] Photosynthetically active radiation, [2] Pyranemometer

manually, on a weekly basis (**II**). 85 days after the sowing the whole experiment area (**II**: Figure 1) was split into several subplots (1 × 0.25 m) and harvested. The dry matter yields of straw and grain were determined from each sub-plot and results of six sub-plots were combined to represent the treatments included in the experiment. The experiment also included a separate area where the timing of fertilizer application during the growing season was preliminarily evaluated. The full description of the experiment for model establishment can be seen in article **II**.

In addition to the fertilizer treatments in the experiment, the effect of additional fertilization during the growing season was preliminarily tested at the area of 0 kg N ha^{-1} fertilization (Supplementary material). Additional fertilization was made with N-P-K fertilizer (28-3-5). The crop WUE was also calculated according to the continuously measured soil moisture content. The results from two different sensors installed at different depths (MP406 at 0.1, 0.2, 0.3 m depths and 5TE at 0.1, 0.2, 0.3, 0.4, 0.5 m depths) were used for calculating the crop water use. Two time periods, 152–162 and 177–186 DOYs, were selected for these calculations. For the first time period the biomass change was calculated from biomass samples taken at the beginning and at the end of the time period. For the second time period the biomass change was calculated from the simulated biomass accumulation because there were no sampling results available at close proximity to the start or end of the time period. Thereafter the WUE was calculated from biomass change and extracted soil water according to the definition of WUE, assuming that all the extracted water had been transpired and all the carbon came from CO$_2$.

3.3 Testing devices for soil moisture content measurements

In addition to biomass accumulation modelling on a radiation basis, crop growth calculation on a water balance basis could be a feasible approach because in many cases water availability is the growth limiting factor. For this purpose continuous information about soil moisture is needed from the crop rooting depth. Therefore

Table 3: Tested devices for measuring the soil moisture content.

Manufacturer	Device or sensor	Range	Resolution	Unit
Decagon	5TE	1–20	0.1	ε_a
		20–80	<0.75	ε_a
		0–0.5	0.0008	m^3 m^{-3}
Delta-T Devices	ThetaProbe M2x/d	0–1	-	m^3 m^{-3}
ICT International	MP406	0–1	0.0001	m^3 m^{-3}
Soil moisture equipment	MiniTrasekit 6050X3K1B	0–1	0.02	m^3 m^{-3}
Spectrum Technologies	TDR300	0–SWC	0.001	m^3 m^{-3}
Visilab	AK30	0–70	0.1	g g^{-1}

ε_a = Dielectric permitivity

measurements from several different depths are required and the resolution of the used sensors must be high enough in order to be able to distinguish the crop water use. Several devices for measuring the soil moisture content (Table 3) were tested for crop growth calculation on a water balance basis (Supplementary material). For this task soil from the previously described field was extracted and dried. Samples with known moisture content were made of the soil and the devices were evaluated in laboratory conditions. After laboratory evaluation, the devices were used in field conditions. The results were compared with oven dried undisturbed soil core samples (200 cm^3).

3.4 Evaluation of yield variation using site- and depth-specific soil properties and a crop model

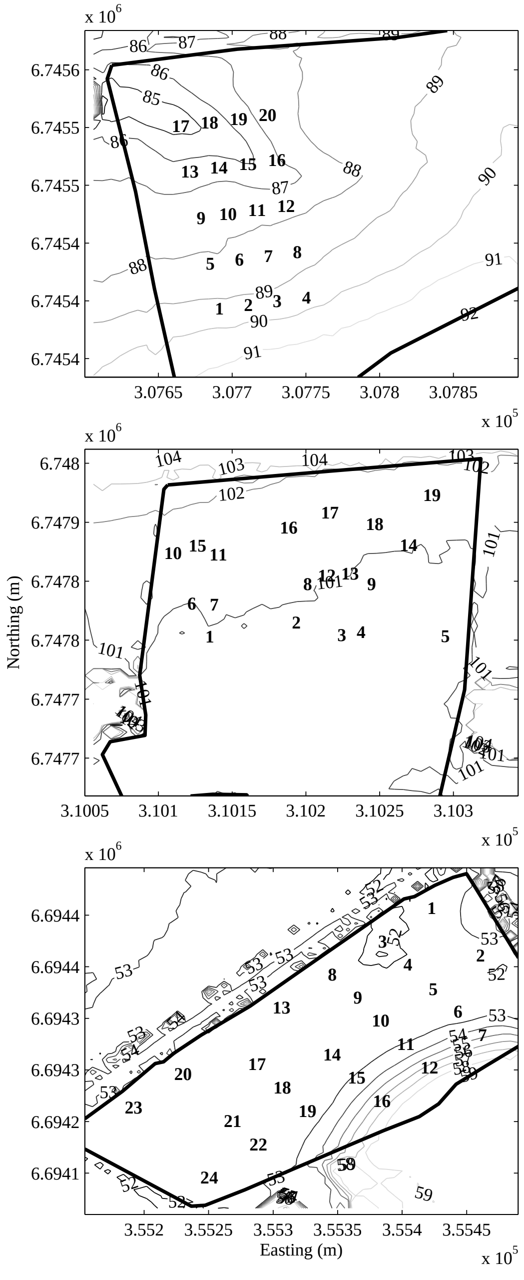
3.4.1 Field properties

The introduced crop and soil models were used with site- and depth-specific soil properties to study the spatio-temporal yield variation in small grain cereals cultivated on clay soil fields (**III**). The data for the study originated from two successive three-year studies carried out at MTT Agrifood Research Finland between 2002 and 2009. The studies included several fields, but three of them were selected for this study. The data collected from the soil of these three fields was the most extensive among the fields participating in the study, the clay content of each field was relatively high and the selected years were those when barley or wheat was cultivated.

The soil of the two first fields (further denoted as Jokioinen 1 and Jokioinen 2) ranged from clay loam to clay and the soils were classified (FAO 1998) as Stagni-Vertic Cambisols (Yli-Halla and Mokma 2001). The fields were located in Jokioinen (60° 49' N, 23° 28' E) and the experiment took place between 2002 and 2004 in the case of these two fields (Table 4). The cultivated crop on both fields during the experiment was spring barley (*Hordeum vulgare* L., varieties Annabelle, Inari and Prestige) (**III**).

The soil of the third field (further denoted as Vihti) ranged from sandy clay loam to silty clay and was classified (FAO 1998) as Stagni-Vertic Cambisols. The field was located in Vihti (60° 21' N, 24° 22' E) and the cultivated crops were spring wheat (*Triticum astivum* L., variety Amaretto), spring oilseed rape (*Brassica napus* L., variety Marie) and spring wheat in the years 2006–2008, respectively (Table 4) (**III**).

Within each field, the information about spatial variation of soil physical properties and crop growth was obtained from 20 (Jokioinen 1), 19 (Jokioinen 2) and 24 (Vihti)



Jokioinen 1	Depth (m)	Average ± S.E.	Min	Max
K_{sat}	0 - 0.2	19.3 ± 3.9	4.6	84.1
(m d^{-1})	0.2 - 0.35	13.3 ± 4.8	0.1	86.7
	0.35 - 0.6	23.3 ± 5.5	2.3	97.7
FC	0 - 0.2	39.8 ± 0.5	33.3	43.5
(vol-%)	0.2 - 0.35	42.9 ± 0.6	36.7	46.6
	0.35 - 0.6	43.8 ± 0.9	32.8	47.3
PWP	0 - 0.2	22.0 ± 0.3	20.3	24.8
(vol-%)	0.2 - 0.35	29.0 ± 0.8	22.1	34.1
	0.35 - 0.6	31.3 ± 0.6	23.1	36.3

Jokioinen 2	Depth (m)	Average ± S.E.	Min	Max
K_{sat}	0 - 0.2	10.4 ± 2.2	0.1	37.0
(m d^{-1})	0.2 - 0.35	1.4 ± 0.8	0.0	12.6
	0.35 - 0.6	0.1 ± 0.04	0.0	0.8
FC	0 - 0.2	46.3 ± 0.8	38.5	51.9
(vol-%)	0.2 - 0.35	50.4 ± 1.2	41.7	59.7
	0.35 - 0.6	52.7 ± 0.8	45.0	56.5
PWP	0 - 0.2	26.1 ± 0.8	18.9	31.5
(vol-%)	0.2 - 0.35	35.5 ± 0.7	27.7	41.2
	0.35 - 0.6	39.9 ± 0.7	33.6	43.4

Vihti	Depth (m)	Average ± S.E.	Min	Max
K_{sat}	0.05 - 0.1	4.6 ± 1.9	0.0	39.4
(m d^{-1})	0.35 - 0.4	1.6 ± 1.1	0.0	26.2
FC	0.05 - 0.1	39.4 ± 0.8	31.5	44.3
(vol-%)	0.35 - 0.4	40.7 ± 0.9	32.7	48.8
PWP	0.05 - 0.1	23.3 ± 0.8	14.6	28.5
(vol-%)	0.35 - 0.4	25.4 ± 1.0	16.3	33.1

Figure 4: The fields Jokioinen 1 (a), Jokioinen 2 (b) and Vihti (c) included in the study on yield variation. The figures present the locations of the sampling sites and the topography of the fields. The tables present the selected physical soil properties from each observed depth in each field. The areas of the fields Jokioinen 1, Jokioinen 2 and Vihti were 3, 3 and 4.5 hectares. (**III**)

Table 4: Weather during the experiment years for the fields Jokioinen 1, 2 and Vihti (**III**). PAR was calculated as an average over the time period from sowing to harvest. The heat summation was calculated with daily average temperatures ($\sum(T_D\text{-}5)$°C) between sowing and harvesting which was also the time interval for the precipitation sum.

	Jokioinen 1			**Jokioinen 2**			**Vihti**		
	2002	2003	2004	2002	2003	2004	2006	2008	
Precip. sum.	174	170	322	184	204	334	74	336	mm
PAR	225	216	195	223	198	194	241	183	W m^{-2}
Heat sum.	1123	1033	898	1079	994	961	1091	1029	°C

locations (Figure 4). Site-specific soil water retention properties including SWC, FC, PWP and K_{sat} were measured from three different depths (0–0.2 m, 0.2–0.35 m, 0.35–0.6 m) in Jokioinen 1 and 2 (**III**; Ristolainen et al. 2006). The same soil properties were measured from Vihti from two different depths (0.05–0.1 m and 0.35–0.4 m) at the defined locations (**III**; Ristolainen et al. 2006).

3.4.2 Yield information

During the growing seasons, crop leaf area, soil moisture content and grain yield were observed from each location (Figure 4) from fields Jokioinen 1, 2 and Vihti (**III**). In the fields Jokioinen 1 and 2 the grain yield was harvested every year from small plots (1.5 × 4 m) from each sampling site. The field Vihti was harvested every year with a combine harvester equipped with a yield monitoring system. Yield monitor results surrounding the sampling site with a 20 m radius were used to obtain a grain yield for each sampling location. The output of the model is the total biomass including all parts of the crop. Therefore the observed grain yield was converted to the biomass of the whole crop using a harvest index (HI) and a fraction of biomass was allocated to crop roots (**III**).

To evaluate differences in the grain yields of a single field between the years and between the yields in Jokioinen 1 and 2, an analysis of variance was conducted. The cultivated crop in Vihti was not the same every year and therefore analysis of variance was conducted only in the years 2006 and 2008 to evaluate differences in the wheat grain yields. Linear relationships between observed soil physical moisture properties (K_{sat} and plant available water capacity (PAWC)) and biomass yield were investigated by calculating the Pearson correlation (Sokal and Rohlf 1981). For this purpose, average values of the observed soil properties were calculated regarding the whole observed soil column. In the fields Jokioinen 1 and 2 the soil samples from different depths were not equal in thickness and weighted average values were calculated for each location (i.e. the average was weighted with the ratio of sample thickness to the total thickness of the observed soil column).

3.4.3 Yield variation due to the observed soil properties

The observed site-specific soil properties were used with the models to simulate the radiation- and water-limited biomass accumulation. The biomass accumulation was simulated for the experiment years using the observed soil properties as soil model parameters and observed weather as inputs (**III**). The simulated biomass accumulation was then compared to the observed biomass yield (calculated from grain yield) in order to estimate the effect of soil properties on the observed yield variation (**III**).

The beginning of the simulation was set in a field- and year-wise manner according to the observations made after the sowing. In the same way, the end of simulations was set according to the observed leaf senescense for each field and year separately, as the model does not include the phenology of the crop.

The effect of site-specific soil properties on the biomass accumulation under varying precipitation conditions was simulated over 1000 years (i.e. growing seasons) by using a precipitation model (Kilpeläinen et al. 2008) for creating realistic precipitation. The only change between the simulated years was precipitation when the growing season length and solar radiation were kept constant (**IV**). Spatial and temporal variation of the simulated biomass accumulation was studied with a temporal variance described by Blackmore et al. (2003). The temporal variance (σ_i^2) was calculated for simulated and observed biomass yields with Eq. 15. In Eq. 15 i is the site on the field, t is the time in years between 1 and n, Y_i is the yield in years t at site i, and $\overline{Y}_t$ is the mean yield for the whole field in years t. Temporal mean yield was calculated for each site as an average over the simulated time period.

$$\sigma_i^2 = \frac{1}{n}\sum_{t=1}^{n}\left(Y_{t,i} - \overline{Y}_t\right) \tag{15}$$

3.5 A simulator for fully automated crop farming

In addition to the challenge in the factors causing the yield variation, the increasing amount of automation in farming machinery is also a challenge. In any attempt to increase the degree of automation in farming machinery, new challenges are faced because tasks from the tractor driver are transferred to the machinery and automation. A simulator for an autonomous crop farm, AutoCrop, was built to enable the study of challenges faced due to the increasing amount of automation in the machinery (**V**). The simulator included separate models for crop, soil, weeds and diseases (Figure 5), but also a model for creating weather for different scenarios (**V**), and the crop model used in this thesis was an alternative option for a more complex model SORGHUM that was calibrated to represent a common Finnish cereal crop (barley) before it was applied to the simulator (**V**).

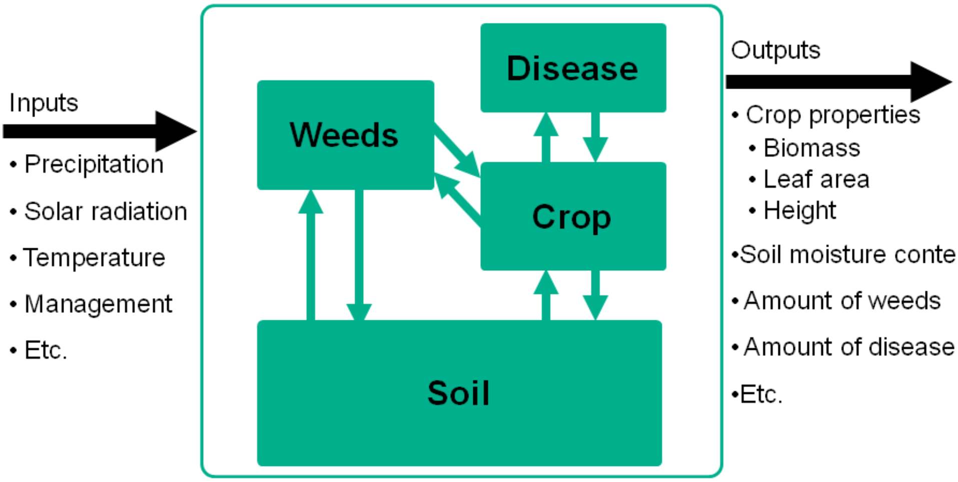


Figure 5: The structure of the model combination built for simulating each cell of the field in the simulator.

In this study the two crop models and two different approaches for building the simulator (Figure 6) were compared in terms of computation time required. The requirement for this kind of simulator is the capability to simulate the phenomenon in both space and time dimensions. Powerful software is available for each dimension separately but therefore software integration was required to include both capabilities in one simulator. The used main tools were ESRI ArcGIS/ArcInfo 9.2, Visual Studio .NET 2005, SQL Server 2005, Matlab R2007a and Simulink 7.0 (**V**).

The models were built in the Simulink environment of Matlab software but the two simulators were built from slightly different approaches (Figure 6). In the first approach, the models were wrapped in an ESRI compatible .NET code that was run in ArcGIS (**V**). In the second approach Matlab was used as a simulation engine and the models were used in a normal way in Simulink through the command line operations (**V**). The approaches were compared according to the time used for conducting similar case simulations.

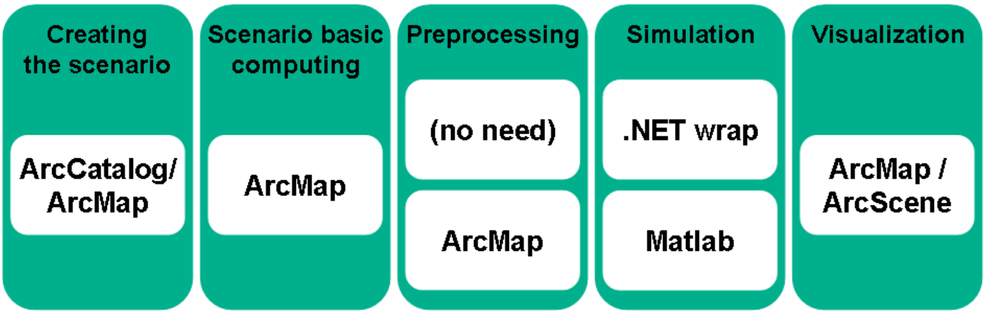


Figure 6: The work flows of the two different approaches for building the AutoCrop simulator (**V**).

4 Results

4.1 Model establishment

Relevant parameter values (Table 5) for simulating the biomass accumulation were measured during the experiment or taken from the literature (**I**). In order to be able to calculate the biomass accumulation, it is necessary to know the values of three independent terms: the crop specific term (SLA× LWR), the agronomic term of the initial biomass per field area (m_s × SD), and the total daily radiation energy per day (I × t) (**I**). In addition to the parameter values in Table 5, the model includes an assumption about optimal growing temperature and freedom from weeds or diseases.

The radiation limited crop leaf area (LAI) and biomass accumulation (Figure 7) were calculated on half-hour basis with parameter values from Table 5. To evaluate the effect of constant PAR in comparison to continuously measured PAR, the biomass accumulation was calculated in three different ways (Figure 7) (**I**). First, biomass accumulation was calculated with Eqs. 4 and 8 using constant PAR and constant day length (Table 5) as a model input. In the second approach the constant PAR was replaced with continuously measured PAR. The third biomass accumulation was calculated on the basis of the measured radiation interception (Eq. 9). The leaf area accumulation based on these three different ways of calculating is presented in Figure 7 together with the observed values (**I**). The continuous leaf area curve (Figure 7) was calculated from the PAR measurement results from above and below the canopy using the same formula as was used in the calculation of the LAI values from LP-80 (Decagon Devices Inc. Pullman, WA, USA).

Effectively the model includes six parameters to describe radiation-limited growth and in order to allow the water availability to limit biomass accumulation, the model needs four parameters more (**I**). A sensitivity analysis was conducted by simulating the radiation-limited biomass accumulation when the parameter values of the model

Table 5: Crop model parameter values used in the simulation of winter and spring wheat during the growing season 2009 (**I**). Values for I, SLA, m_s, LWR, t_{sun}, FC and PWP were measured during the field experiment (**I**).

Parameter	Abbreviation	Value	Unit
Radiation- and leaf-area-limited crop growth			
Radiation use efficiency	RUE	$^{a}2.8 \times 10^{-9}$	kg J^{-1}
Incoming solar PAR	I	250	W m^{-2}
Maximum PAR for leaf	I_{sat}	$^{b}100$	W m^{-2}
Seedling density	SD	500	plants m^{-2}
Specific leaf area	SLA	23	m^2 kg^{-1}
Mass of the seedling	m_s	40	mg $seedling^{-1}$
Leaf weight ratio	LWR	0.4	
Duration of daily sunshine	t_{sun}	12	h
Water-limited crop growth			
Water use efficiency	WUE	$^{c}0.0049$	g_{CO_2} $g^{-1}{}_{H_2O}$
Field capacity	FC	0.37	m^3 m^{-3}
Permanent wilting point	PWP	0.14	m^3 m^{-3}
Daily root growth	r_{growth}	$^{d}0.02$	m d^{-1}
Maximum rooting depth	r_{max}	$^{e}1.0$	m

[a]Monteith and Moss 1977, [b]Hay and Porter 2006, [c]Taiz and Zeiger 1991, [d]Aura 1999, [e]Rötter et al. 2011; **I**

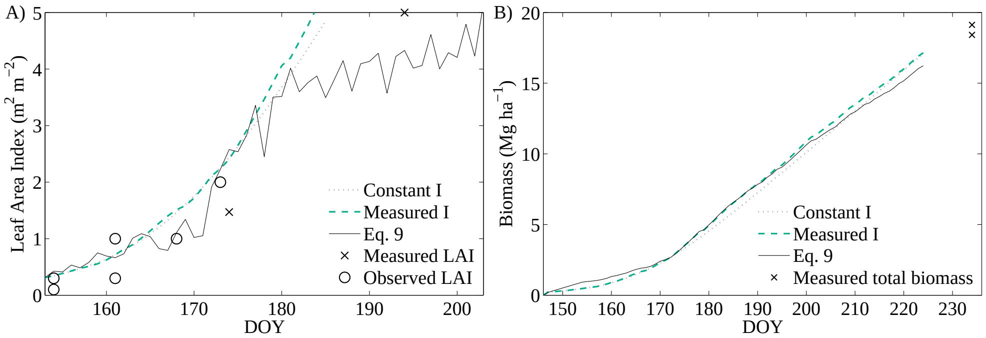


Figure 7: Simulated leaf area development and biomass accumulation during the growing season 2009 (**I**).

were varied one at a time (Figure 8). The solid line in the sub-plot of Figure 8 was obtained from Eqs. 4 and 8 with the parameter values from Table 5. The two phases of the growth are well known: due to the expanding leaf area the growth is exponential in the beginning but later becomes linear as the leaf area is large enough to intercept most of the incoming radiation (Goudriaan and Monteith 1990). In the model, the timing of this moment (t_0) depends significantly on SLA, LWR and I_{sat} (Figure 8), as can be seen from Eq. 6. The slope of the linear growth is dependent on the total daily radiation energy and RUE, although the effect of RUE extends to the exponential growth (Figure 8).

In addition to the solar radiation, water is a major determinant of crop biomass accumulation. In the model, the water availability is limited by root growth (parameters r_{growth} and r_{max}), soil properties (parameters FC and PWP), precipitation and evaporation. A sensitivity analysis for the root growth parameters, evaporation and precipitation was conducted using constant evaporation and precipitation and the results can be found from Figure 3 in article **I**. However, as was noted in article **I**, constant evaporation and precipitation are rather rare and can be assumed to occur only over limited time periods. Therefore a realistic daily precipitation (95 mm over 50 days) was created with a precipitation model presented by Kilpeläinen et al. (2008). By using the created precipitation the water-limited crop growth was calculated (according to Eqs. 4, 8 and 12) and parameters describing the crop water use were altered (r_{growth}, r_{max} and WUE) (Figure 9). The results with realistic precipitation (Figure 9) were only slightly different from those with constant evaporation and precipitation (**I**). The most important result here was the magnitude of the two different sensitivity analyses that were at the same level (Figure 9 vs. Figure 3 in **I**).

4.2 Model evaluation in varying radiation, fertilization and precipitation conditions

4.2.1 Growing conditions and soil moisture conditions

After establishment, the model was evaluated in optimal soil moisture conditions with varying radiation, fertilization and precipitation conditions (**II**). Water availability for the crop was monitored in continuous manner with quantities such as soil water content and potential, root growth, ground water level and the canopy temperature, for example (Table 2). The volumetric soil water content and soil water potential were measured continuously in the treatment of natural precipitation and 50 kg N

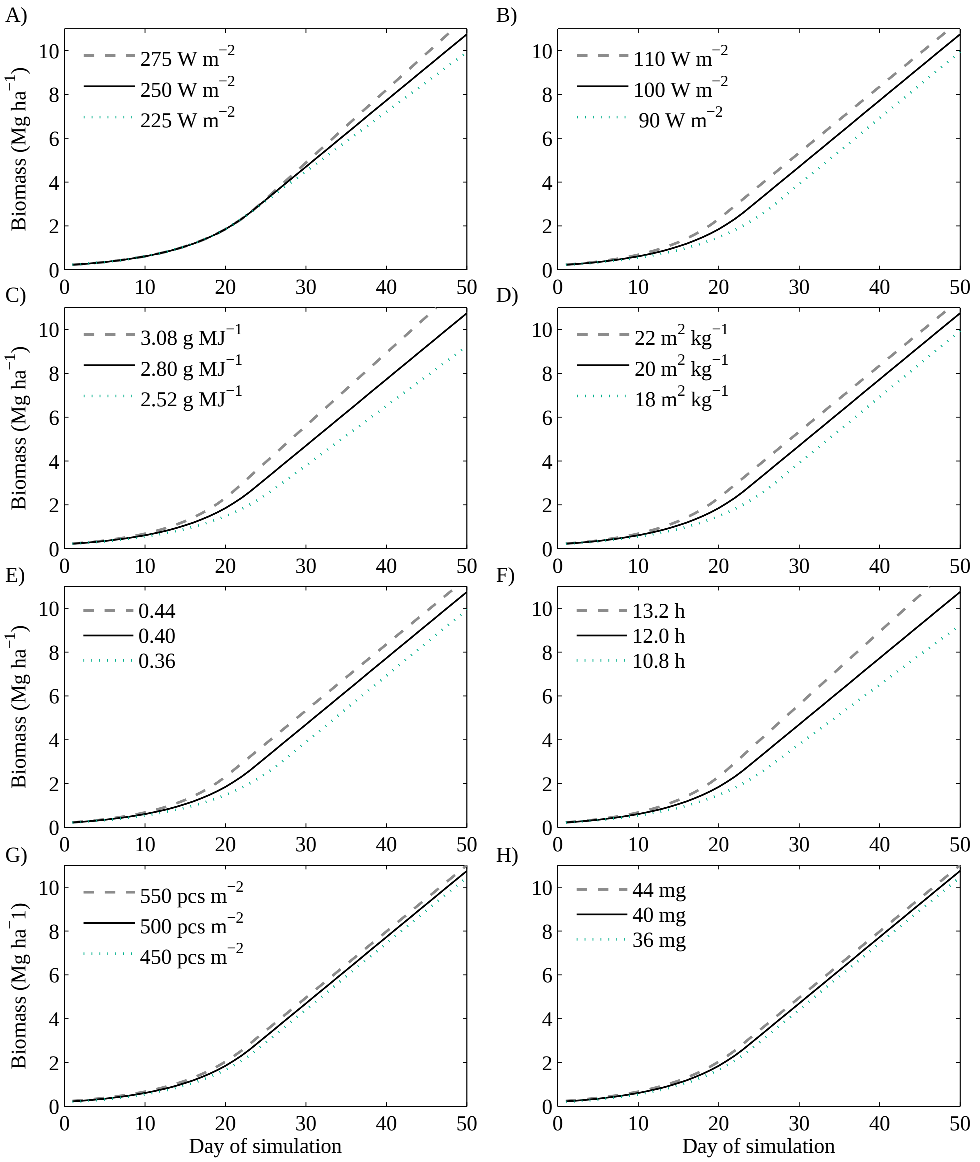


Figure 8: Sensitivity of the radiation-limited biomass accumulation during the first 50 days. Biomass was calculated from Eqs. 4 and 8 with the parameter values given in Table 5 unless otherwise indicated in the legend. The altered parameters were A) I, B) I_{sat}, C) RUE, D) SLA, E) LWR, F) n, G) SD, H) m_s. Dashed and dotted lines are the results of increased and decreased values of the parameter in each sub-plot.

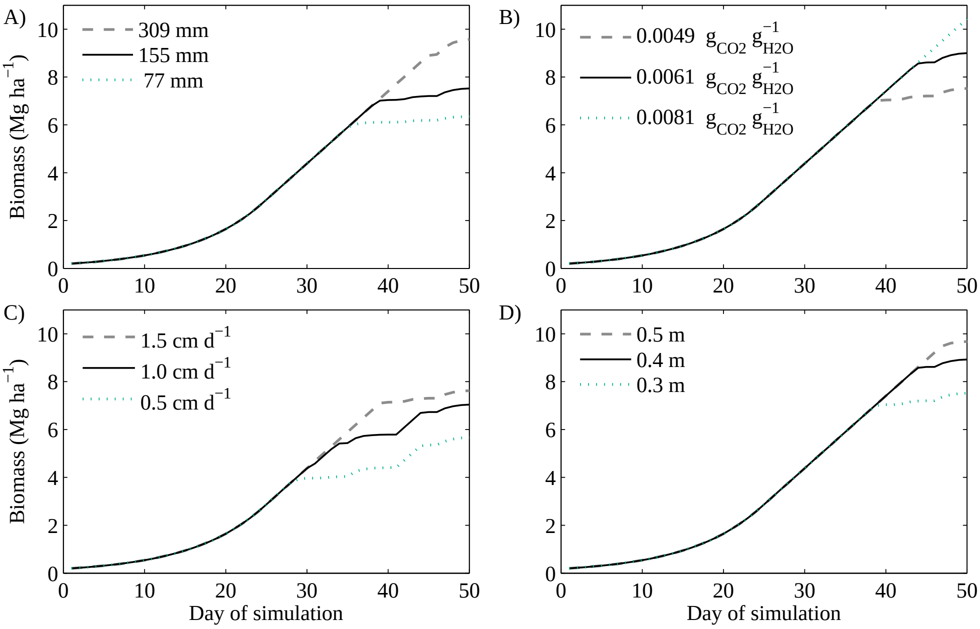


Figure 9: Sensitivity of the water and radiation limited biomass accumulation during the first 50 days. Biomass was calculated as the minimum of Eqs. 4 and 12 during the exponential growth and the minimum of Eqs. 8 and 12 during the linear growth. Precipitation with a sum of 155 mm, 0.6 m maximum rooting depth and parameter values from Table 5 were used unless otherwice indicated. The altered input was A) precipitation and the altered parameters were B) water use efficiency (WUE) , C) root growth rate (r_{growth}) and D) maximum rooting depth (r_{max}).

ha^{-1} fertilization. In addition to the water-related measurements, samples of the crop were taken to determine the crop model parameter values (Table 6).

The treatments of zero and double precipitation were covered with a shelter (Figure 1 in article **II**) which transferred the precipitation from zero precipitation treatment to double precipitation. The used shelter also created the decreased radiation treatment in the experiment. The influence of the shelter material on radiation was determined before the experiment and the shelter material transmittance was measured to be 79.0 ± 0.5% of PAR (**II**). The effect of shelter on the crop canopy microclimate, the air temperature and humidity in the crop canopy was monitored continuously during the experiment. The temperature difference between the canopies below and outside the shelter was 1.0 °C (**II**) and no difference in the relative humidity was observed.

Two types of sensors (MP406 and 5TE, Table 2) were used for monitoring the soil moisture content and they were found to describe the changes in the soil moisture in slightly different ways (Figure 10). The MP406 was found to be more sensitive to changes in the soil moisture due to precipitation, whereas there were only small changes in the 5TE results (DOYs 160–170, Figure 10). This was probably due to technical differences in the sensors or due to differences in the soil structure (e.g. continuous pores). Due to the different behaviour of the sensors they were both selected for more detailed comparison to test different sensor types for practical use in field conditions.

Despite the difference in the results of the two different sensors the changes in the soil moisture content were present in both of the results (**II**). In the beginning of the growing season, the rainfall had clear impact on the sensors in the 0–0.2 m

Table 6: The measured model parameter values used in the simulation spring wheat during the growing season 2010 (**II**). The values for parameters RUE and I_{sat} were the same as in the year 2009 (Table 5). In addition to these parameters, measured PAR was used as an input in the simulations to replace the parameters I and t_{sun} (**II**).

Parameter	**Abbreviation**	**Value**	**Unit**
Radiation- and leaf-area-limited crop growth			
Seedling density	SD	537	plants m^{-2}
Specific leaf area	SLA	30.7	m^2 kg^{-1}
Mass of the seedling	m_s	32.9	mg $seedling^{-1}$
Leaf weight ratio	LWR	0.26	
Water-limited crop growth			
Water use efficiency	WUE	0.0081	$g_{CO_2} g^{-1}{}_{H_2O}$
Field capacity	FC	0.38	m^3 m^{-3}
Permanent wilting point	PWP	0.11	m^3 m^{-3}
Daily root growth	r_{growth}	0.01	m d^{-1}
Maximum rooting depth	r_{max}	0.7	m

topsoil layer, indicating that the clay soil was moist and able to conduct water from the soil surface deeper into the soil (Figure 10). Later showers increased temporary soil moisture content only in the 0–0.05 m surface layer (**II**). The soil water content at the top of the soil (0–0.05 m) had dried due to evaporation, which caused a rapid decrease in the moisture content very soon after the precipitation (e.g. after the 164th DOY, Figure 10A). The crop water consumption (transpiration) was also presented as a steady decrease in both sensor types as the roots had reached the sensor depth (Figure 10). The increasing rooting depth was very clear in the 5TE sensor results (Figure 10A) that were installed down to 0.5 m depth with 0.1 m increments.

The crop model parameter WUE describes the crop water use in relation to the CO_2 intake. The true value of WUE is dependent on prevailing conditions, which vary considerably during the summer, but a constant value was used in the simulations. Therefore the crop water use was calculated from the measured soil moisture content and further crop WUE was calculated with observed biomass during the first time period and with simulated biomass during the second time period (Figure 10). The results from MP406 sensors at depths 0.1, 0.2 and 0.3 and 5TE at depths 0.1–0.5 m were used to calculate the crop water uptake. The timing of the WUE calculations was selected according to the precipitation. During the time interval there was no rainfall and therefore it could be assumed that the changes in the measured soil moisture content were mainly due to crop water uptake and the effect of evaporation was assumed to be negligible from a depth of 0.1 m downwards. In addition it was assumed that the crop water consumption during the selected dry spells was higher than on average during the growing season due presumably to low air humidity, since the time since the last rainfall was long.

The WUE value used in the simulations (Table 6) was closer to the WUE calculated from MP406 results (latter value, Figure 10A). The WUE values calculated from 5TE results were between the values calculated from the MP406 results (Figure 10). This was concluded to be due to the different behaviour of the sensors but in general it highlights the challenge of the measurement very well. The changes in the soil moisture content due to crop water use are relatively small (Figure 10) and therefore only small errors in the soil moisture content measurements lead to large differences in the WUE value.

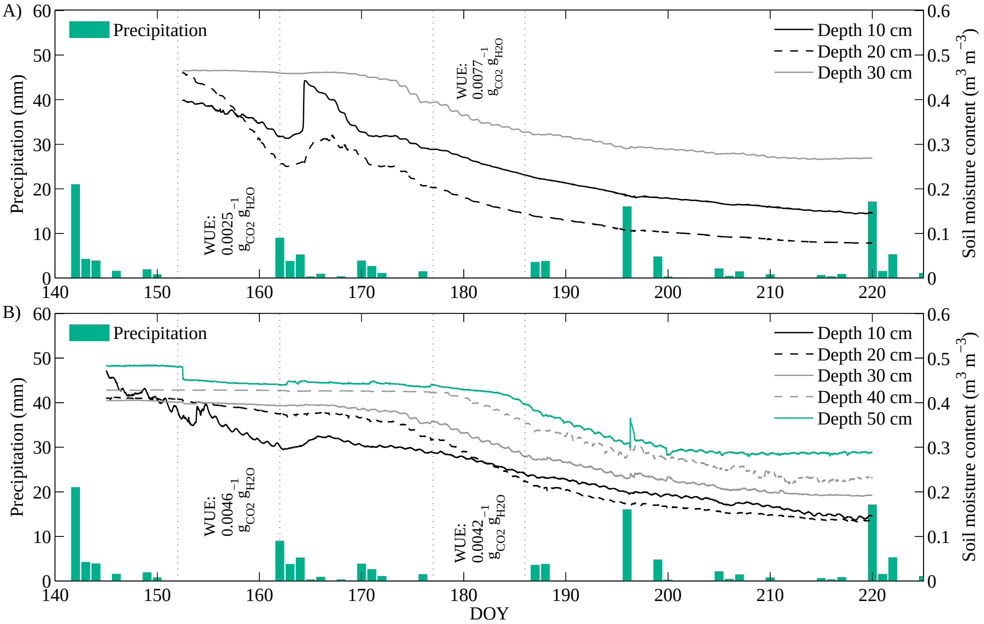


Figure 10: Soil moisture during the growing season from various depths measured with MP406 (A) and 5TE (B) sensors. The crop water use over two different time intervals was calculated according to the decrease in the measured soil moisture content. The change in crop biomass (for calculating the WUE) was calculated from biomass samples (first time interval) and simulated biomass accumulation (second time interval).

4.2.2 Leaf area development and radiation measurements

During the early growth the leaf area accumulation was very similar in all radiation treatments (Figure 11) because of relatively small differences in the incoming PAR (**II**). Therefore the difference in the simulated leaf areas started to appear around the 165th DOY in Figure 11. From this date on the simulated leaf area accumulation rate in the natural precipitation treatment was higher due to the higher incoming PAR that accelerated the leaf area expansion (Figure 11). The model provided the maximal leaf area accumulation that was in agreement with the leaf area calculated from the plant samples (Figure 11). However, the leaf area measured with an optical technique (LP-80, Decagon Devices Inc. Pullman, WA, USA) produced consistently the lowest values (**II**).

The approach of measuring the leaf area in a continuous manner (**I**) was tested with the PAR sensors (Table 2) installed above and below the canopy (**II**). The measurement results from four hours before noon to four hours after noon were used to calculate the canopy-intercepted radiation (Figure 12). For continuous LAI values (Figure 12), an average of canopy-intercepted radiation over the eight hours was divided by the crop theoretical maximal capacity of a leaf (100 W m^{-2}).

The fluctuating radiation intensities were a challenge in the two-radiation-sensor based LAI measurements (Figure 12). A single value measured below the canopy was highly dependent on the measurement device sensing area size, leaf distribution in the canopy and radiation intensity at the measurement moment. A small sensing area together with low canopy leaf area produced varying results since the small sensing head was occasionally covered by a leaf (DOY 161, Figure 12). In practical applications the

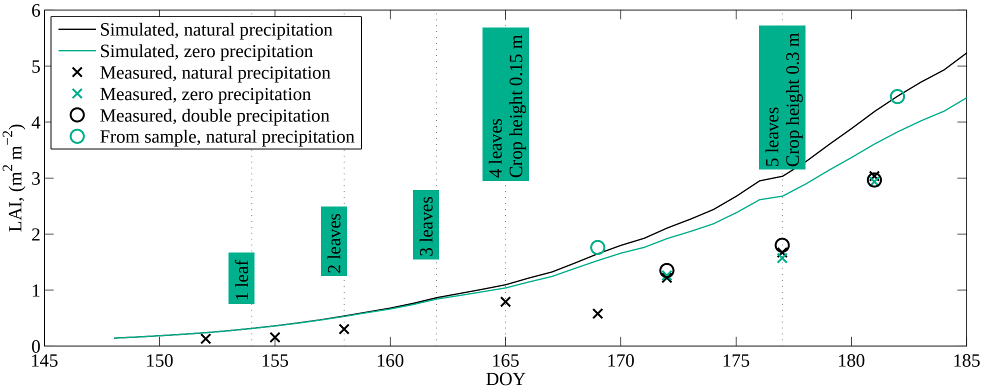


Figure 11: Simulated and observed leaf area accumulations. The simulation result of double precipitation was equivalent to zero precipitation and is not presented. The measured values were derived with the optical device (Decagon LP-80), whereas calculated values originated from the plant samples from the zone of 50 kg N ha^{-1} fertilization (**II**: Figure 1).

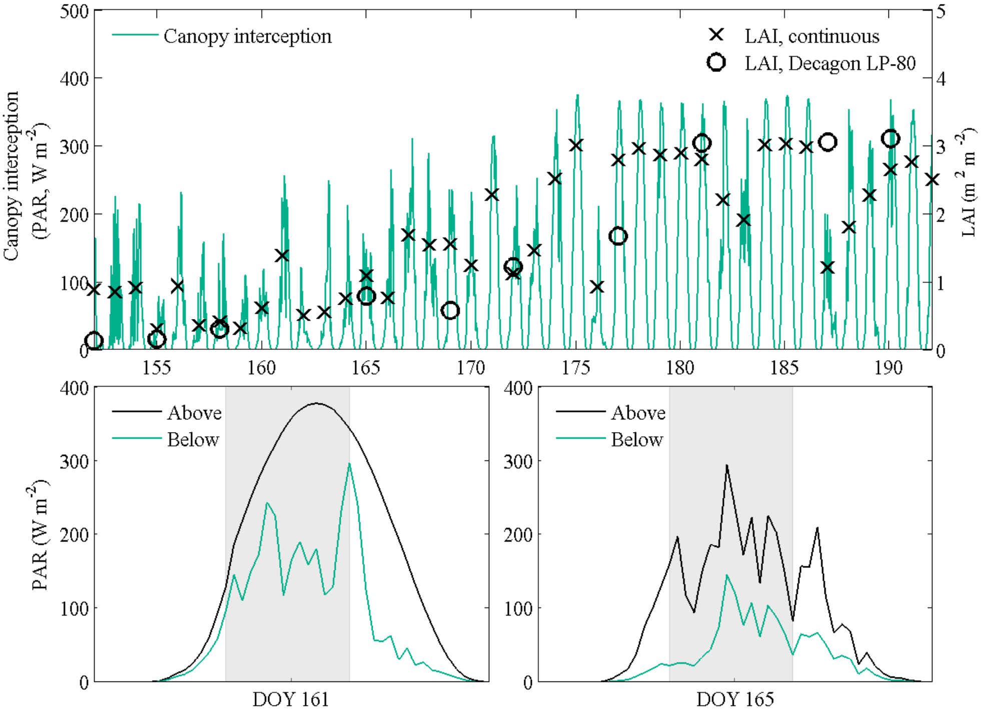


Figure 12: Canopy intercepted radiation and two examples of half hourly radiation intensities (above and below the canopy) from two contrasting days (**II**). The continuous LAI measurement values were calculated from two PAR sensors (Table 2) installed above and below the canopy. The measurements with LP-80 (Decagon Devices Inc. Pullman, WA, USA) were conducted on a weekly basis.

size of the sensing head can be increased up to certain extent and some of the variation can be filtered out in this way (**II**). The changes in the incoming solar radiation during the cloudy days (DOY 165, Figure 12) was another challenge in the radiation-based measurement that cannot be solved with changes in the instrument. With continuous measurement results the appropriate time can be selected or a suitable algorithm can be used. However, the radiation conditions are a limitation for the measurements conducted with specific time intervals when the devices usually have specific requirements for radiation conditions during the measurement (Jonckheere et al. 2004).

4.2.3 Simulated and observed biomass accumulation

The simulated biomass accumulation in different treatments was identical during the early growth, as was found in the case of LAI development (Figure 11). The biomass accumulation during the linear phase of the growth fluctuated slightly (Figure 13), due to the observed changes in the PAR intensity (**II**). The simulated biomass accumulation in precipitation treatments was not visible until the 198th DOY and the effect of water was clearly lower than the effect of radiation (Figure 13). The model does not include the phenology of the crop and therefore the end of simulation was set according to the observed leaf scenesense between the DOYs 205 and 217. To compensate for the gradually decreasing growth, the end of simulation was set at DOY 207, which appears as a sharp corner at the end of the simulated biomass accumulation (Figure 13).

The simulated biomass accumulation in zero and double precipitation treatments was identical if the only growth limiting factor was radiation. However, in the zero precipitation treatment, the decrease in the slope of the biomass accumulation curve (after the 198thDOY) indicated a slight shortage of water (Figure 13). This was not found in the field experiment since the yields in the zero and double precipitation treatments were the same and the effect of drought was not distinct (Table 7). During the root measurements, the tips of the roots were found from the moist soil even during the latest measurement on the 197th DOY when the roots reached the depth of 0.56 m (**II**). Therefore the measurement results indicate a sufficient amount of water available for crop growth during the growing season (**II**).

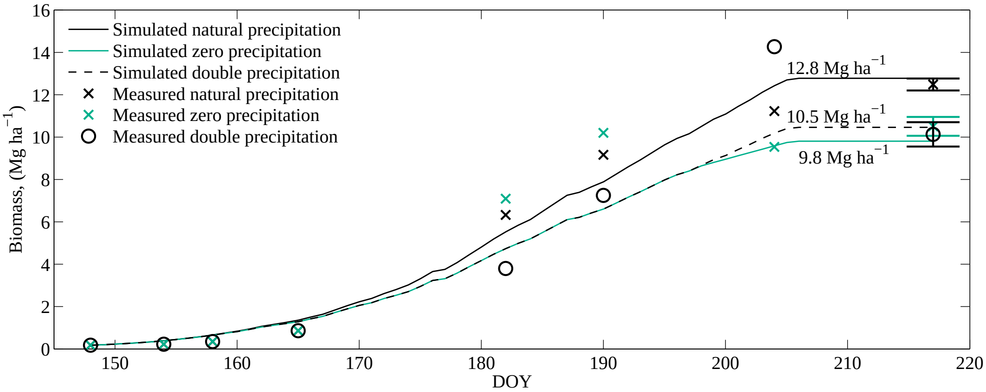


Figure 13: Simulated biomass accumulations and observed biomasses at the highest fertilization treatment (150 kg N ha^{-1}) during the growing season 2010 (**II**).

Table 7: Observed total biomass yield (dry matter). Standard error (±S.E.) and harvest index (grain yield divided by the biomass above ground) were also calculated for the different treatment zones (**II**).

	Nitrogen treatment (kg ha^{-1})			
	15	50	150	
Normal precipitation	9530 ± 120	12300 ±100	12500 ± 300	BM yield (kg ha^{-1})
	0.48	0.48	0.48	Harvest index
No precipitation	7400 ± 400	8900 ± 200	10500 ± 400	BM yield (kg ha^{-1})
	0.48	0.46	0.48	Harvest index
Double precipitation	7900 ± 400	9220 ± 150	10100 ± 600	BM yield (kg ha^{-1})
	0.48	0.45	0.4	Harvest index

The biomass accumulation figures simulated for different precipitation treatments (Figure 13) were applicable for all fertilization treatments (Table 7) because only PAR and water availability are considered as the growth-limiting factors in the model. However, optimal growth conditions (including nutrients) are assumed in the model and therefore the simulated biomass accumulation is in agreement only in the treatments where this assumption is valid (most probably the highest fertilization treatment, Table 7). The effect of fertilization was noticeable in the experiment as the biomass yield increased from the unfertilized treatment (8100 ± 500 kg ha^{-1}) by 17, 52 and 54% for the fertilizer treatments 15, 50 and 150 kg N ha^{-1}, respectively (Table 7, **II**). The highest fertilization treatment produced the highest yield except in the natural precipitation zone where the difference between the two highest fertilization treatments (50 and 150 kg N ha^{-1}) was negligible (Table 7, **II**). The shelter affected the biomass accumulation in the zero and double precipitation treatments, which together form the radiation treatment (**II**). The biomass yield decrease due to reduced radiation (Table 7) was on average 21.3 ± 2.0% and the decrease of radiation due to the shelter was 21.0 ± 0.5%. The effects of the reduction of PAR and differences in precipitation on the harvest index were mainly small (Table 7).

The results from the preliminary experiment on additional fertilization during the growing season showed that the later the additional fertilizer was applied the lower was the yield increase (Table 8). There was one exception when a late fertilizer application was combined with irrigation. In this case the yield increase was notable in comparison with the application preceding and after the irrigation event (Table 8). The biomass yields of additional fertilization treatments are comparable to the result of 50 kg N ha^{-1} treatment with natural precipitation (Table 7), where the total amount of nutrients provided with the fertilizer was the same.

Table 8: Observed biomass yields from a preliminary experiment on additional fertilization treatments. Growth stage at the time of additional fertilization was measured according to the Zadoks scale (Zadoks et al. 1974).

Fertilization DOY	**Growth stage (Zadoks)**	**Add. fert. (kg N ha^{-1})**	**Irrigation (mm)**	**Total BM yield (kg ha^{-1})**
-	-	-	-	8100
162	12	50	0	11400
169	14, 22	50	0	10300
175	31	50	0	9700
182	33	50	30	11500
197	65	50	0	8500

4.3 Devices for soil moisture content measurements

Soil moisture content was measured continuously with two sensors (Table 2). However, some discrepancies between the results from different devices were observed (e.g. Figure 10). Therefore selection of soil moisture sensors (Table 3) capable of measuring soil moisture in a continuous manner was tested in laboratory conditions (Figure 14) (Supplementary material). The linearity of the dependence between the volumetric water content (gravimetrically determined) and measured values was found to increase with the compaction of the sample (Figure 14).

More extensive testing of soil moisture sensors was conducted in field conditions (Supplementary material). The soil water content was measured four times during the growing season from several depths and all the results were combined to Figure 15. All the used sensors showed some variation in the results but the reference method (undisturbed soil core samples and owen drying) also includes some variation (Figure 15). MiniTrase, TDR300 and AK30 were the three sensors with the lowest variation in the results (C, D and E, Figure 15). In addition to the soil moisture sensors the soil temperature was measured with an infrared thermometer (F, Figure 15).

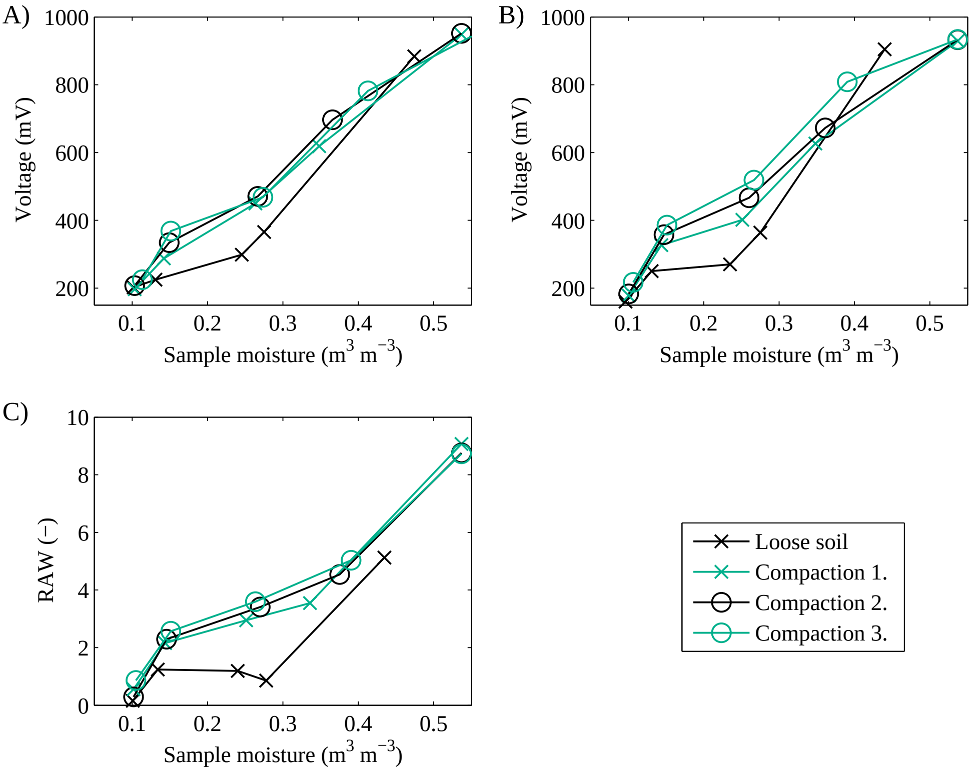


Figure 14: The laboratory test results of three different soil moisture sensors. The tested sensors were A) ThetaProbe M2x/d, B) MP406, C) 5TE. Four different compaction rates of soil were measured. The first was mixed sample with no compaction. For the subsequent measurements from one to three the sample was compressed with a pressure of 7.8, 16.5 and 25.1 kPa, respectively.

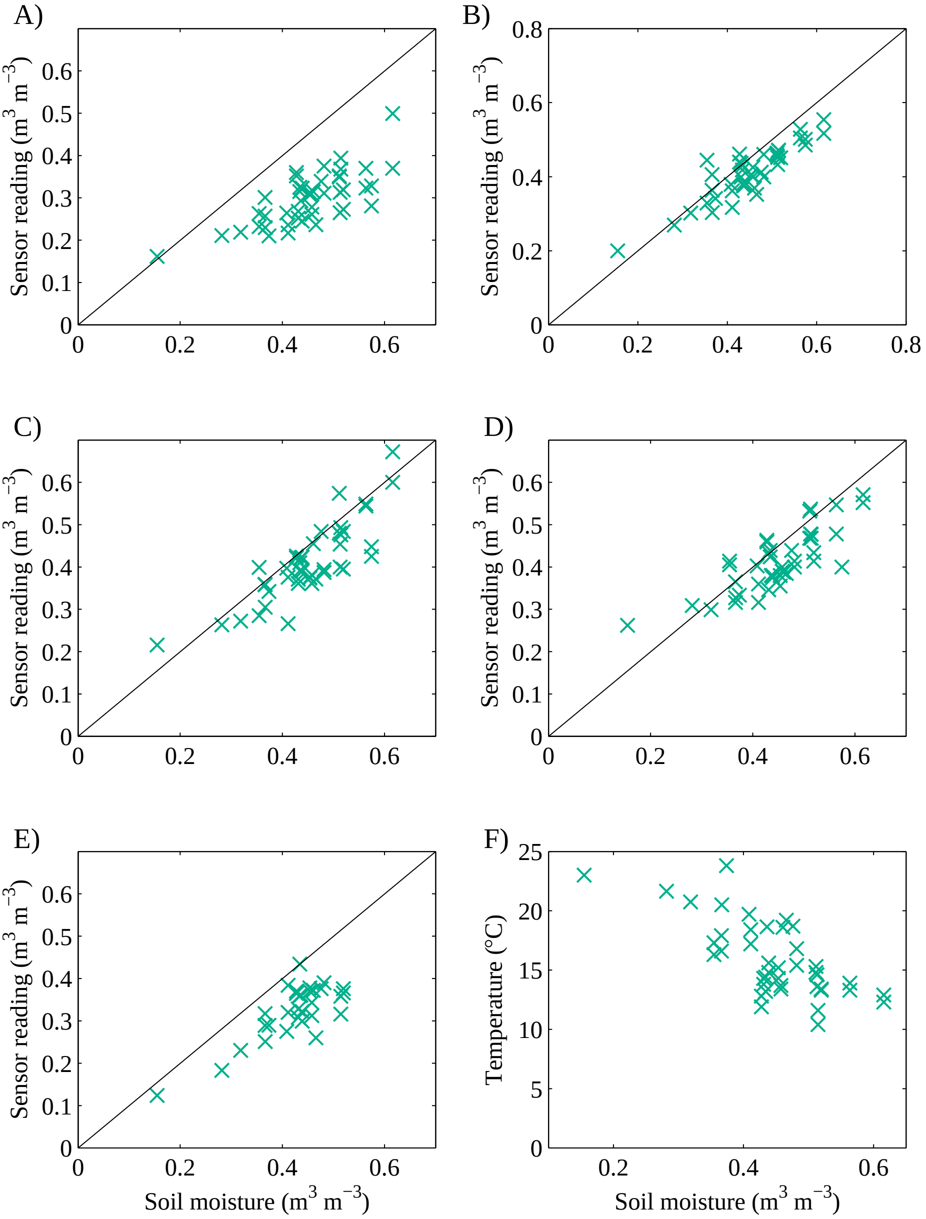


Figure 15: Results of the field measurements of soil water content with several different sensors. The used sensors were: A) 5TE, B) ThetaProbe M2x/d, C) MiniTrasekit, D) TDR300, E) AK30, F) Infrared thermometer (Table 3). In the case of sensor readings of volumetric water content (m^3 m^{-3}) the device default calibration or settings were used.

4.4 Application of the model in the study of yield variation using site- and depth-specific soil properties

4.4.1 Soil properties, observed yields and simulated yields

The K_{sat} and PAWC were both found to be depth dependent and to include considerable spatial variation (**III**: Figures 2 and 3). Differences between the fields were found to be minor in the PAWC (**III**: Figure 2) but greater in the K_{sat} (**III**: Figure 3). The field Jokioinen 1 was an exception because the average K_{sat} remained high throughout the observed soil layer whereas in the fields Jokioinen 2 and Vihti the values clearly decreased when moving deeper in the soil. For the fields Jokioinen 2 and Vihti, variation in the K_{sat} values was higher than in the field Jokioinen 1 and the average K_{sat} of the topsoil was higher in comparison to the lowest observed depth (**III**).

Significant differences in the observed wheat and barley yields were found between the years in all the fields (**III**). Despite very different precipitations during the experimental period (Table 4) and different K_{sat} values between the fields (**III**: Figure 3), the correlations between yield and soil properties were significant only in three cases. In Vihti, the correlation between the average observed K_{sat} and grain yield was significant in 2006 ($r = -0.59$, $P < 0.05$) and 2008 ($r = 0.44$, $P < 0.05$) and in Jokioinen 1 in 2003 ($r = 0.5$, $P < 0.05$) (**III**). In Jokioinen 2, all correlations between grain yield and the average K_{sat} and PAWC were insignificant ($P > 0.05$) (**III**).

In all years of the study, the simulated (maximal) biomass accumulation was higher than the observed, except in the field Vihti in 2006 (**III**; Table 9). The standard deviation (s) in the simulated biomass yield was consistently lower than the observed, except during the year 2002 (Table 9). In Vihti, the highest spatial variability of the biomass yield coincided with notably low precipitation in the year 2006 when the cultivated crop was spring wheat (Table 9) (**III**). During the same year, the simulated biomass accumulation suggested the yield to be reduced due to lack of water even more than was observed (Table 9).

The site or sites with contrasting high or low yield (Figure 16) in comparison with the field mean were interesting because they notably affected the spatial yield variation calculated over the whole field (**III**). In addition the large differences between the observed and simulated yields were interesting for model testing purposes. Therefore some sites were chosen for detailed analysis of simulated and observed yields and soil moisture content.

Table 9: Mean values and standard deviations (s) of the simulated and observed biomasses at the time of harvest. The mean values are the dry biomasses of the whole crop (including leaves, stem, roots and grains) (**III**).

	Jokioinen 1		**Jokioinen 2**		**Vihti**		
	Mean	**s**	**Mean**	**s**	**Mean**	**s**	
	2002		2002		2006		
Observed	9600	400	7100	700	10500	3600	kg ha^{-1}
Simulated	12400	600	12200	900	7200	500	kg ha^{-1}
	2003		2003		2007		
Observed	7400	1000	8200	2000	-	-	kg ha^{-1}
Simulated	11300	500	10300	1100	-	-	kg ha^{-1}
	2004		2004		2008		
Observed	8600	1000	6000	1500	16800	2000	kg ha^{-1}
Simulated	14000	600	14600	900	16500	700	kg ha^{-1}

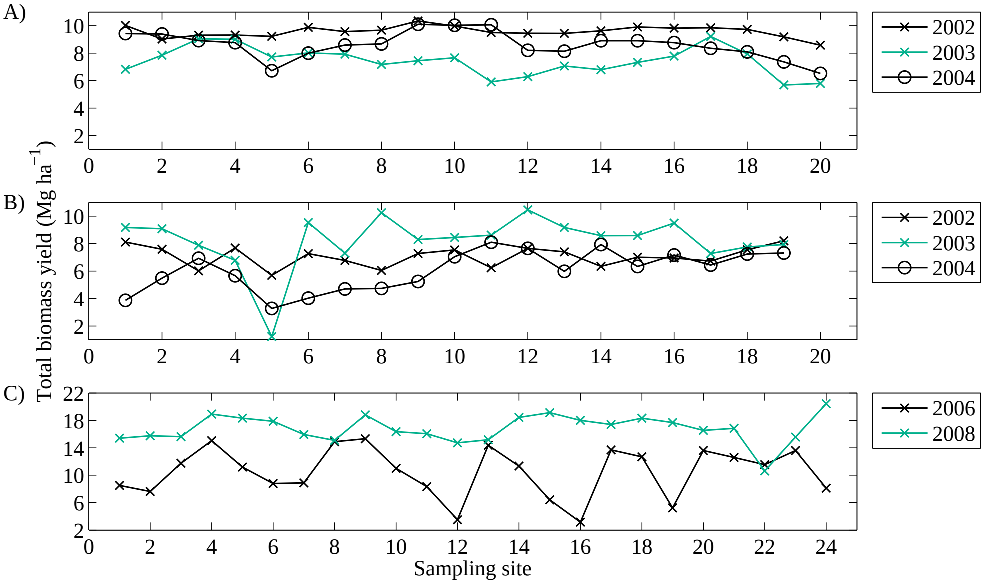


Figure 16: Site-specific total biomass yields on the fields Jokioinen 1 (A), Jokioinen 2 (B) and Vihti (C) during the three years of the experiment (**III**). The biomass yield was calculated from the observed grain yield with harvest index (HI) and root biomass fraction.

4.4.2 Exceptional yield variation in the fields Jokioinen 1 and 2

The soil textures of the fields Jokioinen 1 and 2 (**III**: Figure 2) were very similar according to the soil analysis (**III**; Ristolainen et al. 2006). However, the mean biomass yield in Jokioinen 1 was on average 16% higher than in Jokioinen 2 during the experimental years (Table 9). The fields did not differ in the PAWC although the average water contents at FC and PWP were higher in the field Jokioinen 2 (**III**). The most notable difference between the fields Jokioinen 1 and 2 was the higher mean K_{sat} in Jokioinen 1, especially in subsoil (**III**).

The mean weather conditions in years the 2002 and 2003 were very similar (**III**; Table 4). However, in 2003 the grain and biomass yields were decreased by 23% from the previous year in Jokioinen 1, whereas a yield increase of 13% was observed in Jokioinen 2 (Table 9). A rainy period at the beginning of the growing season 2003 caused a delay in the sowing of the field Jokioinen 2 (**III**). Therefore the growing conditions were different between the fields, e.g. in Jokioinen 2 PAR was lower and precipitation higher (Table 4). The delayed sowing was beneficial in terms of crop biomass yield (Figure 16, Table 9) and LAI development as the highest average LAI in the field Jokioinen 2 was 4.7 ± 0.3 m^2 m^{-2} and significantly higher ($P < 0.01$) than in Jokioinen 1 (3.7 ± 0.1 m^2 m^{-2}). However, the observed yields in the fields Jokioinen 1 and 2 were not significantly different in 2003 (**III**).

The site number five was selected for detailed analysis due to the contrasting low yield in 2003 (**III**; Figure 16). The simulated biomass yield (11.4 Mg ha^{-1}) of site five in the field Jokioinen 2 in 2003 did not differ from the other sites but the observed biomass yield was very low (1.2 Mg ha^{-1}, Figure 16). The highest observed LAI in the site five (1.7 m^2 m^{-2}) remained notably low e.g. when compared to the nearest observed site number four (3.7 m^2 m^{-2}) (**III**). The weak growth in site five was evident from the observed soil water content, that decreased noticeably slower in comparison to site four and the simulation (**III**; Figure 17). Furthermore, the initial moisture content in the site was exceptionally high (Figure 17) when the first observed topsoil soil water content was the same as the SWC of the topsoil (0.57 m^3 m^{-3}) (**III**).

The precipitation in the beginning of the growing season 2004 was low (124–139th DOY, Figure 18) and the lowest observed temperatures were below zero degrees during five days within the same time period (**III**). High overall precipitation was feasible for simulated biomass accumulation and for the observed mean yield of the field Jokioinen 1 (Table 9). However, in Jokioinen 2 the observed mean biomass yield decreased significantly ($P < 0.05$) from the year 2003 (**III**) and the simulated yield deviation was the highest of the three years (Table 9). In Jokionen 2, the decrease in the observed yield was the highest in the sites 1, 2, 6–9 and 13 (**III**; Figure 16). A common feature for these sites (in comparison to the field average values) was the decreased clay content and increased silt content of the plough layer (0–0.35 m) but the sites could not be differentiated with PAWC or K_{sat} values, as suggested by the low correlations with the grain yield (**III**). The soil water content was clearly higher during the growing season 2004 when the 0–0.3 m and 0–0.6 m observations could not be differentiated whereas in the year 2003 the topsoil (0–0.3 m) was clearly drier (Figure 18).

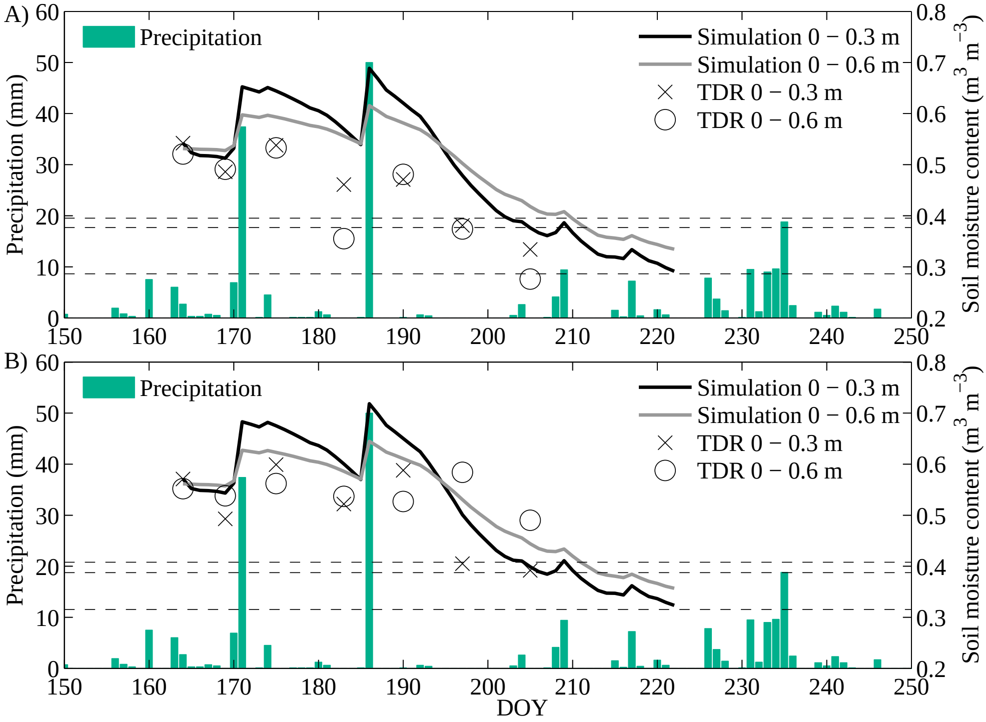


Figure 17: Simulated and observed soil moisture contents in the field Jokioinen 2 (Figure 4) at the sites four (A) and five (B) during the growing season 2003 (**III**). The horizontal dashed lines from down to up are site-specifically observed PWP for depths 0–0.2 m 0.2–0.35 m and 0.35–0.6 m, respectively.

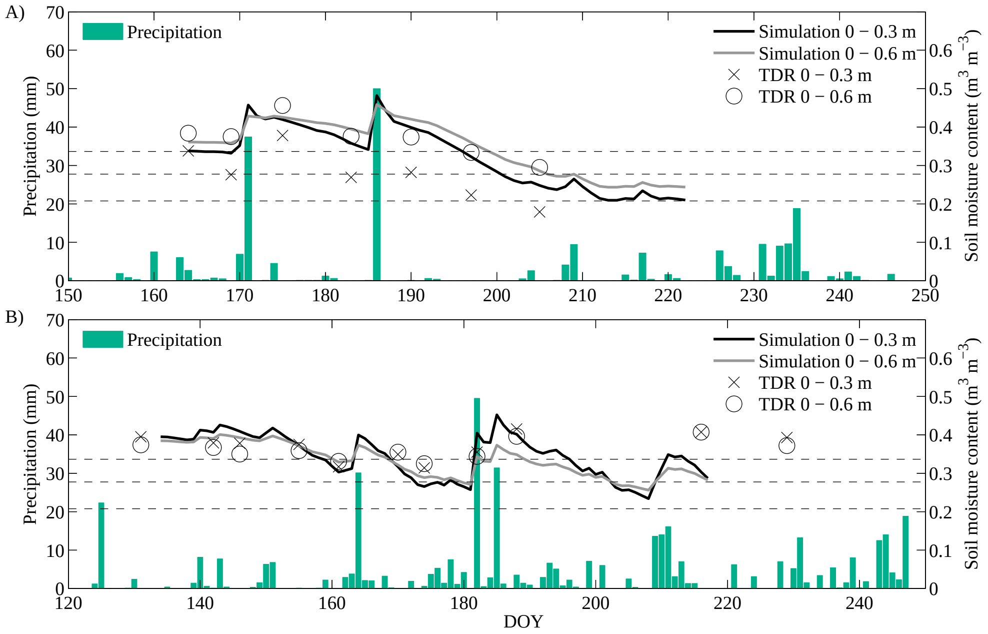


Figure 18: Simulated and observed soil moisture contents during the growing season 2003 (A) and 2004 (B) at site six in the field Jokioinen 2 (**III**). The horizontal dashed lines from down to up are site-specifically observed PWP for depths 0–0.2 m 0.2–0.35 m and 0.35–0.6 m, respectively.

4.4.3 Exceptional yield variation in Vihti

In Vihti the highest spatial variation and the lowest wheat yield were observed at the same time, in 2006 (Table 9). The simulated biomass yield was significantly (P < 0.001) lower than the observed yield and the simulated yield varied less than was observed (Table 9). The simulated biomass yield should not have been lower than the observed yield and therefore the biomass accumulation limited only by radiation was calculated and the result was 3300 kg ha^{-1} higher than the highest observed biomass yield (15300 kg ha^{-1}, Table 9) (**III**). However, the simulated (radiation limited or water and radiation limited) yield did not coincide with the observed low yielding sites (data not shown). Therefore, according to the simulated biomass yield the water should have decreased the growth even more than was found in the observed biomass yield (**III**). The sites with the lowest observed yields (Figure 16) were located at the south-eastern part of the field where the elevation was the highest (Figure 4) and the soil texture was slightly coarser than on average (**III**). A common feature for the low yielding sites was decreased soil water uptake (Figure 8 in article **III**) compared to the high yielding sites with measured soil moisture (**III**). Another common feature for low yielding sites was low observed leaf area (e.g. at the two lowest yielding sites the observed leaf areas were 0.8 and 1.1 m^2 m^{-2}) (**III**).

In 2008, the observed biomass yield was the highest for wheat during the experiment (Table 9). The simulated biomass yield variation was lower than observed (Table 9) and none of the sites with low simulated yield coincided with the sites with low observed yield (**III**; Figure 16). In comparison to the field average yield the sites 22 and 24 had very low and very high yields, respectively (**III**). They had a great impact on the spatial variation of the yield because by neglecting the sites, the yield variation was decreased to 1400 kg ha^{-1} whereas the simulated variation was 800 kg ha^{-1}. Both sites were located in the southernmost corner of the field (Figure 4) and had very similar observed LAI values (**III**). The soil water content observations also failed to explain the yield difference.

4.4.4 Temporal standard deviation of the observed yield

To analyse the variation in the observed (Figure 19, A) and simulated (Figure 19, B) yields, the temporal standard deviation (Blackmore et al. 2003) of the yield was calculated according to Eq. 15 (**IV**). In the article **IV** all sites were combined and treated as if they were observed from one field because the number of observed sites in each field was relatively low. In the results presented in this thesis the fields were treated separately in the calculations. Despite the same cultivated crops (barley) in the fields Jokioinen 1 and 2 the observed mean yields were somewhat lower and the variation higher in Jokioinen 2 (Figure 19). Jokioinen 2 had a slightly higher variation in the soil properties (Figure 4) and the temporal standard deviation of the observed yield was higher than in Jokioinen 1 (Figure 19, A). Non soil-related reasons for the observed yield variation were also found (**III**) and the temporal standard deviations of the simulated biomass accumulation were at the same level in the fields Jokioinen 1 and 2 (Figure 19, B). The observed mean yields in the field Vihti were generally higher (Table 9) but the years (Table 4) and the cultivated crop (spring wheat) were different in comparison to Jokioinen 1 and 2 where barley was grown. The yield variation (Table 9) and the temporal standard deviations (Figure 19) were also the highest of the three fields.

In order to analyse the effect of site-specific soil properties on varying precipitation conditions the biomass accumulation was simulated for 1000 different growing seasons with individual precipitations (**IV**). The year specific precipitation was the only yearly changed variable between the years and was the reason for temporal variation in the simulated biomass accumulations. The spatial variation in the simulated biomass accumulation was solely due to the site-specific soil properties that were used as parameter values in the simulations (**IV**). For more detailed analysis the years with low (precipitation sum <80 mm) and high (precipitation sum >180 mm) precipitations were selected (Figure 20). The temporal mean yield was notably lower at all fields during the years with low precipitation (Figure 20). The changes in the temporal standard deviation due to precipitation were small (Figure 20).

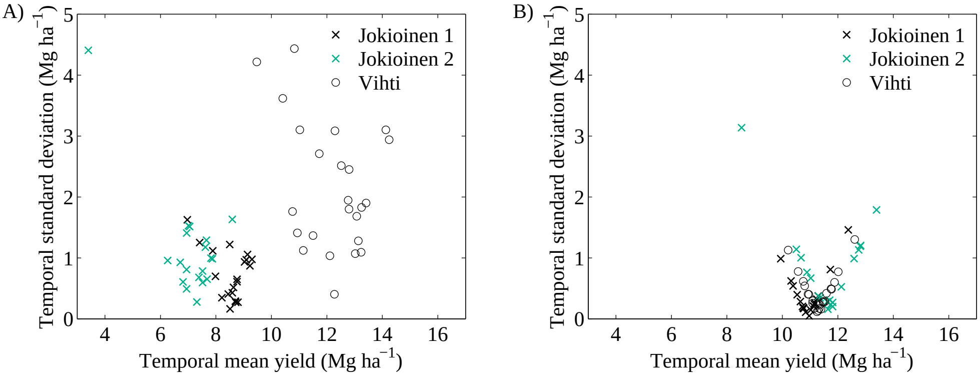


Figure 19: The temporal standard deviation (Eq. 15) of the observed (A) and simulated (B) biomass yields as a function of the site-specific average biomass yield over the observed and simulated years, respectively (**IV**).

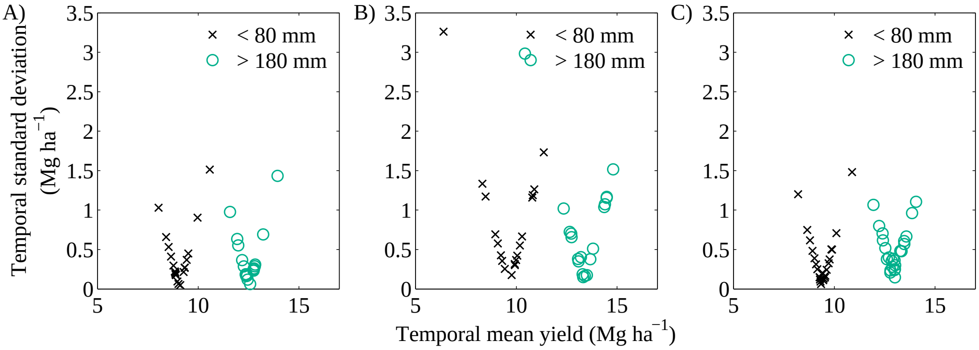


Figure 20: The temporal standard deviation (Eq. 15) of the simulated biomass yields as a function of the site-specific average biomass yield over the observed and simulated years. The results from years with low (precipitation sum <80 mm, n= 48) and high (precipitation sum >180 mm, n=112) precipitation were used to calculate the results from fields A) Jokioinen 1, B) Jokioinen 2 and C) Vihti.

4.5 Application of the model in a fully automatic crop farm simulator

The crop model was applied in a simulator built for simulation of a totally autonomous crop farm (**V**). In this study the two crop models and two different approaches for building the simulator (Figure 6) were compared in terms of computation time required. The approaches were evaluated with a simulation in which a field area containing 9000 cells (5×5 meters) was simulated over a single growing season (from the beginning of April to the end of September) using a simulation time step of one hour. In the first approach the Simulink model was compiled to C++ and further to a .NET component, and running the simulation using ArcGIS was found to be more efficient in terms of the time required to perform the simulations. This approach took less than 2% of the computing time required with the second approach in which Matlab was used as a simulation engine. The computational time required for the second approach was around 10 hours to compute with a P4@3.2GHz processor. Although the first option was more efficient in running the simulations it was more laborious to develop (**V**).

The total computational time depended on the cell count, that was defined by the spatial grid size (how large was the simulated area and how densely it was simulated) and time step parameters (how often the calculations were conducted). In the current simulations the calculations were conducted in about 39 million cells and therefore the total computational time was also heavily dependent on the used models (**V**). In the current solution the time step for the crop model was 1 hour, the changes in the soil moisture content were calculated 10 times an hour and horizontal water flow between the soil cells once a day. The crop model introduced in this thesis (**I**) was found to consume less computational time than was spent with the SORGHUM model. However, a considerable amount of time was spent on calculating the changes in soil moisture content, partly due to the higher frequency of the calculations (**V**).

5 Discussion

The introduced crop model was found to produce the maximal biomass accumulation (**I**; **II**; **III**). In these studies, the most relevant model parameter values were measured and the rest of the parameter values were taken from the literature. Because the model was based on the principles of physics, chemistry and physiology to the very last extent, the parameter values were known to a first degree of approximation (**I**). However, the measured parameter values should be preferred over the literature values in order to enhance the description of the biomass accumulation in the growing conditions during the study. Furthermore, in order to apply the model in other growing conditions than presented here, the parameters can be subjected to changes. The effects of the parameters and of their values are discussed in the following.

5.1 The basis of the model: vegetative growth period and constant parameters

The intended use of the model introduced in this thesis was precision farming of small grain cereals. In order to be able to affect crop growth, the cultivation actions need to be performed during the vegetative growth phase although there may be a need for site-specific actions already before or at the time of sowing. Because the time of interest was limited from emergence of seedlings to the end of the vegetative growth, the model was developed to describe the maximal biomass accumulation of a C3 crop during the vegetative growth phase. The aim to produce the maximal biomass accumulation and the limitation concerning the vegetative growth phase were the two major differences in comparison of the introduced crop model to traditional crop growth models that have had their aim in producing the actual growth and harvest yield in a very detailed manner.

The advantage and the disadvantage of the introduced model was the low number of constant parameters. Due to low number of parameters the model can be easily applied in new situations and on a farm scale (**II**). For the same reason the appropriate value of a parameter can be challenging to determine beforehand because the value must represent the growing conditions over the time period. However, because the maximal radiation-limited biomass accumulation is the required result the necessary parameter values can be regarded more as location specific than season specific. In the case of traditional crop modelling (actual growth or biomass accumulation during the growing season) the parameter values must describe the current growing conditions and are therefore more challenging to obtain.

Constraining the model to maximal biomass accumulation during the vegetative growth phase was essential for the simple structure of the model containing the constant parameter values (**I**). In this way the parameter values could be obtained from physics, chemistry and crop physiology with an assumption that the physical and chemical phenomena leading to the plant growth are ultimately limited by the laws of the physics and chemistry. Accordingly, crop properties or appearance can reduce the rate but not increase it remarkably, at least over the physical or chemical limits. The model was found to produce the maximal biomass accumulation (**I**; **II**; **III**) with constant parameters. However, constant parameters are not mandatory. For example, measured PAR was used as an input in study **II** instead of a constant PAR over the growing season. Therefore measurement results or a function describing the development of the parameter can be used instead of constant values, if necessary (**II**). Crop features such as root growth (e.g. Pietola and Alakukku 2005) or biomass allocation (e.g. Kleemola et al. 1996, 1998) have been found to change due to the growing conditions. Despite this, such features of a crop can be assumed to be constant over a limited time period and thus constant parameter values can be used (**I**). For example, the amount of roots was found to steadily increase around the first two months in a study with barley and oats (Pietola and Alakukku 2005). This time period approximately covers most of the vegetative growth (**II**).

Many crop models (e.g. SUCROS and WOFOST among many others) use equations based on heat summation for considering the changes in the biomass allocation during the growth, i.e. for considering the phenological development (e.g. Bouman et al. 1996; Diepen et al. 1989; van Ittersum et al. 2003). Although the heat summation is a strong indicator of the crop current growth stage the crop biomass allocation is an optimization problem in which photosynthesis and growth are maximized (Taiz and Zeiger 1991). This has been found to be affected by availability of growth resources and their lack (e.g. drought stress), which means balancing between growing roots and leaves (e.g. Charles-Edwards 1976; Xinyou and Van Laar 2005). This has been noted in many studies, and more dynamic approaches for biomass allocation to roots have been proposed (e.g. Kleemola et al. 1996, 1998) to consider the changes in crop structure due to the varying growing conditions and to enhance the simulation results.

The crop model also included an assumption about optimal growing conditions excluding solar radiation and water availability. This means that the air temperature is in the optimal range (not lower or higher), weeds or diseases do not exist and there is no excess water that would limit the root expansion (**I**). The temperature is dependent on the current weather and is rather straightforward to measure. As the model is to be applied in fields where the weeds and diseases are controlled, the assumption of a weed- and disease-free field is justified. The same goes for excess water, which in the fields should be handled via a drainage system.

5.1.1 Intercepting the radiation, parameters I, n and RUE

I and n are the model parameters that define the lighting conditions for the cultivated crop. They belong to the group of three most significant parameters affecting the crop growth during the linear growth phase (Figure 8). The values of these parameters have to be set according to the location where the model is to be applied. The most significant factors are the latitude of the location and possible obstacles surrounding the field and reducing the direct solar radiation for the cultivated crop.

Nobel (1999) found that in C3-plants a leaf was able to intercept PAR up to a certain intensity when the photosynthesis reaction center became saturated. The same phenomenon was found in a study of a wheat flag leaf photosynthesis rate when the rate was found to saturate approximately at 100 W m^{-2}(Marshall and Biscoe 1980) and in a study with well fertilized winter wheat flag leaves at anthesis (Gregory et al. 1981). This observed phenomenon is the basis of the model that furthermore limits the model applicability only to C3 crops due to a different photosynthesis mechanism in C4 crops (**I**). The photosynthesis rate of C4 crops has been reported to increase with increasing PAR after the level when C3 crops have reached the maximum photosynthesis rate (Hay and Porter 2006). The maximum interception capacity of a leaf in the model is described with the parameter I_{sat} and the value 100 W m^{-2} originated from the earlier studies on wheat cultivated with sufficient fertilization (Gregory et al. 1981; Hay and Porter 2006; Marshall and Biscoe 1980). Therefore it follows that the canopy radiation interception capacity is I_{sat} times LAI (Eqs. 4 and 8). This is a rather crude approximation and more accurate equations exist (see e.g. Hay and Porter 2006). However, as Hay and Porter (2006) discussed extensively the canopy photosynthesis of a C3 crop is a complex mechanism in which the photosynthesis rate of a single leaf, leaf angle and distribution in the canopy all have their effects. In this respect the selected approach was efficient in terms of the number of parameters in the model, which would unavoidably have been higher if all these aspects had been considered. Despite the crudeness of the selected approach, it was found to be a reasonable approximation for maximum amount of radiation intercepted as it cannot be exceeded due to unavoidable losses due to e.g. partially overlapping leaves.

After PAR interception, the energy from radiation is used in photosynthesis to form biomass from water and CO_2. Monteith and Moss (1977) studied biomass accumulation of C3 crops and found that the total dry biomass was increased by 1.5 g when 1 MJ of total solar radiation was acquired. This relationship determines the efficiency of a crop to utilize the radiation and is called RUE (Hay and Porter 2006). The parameter RUE (2.8 g MJ^{-1}, Table 5) in the model describes the capability of a C3 crop to produce biomass from a given amount of photosynthetically active solar radiation. This is a property of a crop that has been found to be dependent on the canopy structure and the capacity of the leaves to conduct photosynthesis (Evans 1983, 1987; Hirose and Werger 1987). Evans (1983, 1987) found that the leaf chlorophyll content was approximately proportional to leaf nitrogen content, which furthermore was uniquely related to CO_2 assimilation rate, i.e. growth rate. However, in the same study the increase in nitrogen fertilization was thought to cause only a small increase in the assimilation rate (Evans 1983). In addition, the plants grown with high nitrogen were found to senesce later than the nitrogen deficient plants (Evans 1983). The effect of nitrogen on delayed scenesense may therefore have a higher effect on biomass accumulation, especially in low radiation conditions, such as at high latitudes.

In the case of the whole canopy the situation has been found to be slightly different because the radiation conditions are different for the lower leaves (Hirose and Werger 1987). Therefore the distribution that maximizes the canopy photosynthesis is different from uniform distribution (Hirose and Werger 1987). Hirose and Werger (1987) found the actual distribution to be between optimal and uniform but the actual photosynthetic capacity was only 4.7% less than in the optimal leaf nitrogen distribution. The parameter RUE includes both aspects; the leaf level and the canopy level. At leaf level it is a compromise of distribution within the canopy but the effect on the biomass accumulation is low, as was observed by Hirose and Werger (1987). The parameter RUE is also connected to the leaf chlorophyll content through the photosynthesis rate, which Evans (1983) found to be dependent on the nitrogen availability. However, the leaf chlorophyll content can increase the photosynthesis rate only up to the point at which all the incoming PAR is utilized in the photosynthesis. Therefore a single and constant value of RUE should represent the crop photosynthesis rate well (**I**).

5.1.2 Crop specific parameters: m_s, SD, LWR and SLA

In the case of cultivated field crops, the seedling density and seedling mass are interconnected as seedling density depends on the cultivated crop. The seedling density is basically set at the time of sowing, when the seed rate is set according to the germination percentage of the seeds. However, the soil conditions at the time of germination have been found to affect the seed's germination (Alakukku 2006; Benjamin 1990; Bewley and Black 1985; Tenhovuori 1986), which further can have an effect on the emergence and further to the seedling density. And although the conditions during the germination would be feasible, an extreme weather event (e.g. excess rainfall or long-term drought) can notably decrease the seedling density. Therefore measured seedling density is preferred but the intended seedling density can be used as an initial value for the model before seedling density has been measured.

When considering the germination on a mass basis, after sowing the mass of the seed is slightly decreased because the energy reserve of the seed is used to grow new organs, i.e. roots and leaves (Bewley and Black 1985). At this stage the mass of the seed decreases because the leaves are below the soil surface and therefore incapable of photosynthesis. During the germination, roots and leaves expand and finally when the leaves expand above soil surface the biomass slowly starts to accumulate. Finally at the time of emergence, the mass of the seedling approximately equals the mass of the seed at the time of sowing. Therefore mass of the seed can be used as the value for seedling mass but again, the measured value is preferred (**I**).

The parameter SLA determines how much the leaf area of the crop is increased with a specific amount of biomass. The SLA can be regarded as a crop specific parameter, as it mainly changes according to crop species. However, growing conditions can cause some changes in the SLA, e.g. nutrient composition of the soil. Some studies on nitrogen fertilization have shown changes in SLA, but only with extremely high fertilization rates. With a normal fertilization rate such changes in SLA were not observed. Among SLA, another thing affecting the leaf area development was dry matter allocation, which in the model was described with parameter LWR (**I**). With small grain cereals the assumption of constant LWR is valid during the vegetative growth. However, after vegetative growth the allocation of the biomass changes considerably, leading to e.g. green leaf area decrease, and the assumption of constant LWR is no longer valid. Therefore in order to increase biomass yield at the time of ripening, the simulation must be ended at the onset of leaf area scenesense (**II**), as was done in the studies included in this thesis (**I**; **II**; **III**).

Regarding the structure of C3 photosynthesis the model is applicable to all C3 crops, although constant parameters may cause limitations. For small grain cereals the constant parameters are reasonable during the vegetative growth, which is the time of interest for precision farming purposes (**I**). For other crops the suitability of the model must be evaluated separately. For example, oil seed rape has drastic changes in the leaf area development during early growth and therefore the value of LWR in the model should be changed on a time basis in order to make the leaf area description realistic.

5.1.3 Water-limited biomass accumulation, parameter WUE and soil properties

In rainfed production, the crop water availability is dependent on the field's site-specific water retention properties (Asseng et al. 2001; Timlin et al. 2001; **III**) and the current growing season precipitation (Taylor et al. 2003; Sadras et al. 2012; Basso et al. 2013). A lack of water (i.e. lack of precipitation) in rainfed production may ultimately limit the highest attainable yield, which varies in both space and time (Asseng et al. 2001; Basso et al. 2012; Peltonen-Sainio et al. 2011). In the model the precipitation was an input and the water availability in soil was limited with parameters FC and PWP. The water uptake was limited by the parameters describing the root growth: root growth (r_{growth}) and maximum rooting depth ($r_{\max}$) (Table 5). The root growth in the model was considered to be constant during the simulated time and it was found to be reasonable to calculate the water uptake from soil (**II**). In reality the root growth is more complex. It has been found that plants tend to optimize the carbon gain, which means that the crop expands its roots (i.e. water uptake capacity) and leaf area with such a ratio that the photosynthesis is optimized (e.g. Charles-Edwards 1976; Xinyou and Van Laar 2005). Therefore the actual root growth is presumably a result of growing conditions (precipitation and radiation) and soil properties and thereby can be subjected to changes depending on the year. Despite this fact, several crop growth models (including the introduced one) include linear description of the growth and only in a few cases is the root expansion connected to photosynthesis capacity (e.g. GECROS (Xinyou and Van Laar 2005)).The major reason for this is that sufficiently good results have been obtained by using simple descriptions for the root growth.

In the introduced model the crop water use is described with the parameter WUE that describes water loss during the gas exchange through the stomata of the leaves (**I**). Atmospheric CO_2 is one important determinant of crop water use and its concentration has notably increased during the past 50 years due to burning of fossil fuels (Porter and Semenov 2005). In the case of C3 crops, the higher CO_2 concentration in the air surrounding the leaf has been found to increase the photosynthesis rate (Sicher and Bunce 1997) and to reduce the crop water use (Erbs et al. 2009; Uddling et al. 2008). Despite the inevitable effect of CO_2 on the crop water use and photosynthesis (Ainsworth and Long 2005; Long et al. 2006; Tubiello et al. 2007), the crop yield was increased only in cases when the water availability was limiting the crop growth (Demmers-Derks et al. 1998; Ewert et al. 2002; Manderscheid et al. 2009; Steduto et al. 2007). Furthermore, if some other growth resource limited the crop growth, the yield increasing effect of CO_2 did not necessarily appear in the yield (Manderscheid et al. 2009).

Since the water use for crop growth comes from the soil via root uptake, the WUE was calculated from the measured soil moisture contents. In the field experiment for evaluating the model (**II**) two types of sensors were chosen to monitor the soil water content during the growing season. Two dry spells (10 and 11 days) were chosen for calculating the crop WUE in the experiment. The changes in the soil moisture were smaller in the 5TE sensor results in comparison to the MP406 results (Figure 10). Therefore MP406 produced the highest and the lowest water consumption in comparison to the crop water consumption calculated from the 5TE results (Figure 10). The selected time periods were dry spells and therefore it can be assumed that the water consumption had been higher than during rainy periods. The WUE value used in the simulations was higher than those calculated from the soil moisture measurements. However, the value should be realistic since it describes the growing conditions during the whole growing season and not only during the selected dry spells.

For a detailed description of transpiration in field conditions, the spatial dimension must be considered. For calculation of site-specific transpiration, there must be available site- and time-specific information about microclimate conditions in the crop canopy. Therefore representative information about the site- and time-specific microclimate conditions should be available. In reality this would mean a very high number of continuous measurements from the fields, or at least only a few measurements and a model that can be used to interpolate the microclimate conditions in each location in the field.

5.2 Measuring the soil moisture content

Due to the observed differences in the soil moisture sensors, three sensors were tested in laboratory conditions (Figure 14). In the laboratory tests, the loose soil sample that was not compacted before sensor installation produced the highest variation in the results and even led to very non-linear results with ThetaProbe M2x/d sensor (Figure 14). However, after compacting the samples the differences between the sensors were minor and all the used sensors were found to produce more linear results.

After laboratory analysis six different devices for soil moisture evaluation were further tested in field conditions (Figure 15). The AK30 (Table 3), using near infrared reflectance to measure the soil moisture produced the lowest variation in the results (Figure 15). AK30 and the infrared thermometer were the only devices using optical techniques for conducting the measurement but the infrared thermometer measured only the soil temperature. The challenges of the optical devices have been found to exist in dry and wet conditions (Mouazen et al. 2005, 2007; Tuure 2013). If the soil was very wet and water was covering the soil surface to be measured the reflectance disturbed the measurement, and the same problem occured if dry soil pieces were located on the soil surface to be measured (Tuure 2013). In both these cases the measurement result was something other than the actual water content of soil.

The temperature was found to decrease with the increasing soil moisture content (Figure 15). This result is in line with previous investigations (e.g. Carlson et al. 1994; Davidoff and Selim 1988; Idso et al. 1975; Jackson et al. 1999) and could be one possible method for measuring the soil moisture content over limited time periods, e.g. during sowing or tillage practices. No great differences were found between the devices using soil electromagnetic properties for measuring, but time domain reflectometry - based devices (MiniTrase and TDR300, Table 3) produced somewhat lower variation in the results. It is to be noted that part of the variation in the results of all the devices was from the natural variation of soil moisture in the field.

5.2.1 Aspects of soil moisture for cultivation practices

In the context of precision farming, one of the most important issues in spring cereal cultivation is the timing of sowing. In spring, the soil is moist after the snow cover has melted, but evaporation decreases the amount of water in the soil. In the case of spring cereals, this is a contradictory problem; on the one hand the evaporation is needed to dry the soil in order to carry the field machinery and to enable the tillage, but at the same time the amount of plant available water is decreased. A suitable soil moisture content is essential for a cultivated crop but on the other hand the soil structure is vulnerable to harmful changes such as soil compaction if the soil is too moist when tilled (Alakukku et al. 2003; Chamen et al. 2003). In order to save soil moisture for crop growth and to prevent the soil structure from degradation, a good model for soil moisture and evaporation would be a useful tool in timing the seedbed preparation and sowing.

5.2.2 Soil moisture and modelling

The calculation of crop biomass accumulation was evaluated with a water balance approach by using the continuous soil moisture content measurement results from study **I**. However, the continuous measurement results were found to be insufficient for this purpose. One of the reasons for this may be that with short time periods the amount of water consumed by the crop is low and therefore the change in the soil moisture content due to transpiration is also minor. Despite careful calibration of the sensors, the accuracy of the used sensors was found to be insufficient for water balance calculations with short time intervals. Basically, over longer time intervals the amount of water used by the crop is greater than would be feasible for the sensor but the role of evaporation in water loss from soil is increased. Therefore with longer time intervals it may be necessary to separate the amount of water lost via evaporation, although the expanding canopy decreases the evaporation.

In order to separate the evaporation from transpiration, a preliminary attempt was made to instrument a measurement device that was capable of measuring the evaporation continuously (Hautala et al. 2012). Unfortunately some technical issues remain to be solved in further studies to make the long term measurement reliable. However, a chamber measurement from soil surface was found to be a functional approach although it cannot be used continuously (Hautala et al. 2012).

5.3 Reasons for yield variation

The model was applied to a study concerning spatial and temporal yield variation (**III**). The simulated biomass accumulation was higher than the observed biomass yield in all cases except one. This single case occurred during a year when the precipitation sum over the growing season was the lowest of the six years included in the study (Table 4, **III**).

Simulated yield variation was lower than the observed variation in most of the cases (Table 9). The variation in the simulated biomass yield accumulation was only due to site- and depth-specific soil parameters, as site-specific information about spatial variation in the crop canopy was not available. In previous studies it has been suggested that variability in soil properties can have a high effect on the crop growth (Cox et al. 2003; Derby et al. 2005; James and Godwin 2003; Keller et al. 2012; Timlin et al. 2001). The selected soil properties were found to have a lower impact on the spatial yield variation (simulated yield variation, Table 9) than was observed (**III**). In addition, the observed yield variation was found to be spatially and temporally unstable, as has also been the result of many previous studies on yield variation (Blackmore et al. 2003; Cox et al. 2003; Washmon et al. 2002; Wood et al. 2003).

The simulated biomass yield variation undeniably reveals that the soil properties were responsible for yield variation to some extent. A notable part of the yield variation was concluded to be due to changes in other growth resources than in soil PAWC or K_{sat} because the observed yield variation in most cases exceeded the simulated variation (Table 9). Of course the simulated biomass accumulation could have been different if other models for soil and crop were selected. However, the correlations between soil properties and the yield were found to be low and mostly insignificant in this study (**III**). Therefore it may be that the results would not have been very different, because no model can reproduce the observed variation without information about factors causing the variation that may be in the parameters or model inputs (Irmak et al. 2001; Sadler et al. 2000, 2002). If the correlations would had been higher and significant the situation would have been different. An example of such a case is reported in the study of Basso et al. (2009), in which the site-specific soil properties had high correlation with the site-specific yield and the crop model successfully produced the observed spatial variation in the yield. However, our results were similar to those of many other studies (Blackmore et al. 2003; Cox et al. 2003; Diacono et al. 2012; Marques da Silva 2006; Taylor et al. 2003; Wood et al. 2003) in which the soil properties have not been able to explain the spatial yield variation. Therefore, in addition to the soil properties, it is essential also to consider other sources for spatial yield variation, although they depend on the weather during the growing season (Sadler et al. 2002).

5.3.1 Field specific variation in Jokioinen 1 and 2

In the study of yield variation, two of the fields (Jokioinen 1 and 2) were cultivated during the same years. In Jokioinen 1 the observed yields were higher in comparison to Jokioinen 2, except in the year 2003 (**III**). In 2003, there was a delay in the sowing of the field Jokioinen 1 (**III**), which also decreased the yield in the previous studies (Hakala et al. 2012; Peltonen-Sainio et al. 2011; Taylor et al. 2003). The reason for the higher yield in Jokioinen 1 was concluded to be higher K_{sat} values through the observed soil profile that promoted root growth in depth and increased the water uptake (Aura 1999). The simulated biomass yields did not differ between the fields but the simulated yield variation was consistently higher in Jokioinen 2 (Table 9, **III**). The observed yield variation in Jokioinen 2 was also higher in comparison to the field Jokioinen 1. The difference in the magnitude of observed yield variation between the two fields could be due to the higher variation in the observed PAWC values in Jokioinen 2 (Figure 2 in article **III**), although the PAWC values were not able to explain the spatial variation in the observed yield. However, more research is required to find the true reason for observed differences in the yield variation and level of these two fields. When comparing the simulated and observed soil moisture contents, the excessive rainfalls were not found to increase the soil moisture content as much as was expected due to low observed K_{sat} values in the site (Figure 17A). The explanations for low observed soil moisture contents were concluded to be either surface runoff or bypass flow via formed cracks due to drying of the soil (**III**).

5.3.2 Field specific variation in Vihti

The third field in the study about yield variation was cultivated with spring wheat and produced the highest biomass yields of the three fields included in the study (**III**). The precipitation was very low during the first experimental year (Table 4) and the observed yield was very low at the slope located on the south-eastern part of the field where the elevation was the highest (Figure 4). During the same year a negative correlation between the observed biomass yield and K_{sat} was found (**III**). The sites with a high K_{sat} were located on the slope of the field and therefore the low yield was concluded to be due to water redistribution (and possible nutrient redistribution), as has been found in similar cases in previous studies (Hanna et al. 1982; Norouzi et al. 2010). However, the soil model did not include a calculation routine for water redistribution due to altitude changes and therefore the simulated yield did not show any changes due to the slope (**III**).

5.3.3 Temporal standard deviation of yields

The yield variation in the fields Jokioinen1, 2 and Vihti was studied with temporal standard deviation formula (Blackmore et al. 2003). With the results from the three studied fields the Eq. 15 produced two slopes, the first decreasing towards the grand mean yield and the second increasing from the grand mean. Marques da Silva (2006) studied the spatiotemporal variation of irrigated maize yield in the same manner and his results appeared to be very similar to ours (**IV**). From Eq. 15 it follows that the temporal standard deviation is always increased when the yield of the site is decreased or increased from the annual mean yield. Therefore the temporal standard deviation approach by Blackmore et al. (2003) efficiently highlights the sites that differ from the field average in the yield stability or level. Although the yield level is valuable information, for precision farming purposes it would be advantageous to obtain information about stable yielding sites regardless of the yield level (**IV**). This could be achieved if the subtraction was calculated between the annual yield and the mean yield at a specific site "X" during the years of the study (**IV**). This modification led to lower temporal standard deviation values for low- and high-yielding sites that were still distinguishable with temporal mean yield (**IV**).

5.4 Automated crop farm simulator

The AutoCrop simulator included a fictive farm with five fields and 22.5 ha of farming land. In comparison to the average farm size in Finland (41.5 ha at year 2013 (Tike 2014)), the size is moderate but when the fields were split to separately simulated cells the number of individually simulated units was 9000. This produced a spatial resolution of 5 × 5 meters but if field area increases or higher spatial resolution is desired, the time required for running the necessary models becomes important. The model introduced here was an alternative crop model to the SORGHUM model applied in the AutoCrop simulator. Although the level of details in the SORGHUM model was relatively low the time consumed in the simulation was reduced with the model described here (**V**). However, according to the results of more detailed analysis, the soil moisture simulation took a considerable part of the overall simulation time (**V**). Therefore the model for soil moisture was considered as the primary target of further development of the models. All the cells of the fictive farm were simulated separately and the cells similar to each other were not clustered in order to decrease the number of simulated cells. This is another topic for future research if the simulation time is to be reduced.

Matlab and ArcGIS were the tools selected for building the simulator, and two different approaches were evaluated in building the simulator (**V**). In the first approach all the calculations were made in ArcGIS but first the models were built to a .NET component that could be used in ArcGIS. In the second approach, Matlab was used as a simulation engine to run the soil and crop models. When measured by time consumed in simulation the first approach was found to be more efficient but it was also more laborious to build (**V**). Despite the laborious building phase the first approach was found to be more suitable for the purpose of the study, i.e. for building a simulator.

The simulator included a collection of models that were used to simulate the soil moisture, cultivated crop, weed, pests and diseases in each cell of the fictive farm. The models were taken from the literature and constructed in Simulink. From existing soil and crop models it was found that the different phenomena were well regarded when using the models in a single site (Batchelor et al. 2002; Sadler et al. 2000). However, the spatial connection of the grid cells was found to be less extensively included in the models, although it would be important in precision farming because the spatial phenomena above and below the soil surface may be important factors for yield variation (Batchelor et al. 2002; Pierce and Nowak 1999; Sadler et al. 2000). In the AutoCrop simulator the spatial connection was the water surface runoff from one cell to another according to the slope of the cell. The spatial connection between the cells was required for only a relative low amount of the calculation time. The spatial phenomena could deserve more research efforts in the future.

5.5 Further use of the model in enhancing fertilization practices

One of the traditional challenges for precision farming is sizing of the amount of applied fertilizer according to the growth conditions in order to increase the nutrient use efficiency (Auernhammer 2001; Earl et al. 2003; McBratney et al. 2005; Pierce and Nowak 1999). In Finland, spring cereals are most often fertilized at sowing, when the seeding machine applies fertilizer between every second seed row and approximately 30–60 mm deeper than the actual seeds (Aura 1967; Kähäri and Elonen 1969; Salo 1999). The fertilizer placement between the seed rows and deeper than the seeds increases the availability of fertilizer nutrients for the crop and minimizes the risk of nutrient leaching via surface runoff (Esala and Larpes 1984; Haby 2006). Fertilizer application for spring cereals is usually uniform and the dosage is high enough to cover the needs of the crop during the forthcoming growing season. The cultivated crop, targeted yield level and soil properties are considered in sizing the fertilizer dosage according to the Nitrate Decree (Government Decree (931/2000) in Finland, Nitrates Directive (91/676/EEC) in EU). In addition, the rules of subsidies which the farmer is applying for production may further limit the use of fertilizer (Maaseutuvirasto 2014). From the farmer's point of view the fertilizer placement is efficient in terms of time used for field work in spring because sowing and fertilization are performed at the same time, which is an important benefit (Haby 2006). Because the growing season is very limited in Nordic conditions (Peltonen-Sainio et al. 2011), the sowing of spring cereals should be done as early as possible in order to maximize the growing time of the crop.

Despite the undeniable advantages of the fertilizer placement, the size of the dosage is a challenge. The growing conditions of the forthcoming season and furthermore the exact need for nutrients cannot be known at the time of sowing. The amount of fertilizer applied is significant factor for responsive nitrogen management and also for increasing the nutrient use efficiency (Asseng et al. 2001; Basso et al. 2011; López-Bellido et al. 2006; Raun et al. 2002; Shanahan et al. 2008; Walsh et al. 2013). For this reason the fertilizer application as a single application (regardless of the technique used) is a potential risk for insufficient fertilization during years with good growing conditions or excessive fertilization during years with poor conditions (Basso et al. 2011, 2012, 2013; Peltonen et al. 1995). Thus, in order to adapt the amount of fertilizer to the prevailing conditions, two or more fertilizer applications are inevitably needed. Fertilizer can still be applied at the time of sowing and fertilizer placement can be used as an application technique, but the amount of fertilizer applied should be reduced from the amount required for the whole forthcoming growing season. The rest of the necessary fertilizer must be applied at some time during the growing season. However, the second application can not be postponed for very long because the later the application the lower is the yield increase (Table 8), as has been found in earlier studies (Finney et al. 1957; Jenner et al. 1991; Kraybill 1932; Spiertz and De Vos 1983).

For determining the correct fertilizer amount to be applied during the growing season, relevant information about current growth conditions and crop status is needed (Asseng et al. 2001; Basso et al. 2011, 2012; Hakojärvi and Hautala 2010; Walsh et al. 2013). The crop growth can be estimated through canopy observations, e.g. leaf area, light reflectance in the field (Schmidhalter et al. 2008) or with soil measurements, e.g. soil water (Tiusanen 2009) or nutrient content (Schmidhalter et al. 2008). For an effective decision about the necessary amount of fertilizer the information must represent the current conditions, which is why the measurements are proposed to be conducted in real time or at least close to real time. The most recent information about crop and soil can be obtained with on-the-go measurements (Adamchuk et al. 2004; Schmidhalter et al. 2008), but other ways such as remote sensing (e.g. Laurila et al. 2009; Schmidhalter et al. 2008; Pierce and Nowak 1999) or autonomous robots conducting measurements by scouting (Hautala et al. 2014) can also provide good solutions.

In addition to the canopy measurements, a crop growth model is needed in order to be able to estimate the effect of prevailing growing conditions on the cultivated crop growth. This is proposed because the measurements can provide only the current state of the crop (**II**) but not information about the growth dynamics, i.e. has the growth been limited by some resource and if it has, how much has the growth decreased so far.

The introduced crop model was applied in a simulation study regarding fertilization with two applications (Hakojärvi and Hautala 2010). In this simulation study a simple formula describing nitrogen use according to the biomass growth was introduced to the model. The modified model was used to calculate the nitrogen-limited biomass accumulation. The result was compared to simulated radiation- and water-limited biomass accumulation and the result of comparison together with the weather forecast was used in determination of the amount of fertilizer given in the second application. The simulation results showed that the amount of residual fertilizer nutrient in soil was reduced considerably, without a significant loss in the biomass yield (Hakojärvi and Hautala 2010). However, more research is needed in order to determine whether the result would be the same in practice.

The use of the model in the simulated fertilization study was fundamentally similar to the previously proposed solution in which the sufficient-nitrogen reference (a specific area where nitrogen availability was not limiting the crop growth) was proposed to be applied to the fields (Peltonen et al. 1995; Pierce and Nowak 1999; Plant 2001; Schepers et al. 1992; Shanahan et al. 2008). In this approach the crop growth in other areas of the field is compared to the sufficient-nitrogen reference and the amount of nitrogen in the second application is determined according to the difference in e.g. chlorophyll content (Peltonen et al. 1995; Schepers et al. 1992; Shanahan et al. 2008). However, the sufficient-nitrogen reference is always a limited area of the field. Therefore this area may be challenging to place in a field (Shanahan et al. 2008), where the growing conditions have spatial variation due to variation in e.g. soil properties (Basso et al. 2011; Ferguson et al. 2002; Fleming et al. 2000; Fridgen et al. 2004; Godwin and Miller 2003; Miao et al. 2006; Shanahan et al. 2008). Although this area can be made as a strip along the field (Pierce and Nowak 1999; Plant 2001), it can still be challenging to cover all variation in the field. For overcoming these challenges the use of the biomass accumulation model described in this thesis is proposed as a sufficient-nitrogen reference, as the model can be used to produce the radiation- and water-limited reference in a site-specific manner (**I**;**III**). By using the model the spatial variation can also be considered assuming that spatial information is available about the field. However, these two ways should be compared in future studies.

In some European countries split application of fertilizer is already a used or recommended practice (e.g. in Great Britain (Godwin et al. 2003; HGCA 2008, 2009), in Italy (Basso et al. 2011) and in Denmark (Jørgensen and Jørgensen 2007)). However, there are two practical challenges remaining. The first challenge is the feasibility of split application for the farmer. Due to the expenses (fertilizer, fuel, labour and machinery) in comparison to the income (grain price), two or more applications may not be economically feasible for the farmer (Godwin et al. 2003; Raun et al. 2002; Shanahan et al. 2008; Wood et al. 2003). This is because of limited possibility to affect the crop growth with fertilizer (Godwin et al. 2003; Wood et al. 2003) and increased expenses due to increasing the number of applications. The feasibility can be increased if the fertilizer application can be combined with an other necessary action such as crop protection, but this may not always be possible. The second challenge is the availability of nutrients to the crop. The fertilizer application must be made in such a way that the nutrients are available for crop uptake after a suitable period of time post-fertilization (Shanahan et al. 2008). In addition to the used technique, the weather probably has an important effect on the fertilization results, as a late fertilizer application was found to lead to higher yield increase when combined with irrigation in the preliminary experiment of additional fertilization (Table 8). Therefore, if granular fertilizer is used it would be appropriate to aim the time of application according to the weather forecast, i.e. application before rainfall.

6 Concluding remarks

A model describing maximal biomass accumulation for a C3 crop was introduced (**I**). The model was applicable for C3 crops and only during the vegetative growth phase, since it was developed for precision farming purposes. The strength of the model was constant parameters that were also easy to measure in practice. The measured parameter values enhance the model performance with cultivated crop and current growth conditions. Literature values can be used for parameter values, but measured values should be preferred in all cases. The constant parameters can limit the model applicability. For example in the case of oilseed rape, the leaf area expansion during early growth is so rapid that a constant LWR is not sufficient to describe the leaf area expansion in a realistic way. However, in case of small grain cereals and under the studied conditions the assumption of constant parameters was found sufficient.

The model was evaluated with field experiments including two radiation, three precipitation and fertilizer treatments in which the crop growth was evaluated in different radiation and nitrogen conditions (**II**). The model produced the maximal biomass accumulation, which was not exceeded in the field experiments.

After the evaluation, the model was applied to compare the yield variation with selected soil physical properties from three different clay soil fields (**III**). In most cases the model produced the maximal biomass accumulation successfully. The spatial variation in the simulated biomass accumulation was due to site- and depth-specific soil parameter values and the simulated yield variation was found to be lower than the observed yield variation in most cases. The observed yield was also found to be weakly correlated with the observed soil properties. Therefore the selected soil physical properties were found to be insufficient to explain the yield variation. In finding the reasons for yield variation the canopy observations during the growing season were essential. Such measures will also be valuable in the future and should therefore be developed further, especially in the spatial dimension. The study described here was conducted on three clay soil fields and therefore more research on the reasons for yield variation is required in other soil types.

The model was applied in a simulator of a fully automated crop production (AutoCrop, **V**). During the simulator establishment several existing models were included in the simulator to describe e.g. cultivated crop, weeds, soil moisture content, etc. The simulation of fields in a spatial manner means that there is a need for spatial information about field properties. Furthermore the simulation must be made in a spatial manner. This has a notable effect on the calculation time of the simulator and the model represented here was found to reduce the time required for simulations.

The model was applied in a simulation study of two phase fertilization in which the use of the model was found to enhance the utilization of nutrients from the fertilizer. Although the fertilizer nutrient utilization can be increased by dividing the fertilizer application into two phases and using the model, the problem of unpredictable future growing conditions cannot be completely avoided in this way. Another challenge in two phased application is the availability of fertilizer nutrients for the crop. The secondary application must be made in such a way that the nutrients from the fertilizer are available for the crop after a suitable period of time post-fertilization.

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