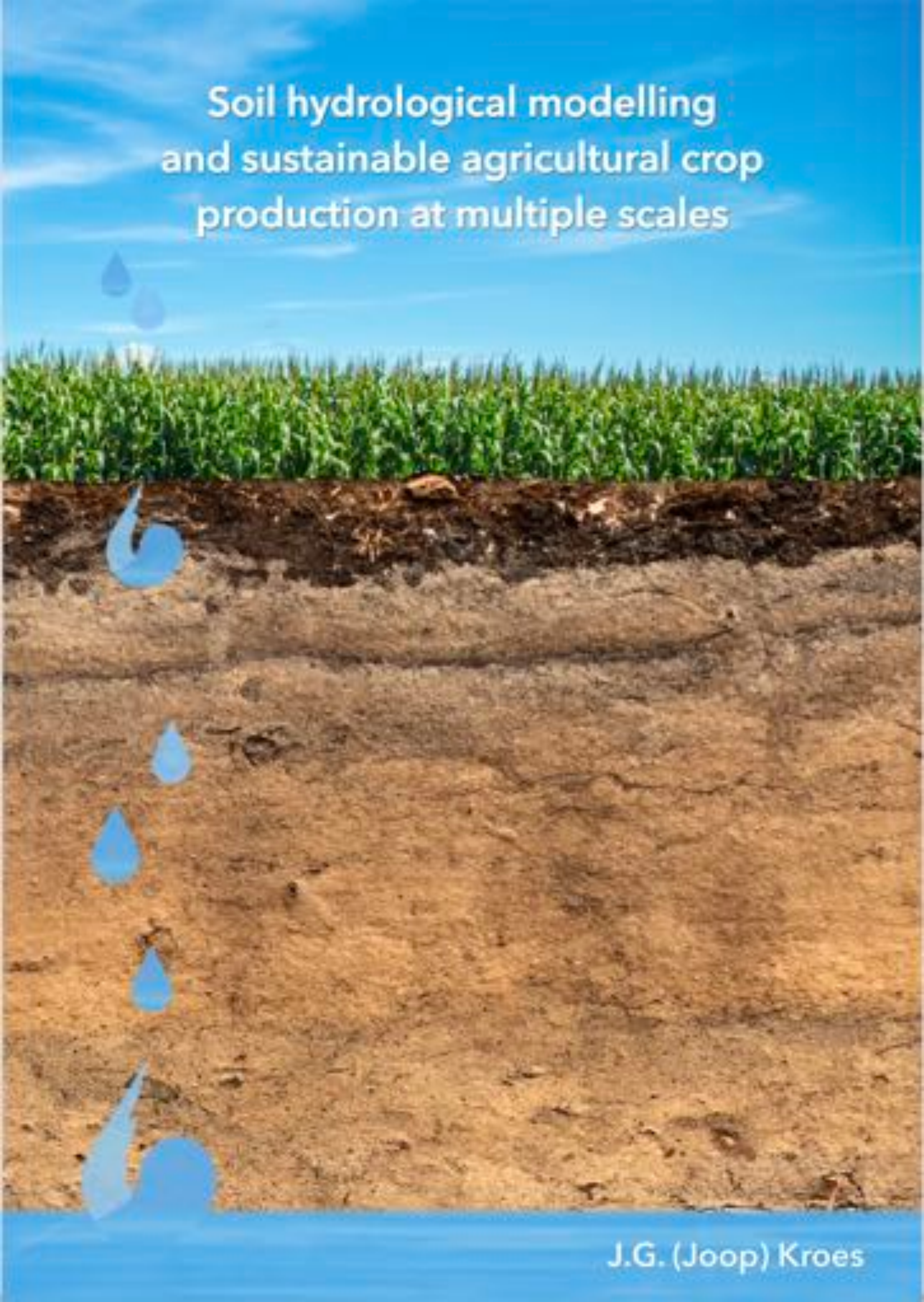

Soil hydrological modelling and sustainable agricultural crop production at multiple scales

J.G. (Joop) Kroes

PROPOSITIONS

1. Physically based soil hydrological modelling is needed for accurate predictions of upward water flow in soils.
   (this thesis)

2. Recirculation of percolated groundwater is an underestimated phenomenon in crop growth modelling.
   (this thesis)

3. The relation between transpiration and dry matter production is not always linear because it is influenced by management and environmental conditions.

4. A diverse cropping pattern is required to attain sustainable agricultural systems.

5. Fortran remains one of the best programming languages for scientific modelling.

6. Transparency and reproducibility are essential for the creation of falsifiable results.

7. If we are unable to limit population growth, dealing with environmental problems is like 'fighting a running battle'.

8. Writing a thesis at the end of a career is highly recommendable.

Propositions belonging to the thesis, entitled:

'Soil Hydrological modelling and sustainable agricultural crop production at multiple scales'.

J.G. (Joop) Kroes

Wageningen, 25 October 2018

Soil hydrological modelling and sustainable agricultural crop production at multiple scales

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J.G. (Joop) Kroes

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1. General introduction

1.1 Problem description

The growing world population exerts increasing pressure on agriculture, the environment and fresh water resources. With only 2.5% of the water on earth available as fresh water (PBL, 2018) the security of its supply for food will become increasingly uncertain. Global institutes try to find means to improve distribution and security of water and food. Water security is defined by UN water (2013) as “the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability”. Food security is defined by FAO (2015a) as the state in which “all people at all times have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active, healthy life’. Agriculture uses 70% of available fresh water making it by far the largest consumer. Water resources are finite and the need for new approaches to deal with increasingly complex water and food issues has been identified numerous times, see e.g. Falkenmark (1986), Pachepsky, et al., (2004), UN Water (2013), UN (2015), PBL (2018). This thesis contributes to addressing this vital need.

Use of modelling and monitoring in the soil water and plant domain to improve land and water management can contribute significantly to a sustainable increase of food security (UN, 2015, Keesstra et al., 2016). Soil hydrological modelling can be carried out to quantify the relation between water flow and crop growth. Modelling is often carried out at regional (Rijtema et al., 1999) and global scale (Fan et al., 2013) using models that mostly have their base at field scale (Mueller et al., 2017). Water limited crop growth under different land use and climate conditions is difficult to quantify and often modelled using either simplified lumped approaches to quantify evapotranspiration flows, or very detailed complex multi-dimensional models. Both approaches have their strengths and weaknesses which are described in detail by Hrachowitz & Clark (2017). To reduce the uncertainties in food security, integrated tools are required that dynamically link soil hydrology and crop growth (Vereecken et al, 2016).

Field scale tests with integrated approaches between crop and soil are required to make progress at large (catchment, country, continent) scales and allow upscaling (Vereecken et al., 2016). Such field scale experiments are needed to test the correctness and added predictive value of new theories with the soil water balance as a central core to explain impacts and changes. For example, upward vertical water flow to the root system is an essential part of the water balance and an important driver for transpiration of crops. However, this upward flow includes capillary rise and recirculation of percolation water and this is not accurately approached in most modelling tools. A physical approach to quantify this vertical water flow should therefore be compared with more simplified approaches and quantified using field experimental data.

This thesis aims to show that using physically based processes in soil hydrological modelling will contribute to more accurate crop growth predictions by means of improved water balance predictions and accounting for environmental impact. The focus of this thesis is on vertical water flows. To be able to produce sound water balance predictions, actual yields have to be modelled, because actual transpiration is directly related to actual dry matter production. This in turn requires the ability to simulate actual crop growth and the need to account for actual water and crop management. More accurate crop growth prediction will facilitate several planning activities in land and water management and reduce uncertainties in food security.

1.2 Comparison with state-of-the-art approaches

Several tools are available for soil hydrological modelling based on the process-oriented Richards equation. Parallel to this, separate tools for physically based crop growth modelling are available. Comparisons between different soil hydrological models and crop growth models have been given by several authors like Eitzinger et al., 2004, Wolf et al., 2002, Bastiaanssen et al., 2004, Kramers et al., 2005, VanderBorght et al., 2005, Kersebaum et al., 2007, Bonfante et al., 2010, Bonfante et al., 2011, Rallo et al., 2012, Rötter et al., 2012, Janssen et al., 2013, Ahuja et al., 2014, Groenendijk et al., 2014, Oster et al., 2012, Camargo et al., 2016, Mueller et al., 2017. These comparisons served different purposes but generally concluded that each model works best in the domain and for the purpose it was designed for.

Some crop growth models like APSIM (Holzworth et al., 2014), CROPSYST (Stöckle et al., 2003) and DAISY (Hansen et al., 2012) have incorporated a Richards equation-based approach for soil hydrological modelling. Others integrate crop and Richards equation-based models like WOFOST-HYDRUS (Zhou et al., 2012), DSSAT-RZWQM2 (Sun et al., 2016) and WOFOST-HYDRUS-MODFLOW (Peña-Haro et al., 2012). Some crop models apply special functions to approach capillary rise; like AQUACROP (Vanuytrecht et al., 2014) and GLEAM (Martens et al., 2017).

Modelling has become common practice to analyse experiments at different scales, ranging from field to global scale. Increase of scale may increase uncertainty, especially when complexities in the system are simplified to provide manageable modelling input (Oreskes, 1998). To reduce uncertainty it is often recommended to perform, in sequence, sensitivity analysis - parameterisation - calibration – validation (Refsgaard et al., 1997, Scholten et al., 2007). The term validation might be confusing and may better be replaced by 'verification' because the word 'valid' implies a legitimacy that cannot be justified when modelling complex natural systems (Konikow & Bredehoeft, 1992; Oreskes & Belitz, 2001; Rossiter, 2017). As philosopher of science, Karl Popper stated that no scientific theory or model can ever be proved right, only wrong (Popper, 1934). Passioura (1996) stated that 'We do not know enough about the structure of the soil-plant-atmosphere system to expect models to be accurate' and I am convinced that this statement is still 'valid'. The natural domains described in this thesis require extensive field tests and verifications at different scales.

Sensitivity analysis helps to get a better grip on the different sources of input and support the selection of field observations (Wesseling et al., 1997). The sensitivity analysis carried out for the Argentina case (Chapter 6) illustrates the importance of soil physics in predicting crop yield. Bringing the domains of soil and plant closer together requires multi-disciplinary activities which are not always easy but very necessary.

Models with a physically based dynamic interaction between the soil water and crop domains are rather scarce (Vereecken et al., 2016). The integration of models for Richards equation-based soil hydrology (SWAP) and process-oriented crop growth (WOFOST) with an interaction on a daily base, creates new avenues to analyse the two domains. The approach is illustrated in this thesis in 4 cases (Chapters 3-6), where each case is a multi-scale application which combines field experiments with a regional analysis. Field experiments are the starting point to verify results. However, field experiments may also be the final stage, when results from regional analyses lead to policy measures to be applied at the field scale by farmers. This upscaling and downscaling of experimental results requires complex models because it involves a well understood starting point (field) and a unified representation (region) that covers the hierarchy of significant process scales (Harter & Hopmans, 2004).

1.3 Research questions and objective

The problems outlined above lead to the following research questions:

1. What is the role of the vertical water flows capillary rise and recirculated percolation water in the determination of crop yields?

2. How can we model drought, salinity and oxygen crop stress to predict actual yields?
3. Can we predict the impact of different stresses on actual grassland production in the Netherlands?
4. How do changes of groundwater levels and land use affect actual crop yields and groundwater recharge?

The relation between the research question is illustrated (Figure 1.1) and discussed in the next chapters.

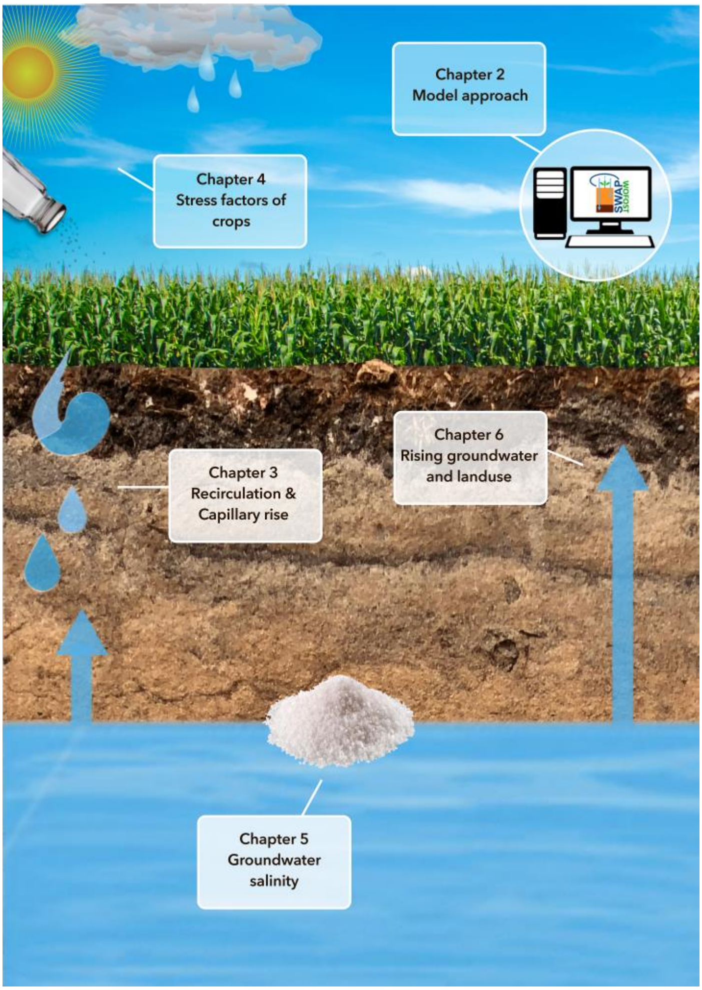

Figure 1.1 *Relation between research topics discussed in this thesis.*

Answers to these questions will contribute to a better understanding of the underlying processes and contribute to more advanced process-oriented research approaches.

1.4 Thesis outline

The relation between the research items of chapters 2 to 6 is given in Figure 1.1.

Chapter 2 describes the model approach and theory of the integrated model (SWAP version 4) for soil hydrology and crop growth as it is described and discussed in this thesis. The case studies described in chapters 4 and 5 used a previous version (SWAP version 3.2) but the core of the model has not changed and results will be similar. The coupling of the hydrological model SWAP and the crop growth model WOFOST resulted in SWAP version 3 and 4. To avoid confusion the name SWAP is used throughout this thesis.

Chapter 3 describes the role and importance of the vertical flow processes capillary rise and recirculated percolation water; the contribution of these processes are quantified with different methods to simulate crop yields of grassland, maize and potatoes.

Chapter 4 describes the approach for source-partitioning of stress-causes under wet, dry and saline conditions for grassland and maize.

Chapter 5 quantifies the impact of saline groundwater on crop yields of grassland is quantified for current and future meteorological conditions.

The activities described in chapters 3 to 5 are based on research in the Netherlands.

Chapter 6 deals with rising groundwater and its relation with land use in Argentina, resulting in an application at multiple scales.

The final chapter 7 describes a synthesis of this thesis, summarizes major findings and conclusions of the previous chapters. Furthermore, it discusses limitations and recommendations for future research.

2. Soil water and crop growth simulated by SWAP version 4

This chapter describes the modelling tool SWAP version 4 as it was applied in this thesis. A historical overview of 40 years modelling history is given followed by a brief description of Richards equation-based modelling of soil water flow and a description of dynamic crop growth modelling based on WOFOST. Solute transport is described as it was used in chapter 5 to simulate capillary rise effects of saline groundwater. Soil organic matter, soil nitrogen and crop nitrogen are described because these options are applied in chapter 6 to simulate nitrogen flows in soybean and soils in Argentina. Additional options are summarized with references to publications with detailed descriptions and integrated applications.

2.1. Introduction

The numerical results in this thesis are based on two simulation models that describe soil hydrological and crop growth processes. A history of more than 40 years counts for both models: SWAP and WOFOST.

The first version of the model now called SWAP (Soil-Water-Atmosphere-Plant) was called SWATR (Feddes et al., 1978). During its history updates were regularly spread with derived acronyms SWATRE (Belmans et al., 1983), SWACROP (Kabat et al., 1992), SWAP93, and SWAP (Van Dam et al., 1997). All updates were open source and distributed across the world. Recent versions were published on the internet (swap.wur.nl) as SWAP version 3.2.36 by Kroes et al. (2009) and SWAP version 4.0.1 (Kroes et al., 2017a). This thesis describes SWAP version 4, which includes WOFOST 7.17 (Boogaard et al., 2014).

The first version of WOFOST (WOrld FOod STudies) was based on crop growth models for the potential production situation: BACROS (BAsic CROp growth Simulator) and SUCROS (Simple and Universal CROp growth Simulator), both developed by De Wit and co-workers (De Wit, 1978; Goudriaan, 1977; Penning de Vries & Van Laar, 1982). SUCROS formed the basis of a range of Wageningen crop models, as reviewed by Bouman et al. (1996) and Van Ittersum et al. (2003). SUCROS also formed the base for WOFOST which was initially developed by Van Keulen and Wolf (1986) and Van Diepen et al. (1989). Supit et al. (1994) gave a first detailed system description. Recent versions are published on the internet (wofost.wur.nl) and an overview of 25 years WOFOST modelling is given by De Wit et al. (2018).

In 2008 we envisioned developments for the SWAP model for the coming 5-10 years (Van Dam et al., 2008) and we anticipated that 1D models like SWAP would continue to be used for at least 10 years. It is now 2018 and we are convinced that agro-hydrological 1D models like SWAP will continue to be important in research and education for at least another 10 years. In 2008 we also noticed large differences in modelling at regional scale where relatively simple bucket type approaches were common and more complex multi-dimensional models were rarely used. This difference is getting smaller and the use of the more complex Richards and convection-dispersion equation for unsaturated flow of water and solutes is common in advanced soil hydrological models (Vereecken et al., 2016).

Several multi-dimensional models exist nowadays that enable the use of the Richards equation for unsaturated flow; examples are PARFLOW (Kollet & Maxwell, 2006), FUSSIM2D (Heinen, 2001), FUSSIM 3D (Heinen, 2013), DAISY2D (Mollerup, 2010), MIKE SHE (DHI, 2017) and HYDRUS-2D and -3D (Šimůnek et al., 2016). In some cases, packages were made from models or modules to interact with MODFLOW. Examples are: packages UFZ (Niswonger et al., 2006), HYDRUS-1D (Seo et al., 2007) and metaSWAP (Van Walsum and Supit, 2012; De Lange et al., 2014).

Although the developments of multi-dimensional models are promising, the data and computation demand of multi-dimensional models of the biosphere is huge. Therefore these models are mainly used for detailed research applications and are less suitable for regional operational research involving multiple years in the atmosphere-plant-soil domain.

The demand for accurate soil water flow simulations increased and therefore some crop growth models incorporated modules for a Richards equation-based approach, like the models APSIM (Holzworth et al., 2014) and CROPSYST (Stöckle et al., 2003). Others integrate crop and Richards equation-based models like WOFOST-HYDRUS (Zhou et al., 2012), DSSAT-RZWQM2 (Sun et al., 2016) and WOFOST-HYDRUS-MODFLOW (Peña-Haro et al., 2012). Some crop models apply special functions to approach capillary rise; like AQUACROP (Vanuytrecht et al., 2014) and GLEAM (Martens et al., 2017).
Accurate Richards equation-based calculations of soil hydrological flow processes are important and neglecting these processes may have a considerable impact on the simulated crop yield and groundwater recharge (Kroes et al., 2018). The relative simplicity of 1D Richards equation-based models and their implementation using fast grid-based computing systems facilitates calculations for sensitivity analyses and regional distributed simulations. This motivated and enabled us to maintain the Richards equation-based core of the SWAP model. We carried out extensive testing and introduced new concepts for hydrological flows and for the dynamic interaction with the existing WOFOST model for crop growth. The resulting SWAP version 4 has been documented in reports for soil hydrology (Kroes et al., 2017a) and for nitrogen-limited crop growth (Groenendijk et al., 2016).

This chapter presents an overview of the theory of SWAP version 4 that was applied in a large part of the remainder of this thesis. The dynamic coupling between soil hydrological transport and crop growth is applied for various environmental issues in the chapters 3 – 6 of this thesis. A critical discussion about the model approach is given in chapter 7, the synthesis of this thesis.

2.2 Domain of the model

SWAP (Soil-Water-Atmosphere-Plant) simulates the transport of water, solutes and heat in the vadose zone in interaction with vegetation development. In the vertical direction the model domain reaches from a plane just above the canopy to a plane in the shallow groundwater. In this zone the transport processes are predominantly vertical, therefore SWAP is a one-dimensional, vertically directed model. In the horizontal direction, SWAP's focus is the field scale (Figure 2.1). At this scale most transport processes can be described in a deterministic way, as a field generally can be represented by one microclimate, one vegetation type, one soil type, and one drainage condition. Also, many cultivation practices occur at field scale, which means that many management options apply to this scale. Upscaling from field to regional scale for broader management policy studies is possible using geographical information systems.

The smallest time steps in SWAP are in the order of seconds for fast transport processes such as those occurring during intensive rain showers with runoff or referring to flow in macroporous clay soils. These time steps are automatically increased in periods with less dynamic flow conditions. Depending on simulation complexity, computation times for a 50-year period range from 30 to 500 seconds on ordinary personal computers. With grid-based computer systems, CPU-time is not regarded anymore as a limiting factor for regional, long term applications.

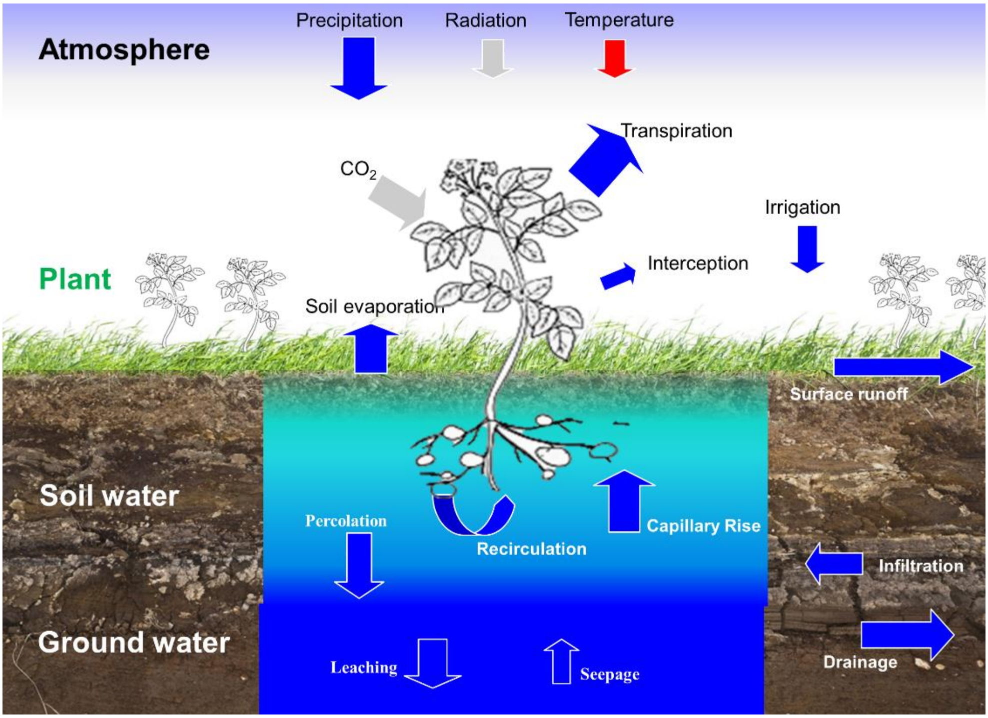

Figure 2.1 *Domain of SWAP version 4 at field scale.*

2.3 Soil Water Flow

2.3.1 Basic equations

Gradients of the soil water potential cause soil water movement. Darcy's equation is commonly used to quantify this soil water movement. For one-dimensional vertical flow, Darcy's equation can be written as:

$$q = -K(h)\frac{\partial(h+z)}{\partial z} \qquad (2.1)$$

where q is soil water flux density (positive upward) (cm^3 cm^{-2} d^{-1} = cm d^{-1}), $K(h)$ is hydraulic conductivity (cm d^{-1}), h is soil water pressure head (cm) and z is the vertical coordinate (cm), taken positively upward.

Water balance considerations of an infinitely small soil volume result in the continuity equation for soil water:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S_a(h) - S_d(h) - S_m(h) \qquad (2.2)$$

where θ is volumetric water content (cm^3 cm^{-3}), t is time (d), $S_a(h)$ is soil water extraction rate by plant roots (cm^3 cm^{-3} d^{-1}), $S_d(h)$ is the extraction rate by drain discharge in the saturated zone (cm^3 cm^{-3} d^{-1}) and $S_m(h)$ is the exchange rate with macro pores (cm^3 cm^{-3} d^{--1}).

Combination of Eqs. (2.1) and (2.2) provides the general water flow equation in variably saturated soils, known as the Richards equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S_a(h) - S_d(h) - S_m(h) \qquad (2.3)$$

SWAP applies the Richards equation integrally for the unsaturated-saturated zone, including possible transient and perched groundwater levels. SWAP solves Eq. 2.3 numerically, using specified boundary conditions and the Mualem-Van Genuchten functions (Mualem, 1976; Van Genuchten, 1980) for relations between θ, h and K.

Currently SWAP does not include alternative relations between θ, h and K in addition to those of Mualem-Van Genuchten. Instead, the user is given the possibility to supply $\theta(h)$ and $K(h)$ relationships as tabulated input. In that way any shape of these relationships can be considered.

The 1-dimensional Richards equation is solved using a numerical implicit, backward, finite difference scheme with explicit linearization of hydraulic conductivities as described by Van Dam and Feddes (2000) and Van Dam et al. (2008) with several adaptations and options to increase and stabilize the solutions (Kroes et al., 2017a). Since SWAP is designed to describe a wide range of layered soil profiles combined with different types of boundary conditions, the nodal distance may vary. The resulting matrix of equations is solved efficiently and accurately (Van Dam et al., 2008).

The numerical solutions result in water balances for the entire profile and for model compartments separately. A water balance for the first (surface) compartment looks like:

$$\frac{\Delta\theta}{\Delta t} = \frac{\left(q_{rain}+q_{irrig}+q_{snw}+q_{upw}+\sum_{i=1}^{5} q_{inf}(i)\right)-\left(q_{Es}+q_{Et}+q_{Ei}+q_{Ep}+q_{dwn}+\sum_{i=1}^{5} q_{dra}(i)\right)}{\Delta z} \quad (2.4)$$

where $\Delta\theta$ is change of volumetric water content, Δt is the change of time (d), q_{rain} is rainfall, q_{irrig} is irrigation, q_{snw} is snow melt, q_{upw} is the upward flux from the second compartment, q_{inf} is infiltration from drainage systems i=1-5, q_{Es} is Evaporation by soil, q_{Et} is Evaporation by crop (=Transpiration), q_{Ei} is Evaporation by interception, q_{Ep} is Evaporation by ponding, q_{dwn} is the downward flux to the second compartment, q_{dra} is drainage to a maximum of 5 drainage systems i=1-5, (all fluxes q are in cm d^{-1}), Δz is the compartment size (cm)

An example of a water balance for the entire profile is given in figure 2.2 which also shows separate water balances for the subsystems Plant, Snow, Pond and Soil.

2.3.2 Boundary conditions

The upper boundary is defined by meteorological conditions, irrigation and the presence of a crop, conditions which are described in respectively paragraphs 2.4, 2.3.3 and 2.7.

The bottom boundary is either in the unsaturated zone or in the upper part of the saturated zone and depends on the application and the relevant spatial scale. Five types of lower boundary conditions are distinguished:

a) *The Dirichlet condition:* a soil water pressure head h_{bot} is imposed at the node of the lower boundary;
b) *The Neumann condition:* a soil water flux q_{bot} at the bottom of the considered soil profile is defined. This flux can be given as a time series in a table, it can be related

to a groundwater level or a zero flux may be applied for an impermeable layer at the bottom of the profile;

c) *The Cauchy condition:* the bottom flux q_{bot} is defined by the difference of the total head (h+z) and the hydraulic head ϕ (cm) of the regional groundwater below the flow domain described by the model, divided by a flow resistance c (d). This condition is often used in combination with a regional groundwater flow model;
d) *The lysimeter condition:* a seepage face is simulated at the lower boundary to simulate moisture flow in a lysimeter or above a coarse gravel layer. This condition combines a head controlled and zero flux controlled condition;
e) *The free-drainage condition:* a condition of unit hydraulic gradient is assumed. This conditions is generally applied when groundwater is very deep.

```
Period             :  2002-01-01  until  2002-12-31
Depth soil profile :  200.00 cm
==========================================+==========================================
INPUT                                     | OUTPUT
                 PLANT  SNOW  POND   SOIL |                 PLANT  SNOW  POND   SOIL
==========================================+==========================================
Initially Present        0.00  0.00  71.60 | Finally present        0.00  0.00  76.04
Gross Rainfall   84.18                     |
Nett Rainfall            0.00 80.44        | Nett Rainfall   80.44
Gross Irrigation  0.50                     |
Nett Irrigation                0.50        | Nett Irrigation  0.50
                                           | Interception     3.74
Snowfall                 0.00              |
Snowmelt                       0.00        | Snowmelt               0.00
                                           | Sublimation            0.00
                                           | Plant Transpiration                 30.86
                                           | Soil Evaporation            16.09
Runon                          0.00        | Runoff                       0.00
Inundation                     0.00        |
Infiltr. Soil Surf.                  72.64 | Infiltr. Soil Surf.         72.64
Exfiltr. Soil Surf.            7.79        | Exfiltr. Soil Surf.                  7.79
Infiltr. subsurf.                          | Drainage
- system 1                            0.00 | - system 1                          29.55
Upward seepage                        0.00 | Downward seepage                     0.00
==========================================+==========================================
Sum              84.68   0.00 88.73 144.24 | Sum             84.68   0.00 88.73 144.24
==========================================+==========================================
Storage Change           0.00  0.00   4.44
Balance Deviation 0.00   0.00  0.00  -0.00
=====================================================================================
```

Figure 2.2 *Example of a water balance for various sub systems.*

Surface runoff occurs when the water storage in the ponding layer exceeds a given critical depth.

The lateral boundary is used for the interaction with a surface water system. Lateral discharge may occur by different processes:

a) *Interflow:* This is a rapid discharge with short residence times of the water in the soil system. It occurs when the groundwater level is higher than the hydraulic head of the interflow drain;

b) *Drainage/Infiltration:* Depending on the spatial scale one may introduce drainage options using a maximum of 5 drainage levels. Additionally, options are available to account for the influence of surface water management strategies on soil water flow and drain discharge. Drainage systems may also infiltrate water. The drainage boundary condition is extensively described by Kroes et al. (2017a).

The initial soil water condition may be given as soil water pressure head as a function of depth, static equilibrium with a specified groundwater level or as the final soil water pressure heads obtained from a previous simulation.

2.3.3 Irrigation

The model may be used to develop optimal irrigation schedules by evaluating various application strategies. Irrigation strategies may be applied with a fixed or a scheduled regime.

The fixed regime is defined by the time and depth of irrigation application. The scheduled regime is defined by different criteria for time and depth of an irrigation application. A combination of a fixed and a scheduled regime is also possible. This regime allows the evaluation of water productivity and water footprints in relation to several degrees of water stress. Surface irrigation or flooding may also be simulated using supply of water from a nearby field or from surface waters.

2.4 Rainfall and Evapotranspiration

In general, the sums of rainfall+irrigation and transpiration+evaporation+interception are large compared to their difference, which equals infiltration+runoff. Usually runoff is a small fraction of infiltration. This means that relative errors in rainfall and evapotranspiration will magnify in relative errors of infiltration and resulting groundwater fluxes. Therefore, reliable soil water and groundwater fluxes require accurate knowledge of rainfall values and proper simulation of evapotranspiration fluxes.

2.4.1 Rainfall, Interception and ponding

Rainfall is input to the model and may be given as daily amounts, optionally with a duration or a mean intensity. It is also possible to use rainfall events originating from tipping bucket type rain gauges that collect rainfall amount with different time intervals.

The interception and evaporation of rainfall or irrigation by plants before it reaches the soil can be simulated using two methods:

1) for agricultural crops the methods proposed by Von Hoyningen-Hüne (1983) and Braden (1985);
2) for forests the method proposed by Gash (1979) and Gash et al. (1995).

2.4.2 Potential evapotranspiration

Evapotranspiration refers to both *transpiration* of the plants and *evaporation* of the soil or of water intercepted by vegetation or ponding on the soil surface. The addition 'potential' refers to non-limiting soil conditions. The potential evapotranspiration flux is therefore sink-limited and only determined by atmospheric conditions and plant (shoot) characteristics. In SWAP we assume the atmospheric conditions to be external, representative for the area for which the simulations are performed.

Starting point in the calculations is the determination of the potential evapotranspiration (ET_{pot}), which can be calculated using a reference evapotranspiration with crop factors as input or by using the Penman-Monteith method (Allen et al., 1998).

Two methods can be used to partition ET_{pot} over potential transpiration of a crop (T_p) and potential soil evaporation (E_p) (Figure 2.3): a) use the Leaf Area Index or Soil Cover data specified in the input file, or b) use a direct partitioning of Penman-Monteith obtained from given resistances for soil and crop stomata. Extensive descriptions are given in Chapter 3 and Appendix 1 of Kroes et al. (2017a).

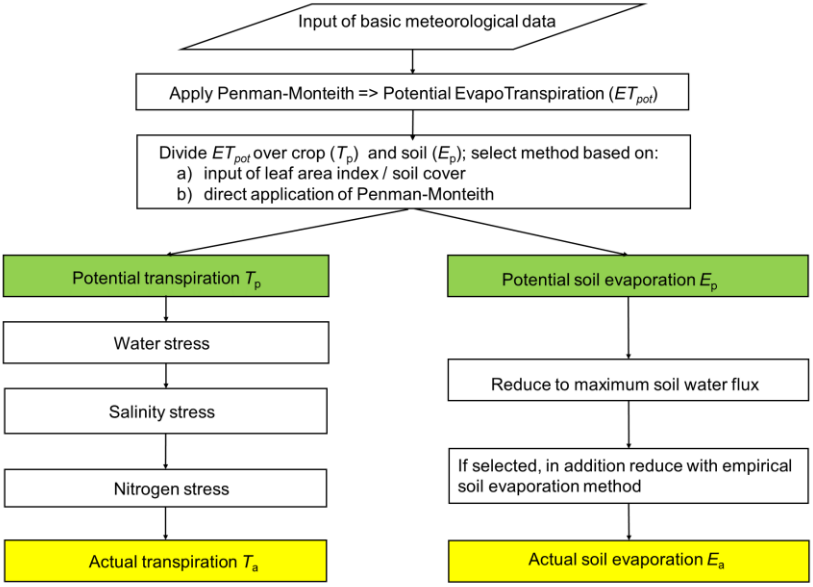

Figure 2.3 *Procedure used in SWAP version 4 to derive actual transpiration and soil evaporation from basic input data.*

2.4.3 Actual transpiration

The actual transpiration (T_a) or root water uptake results from T_p and depends on the stress due to lack of oxygen, drought, salinity and nitrogen (Figure 2.3).
The potential root water uptake at a given depth *z* is derived from the potential root water uptake by taking into account the relation between the actual root length density and the total root length density. We then use a multiplication of stress reduction factors to derive actual S_a from potential root water uptake S_p for each depth z:

$$S_a = \alpha_{rw} * \alpha_{rd} * \alpha_{rs} * \alpha_{rf} * \alpha_{rn} * S_p \quad (2.5)$$

Where S_a and S_p are the actual and potential root water uptake of a compartment at depth *z*; α_{rw},, α_{rd} , α_{rs} , α_{rf} and α_{rn} are the reduction factors for stress due to oxygen stress, drought, salinity, frost and nitrogen stress, respectively.

For the reduction factors oxygen (α_{rw}) and drought stress (α_{rd}), the function proposed by Feddes et al. (1978) may be applied (Figure 2.4). In the soil pressure head range $h_3 < h < h_2$ root water uptake is optimal.

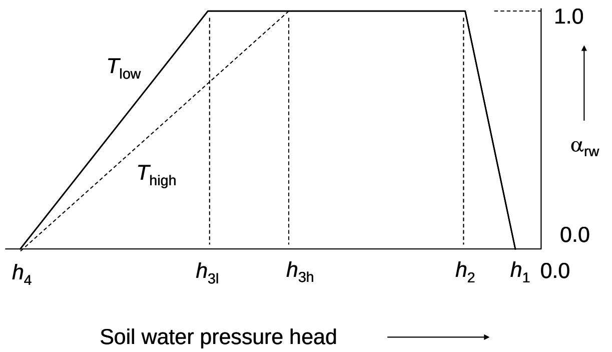

Figure 2.4 *Reduction coefficient for root water uptake, α_{rw}, (and α_{rd}) as function of soil water pressure head h (after Feddes et al., 1978).*

For oxygen stress (α_{rw}), an alternative method is also implemented which uses abiotic and biotic factors and has a more process-oriented physical base. This method calculates potential root respiration as affected by by plant characteristics and soil temperature. SWAP simulates also vertical oxygen diffusion into the soil and lateral diffusion towards the roots. The potential root respiration and the actual oxygen supply at different root depths determine the actual root respiration. Simulation of the actual root respiration for a crop requires actual data on soil type, daily soil temperature and daily gas-filled porosity in each soil layer. Between the limits α_{rw} = 1 and α_{rw} = 0, it is assumed that the reduction of root water uptake is directly proportional to the reduction in root respiration. The oxygen reduction factor α_{rw} thereby becomes a function of plant characteristics and plant physiological processes, rooting depth, gas filled porosity, soil temperature, soil physical properties and soil microbial activity (Bartholomeus, 2008).

Salinity stress (α_{rs}) occurs when the salt concentration exceeds a threshold value which is calculated according to Maas and Hoffman (1977), linearly related to the salinity concentration:

$$\alpha_{rs} = (1 - (c - S_{max})S_{slope} \quad (2.6)$$

where c is the concentration of salts in soil water or groundwater (mg cm^{-3}), S_{max} is the salinity threshold value (mg cm^{-3}) and S_{slope} is the decline of the root water uptake factor per unit increase of salinity concentration (cm^3 mg^{-1}) (Figure 2.5).

Frost stress (α_{rf}) occurs when root water uptake is reduced due to freezing of soil water. SWAP simulates freezing of soil water when soil temperature drops below a threshold value. A soil temperature range in which soil water flow is reduced is input to the model.
Frost conditions also reduce hydraulic conductivity, drainage fluxes and bottom flux.

Nitrogen stress *(*α_{rn}) occurs only when dynamic crop modelling (WOFOST) is applied. Stress of the crop growth takes place when the supply of nitrogen to the crop is lower than its demand which implies a reduced plant growth and will also limit transpiration (see also paragraph 2.7.5)

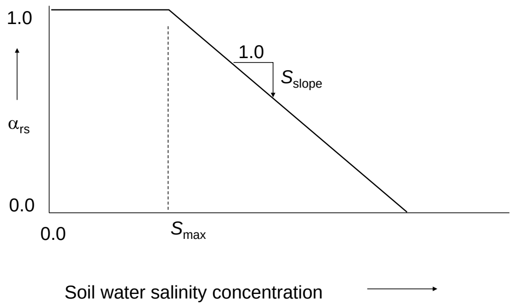

Figure 2.5 *Reduction coefficient for root water uptake,* α_{rs}*, as function of soil water salinity concentration (after Maas and Hoffman, 1977).*

2.4.4 Actual soil evaporation

Soil evaporation from a wet soil is sink-limited and equals the potential rate E_p. This also applies to ponded conditions, during which SWAP will increase E_p to the evaporation rate of (free) water. When the soil becomes drier, the soil hydraulic conductivity decreases and at a certain point evaporation becomes sink-limited, reducing from E_p to actual evaporation rate, E_a (cm d^{-1}). In SWAP, the maximum actual evaporation rate that the top soil can sustain, E_{max} (cm d^{-1}), is calculated according to Darcy's law:

$$E_{max} = K_{1/2}\left(\frac{h_{atm}-h_1-z_1}{z_1}\right) \qquad (2.7)$$

where $K_{½}$ is the average hydraulic conductivity (cm d^{-1}) between the soil surface and the surface node, h_{atm} is the soil water pressure head (cm) in equilibrium with the air relative humidity, h_1 is the soil water pressure head (cm) of the first node, and z_1 is the depth (cm) of the first node. However, E_{max} as described above may not adequately describe evaporation. E_{max} is essentially governed by the soil hydraulic functions $\theta(h)$ and $K(h)$. It is still not clear to which extent the soil hydraulic functions, that usually represent a top layer of a few decimeters, are valid for the top few centimeters of a soil, which are subject to splashing rain, dry crust formation, root extension and various cultivation practices, including mulch additions. Therefore empirical evaporation functions may be employed, which require calibration for the local climate, soil, cultivation and drainage situation. SWAP has the option to choose the empirical evaporation functions of Black et al. (1969) or Boesten & Stroosnijder (1986).

2.5 Soil temperature

Soil temperature affects many physical, chemical and biological processes in the top soil. Currently, SWAP uses soil temperature to quantify the following processes:

- suppression of grass growth due to low temperatures
- reduction of hydraulic conductivity and root water uptake at low temperatures
- nitrogen mineralization rate
- root respiration rate (and some other oxygen related processes, see paragraph 2.4.3)
- solute decomposition rate

SWAP calculates the soil temperatures either analytically or numerically. The analytical solution considers a sine function of the temperature as surface boundary condition, yielding a solution which includes a fixed soil thermal diffusivity. The numerical approach allows to consider the influence of soil moisture on soil thermal diffusivity. The top boundary condition may include air temperatures or soil surface temperatures. At the bottom of the soil profile either soil temperatures or a zero-heat flux condition can be specified. The latter option may be considered valid for deep soil profiles.

2.6 Soil organic matter and soil nitrogen

2.6.1 Soil organic matter

Dead plant parts and all other organic materials added to the soil are given as additions of fresh organic materials. Living plant roots excrete soluble organic materials into the soil solution, but also dead root cells during growth. These products become available for decomposition and take part in the carbon and nutrient cycles. When this material starts to decompose, it is partly oxidized to CO_2 and H_2O and partly transformed into biomass.

The structure of the RothC-26.3 model (Coleman et al., 1997) is the starting point for the development of an organic matter module. RothC-26.3 is widely used for research of the development of organic matter stocks in relation to the sustainability of agricultural systems. RothC-26.3 is relatively simple and describes the organic matter cycle with 4 biological transformable pools (Figure 2.6).

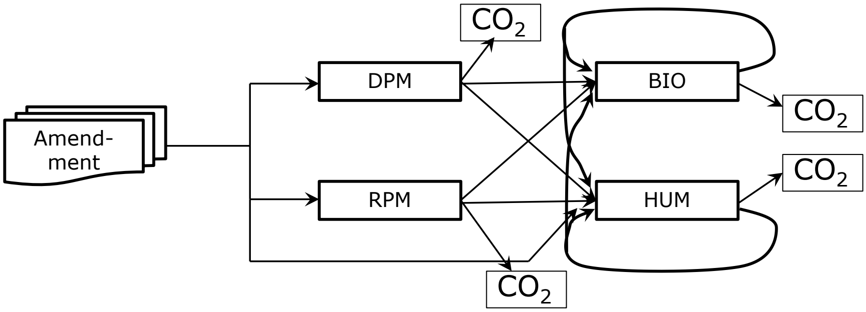

Figure 2.6 *Schematic representation of organic matter stocks and transformation in the RothC-26.3 model. DPM = Decomposable Plant Material, RPM = Resistant Plant Material, BIO = microbial BIOmass, HUM= HUmified organic Material.*

The transformations are described as first order rate processes where the rates depend on the amounts of organic matter in the pools. The most important adjustment of the RothC-26.3 is the description of the interdependence of the BIO-pool and the HUM-pool which is mathematically expressed by describing the processes as a set of linear differential equations (see also Groenendijk et al., 2005; Heinen & De Willigen, 2005; De Willigen et al., 2008). The transformation rates at optimal conditions are taken from literature (Jenkinson, 1990; Coleman et al., 1997). An analytical solution of the linear differential equations results in quantities of nitrogen mineralized and carbon dioxide produced by multiplying the different process rates with a nitrogen fraction and carbon fraction, respectively, and deriving balances according to the transformation scheme (Groenendijk et al., 2016).

2.6.2 Soil nitrogen

The nitrogen balance of the soil is implemented parallel to the organic matter balance. Nitrogen supplied to the soil through fertilizer applications and organic matter decay is stored in the soil. Mineralization rates of ammonium (NH_4-N) and nitrate (NO_3-N) control the nitrogen mineralization and immobilization in relation to the processes in the organic matter cycle.

Ammonium and nitrate balances are calculated as a result of mineralization, nitrification, denitrification, plant uptake and nitrate leaching rates (Figure 2.7). Both the amounts of organic matter and the associated N-contents of crop residues are calculated by the WOFOST module and passed to the Soil-N module. The SWAP module provides information on daily water balances of the single compartment Soil-N module. The Soil-N module provides information on the resulting daily plant uptake rates which equals the minimum of the uptake demand and the mineral nitrogen availability in the soil.

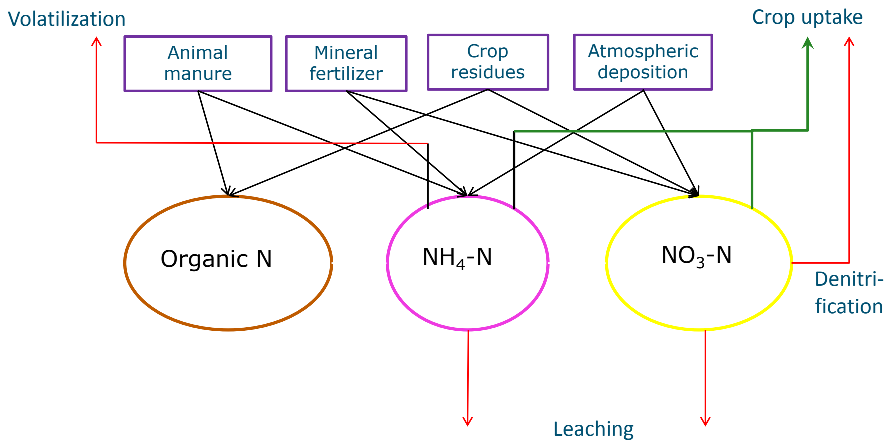

Figure 2.7 *Schematic representation of the nitrogen pools, transformations and transport described in the Soil-N module.*

2.7 Crop growth

SWAP contains three crop growth routines: a simple module for a static crop and two detailed modules for dynamic crops: one for arable crops (WOFOST), and a detailed module for grass (re)growth. A static crop has a fixed development of leaf area index and rooting depth, independent of climatic conditions, whereas development of a dynamic crop changes with weather and soil conditions.

2.7.1 Static crop growth

The main function of the simple module for static crops is to provide proper upper boundary conditions for soil water movement. The simple model is useful when crop yield doesn't need to be simulated or when crop growth input data are insufficient.

2.7.2 Dynamic growth of arable crops

2.7.2.1 General

Three groups of growth factors (Figure 2.8) can be distinguished to obtain a hierarchy of production levels in crop production (Van Ittersum et al., 2003). Growth defining factors, such as radiation intensity, carbon dioxide concentration, temperature and crop characteristics determine the potential production that can be achieved for a given plant species. To achieve the potential production the crop must be optimally supplied with water and nutrients and completely protected against weeds, pests, diseases and other factors that may reduce growth.

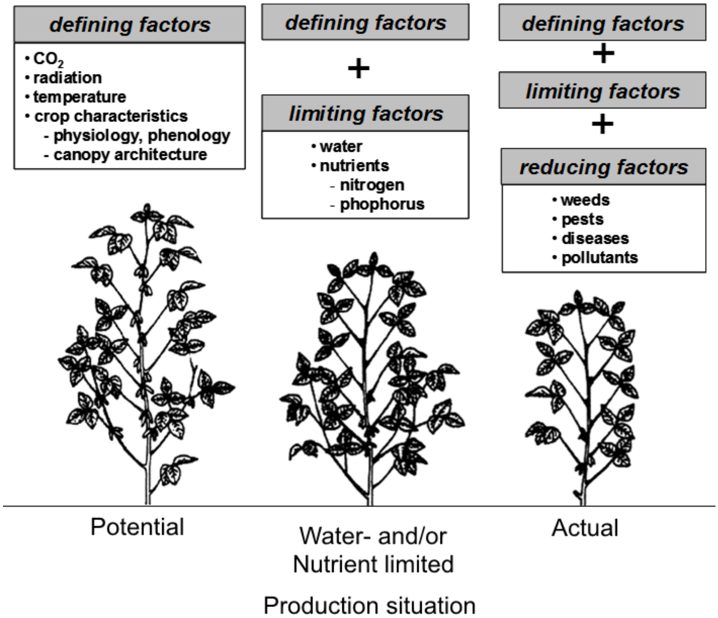

Figure 2.8 *A hierarchy of growth factors, production situations and associated production levels (Van Ittersum et al., 2003).*

The water balance approach of the SWAP modules is the central core of the integrated model. Realistic simulation of the actual transpiration is required to simulate actual crop growth because the relation between actual transpiration and actual crop growth is generally linear (De Wit (1958), Feddes (1988), Ben-Gal et al., (2003), Bierhuizen & Slatyer (1965) en Ehlers & Goss (2003)). A dynamic simulation of the real world is not possible because there is too much uncertainty in several natural processes and management behavior. To close the gap between actual simulated and actual measured yield, a management factor was added. A calibration procedure may be applied to calibrate this management factor. Field experiments should preferably be used to calibrate the dynamic crop growth model and after calibration of the management factor upscaling to regions and other time periods may be performed.

2.7.2.2 Phenology

For many annual crops, the phenological development can be expressed as a development stage D_s (-), increasing from 0 at seedling emergence to 1 at flowering and 2 at maturity (Van Heemst, 1986a; 1986b). The most important phenological change is the one from vegetative ($0 < D_s < 1$) to reproductive stage ($1 < D_s < 2$). At the transition ($D_s = 1$), dry matter allocation changes drastically towards the storage organs.

Crop growth simulation starts either at sowing or at emergence. The sowing or emergence date should be specified by the user. A crop passes through successive phenological development stages, of which the length depends on the development rate. Development rates before floral initiation or anthesis ($D_s = 1$) are controlled by temperature and may be defined to depend on daylength as well. After anthesis, the development rate only depends on the temperature. Higher temperatures accelerate the development rate, leading to shorter growing periods. It has often been demonstrated that the development rate increases linearly with temperature (Van Dobben, 1962; Van Keulen & Seligman, 1987). Therefore, WOFOST uses the temperature sum to describe the development stage. For some species or cultivars, the daylength during the vegetative stage is also important and a reduction factor for the development rate as function of day length may be defined.

Crop growth simulation stops when the development stage reaches maturity ($D_s = 2$) or when the crop will be harvested (i.e. before ripeness). In this latter case the harvest date should be defined.

2.7.2.3 Germination

The germination of *arable crops* depends on temperature and soil moisture conditions (Van Wijk et al., 1988) and is simulated in SWAP according to Van Walsum & Van der Bolt (2013). Germination of *arable crops* depends on *temperature* according to:

$$T_{av} < T_{min}^{germ} \quad : \quad T_{sum}^{germ} = T_{sum}^{germ} \tag{2.8}$$

$$T_{min}^{germ} > T_{av} < T_{max}^{germ} \quad : \quad T_{sum}^{germ} = T_{sum}^{germ} + \frac{T_{sum}^{eme,opt}}{T_{sum}^{eme,sub}}\left(T_{AV} - T_{min}^{germ}\right) \tag{2.9}$$

$$T_{av} > T_{max}^{germ} \quad : \quad T_{min}^{germ} = T_{sum}^{germ} + \frac{T_{sum}^{eme,opt}}{T_{sum}^{eme,sub}}\left(T_{max}^{germ} - T_{min}^{germ}\right) \tag{2.10}$$

where T_{av} is the mean daily air temperature (°C) (= 0.5·(T_{min}+T_{max})), T_{min}^{germ} is the minimum temperature-sum for T_{sum} calculation (°C·d), T_{max}^{germ} is the maximum temperature-sum for T_{sum} calculation (°C·d), T_{sum}^{germ} is the T_{sum} during the germination period (°C·d), $T_{sum}^{eme,opt}$ is the T_{sum} for crop emergence under optimal soil moisture and temperature-sum conditions (°C·d), and $T_{sum}^{eme,sub}$ is the T_{sum} for crop emergence under sub-optimal soil moisture and temperature-sum conditions (°C·d).

Germination of *arable crops* depends on *soil moisture* using T_{sum} under sub-optimal soil moisture and temperature-sum conditions:

a. too dry conditions as: $T_{sum}^{eme,sub} = a \cdot log10(-h_{rz}) + c$ (2.11)

b. too wet conditions as: $T_{sum}^{eme,sub} = -\, a \cdot log10(-h_{rz}) + b$ (2.12)

c. optimal conditions as: $T_{sum}^{eme,sub} = T_{sum}^{eme,opt}$ (2.13)

where *a*, *b*, and *c* are input parameters, and h_{rz} (cm) is the average soil water pressure head in the upper 10 cm of the soil.

Emergence occurs when: $T_{sum}^{germ} > T_{sum}^{eme,opt}$.

For the germination of *grassland* two options are implemented using different thresholds to start growth, using

a) the sum of air temperatures or
b) the soil temperature at a particular depth

Method a) initiates germination when the sum of air temperatures > 200 ^{o}C.d. Method b) initiates germination when the soil temperature at a particular depth exceeds a given threshold. This requires the specification of the temperature threshold, the relevant depth and a time interval (days) during which the threshold should be exceeded to initiate germination.

2.7.2.4 Dry matter partitioning

During crop growth, the increase in total dry weight is partitioned over the different plant organs: roots, leaves, stems and storage organs. This is simulated in SWAP based on development stage dependent partitioning factors. Figure 2.9 shows a typical example. The partitioning factors are input to the model. WOFOST first divides the gross dry matter among roots and shoots (leafs, stems and storage organs together), using the partitioning factor for roots. Next WOFOST divides the gross dry matter directed to the shoots among leafs, stems and storage organs, using the partitioning factors for these plant organs.

2.7.2.5 Biological nitrogen fixation

Nitrogen fixation is based on a simple approach, assuming that N_2 fixation from the air is potentially unlimited. This approach is applied for a limited amount of crops (Leguminosae like soybean) that have the ability to use nitrogen from the air. The crop defines the demand for nitrogen and a user-defined fraction indicates the amount of nitrogen demand which is met by N-fixation from air and N-mineralisation from soil.

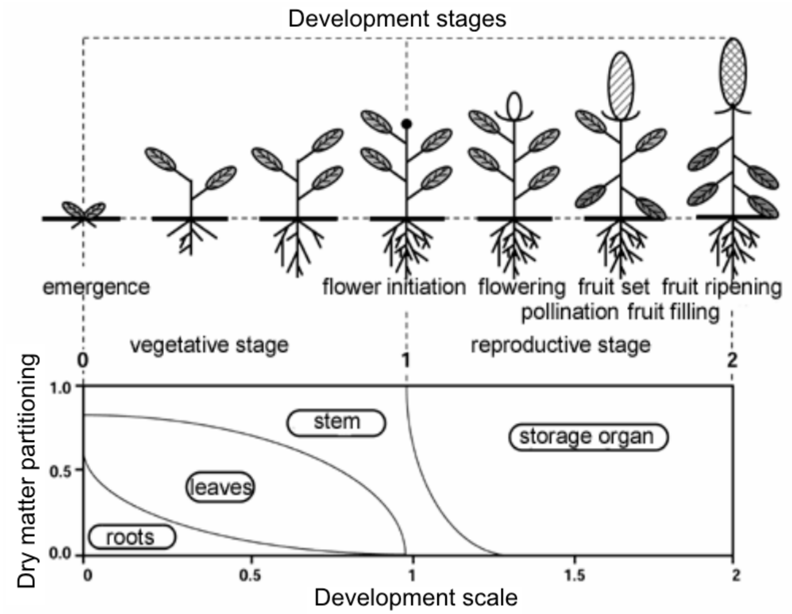

Figure 2.9 *Typical partitioning of assimilated dry matter among leaves, stem, roots and storage organs as function of development stage or scale.*

Crop growth and the corresponding N-demand are already limited by drought, which is simulated using the detailed hydrology from the SWAP model.

2.7.2.6 Nitrogen balance

The nitrogen distribution within a crop in WOFOST is simulated based on Shibu et al. (2010). Nitrogen demand of the individual organs is calculated as the difference between maximum and actual organ nitrogen contents. Nitrogen uptake is determined by crop demand, indigenous soil nitrogen supply and fertilizer application. Nitrogen uptake processes like mass flow and diffusion are not explicitly simulated in the model. Crop N uptake is estimated by balancing crop demand and availability from different sources. If there is not enough nitrogen available, the crop growth will be reduced. Nitrogen from indigenous sources is assumed to have a higher (nearly 100%) recovery compared to applied fertilizers, as it is the amount of N actually taken up by a crop under zero nitrogen fertilizers. Therefore, in the model, it is assumed that the crop first takes up nitrogen mineralized from indigenous organic matter, and only after its depletion the fertilizer N will be used. The nitrogen uptake is assumed to stop at a predefined development stage (after anthesis), as nitrogen content in the vegetative parts hardly increases (Groot, 1987; Sinclair & Amir, 1992). Nitrogen demand of the storage organs is also assumed to be met exclusively by translocation from leaves, stems, and roots as soon as grain formation starts. Hence, the rate of nitrogen accumulation in the storage organs is determined by their nitrogen demand calculated by the maximum N content and the actual N content and by the total amount of translocatable nitrogen in the other crop organs. Total translocatable nitrogen in the crop equals total nitrogen content of the organs, minus their residual non-transferable nitrogen content, which is the nitrogen incorporated in structural crop components.

A crop is assumed to experience N stress at N concentrations below a critical value for unrestricted growth. The critical crop nitrogen concentration is defined as the lower limit of canopy nitrogen concentration in leaves and stems required for unrestricted growth. It is assumed to be half of the maximum nitrogen concentration (Porter, 1993; Jamieson et al., 1998).

The nitrogen balance of the crop is generated as follows:

$$(N_t^{lv} + N_t^{st} + N_t^{rt} + N_t^{so}) - (N_{t-1}^{lv} + N_{t-1}^{st} + N_{t-1}^{rt} + N_{t-1}^{so}) =$$

$$N_{\Delta t}^{up} + N_{\Delta t}^{fx} - N_{\Delta t}^{lv} - N_{\Delta t}^{rt} - N_{\Delta t}^{st} - N_{\Delta t}^{lv2s} - N_{\Delta t}^{harv} \qquad (2.14)$$

where $(N_t^{lv} + N_t^{st} + N_t^{rt} + N_t^{so})$ is the amount of Nitrogen at the end of the time step t (day) in leaves (*lv*), stems (*st*), roots (*rt*) and storage organs (*so*); $(N_{t-1}^{lv} + N_{t-1}^{st} + N_{t-1}^{rt} + N_{t-1}^{so})$ is the sum at the beginning of the day; $N_{\Delta t}^{up}$ is the crop uptake of N during the day; $N_{\Delta t}^{fx}$ is the biological N-fixation during the day; $(N_{\Delta t}^{lv} - N_{\Delta t}^{rt} - N_{\Delta t}^{st})$ is the N loss from leaves, roots and stems due to senescence; $N_{\Delta t}^{lv2s}$is the N loss from deceased leaves to the soil; $N_{\Delta t}^{harv}$is the loss of N at harvest; unit of all balance terms is kg ha^{-1} N.

2.7.3 Dynamic growth of grassland

The detailed module for dynamic growth of grass is a modified version of WOFOST. Unlike common agricultural crops, grass is perennial and remains in the vegetative stage during most of its growing season. Therefore, the grass growth module differs from the standard WOFOST. For instance, the forcing functions are a expressed in terms of Julian day number instead of crop development stage. Another example is grass rooting depth, which is directly related to simulated root dry matter.

Grass may be regularly mowed or grazed by cattle. Mowing van be simulated either at a defined amount of above ground dry matter, or at a fixed date. Cattle is simulated to enter the field after a specified minimum amount of above ground dry matter is exceeded. Grazing by cattle differs from mowing in this respect that the consumed biomass depends on the grazing days and the livestock density. In this context, relevant model parameters are the relation between livestock density, biomass consumption as well as dry matter losses due to manure droppings and treading.

2.7.4 Impact of atmospheric CO_2

The effect of increasing atmospheric CO_2 concentrations can be simulated using input of CO_2 concentrations and defining the relation between CO_2 concentration and maximum assimilation rate A_{max}, light use efficiency and potential transpiration rate T_p, respectively. These relations vary per crop and allow distinction between C_3 and C_4 crops. An example and more detailed explanations are given by Groenendijk et al. (2016).

2.8 Solutes

2.8.1 Basic equations

SWAP simulates the three main solute transport mechanisms in soil water: diffusion, convection and dispersion. An explicit, central finite difference scheme is used to solve the general convection-dispersion equation for dynamic, one-dimensional, convective-dispersive mass transport, including non-linear adsorption, linear decay and proportional root uptake in unsaturated/saturated soil (Van Genuchten & Cleary, 1979; Nielsen et al., 1986; Boesten & Van der Linden, 1991)

2.8.2 Boundary conditions

As *initial condition*, the solute concentrations c_i (mg cm^{-3} soil water) at different soil depths is specified.

At the *top boundary*, the solute concentrations in irrigation and rain water, c_{irr} and c_{prec} (mg cm^{-3}), need to be specified.

At the *lateral drainage boundary*, during drainage the solute flux that leaves the one-dimensional soil profile is accumulated for each compartment below groundwater level. In scenarios with lateral infiltration, the solute concentration of the infiltration water should be specified.

At the *bottom boundary*, SWAP multiplies the water flux at the bottom of the soil profile by the respective solute concentration. For upward flow conditions, the groundwater solute concentration is used.

2.8.3 Salinity stress

If salts are simulated as an inert tracer, transformation processes like sorption and degradation should be switched off. Salts can enter the system via one of the boundary conditions (par. 2.8.2) resulting in salt concentrations in soil water. Salinity stress is related to the salt concentration in soil water (Figure 2.5) and reduces root water uptake and plant growth.

2.9 Additional options

This paragraph refers to additional options which were not used in this thesis, but may be of interest in other studies. Details of the options are given by Kroes et al. (2017a).

The lateral boundary may be used to simulate drainage fluxes with a specific vertically distribution to introduce travel times of water discharge to drainage systems (Groenendijk and van den Eertwegh, 2004).

The water balance of a simplified surface water system can be calculated to analyse water management options. Surface water levels can be imposed, or derived by setting soil moisture criteria (groundwater level, pressure head, minimum storage) in combination with a weir.

Macroporosity is commonly present in soils due to pedogenesis, including shrinking and swelling, plant root penetration, freezing and thawing, soil fauna activity, or by tillage operations. The macropore module in SWAP includes infiltration into macropores at the soil surface, rapid transport in macropores to deeper layers, lateral infiltration into and exfiltration out of the soil matrix, water storage in macropores, and rapid drainage to drainage systems.

Soil moisture and groundwater age can be calculated as the time elapsed after entering the soil water domain described by the SWAP model. Following the method used by Goode (1996) and Lemieux & Sudicky (2010), the soil moisture age is calculated with the convection-dispersion equation for an inert solute.

In addition to the macroscopic root water uptake, SWAP may simulate microscopic water flow to roots, including radial and axial hydraulic resistances within the plant system from root surface to leaf stomata (De Jong van Lier et al., 2013).

2.10 Conclusions

The model SWAP version 4, as described in the previous paragraphs, is well suited to carry out complex studies. This has been demonstrated in several studies referred to at the web site (http://swap.wur.nl). Recently the Dutch Watervision project (chapter 4) applied the process-based model SWAP and made it suitable for use by farmers, regional government, water boards and others to assess crop yield reduction as a function of groundwater characteristics or as a function of the salt concentration in the root zone for the various soil types. Other examples of applications are given for a case study about the impact of saline groundwater on grassland yields in the Netherlands (Chapter 5) and the impact of land use on rising groundwater levels in the pampas of Argentina (Chapter 6).
The model approach and the examples illustrate how a physically based dynamic interaction between the domains soil water and crop is operational and supports complex research questions as proposed by Vereecken et al. (2016).

Software availability:
All software of SWAP version 4 is free, open and distributed with examples and datasets (http://swap.wur.nl).

3. Impact of capillary rise and recirculation on simulated crop yields

Upward soil water flow is a vital supply of water to crops. The purpose of this study is to determine if upward flow and recirculated percolation water can be quantified separately, and to determine the contribution of capillary rise and recirculated water to crop yield and groundwater recharge. Therefore we performed impact analyses of various soil water flow regimes on grass, maize and potato yields in the Dutch delta. Flow regimes are characterized by soil composition and groundwater depth and derived from a national soil database. The intermittent occurrence of upward flow and its influence on crop growth are simulated with the combined SWAP-WOFOST model using various boundary conditions. Case studies and model experiments are used to illustrate impact of upward flow on yield and crop growth. This impact is clearly present in situations with relatively shallow groundwater levels (85% of the Netherlands), where capillary rise is a well-known source of upward flow; but also in free-draining situations the impact of upward flow is considerable. In the latter case recirculated percolation water is the flow source. To make this impact explicit we implemented a synthetic modelling option that stops upward flow from reaching the root zone, without inhibiting percolation. Such a hypothetically moisture-stressed situation compared to a natural one in the presence of shallow groundwater shows mean yield reductions for grassland, maize and potatoes of respectively 26, 3 and 14 % or respectively about 3.7, 0.3 and 1.5 ton dry matter per hectare. About half of the withheld water behind these yield effects comes from recirculated percolation water as occurs in free-drainage conditions and the other half comes from increased upward capillary rise. Soil water and crop growth modelling should consider both capillary rise from groundwater and recirculation of percolation water as this improves the accuracy of yield simulations. This also improves the accuracy of the simulated groundwater recharge: neglecting these processes causes overestimates of 17% for grassland and 46% for potatoes, or 63 and 34 mm yr^{-1}, respectively.

Based on:

Kroes, J.G., Supit, I., Van Dam, J.C., Van Walsum, P.E.V., and Mulder, H.M., 2018. Impact of capillary rise and recirculation on simulated crop yields. Hydrol. Earth Syst. Sci., 22, 2937-2952, https://doi.org/10.5194/hess-22-2937-2018.

3.1 Introduction

Crop growth strongly depends on soil moisture conditions. Climate variables determine these conditions through rain excess that penetrates directly into the root zone or comes available via lateral flow. The moisture distribution in the soil strongly depends on soil physical properties that determine water and solute flow. Upward soil water flow becomes an especially vital supply term of a crop when the soil water potential gradient induced by the root extraction manages to bridge the distance to the capillary fringe, inducing increased capillary rise. In this paper we follow the definition of capillary rise, given by the Soil Science Society of America (SSSA, 2008), as the "phenomenon that occurs when small pores which reduce the water potential are in contact with free water". This implies that capillary rise as a source for upward flow to crop roots requires the presence of a groundwater table. In conditions without a groundwater table there may also be a contribution of upward flow to crop roots through the process of recirculation. Recirculation is a known process discussed already by Feodoroff (1969) but has never been quantified. We quantified recirculation separately from capillary rise using model experiments.

The contribution of (intermittent) upward flow to the total water budget can be significant. For example Kowalik (2006) mentions that during the grass growing season, in soils with the groundwater close to the soil surface (Aquepts), the capillary rise induced by root extraction varies between 60 and 150 mm per year. Babajimopoulos et al. (2007) found that under the specific field conditions about 3.6 mm d^{-1} of the water in the root zone originated from the shallow water table, which amounts to about 18% of the water transpired by a maize crop. Fan et al. (2013) analysed the groundwater depth globally and concluded that shallow groundwater influences 22 to 32% of global land area, and that 7 to 17% of this area has a water table within or close to plant rooting depths, suggesting a widespread influence of groundwater on crops. This is especially the case in delta areas where high population densities occur and agriculture is the predominant land use.

Wu et al. (2015) showed that capillary rise plays a main role in supplying the vegetation throughout the season with water, hence a strong dependence of vegetation upon groundwater. Han et al. (2015) applied HYDRUS-1D with a simplified crop growth model for cotton in a northwestern part of China and concluded that capillary rise from groundwater contributes to almost 23% of crop transpiration when the average groundwater depth is 1.84 m. According to Geerts et al. (2008) the contribution from capillary rise to the quinoa [*Chenopodium quinoa* Willd.] production in the Irpani region (Bolivia), ranges from 8 to 25% of seasonal crop evapotranspiration (ETc) of quinoa, depending mostly on groundwater table depth and amount of rainfall during the rainy season. The contribution from a groundwater table located approximately 1.5 to 2 m deep may represent up to 30% of the soybean [*Glycine max* (L.) Merr.] water requirements in sandy pampas (Videla Mensegue et al., 2015).

In 85% of the area in the Netherlands the average groundwater table is less than 2 meters below the soil surface (De Vries, 2007), where root extraction can induce capillary rise from groundwater. Wesseling & Feddes (2006) report that in summers with a high evapotranspiration demand, crops partially depend on water supply from soil profile storage and induced capillary rise. Van der Gaast et al. (2009), applying the method of Wesseling (1991), found for the Netherlands a maximum capillary flow of 2 mm d^{-1} to the root zone in loamy soils where the groundwater level is at 2.5 meter below the soil surface.

Although the contribution of capillary rise to the total water budget can be significant, it is an often neglected part of the crop water demand in situations of shallow groundwater levels (Awan et al., 2014). The capillary properties of a soil strongly depend on soil type. Rijtema (1971) estimated that loamy soils have an almost 2 times higher capillary rise than sandy soils.

Integrated approaches are needed to relate water availability to crop yield prognosis (Van der Ploeg & Teuling, 2013; Norman, 2013). The importance of capillary rise as supplier of water to crops has been shown by many researchers (e.g. Hooghoudt, 1937; Huo et al., 2012; Talebnejad & Sepaskhah, 2015; Han et al., 2015); however, we found only a few studies that use an integrated modelling approach (Xu et al., 2013; Zipper et al. 2015) to quantify capillary rise for different hydrological conditions (including free-drainage) using physically based approaches. In this study we explicitly consider the effect of crop type, soil type, weather year and drainage condition on capillary rise. Zipper et al. (2015) introduced the concept of groundwater yield subsidy as the increase in harvested yield (kg ha^{-1}) in the presence of shallow groundwater compared to free-drainage conditions. Following their approach we introduce the concept of soil moisture yield subsidy as the yield increase in free-drainage conditions due to recirculation of percolated soil moisture.

The driving force for induced capillary rise and recirculation is the difference in soil water potential, sometimes referred to as heads, at different soil depths. There are several models available that solve these head differences numerically. Ahuja et al. (2014) evaluated 11 models commonly applied for agricultural water management. Six of these models use simple 'bucket' approaches for water storage and have in some cases been extended with empirical options for capillary rise. Five models have the ability to numerically solve the

Richards equation for water movement in the soil. Examples are HYDRUS (Šimůnek et al., 2008) and SWAP (Feddes et al., 1988, Van Dam et al., 2008).

We applied the integrated model SWAP-WOFOST (acronyms for Soil Water Atmosphere Plant - WOrld FOod STudies) to solve head differences and crop yield simulations. Kroes & Supit (2011) applied the same integrated model to quantify the impact of increased groundwater salinity on drought and oxygen of grassland yields in the Netherlands. They recommended further analyses using different crops and different boundary conditions. We now apply this model with different boundary conditions using 45 years of observed weather and three different crops. For the lower boundary we use different hydrologic conditions that influence the vertical flow. For the soil system itself we use a wide range of soil physical conditions. The importance of the soil system was already stated by several authors like Supit (2000). We build on their suggestions and apply the tools for different crops and boundary conditions. Before we applied the model to different boundary conditions, we validated it at the field scale.

This paper quantifies the effects of (intermittent) upward flow on crop growth under different conditions of soil hydrology, soil type and weather. The effects are separately quantified in terms of flow source, namely capillary rise and recirculated percolation water. Therefore, we introduced a synthetic model option and performed a numerical experiment. We studied forage maize, grassland and potatoes and we hypothesize that neglecting upward flow will result in neglecting a considerable amount of soil moisture that is available for crop growth. We quantify this amount and show the importance of including upward flow for crop growth modelling. Our main research questions are the following. i) Can upward flow with capillary rise and recirculated percolation water as source be quantified separately?, ii) What is the contribution of capillary rise and recirculated water to crop yield and groundwater recharge?

3.2 Materials and methods

3.2.1 Modelling approach

We applied the coupled SWAP and WOFOST modelling system, using a 1-day time step. SWAP (Van Dam et al., 2008; Kroes et al., 2017a) is a one-dimensional physically based transport model for water, heat and solute in the saturated and unsaturated zone, and includes modules for simulating irrigation practices. The first version of SWAP, called SWATRE, was developed by Feddes et al. (1978). This version also included a module for

crop production, CROPR that applied principles of De Wit (1965) and is still applied in several countries.
SWAP simulates the unsaturated and saturated water flow in the upper part of the soil system, using a numerical solution of the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_a(h) - S_d(h) - S_m(h) \qquad (3.1)$$

where: θ is volumetric water content (cm^3 cm^{-3}), *t* is time (d), *K*(*h*) is hydraulic conductivity (cm d^{-1}), *h* is soil water pressure head (cm), *z* is the vertical coordinate (cm), taken positively upward, $S_a(h)$ is the soil water extraction rate by plant roots (d^{-1}), $S_d(h)$ is the extraction rate by drain discharge in the saturated zone (d^{-1}) and $S_m(h)$ is the exchange rate with macro pores (d^{-1}).

The numerical solution for this equation uses variable time steps that depend on boundary conditions and an iteration scheme. For example, high fluxes require time steps that are much smaller than 1 day (see Kroes et al, 2017a, for a detailed explanation).

Root water extraction and lateral exchange with surface water were accounted for. In this study we did not use the option to exchange water flow with macro pores.
The soil hydraulics were described by the Mualem–van Genuchten relations and the potential evapotranspiration was calculated with the Penman–Monteith equation (Allen et al., 1998). At the bottom boundary water fluxes, supplied by a separate regional hydrological model were used. Drainage and infiltration through the lateral boundary accounted for the flow to surface water. The surface water system was simulated using a simplified, weir controlled, water balance. Note that the surface water system in its turn interacted with the groundwater system. In previous years, SWAP has been successfully used to study soil-water-atmosphere-plant relationships in many locations with various boundary conditions (e.g. Feddes et al., 1988; Bastiaanssen et al., 2007). See Van Dam et al. (2008) for an overview. A recent list is available at http://swap.wur.nl/ (accessed on 7 May 2018). Eitzinger et al. (2004), Bonfante et al. (2010), Oster et al. (2012), and Rallo et al. (2012) amongst others tested the model performance.

WOFOST is a crop growth simulation model, its principles are explained by Van Keulen & Wolf (1986). Van Diepen et al. (1989) presented the first WOFOST version. WOFOST is applied in many studies (e.g. Rötter, 1993; Van Ittersum et al., 2003; De Wit & Van Diepen, 2008; Supit et al., 2012; De Wit et al., 2012). Crop assimilation is calculated as function of solar radiation and temperature, using a 3-point Gaussian integration method accounting for leaf angle distribution and extinction of direct and diffuse light. The assimilation is reduced when water stress occurred. Subsequently, the maintenance respiration is subtracted and the remaining assimilates are partitioned between the plant organs (i.e. leaves, stems, roots and storage organs). For maize and potatoes the partitioning is development-stage dependent. For perennial grass however, a constant partitioning factor is assumed. By integrating the difference between growth and senescence rates over time, dry weights of various plant organs are established.

In SWAP, crop assimilation depends on the ambient CO_2 concentration as well (see: Kroes & Supit, 2011; Supit et al., 2012). To account for unknown residual stress caused by diseases, pests and/or weeds an additional assimilation reduction factor was introduced. The rooting density decreased exponentially with depth. To simulate water withdrawal from deeper soil layers for crop uptake a form of compensatory root uptake was used in case the upper part of the soil was very dry (Jarvis, 1989 and 2011). The increasing atmospheric CO_2 concentrations during relatively long historical simulation periods (>20 years) was accounted for.

3.2.2 Case studies for validation

SWAP was validated using *results* of seven case studies at six locations in the Netherlands (Figure 3.1) where grassland, maize and potatoes are grown and observations were available from hydrology, soil and crop. The main characteristics of the seven cases are summarized in Table 3.1. The soil texture ranged from sand to clay. The observations included parameters such as groundwater levels and yields and in some cases soil moisture contents, soil pressure head and evapotranspiration. The weather data were collected from nearby weather stations or from on-site measurements. Observations for case studies 1 and 2 (DM-Grass and DM-Maize in Table 3.1) were available for a period of 22 years (1992-2013) from one field where grassland and maize were grown for respectively 7 and 15 years.

We used the model calibrations carried out by Kroes et al. (2015) and Hack-ten-Broeke et al. (2016) and limited our calibration efforts to parameter values for drought and management (Table 3.1), focussing on validation of results. Planting and harvest dates were given. Oxygen and drought stress reduced transpiration which subsequently reduced crop assimilation. Oxygen stress was described with the process-based method of Bartholomeus et al. (2008) and parameterized as described by Hack-ten-Broeke et al. (2016). Drought stress was parameterized using the dry part of the reduction function proposed by Feddes et al. (1978). Drought stress was absent when the soil pressure head *h* exceeded the critical value of *h3*. Drought stress increased linearly between *h3* and at *h4* (wilting point). The critical pressure head *h3* differed between lower and higher potential transpiration (respectively *h3l* and *h3h*) rates. In conditions with drought or oxygen stress, the reduction in stressed parts was partly compensated by extra root water uptake in those parts of the root zone with more favourable soil moisture conditions (Jarvis, 1989 and 2011).

Legend

Location no.	Location Name
1	DeMarke21
2	Cranendonck16
3	Dijkgraaf
4	Borgerswold03
5	RusthoeveB7
6	Vredepeel26

Figure 3.1 *Location of the case studies for grassland, maize and potatoes; location De Marke has a rotation of grassland and maize on the same field.*

For all cases a so-called management factor was used to close the gap between observed and simulated actual yield. The input crop parameters for maize only differed with respect to the management factor which ranges from 0.85 to 0.95. The management factors were relatively high because the case study locations have good management. It is very likely that we missed some processes even though our modelling approach is mechanistic, because it is still relatively simple. Some processes like the impact of pests and diseases were not included and may have played a role in the field; the calibration was done on experimental farms where the impact from diseases and pests was minimal.

For potatoes the input crop parameters were kept the same for all three cases (Table 3.1). Maximum rooting depth for grassland, maize and potatoes were respectively 40, 100 and 50 cm.

Soil water conditions were different for all locations and boundary conditions varied, depending on local situation and available data (Table 3.1). In most cases a Cauchy bottom boundary condition was applied using a hydraulic head based on piezometer observations from the Dutch Geological Survey (https://www.dinoloket.nl/, accessed on 7 May 2018). Observed groundwater levels were used as a lower boundary condition for Borgerswold (crop: potato). In two cases a lateral boundary condition was applied with drainage to a surface water system (Table 3.1). The simulation results were analysed using the R-package hydroGOF (Bigiarini, 2013) and the resulting statistics are presented in Table 3.2.

Table 3.1 *Main characteristics of the case studies used to verify the setup of the model combination SWAP-WOFOST.*

Case study[1]	Crop	Location	Period	Soil	Observations[2]	Reference	Drought stress[3]	MF[4]	RZ[5]	BBC[6]	Lateral Boundary
DM-Grass	Grass	De Marke	1995-1996, 2005-2008, 2013	dry sandy soil	Gwl, Yield, Theta20cm	Hack et al. (1996); Verloop et al., (2014)	h3h = -200.0 cm h3l = -800.0 cm h4 = -8000.0 cm	0.8	40	Cauchy	No Drainage
DM-Maize	Silage maize	De Marke	1992-1994, 1997-2003, 2009-2012	dry sandy soil	Gwl, Yield, Theta20cm	Hack et al. (1996); Verloop et al., (2014)	h3h = -400.0 cm h3l = -500.0 cm h4 = -10000.0 cm	0.85	40	Cauchy	No Drainage
C-Maize	Silage maize	Cranendonck	1974-1982	Cumulic Anthrosol	Gwl, Yield	Schröder (1985)	see DM-Maize	0.9	40	Cauchy	No Drainage
D-Maize	Silage maize	Dijkgraaf	2007	Umbric Gleysol	Gwl, Yield, ET,Theta20cm	Elbers et al. (2009)	see DM-Maize	0.95	100	Cauchy	No Drainage
B-Potato	Potato	Borgerswold	1992, 1994	Sandy loam	Gwl, Yield	Dijkstra et al., (1995)	h3h = -300.0 cm h3l = -500.0 cm h4 = -10000.0 cm	0.8	100	Observed groundwater	No Drainage
R-Potato	Potato	Rusthoeve	2013	Clay	Gwl, Yield, Qdrain	Van Den Brande (2013)	see B-Potato	0.8	100	Cauchy	Drain tubes at -90 cm
V-Potato	Potato	Vredepeel	2002	Sandy loam	Gwl, Yield	De Vos et al., (2006)	see B-Potato	0.8	50	Closed	Drain ditch at -100 cm

Table 3.1 *Continued.*

[1] The name of each Case study is a combination of an acronym for the Location and the crop type, using the acronyms DM=De Marke, C=Cranendonck, D=Dijkgraaf, B=Borgerswold, R=Rusthoeve and V=Vredepeel

[2] Gwl = Groundwater level, Yield = Actual Yield as Dry Matter of Harvested product, Theta20cm= Soil moisture content at a depth of 20cm below surface, Qdrain = drainage from field to surface water via tube drains, ET = Evapotranspiration measured via Eddy Correlation method.

[3] h3h = h below which water uptake reduction starts at high Tpot; h3l = h below which water uptake red. starts at low Tpot; h4 = No water extraction at lower pressure heads; Drought stress was parameterised using the dry part of the reduction function proposed by Feddes et al. (1978), Drought stress is absent when the soil pressure head h exceeds the critical value of h3. Drought stress increases linearly between h3 and at h4 (wilting point). The critical pressure head h3 differs between lower and higher potential transpiration (Tpot) (respectively h3l and h3h) rates.

[4] MF = Management Factor to account for imperfect management

[5] RZ = Maximum depth of root zone (cm)

[6] BBC = Bottom Boundary Condition. The Cauchy bottom boundary condition uses a hydraulic head based on piezometer observations from an open data portal (see text)

Table 3.2 *Results of Case studies: simulated and observed values.*

Case study	Name[1]	Unit	Simulated mean	Observed mean	ME[2]	RMSE[3]	NS[4]	d[5]	n[6]
DM-Grass	Yield	kg ha^{-1} yr^{-1}	11183	11049	133	1347	0.6	0.9	7
	Gwl	m	-1.31	-1.30	-0.01	0.45	0.3	0.9	77
	Theta	m^3 m^{-3}	0.28	0.27	0.01	0.05	0.5	0.9	43
DM-Maize	Yield	kg ha^{-1} yr^{-1}	11593	11850	-257	2864	-3.3	0.4	14
C-Maize	Yield	kg ha^{-1} yr^{-1}	14097	13788	310	2595	-1.2	0.7	9
	Gwl	m	-1.41	-1.36	-0.05	0.25	0.4	0.9	61
D-Maize	Yield	kg ha^{-1} yr^{-1}	15973	16306	-333				1
	LAI	m^2 m^{-2}	2.08	2.47	-0.34	0.62	0.7	0.9	10
	ETact	mm yr^{-1}	1.33	1.93	-0.61	0.89	0.5	0.9	232
	Gwl	m	-1.03	-1.07	0.03	0.06	0.9	1.0	112
	Theta	m^3 m^{-3}	0.29	0.27	0.01	0.03	0.5	0.8	219
B-Potato	Yield	kg ha^{-1} yr^{-1}	10543	9246	1297				2
	Gwl	m	-1.10	-1.10	0.00	0.03	1.0	1.0	123
R-Potato	Yield	kg ha^{-1} yr^{-1}	9984	8610	1374				1
	Gwl	m	-1.07	-1.10	0.03	0.19	0.6	0.9	887
	qDrain	mm	1.06	0.62	0.44	1.41	0.4	0.8	1084
V-Potato	Yield	kg ha^{-1} yr^{-1}	11071	11359	-288				1
	Gwl	m	-1.03	-1.07	0.04	0.12	0.8	0.9	353

[1] Gwl = Groundwater Level below the soil surface; Theta = Volumic Soil Moisture Content at a depth of 20 cm below the soil surface; LAI=Leaf Area Index; ETact = actual EvapoTranspiration; qDrain = Drainage flux

[2] ME: Mean Error between simulated (sim) and observed (obs), in the same units of sim and obs, with treatment of missing values. A smaller value indicates better model performance

[3] RMSE: Root Mean Square Error between sim and obs, in the same units of sim and obs, with treatment of missing values. A smaller value indicates better model performance.

[4] NS: Nash-Sutcliffe efficiencies range from $-\infty$ to 1. Essentially, the closer to 1, the more accurate the model is.

[5] d: The Index of Agreement (d) developed by as a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all.

[6] n: the number of values used with the 4 statistical criteria to compare simulated and observed results.

3.2.3 Soil crop experiment to analyse the role of recirculation and capillary rise

To analyse the impact of soil type on upward soil water flow we modelled soil-crop experiments using 72 soils. Each soil consisted of one or more soil horizons, each with different soil physical properties. The method was described in detail by Wösten et al. (2013a). The 72 soils were aggregated from 315 soil units of the 1:50000 Dutch Soil Map using soil hydraulic clustering methods and considering the following properties: maximum groundwater depth, saturation deficit between a certain depth and the soil surface, transmissivity for horizontal water flow, resistance for vertical water flow and availability of water in the root zone (Wösten et al., 2013b). The resulting soil hydraulic properties were subsequently used as SWAP input. The bottom of the soil profile was set at 5.5 meter below the soil surface. At this depth, the simulated root zone soil water fluxes are not affected anymore by the actual depth of the soil profile bottom. The root zone lower boundary was dynamic, it depended on root growth and consequently varied in time.

For each soil we applied three hydrological conditions (Figure 3.2), ranging from relatively dry (condition a; Figure 3.2a) to relatively wet (condition c; Figure 3.2c). The latter is the natural situation in most of the Netherlands. This hydrological condition had a fluctuating groundwater level derived from a national study (Van Bakel et al., 2008). This national study used simulation units which are unique in land use, crop type and drainage conditions resulting in daily groundwater fluctuations. Lateral infiltration and drainage were accounted for ($q_{infiltration}$ *and* $q_{drainage}$ in Figure 3.2 c). We selected three large simulation units for grassland, maize and potato with long-term average groundwater levels between 40 and 120 cm below the soil surface, covering respectively 1806, 794 and 58102 ha using data from Van Bakel et al. (2008). See supplementary material of Kroes & Supit (2011) for an additional explanation of the study from Van Bakel et al (2008).

The other two conditions (a) and (b) were unsaturated and had no groundwater due to a free-draining bottom boundary ($q_{leaching}$, see Figure 3.2 conditions a and b). Condition (a) has been included in this study to explicitly demonstrate the role of recirculation as a source of upward flow. A synthetic modelling option has been implemented to stop upward flow from reaching the root zone, without inhibiting percolation. This option was implemented in the numerical solution of the Richards equation and minimized vertical conductivity just below the root zone in situations when the model simulated upward vertical flow. We did use an implicit scheme for the conductivity in such situations. Code adjustment was necessary to carry out the model experiment (no recirculation) and to demonstrate (quantitatively) the added value of simulating more detailed water fluxes in the soil profile in comparison to bucket approaches. When crop models are used for yield forecasting these detailed processes play an important role; neglecting them may cause large errors.

The upward flux across the bottom of the root zone can either stem from capillary rise or from percolation water that is recirculated (q_{recirc} and $q_{caprise}$, see Figure 3.2 conditions b and c). The capillary rise (Figure 3.2 c) has two sources: i) groundwater and ii) recirculated percolation water. In all hydrological conditions, percolation across the root zone and leaching across the lower boundary of the model profile occurs ($q_{percolation}$ and $q_{leaching}$ in Figure 3.2). All fluxes were calculated using small variable time steps (< 1 day); however results were accumulated to daily net fluxes, which implies that small variations within a day cannot be seen from the results. Recirculation depends on crop water demand, soil hydraulic properties and the presence of soil moisture.

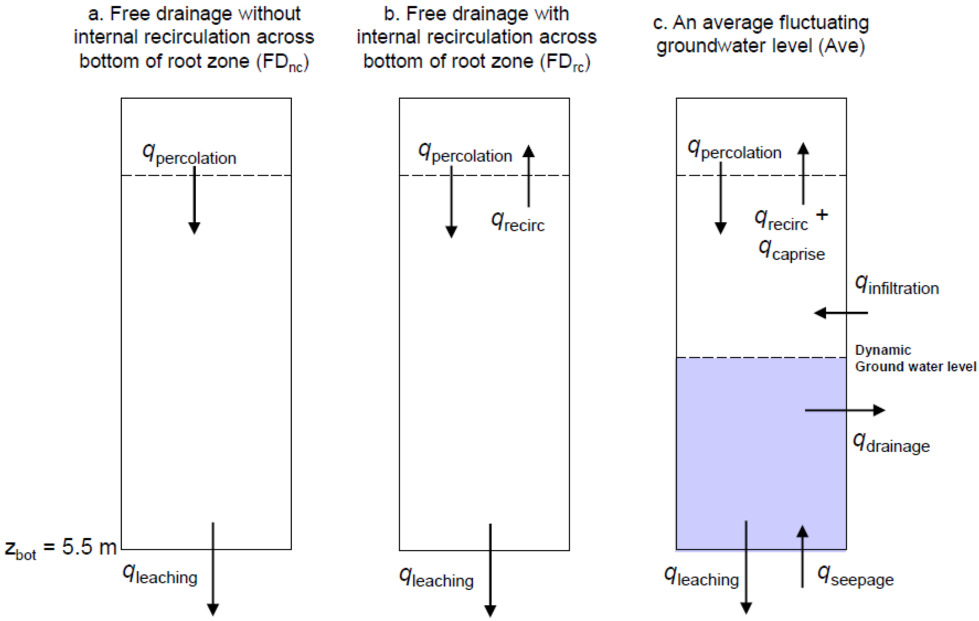

Figure 3.2 *Schematization of three hydrological conditions: (a) free-drainage without recirculation across the bottom of the root zone (FD_{nc}); (b) free-drainage with recirculation across the bottom of the root zone (FD_{rc}); (c) average fluctuating groundwater level (Ave). Conditions (a) and (b) have free-draining bottom boundary conditions without groundwater. Condition (a) is artificially created to explicitly demonstrate the role of recirculating percolation resulting in upward flow to the root zone. Condition (b) is a common free-drainage situation which includes upward flow due to recirculating percolation water. Condition (c) is the natural situation in most of the Netherlands. This hydrological condition has a fluctuating groundwater level derived from a national study (Van Bakel et al., 2008). The bottom of the root zone is indicated with a dotted line in (a), (b) and (c).*

The crop parameters were kept the same as for the case studies, with a few exceptions: i) for grassland an average management factor of 0.9 was used, ii) timing of grass mowing was done when a dry matter threshold of 4200 kg.ha^{-1} DM (dry matter) was exceeded and iii) for maize and potatoes the harvesting dates were respectively set to 25-Oct and 15-Oct.

The three crops and three lower boundary conditions resulted in nine combinations. Each combination was simulated with 72 soils for a period of 45 years (1971-2015) with meteorological data from the station De Bilt (KNMI, 2016). In a subsequent analysis we grouped the results of these 72 soils to five main soil groups clay, loam, peat, peat moor and sand (Figure 3.3) to be able to analyse the impact at grouped soil types.

The implementation of the synthetic modelling option is explained in the supplementary material of Kroes et al. (2018) with references to the open-source model SWAP version 4.0.1, which was used to carry out all the simulations.

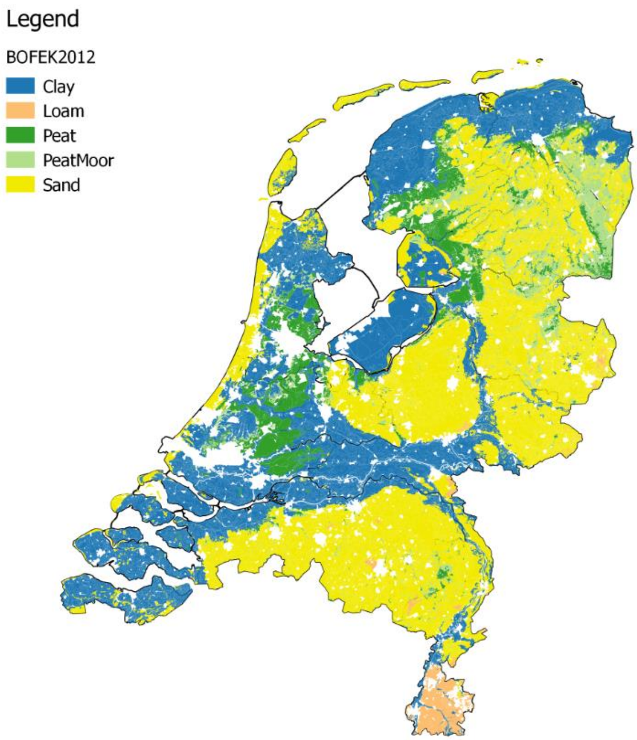

Figure 3.3 *Five grouped soil types, based on 72 soils of the Soil Physical Map of the Netherlands (Wösten et al., 2013a).*

3.3 Results

3.3.1 Case studies for validation

The first two case studies are from one location (De Marke), where a grassland-maize rotation was practised. The results show that the hydrological conditions (Figure 3.4 and Table 3.2) were simulated accurately for those years for which observed data were available (1991-1995). From 1995-1997 the groundwater levels dropped as a result of relatively low precipitation (about 700 mm yr^{-1}). The autumn of the year 1998 showed rising groundwater levels that corresponded well with very wet conditions at that time. The simulated grassland yields were overestimated by 133 $kg.ha^{-1}$ DM and the simulated maize yields were underestimated by 257 kg.ha^{-1} DM and differences were well within acceptable ranges (Figure 3.5 and Table 3.2).

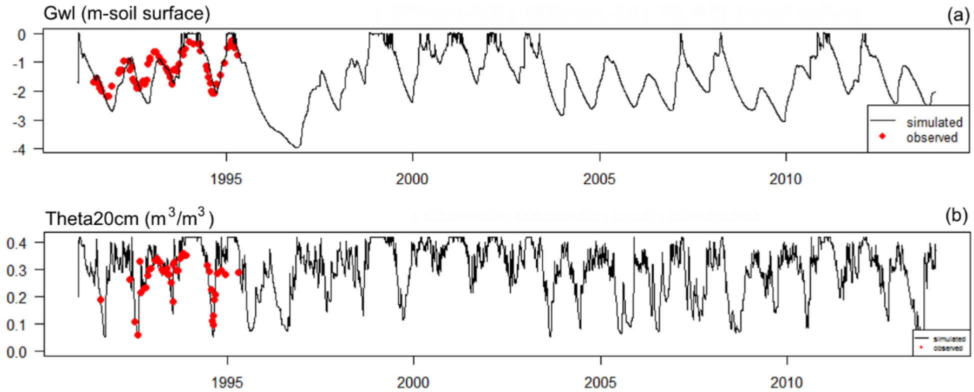

Figure 3.4 *Results of case studies for grassland at location 1 (De Marke): (a) groundwater level (Gwl in meters below soil surface); (b) soil moisture content (Theta20cm in m^3.m^{-3}) at 20 cm below the soil surface.*

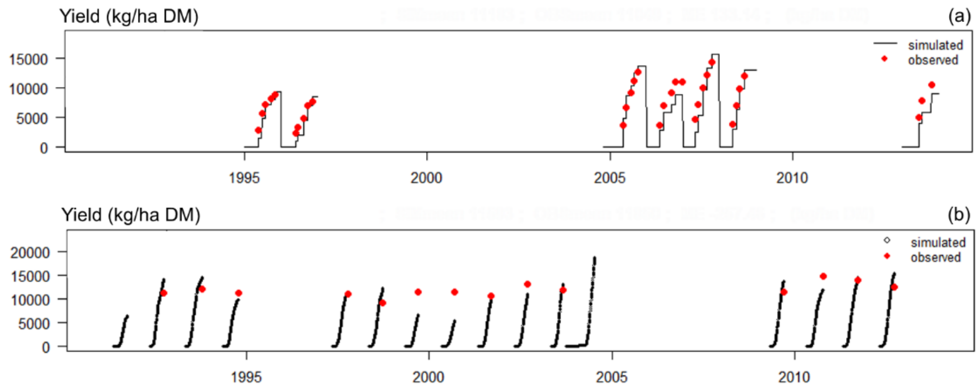

Figure 3.5 *Results of case studies at location 1 (De Marke) : observed yields (kg.ha^{-1}DM) as red dots and simulated yields as black lines or as black dots: (a) for yields (kg.ha^{-1} DM) of grassland; (b) for yields (kg.ha^{-1} DM) of maize.*

For the other two maize case studies (C-Maize and D-Maize) groundwater levels and soil moisture were well simulated (Table 3.2). The simulated maize yields (Table 3.2) were less acceptable for case C-Maize as indicated by a zero or negative Nash-Sutcliffe efficiency (NS) which suggests that the observed mean was a better predictor than the model. One should consider that the NS efficiency is sensitive to sample size and outliers. In 1976, a very dry year, the soil hydrology dynamics and the resulting yield were well captured. The yield of case study D-Maize had a small bias of 333 kg.ha^{-1} DM between observed and simulated values.

The simulated hydrological conditions for the three fields of the potato cases, B-potato, R-Potato and V-Potato, showed a good fit with the observed (Table 3.2). The simulated yields (Table 3.2) showed the largest deviation from the observed for the case B-Potato. The more recent experiments of potato case studies, R-Potato and V-Potato, showed differences between simulated and observed yields of respectively 1374 and -288 kg.ha^{-1} DM (Table 3.2). These case studies unfortunately covered only 1 year. The case R-Potato performed less due to the complex situation in the subsoil with drainage conditions that require more observations to improve the simulations.

However, one has to bear in mind that perfect calibration is not the objective of this study; we used calibration values from earlier studies (Kroes et al., 2015 and Hack et al., 2016). No detailed assimilation measurements were executed on the fields and the meteorological data were not measured on site, but taken from meteorological stations sometimes more than 30 km away. Furthermore, no detailed information concerning fertilizer applications and soil carbon was available, therefore we considered it constant in time.

Even though some yields were not accurate enough to satisfy statistical criteria for good model performance, we believe that the dynamics of soil hydrology and crop yield were acceptably captured. With more field information and calibration a better result could be achieved but we think that current tuning of SWAP for the three crops allowed for an application at a larger scale with various hydrological boundary conditions.

Before the analysis at a larger scale we simulated the impact of upward flow for the case studies. We carried out additional simulations without upward flow towards the root zone, using the specially programmed synthetic model option. Results of these three cases are given in Table 3.3 for the situation with and without upward flow. This table shows that suppressing upward flow lowered yields by 6, 3 and 20% respectively for grassland, maize and potato. The groundwater recharge was reduced with respectively 3, 4 and 94% (Table 3.3).

In a next step, we carried out a larger-scale experiment to quantify this impact for different soil crop and climate conditions.

Table 3.3 *Results of the case studies: values and differences in yield, capillary rise and percolation fluxes, resulting from simulations with and without capillary rise.*

		Condition		*Differences*		*Differences (%)*
Case study[1]	*Model result*	*A*[2]	*B*[3]	*A-B*	*Unit*	*100*(A-B)/A*
DM-Grass	Y_{act}	*12928*	*12213*	*715*	$kg.ha^{-1}.\ season^{-1}$ *DM*	*6*
	$q_{caprise}$	*30*	*0*	*30*	$mm.season^{-1}$	*100*
	$q_{percolation}$	*313*	*305*	*9*	$mm.season^{-1}$	*3*
DM-Maize	Y_{act}	*12803*	*12788*	*15*	$kg.ha^{-1}.\ season^{-1}$ *DM*	*0*
	$q_{caprise}$	*7*	*0*	*7*	$mm.season^{-1}$	*100*
	$q_{percolation}$	*91*	*88*	*3*	$mm.season^{-1}$	*4*
V-Potato	Y_{act}	*11071*	*8877*	*2194*	$kg.ha^{-1}.\ season^{-1}$ *DM*	*20*
	$q_{caprise}$	*101*	*0*	*101*	$mm.season^{-1}$	*100*
	$q_{percolation}$	*16*	*1*	*15*	$mm.season^{-1}$	*94*

[1] Cases studies DM-Grass and DM=Maize were simulated for limited periods of respectively 2005-2008 and 1991-1994 to have a continuous sequence of years, Case study V-Potato was simulated for one year;

[2] Condition A has actual bottom boundary conditions according to column BBC in Table 3.1;

[3] Condition B has actual bottom boundary conditions according to column BBC in Table 3.1, but without capillary rise to root zone.

3.3.2 Soil crop experiment to analyse the role of capillary rise

The three crops from the case studies were simulated with 72 soils from the national database using three different bottom boundary conditions and 45 years with weather from 1970 to 2015.

Results of simulated upward flow of 45 years of weather, 72 soils and three lower boundary conditions are summarized with mean values in Table 3.4. The highest values for upward flow to the root zone during crop growth were found for average groundwater conditions (Ave) with long-term mean values for grassland, maize and potatoes of respectively 194, 74 and 112 mm yr^{-1}. Differences among hydrological conditions at the bottom of the root zone were caused by differences in weather, growing season, dynamic position of the root zone and demand of root water uptake. Even in free-drainage situations the upward flow to the root zone caused by soil water recirculation was considerable, ranging from 17 to 78 mm long-term average (FD_{rc} in Table 3.4). In free-draining soils the variation in upward flow to the root zone ranged from about 10 mm in wet and cold to 120 mm in dry and warm years with a high evaporative demand (Figure 3.6, upper part). In general, upward flow was highest in loamy soils where soil physical conditions were optimal. Especially in the presence of a groundwater level, differences in upward flow between soils were relatively small compared to differences among years and within one grouped soil type (Figure 3.7, lower part).

Table 3.4 *Results of soil crop experiments: mean values of six model results from three different hydrological conditions: FD_{nc} (free-drainage with no recirculation), FD_{rc} (free-drainage with recirculation) and Ave (average drainage conditions).*

Crop	*Model Result*	*FD_{nc}*	*FD_{rc}*	*Ave*	*Unit*
Grassland	Y_{act}	*10494*	*12147*	*14177*	$kg.ha^{-1}.season^{-1}$ *DM*
	$q_{caprise}$			*194*	$mm.season^{-1}$
	q_{recirc}	*0*	*78*		$mm.season^{-1}$
	$q_{percolation}$	*317*	*338*	*380*	$mm.season^{-1}$
	$q_{seepage}$	*0*	*0*	*227*	$mm.yr^{-1}$
	$q_{leaching}$	*301*	*257*	*0*	$mm.yr^{-1}$
Maize	Y_{act}	*12318*	*12378*	*12643*	$kg.ha^{-1}.season^{-1}$ *DM*
	$q_{caprise}$			*74*	$mm.season^{-1}$
	q_{recirc}	*0*	*17*		$mm.season^{-1}$
	$q_{percolation}$	*52*	*57*	*47*	$mm.season^{-1}$
	$q_{seepage}$	*0*	*0*	*155*	$mm.yr^{-1}$
	$q_{leaching}$	*396*	*394*	*0*	$mm.yr^{-1}$
Potato	Y_{act}	*8864*	*9521*	*10365*	$kg.ha^{-1}.season^{-1}$ *DM*
	$q_{caprise}$			*112*	$mm.season^{-1}$
	q_{recirc}	*0*	*42*		$mm.season^{-1}$
	$q_{percolation}$	*39*	*50*	*73*	$mm.season^{-1}$
	$q_{seepage}$	*0*	*0*	*291*	$mm.yr^{-1}$
	$q_{leaching}$	*432*	*416*	*0*	$mm.yr^{-1}$

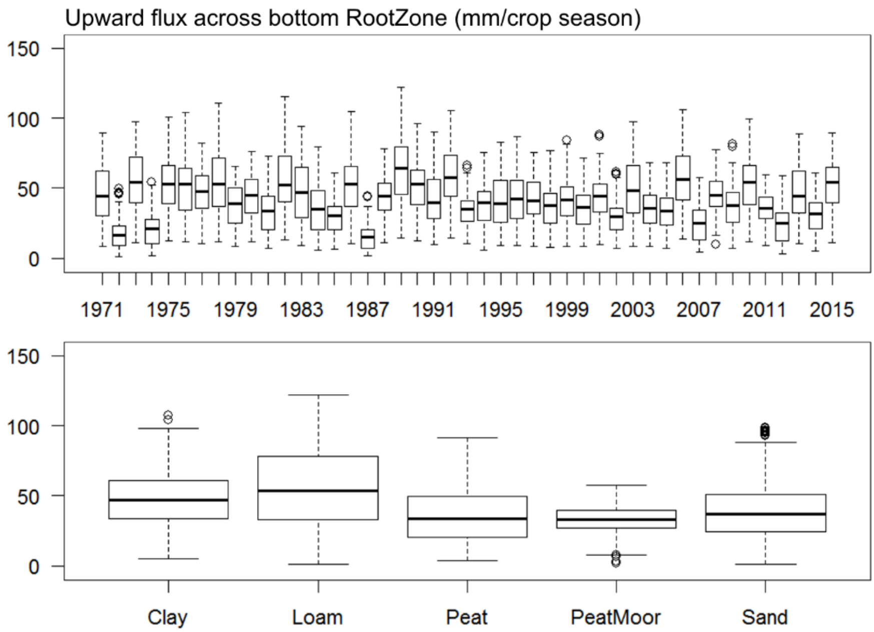

Figure 3.6 *Results of the soil-crop experiment for potato: upward flux across the bottom of the root zone (q_{recirc} in mm.crop season^{-1}) for hydrological conditions with free-drainage (FD_{rc}); Upper figure: results for all 72 soils for the period 1971-2015; Lower figure: results as boxplots for clustered soil types.*

The upward flow was inversely related to the rooting depth: the larger the rooting depth the smaller the upward flow. Grassland, potatoes and maize had rooting depths of respectively 40, 50 and 100 cm and an upward flow of respectively 194, 112 and 74 mm per growth season (Table 3.4). Note that the high value for perennial grassland was also caused by a much longer growing season. The percolation was highest for grassland for the same reasons (Table 3.4). These high values were largely due to the precipitation excess during winter in the Netherlands.

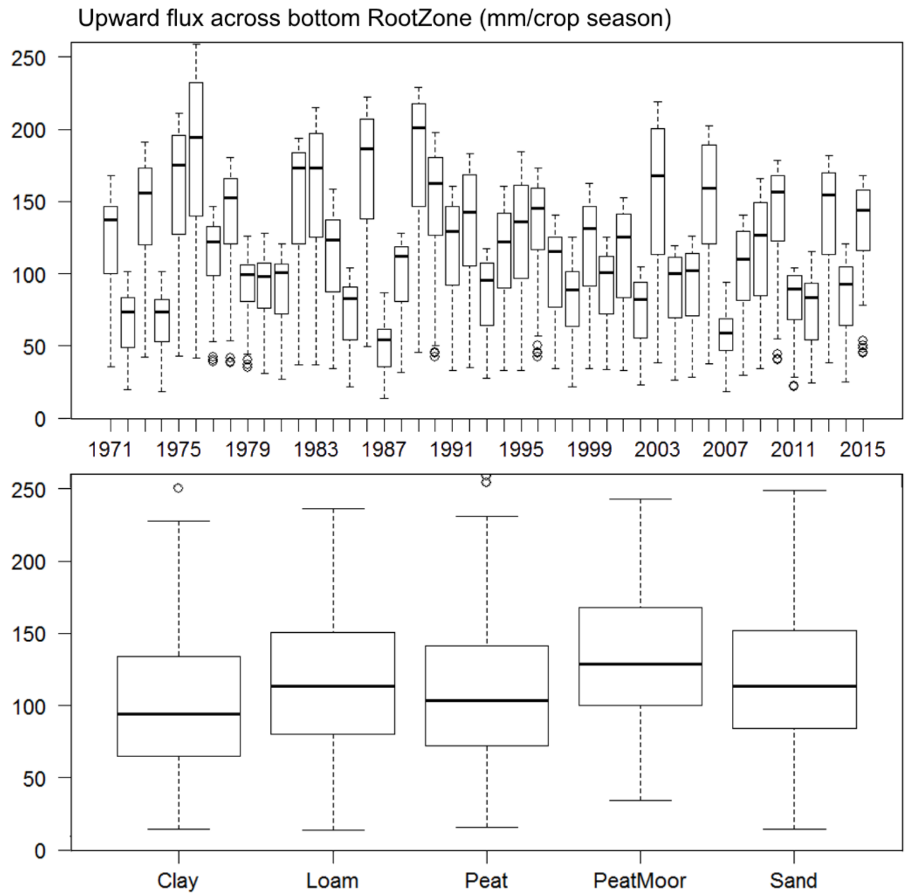

Figure 3.7 *Results of the soil-crop experiment for potato: upward flux across the bottom of the root zone ($q_{caprise}$ in mm.crop season^{-1}) for hydrological conditions with average groundwater level (Ave); Upper figure: results for all 72 soils for the period 1971-2015; Lower figure: results as box plots for clustered soil types.*

Upward seepage across the bottom boundary did not occur in the free-drainage conditions (Figure 3.2 a and b). Leaching was highest (Table 3.4) in the synthetic free-drainage condition without capillary rise (Figure 3.2 a). Note that the values in Table 3.4 for seepage and leaching were given for a calendar year, whereas the other mean values were given for a growing season. Yearly values were used for the bottom boundary because these values give an indication for the yearly deeper groundwater recharge which may also be influenced by variations in vertical fluxes close to the root zone during the remainder of the year. The leaching flux at 5.5 m depth (Table 3.4, $q_{leaching}$) increased when upward flow was suppressed (lower transpiration, more groundwater recharge), with respectively 44, 2 and 16 mm yr^{-1} for grassland, maize and potatoes. The shallow groundwater in Dutch conditions (Figure 3.2 c) often does not have leaching at greater depth because excess precipitation or upward seepage is discharged via drainage systems. The average condition we used had no leaching but seepage of 227, 155 and 291 mm yr^{-1} for grassland, maize and potatoes (Table 3.4, $q_{seepage}$).

As can be expected, the synthetic condition without upward flow and without groundwater (Figure 3.2 a), had the lowest simulated mean yields for all crops (Table 3.4). The highest mean yields were simulated when average groundwater situations including capillary rise were considered (Table 3.4, column Average). The relative mean yield increase was lowest for maize and highest for grassland (Table 3.5) which was probably caused by the difference in rooting depth.

The simulation results with three different lower boundary conditions (Figure 3.2 conditions a, b and c) were also compared by subtraction. The subtraction enables a quantification of the contribution of the two different sources of upward flow: groundwater and recirculating percolation water.

Table 3.5 *Results of soil-crop experiments: differences (%) between results from three different hydrological conditions: FD_{nc} (free-drainage with no recirculation), FD_{rc} (free-drainage with recirculation) and Ave (average drainage conditions).*

		Differences (%)		
Crop	*Model result*	*100*(FD_{rc} - FD_{nc}) / FD_{rc}*	*100*(Ave- FD_{rc}) / Ave*	*100*(Ave- FD_{nc}) / Ave*
grassland	Y_{act}	*14*	*14*	*26*
	$q_{percolation}$	*6*	*11*	*17*
maize	Y_{act}	*0*	*2*	*3*
	$q_{percolation}$	*9*	*-22*	*-11*
potato	Y_{act}	*7*	*8*	*14*
	$q_{percolation}$	*22*	*31*	*46*

The elimination of recirculating percolation water to the root zone in free-drainage conditions (synthetic condition a compared to b, Figure 3.2) reduced grassland, maize and potato yields with respectively 14, 0 and 7 % (Table 3.5). The higher yields were caused by upward flow using recirculating percolation water as source.

A comparison between situations with free-drainage (condition b, Figure 3.2) with average groundwater levels (condition c, Figure 3.2) showed a similar yield reduction: respectively 14, 2 and 8 %. The higher yields were caused by capillary rise with groundwater and recirculation as source.

When one compares situations with free-drainage conditions without upward flow (synthetic condition a, Figure 3.2) with average groundwater levels (condition c) yield reductions of grassland, maize and potatoes were respectively 26, 3 and 14 % (Table 3.5) or respectively about 3.7, 0.3 and 1.5 $ton.ha^{-1}$ DM (Table 3.4). These yield differences quantify the contribution to the sum of the two different sources of upward flow: groundwater and recirculating percolation water.

The impact of upward flow on groundwater recharge was highest for potatoes and lowest for maize. For grassland, maize and potatoes differences between downward flux across the bottom of the root zone ($q_{percolation}$ in Figure 3.2) of three hydrological conditions were calculated of respectively 17, -11 and 46 % ($q_{percolation}$ in Table 3.5) or 63, -5 and 34 mm ($q_{percolation}$ in Table 3.4). Low recharge values for maize were caused by deeper rooting systems which reduced these differences because groundwater levels were closer to the bottom of the root zone. For potatoes this difference in yield did reach values of more than 4 $ton.ha^{-1}$ DM in stress conditions (Table 3.6). The results are presented in more detail in the supplementary material of Kroes et al., (2018).

3.4 Discussion

The case studies and soil-crop experiments in this paper demonstrate the combined interaction of recirculation and capillary rise on crop yields. This impact is clearly present in situations where a groundwater level is present (85% of NL) but also in free-draining situations the impact of upward flow is considerable. According to our simulation results, grassland, maize and potato yields increased with respectively 14, 0 and 7% in free-drainage conditions when upward flow was included (Table 3.5). This increase was mainly caused by internal recirculation, i.e. a part of the downward flux past the root zone was redirected upward to the root zone as a result of gradient-driven flow. When upward flow also has groundwater as a source, simulated yields increased by another 14, 2 and 8% respectively. This increase was supported by a stronger capillary rise due to proximity to the groundwater. Comparing the simple simulations (no upward flow, no groundwater influence) to those with an average groundwater level and capillary rise shows yield increases of 26, 3 and 14%. About half of these yield increases were caused by internal recirculation as occurs in free-drainage conditions and the other half was caused by an increased upward capillary flow from the groundwater.

Table 3.6 *Results for potatoes in the soil crop experiments for each clustered soil type: capillary rise, recirculation and yield from three different hydrological conditions: FD_{nc} (free-drainage with no recirculation), FD_{rc} (free-drainage with recirculation) and Ave (average drainage conditions). Results for upward flow of FD_{nc} are zero and therefore not given.*

Hydrological condition		Statistic	Values per clustered soil type: Clay	Loam	Peat	Moor	Sand	Unit
FD_{rc}	q_{recirc}	min	5	1	4	8	1	mm/crop season
		lower quartile	34	33	20	27	24	mm/crop season
		median	47	54	34	33	37	mm/crop season
		upper quartile	61	78	50	39	51	mm/crop season
		max	98	122	91	58	88	mm/crop season
Ave	$q_{caprise}$	min	14	14	15	34	15	mm/crop season
		lower quartile	65	80	72	100	84	mm/crop season
		median	94	113	104	129	113	mm/crop season
		upper quartile	134	151	141	168	152	mm/crop season
		max	227	236	231	243	249	mm/crop season
FD_{nc}	Y_{act}	min	3.1	5.4	2.8	2.8	1.2	1000 kg/ha DM
		lower quartile	7.4	8.7	7.5	6.9	6.9	1000 kg/ha DM
		median	9.6	10.3	9.8	9.3	9.2	1000 kg/ha DM
		upper quartile	10.7	10.9	10.7	10.7	10.7	1000 kg/ha DM
		max	12.2	12.2	12.2	12.2	12.2	1000 kg/ha DM
FD_{rc}	Y_{act}	min	5.0	7.5	4.8	3.4	3.3	1000 kg/ha DM
		lower quartile	8.5	9.6	8.4	7.6	7.8	1000 kg/ha DM
		median	10.2	10.6	10.1	9.8	9.9	1000 kg/ha DM
		upper quartile	10.9	11.1	10.9	10.8	10.8	1000 kg/ha DM
		max	12.4	12.4	12.4	12.4	12.4	1000 kg/ha DM
Ave	Y_{act}	min	7.4	8.0	7.8	7.8	7.7	1000 kg/ha DM
		lower quartile	9.6	9.8	9.8	9.8	9.7	1000 kg/ha DM
		median	10.5	10.7	10.7	10.7	10.7	1000 kg/ha DM
		upper quartile	11.1	11.2	11.1	11.2	11.1	1000 kg/ha DM
		max	12.6	12.6	12.6	12.6	12.6	1000 kg/ha DM

Crop models that apply the bucket approach consider the soil system as a reservoir with only percolation and no upward flow (an overview with a model comparison is provided by Ahuja et al, 2014). Such models do not account for soil moisture redistribution within and below the root zone. Similar to Guderle & Hildebrand (2015) our simulation results show that a detailed vertical flow improves predictions of root water uptake. Bucket models generally overestimate drought stress and groundwater recharge and subsequently underestimate crop yield. The irrigation demand will then be overestimated as well. The high predicted percolation may also result in overestimation of groundwater recharge (leaching). Groundwater depth is important, because it determines the distance that the capillary flux has to bridge to reach the root zone and should be accounted for in crop modelling.

In the ideal situation one should compare the bucket approach to the approach with full simulation of capillary rise and recirculation using independent data sets. However, the measured data sets were insufficient to calibrate and validate the soil and crop parameters in such detail that they could allow proper statistical evaluation of the two approaches. The calibration of both model approaches had too much freedom with the available data sets, which affect a reliable validation. Therefore, we used the measured data sets to illustrate that with common soil and crop input values, SWAP yielded realistic and plausible results for the crops considered in this study. Further, crop growth and soil water flow were simulated by SWAP with novel concepts. Therefore we may expect that the model itself can be used to show the effect on crop yield of different boundary conditions with respect to zero flux, recirculation and capillary rise.

Our hypothesis is that simulating the process of recirculation makes crop modelling more accurate. To demonstrate and support our hypothesis we added another case study. This is reported in section S5 of the supplementary material of Kroes et al., (2018). In this section we demonstrated the difference in soil water pressure head in the upper part of the root zone as caused by drying of the soil due to a lack of recirculating water in the hydrological condition (Figure 3.2a). This resulted in a lowering of average yields with 609 kg/ha (from 7132 to 7741 kg/ha DM, which is about 9% yield reduction due to recirculation. This supports the recommendation to use tools that simulate this process of recirculation in conditions where the vertical water fluxes across the root zone are relatively high. This will clearly be the case in delta regions where a precipitation excess is common.

A bucket approach generally underestimates water availability in the rooting zone and consequently overestimates drought stress (Boogaard et al., 2013). We suggest to generate additional relations for the contribution of recirculation and capillary rise to upward flow to the root zone. Such an approach has been used in AQUACROP to derive a relation between capillary rise and groundwater (Van Gaelen et al., 2017). Another approach is to calibrate the conceptual parameters of a bucket model with agro-hydrological models like SWAP as done by Romano et al. (2011).

Our analysis shows that soil properties and soil profile layering are important because differences in soil hydraulic properties influence vertical water flow. High upward flow values were found in loamy soils as was expected (Table 3.6, max row), but if water stress was high and upward flow was low the influence of soil type decreased and low upward flow values were found for loamy soils (Table 3.6, min row). Comparing the minimum yield values showed that there was a large difference between these soil types in free-drainage conditions with and without upward flow. This means that the storage capacity of loamy soils was larger than the one of sandy soils as could be expected. The yield variation between soil types in water stress conditions was large and illustrated the need for a proper soil schematization, especially in stress full hydrological conditions. As the influence of recirculation increased, the yield variation became less and the influence of soil type decreased. In situations without water stress the soil type was less important. In conditions where groundwater and capillary rise occurred, yield variation was hardly influenced by soil type.

Therefore, modelling concepts should consider dynamic interactions between soil water and crop growth. Crop models in general should consider recirculation of soil water and, especially in low-lying regions like deltas, groundwater dynamics should be considered as well.

Precipitation, soil texture and water table depth jointly affected the amount of groundwater recharge and time lag between water input and groundwater recharge (Ma et al., 2015). We quantified some of these issues, but several items remain, such as the impact of rooting depth on crop yield and transpiration. Also, soil and water management practises like ploughing and irrigation were not considered. Furthermore the rooting pattern needed a more detailed analysis; we applied an exponential decrease in root density and compensation of root uptake according to Jarvis (1989, 2011) but the macroscopic root water uptake concept was still simple and may require a more detailed analysis (Dos Santos et al. 2017). Another item we neglected is the preferential flow of water by the occurrence of non-capillary sized macropores (Bouma, 1981, Feddes et al., 1988), which is especially relevant in clay soils. Hysteresis of the water retention function was also not considered. An additional analysis of these issues is recommended, especially the impact of different rooting patterns on capillary rise should be addressed.

The impact of soil type on yield increased when environmental conditions became drier; situations without groundwater and without recirculation had less yield and higher yield variation than situations where groundwater influenced capillary rise.

3.5 Conclusions

We quantified the impact of upward flow on crop yields of grassland, maize and potatoes in layered Dutch soils. We compared situations with average groundwater levels to free-drainage conditions with and without upward flow. The largest impact of upward flow on crop yields was found when one compares situations with average groundwater levels with free-drainage conditions without upward flow. From these differences one may conclude that neglecting upward flow has a large impact on simulated yields and water balance calculations especially in regions where shallow groundwater occurs. The comparison showed long-term average yield reductions for grassland, maize and potatoes of respectively 26, 3 and 14 % (Table 3.5) or respectively 3.7, 0.3 and 1.5 ton DM per hectare (Table 3.4). Reduction of the percolation flux can be considerable; for grassland and potatoes the reduction was 17 and 46% (Table 3.5) or 63 and 34 mm (Table 3.4).

About half of the yield increases was caused by internal recirculation as occurs in free-drainage conditions and the other half was caused by an increased upward capillary flow from groundwater. Improved modelling should consider upward flow of soil water which will result in improved estimates of crop yield and percolation.

The quantification of recirculation for crop yield is a novelty, especially recirculation as part of upward flow and its relation to capillary rise and crop growth. Studies about the relation between soil hydrology and crop growth should quantify this upward flow because neglecting this flow and its impact implies neglecting yield changes which may have a large economic value in the Dutch delta and in other deltas in general. Another aspect, which could not be found in the referenced studies, is the lack of a quantification of the impact of recirculation on crop yields. Correct quantification of water fluxes contributes to the understanding of crop production and will help the institutions in charge of yield forecasting.

4. Drought, oxygen and salinity stress of agricultural crops in the Netherlands

For calculating the effects of hydrological measures on agricultural production in the Netherlands, a new comprehensive and climate proof method is being developed: WaterVision Agriculture (in Dutch: Waterwijzer Landbouw). End users have asked for a method that considers current and future climate, that can quantify the differences between years and also the effects of extreme weather events. Furthermore, they would like a method that considers current farm management and that can distinguish three different causes of crop yield reduction: drought, saline conditions or too wet conditions causing oxygen shortage in the root zone.

WaterVision Agriculture is based on the hydrological simulation model SWAP and the crop growth model WOFOST. SWAP simulates water transport in the unsaturated zone using meteorological data, boundary conditions (like groundwater level or drainage) and soil parameters. WOFOST simulates crop growth as a function of meteorological conditions and crop parameters. Using the combination of these process-based models we have derived a meta-model, i.e. a set of easily applicable simplified relations for assessing crop growth as a function of soil type and groundwater level. These relations are based on multiple model runs for at least 72 soil units and several possible groundwater regimes in the Netherlands. So far, we parameterized the model for the crops silage maize and grassland. For the assessment, the soil characteristics (soil water retention and hydraulic conductivity) are very important input parameters for all soil layers of these 72 soil units. These 72 soil units cover all soils in the Netherlands. This paper describes i) the setup and examples of application of the process-based model SWAP, ii) the development of the simplified relations based on this model and iii) how WaterVision Agriculture can be used by farmers, regional government, water boards and others to assess crop yield reduction as a function of groundwater characteristics or as a function of the salt concentration in the root zone for the various soil types.

Based on:

Hack-ten-Broeke, M. J. D., Kroes, J. G., Bartholomeus, R. P., Dam, J. C. Van, Wit, A. J. W. De, & Supit, I., Walvoort, D.J.J., Bakel, P. J.T. van, Ruijtenberg, R., 2016. Quantification of the impact of hydrology on agricultural production as a result of too dry, too wet or too saline conditions. SOIL, 2, 391-402.

4.1 Introduction

The United Nations formulated 17 Sustainable Development Goals (SDG) for the period 2015-2030 (http://sustainabledevelopment.un.org/focussdgs.html). Prominent goals are 'End hunger, achieve food security and improved nutrition and promote sustainable agriculture' (SDG 2) and 'Ensure availability and sustainable management for water and sanitation for all' (SDG 6). A key factor to achieve these goals is efficient use of water in agriculture. Currently, agriculture corresponds to 92% of the global fresh water use, exceeding by far the use by industry or households (Keesstra et al., 2016; Hoekstra & Mekonnen, 2012). We may release large amounts of water for extra food production or other pressing human or natural needs by increasing the water productivity in agriculture. However, this requires a profound knowledge of the effects of dry, wet, and saline conditions on growth and yield of agricultural crops.

The changing climate and weather conditions aggravate the need for reliable tools to assess crop yields in view of water stresses. Furthermore, increased water extraction from aquifers, deteriorating water quality and rationed water supply and irrigation services are some reasons for increased agricultural drought stress in arid and semi-arid regions. Over the past 60 years, soil water conditions have been generally wetting over the western hemisphere and drying over the eastern hemisphere, mostly in Africa, East Asia and Europe. Trends over the past 20 years indicate intensification of drying in northern China and southeast Australia, and switches from wetting to drying across much of North America, and southern South America, in part because of several large-scale and lengthy drought events (FAO, 2015a). Hotspots of pressures on soil water quantity and quality are e.g. the North China Plain, Australia, the southwestern United States and Middle East and North Africa (MENA) region. The World Bank took the initiative to generate an improved understanding of water issues in the MENA region, including associated marginal cost of water supply to meet the growing water need. Unmet demand for the entire MENA region, expressed as percentage of total demand, will increase from 16% currently to 37% in 2020-2030 and 51% in 2040-2050. A large number of measures were evaluated to meet the demand. The measure with the highest benefit/cost ratio is increase of agricultural water productivity, which requires proper attention for both drought and waterlogging risks during crop production (FutureWater, 2011).

Although salt-affected soils are widespread and an increasingly severe problem, no accurate recent statistics are available on their global extent (FAO, 2015a). The best available estimates suggest that about 412 million ha are affected by salinity and 618 million ha by sodicity (UNEP, 1992), but this figure does not distinguish areas where salinity and sodicity occur together. The Soil Map of the World (FAO/UNESCO, 1980) depicted a similar extent of 953 Mha affected by salinity (352 million ha) and sodicity (580 million ha). According to Jones et al. (2012) excess levels of salts in soils are believed to affect around 3.8 million ha in Europe. Naturally saline soils can be found in Spain, Hungary, Greece and Bulgaria. As an effect of irrigation artificially induced saline soils occur in Italy, Spain, Hungary, Greece, Portugal, France, Slovakia and Romania.

In the Netherlands salinization is not caused by accumulation of salts, but occurs in dry summers when crops are irrigated with salt-rich water from the ditches in the western part of the country near the sea. Excess rainfall in the subsequent winter season will normally wash away these excess salts from the root zone in these areas. Yet, these conditions negatively affect crop production.

Models on soil hydrology and crop growth evolve and both integrate and simulate not only the natural interactions but also the effect of farm management decisions. As a consequence, the currently used instruments for quantifying the effect of hydrological conditions in the root zone on agricultural production, for instance in the Netherlands, are no longer sufficient. Different groups of users, like water boards, provinces, drinking water companies and the National Department of Waterways and Public Works are therefore demanding an instrument that can determine crop yield effects as a result of drought, too wet or too saline conditions for both current and future climatic conditions. In order to be applicable to future climate conditions the system has to be based on process-based models; implicit incorporated expert knowledge cannot be extrapolated to unknown conditions. Other important specifications are that the results must be reproducible, that farm management is included, and that new insights can be added in the future.

WaterVision Agriculture should become that new instrument, based on linked model simulations for soil hydrology (SWAP) and crop growth (WOFOST) on the basis of different weather conditions and future climate. Plant growth is determined by the availability of solar radiation, CO_2, water, oxygen and soil nutrients. To achieve maximal growth, plants should take up sufficient water and oxygen from the soil. When the availability of water (too dry) or oxygen (too wet) in the root zone is insufficient, plants experience either drought or oxygen stress. When the salt concentration in soil water is too high, the water uptake will also decrease.

In WaterVision Agriculture the agrohydrological simulation model SWAP (van Dam et al., 2008) and the crop growth simulation model WOFOST (van Diepen et al., 1989) together form the core of the calculation of crop yields as a function of soil moisture conditions. We have linked these models on a daily basis to ensure realistic interaction between water in the root zone and crop growth. For instance: dynamic root growth as a function of weather and soil conditions instead of assuming a static rooting depth will influence predicted water uptake and yield reduction, caused by drought or oxygen stress. This will reduce predicted leaf area and this in turn will reduce transpiration prediction in a more realistic way than when assuming average annual crop development. Furthermore, the linkage of these models enables us to assess the effects of future climate on the interaction between hydrology and crop growth.

Based on these complex process-based models we want to develop an easily applicable method with direct relationships between groundwater characteristics and crop growth. For this we have derived a meta-model, which mimics the relevant processes involved and generates roughly the same model results as the SWAP model would do, using much less input data. This facilitates the practical application of scientific knowledge. In this paper we describe how this meta-model for WaterVision Agriculture was derived for grassland and silage maize and how it can be used. The ultimate project goal is to develop a comprehensive method for quantifying agricultural effects of hydrological change.

4.2 Materials and methods

First we describe the simulation models used for WaterVision Agriculture, followed by data used for model testing. Then we describe the production of the meta-model and the data required for this action.

4.2.1 SWAP

The SWAP (Soil-Water-Atmosphere-Plant; Van Dam et al., 2008) model is the core of WaterVision Agriculture and is a widely used model for the determination of the actual evapotranspiration as a function of meteorological data, combined with crop and soil data (Feddes & Raats, 2004). The model simulates water flow in the unsaturated and saturated upper part of the soil profile, where the interaction between groundwater and surface water is important. The model SWAP calculates the water transport, dissolved substances and soil temperature (Figure 4.1).

Water transport simulation is based on the Richards equation with a variable sink term for root water extraction. The potential transpiration rate depends on atmospheric conditions (air temperature, wind speed, solar radiation and air humidity) and plant characteristics (reflection coefficient, stomatal resistance, plant height and leaf area index). The potential root water extraction rate at a certain depth, $S_p(z)$ (d^{-1}), is considered to be proportional to the root length density and the potential transpiration rate:

$$S_p(z) = \frac{L_{root}(z)}{\int_{-D_{root}}^{0} L_{root}(z)\,dz} T_p \qquad 4.1$$

with L_{root} the root length density (cm^{-2}) and D_{root} the root layer thickness (cm).

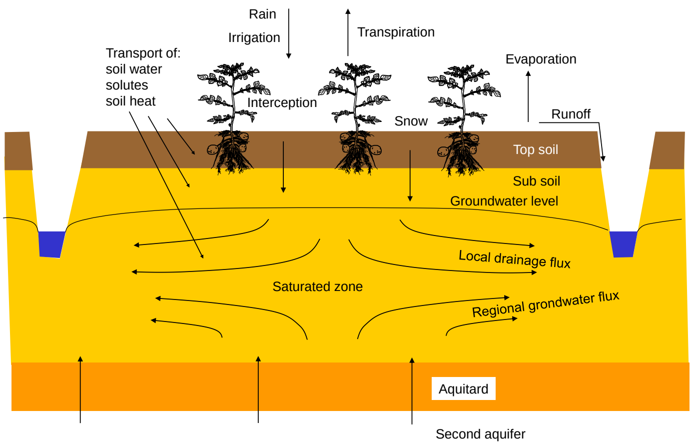

Figure 4.1 *Transport processes and modelling domain of SWAP.*

Stresses due to dry or wet conditions and/or high salinity concentrations may reduce $S_p(z)$. The drought stress in SWAP is described by the dry part of the reduction function proposed by Feddes et al. (1978), which is depicted in Fig. 4.2a. In the moderate pressure head range $h > h_3$ root water uptake is optimal. Below h_3 root water uptake linearly declines due to drought until zero at h_4 (wilting point). The critical pressure head h_3 increases for higher potential transpiration rates of T_p.

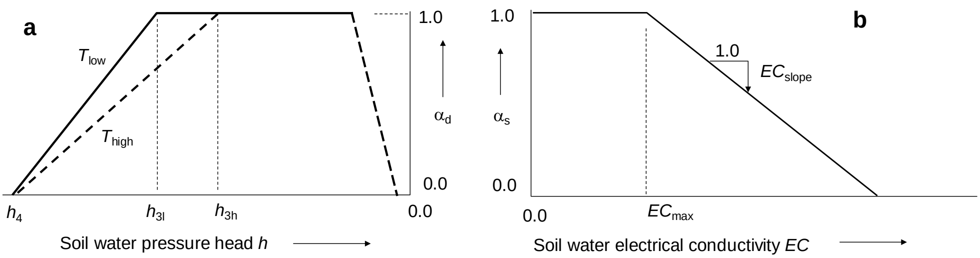

Figure 4.2 *a: Transpiration reduction factor α_s as function of soil water pressure head and b: Transpiration reduction factor α_s as function of soil water electrical conductivity.*

Oxygen stress, defined as daily respiration reduction (i.e. potential minus actual respiration) is calculated with the process-based method of Bartholomeus et al. (2008) for oxygen transport and consumption, which uses generally applied physiological and physical relationships to calculate both the oxygen demand of and the oxygen supply to plant roots (Figure 4. 3). Oxygen stress occurs when the actual root respiration is lower than the potential root respiration, i.e. when the oxygen supply cannot meet the oxygen demand of plant roots. Root respiration is determined by interacting respiratory (i.e. oxygen consuming) and diffusive (i.e. oxygen providing) processes in and to the soil. Plant roots respire at a potential rate under optimal soil aeration and thus non-limiting oxygen availability. This potential root respiration is in equilibrium with the oxygen demand of plant roots, which is determined by plant characteristics and soil temperature (Amthor, 2000) only. Upon increasingly wetter conditions, however, the gas-filled porosity of the soil decreases and oxygen availability becomes insufficient for potential root respiration. The method of Bartholomeus et al. (2008) is applied to all soil layers of SWAP, to account for layer-specific soil physical properties, moisture contents and temperatures.

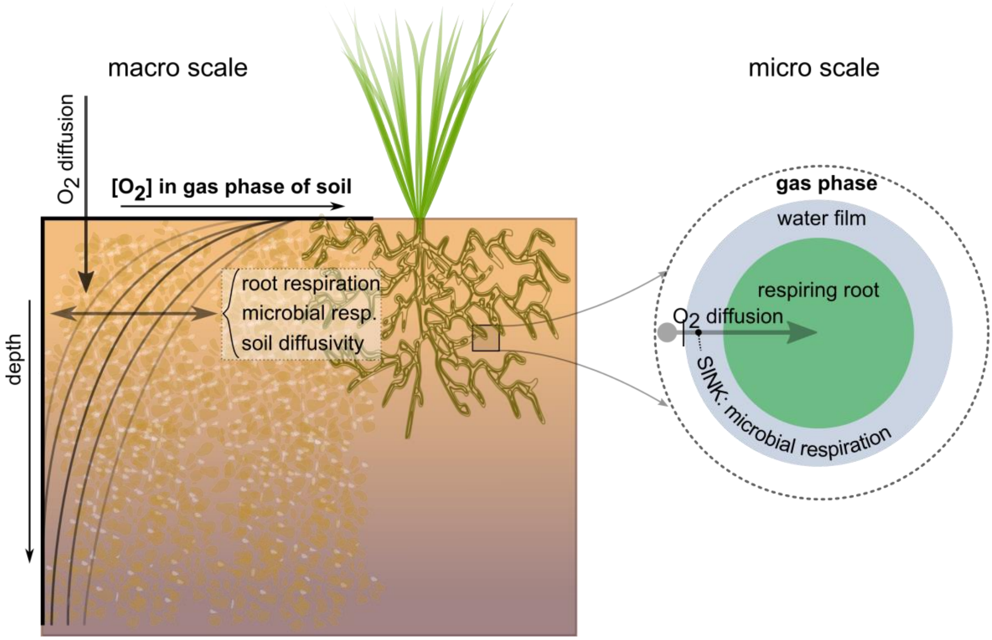

Figure 4.3 *Schematization of the oxygen module used to simulate daily respiration reduction. The model combines interacting physiological processes (i.e. root respiration and microbial respiration) and physical processes (i.e. macro-scale and micro-scale oxygen diffusion). Details of equations involved are given in Bartholomeus et al. (2008).*

SWAP uses the response function of Maas & Hoffman (1977) for salinity stress (Figure 4.2b). Below the critical concentration of EC_{max} (dS m^{-1}) no salinity stress is assumed. At salinity levels above EC_{max} the root water uptake declines with a constant slope of EC_{slope} (m dS^{-1}).

The actual root water flux, $S_a(z)$ (d^{-1}) is derived in SWAP by multiplication of the stress factors due to drought, oxygen and salt stress:

$$S_a(z) = \alpha_d(z)\,\alpha_o(z)\,\alpha_s(z)\,S_p(z) \qquad 4.2$$

where α_d (-),α_o (-) and α_s (-) are reduction factors due to drought, oxygen and salinity stress, respectively.

Integration of the actual root water flux over the root zone yields the actual transpiration rate T_a (cm d^{-1}):

$$T_a = \int_{-D_{root}}^{0} S_a(z)\,\partial z \qquad 4.3$$

Oster et al. (2012) compared five agrohydrological models (ENVIRO-GRO, HYDRUS, SALTMED, SWAP and UNSATCHEM) that simulate the effect of continually changing salinity and matric stress on crop yields. These models all assume a linear relation between relative crop transpiration and relative dry matter production. As input they used soil and climatic conditions of the San Joaquin Valley in California to simulate the yields of forage corn for various amounts of irrigation and water quality. The results show that SALTMED simulates lower relative yields than the other models for all combinations of irrigation amounts and water quality. For the other models, including SWAP, relative yield values were similar (within about 7% or less) for all irrigation amounts with electrical conductivity below 3 dS m^{-1}.

The SWAP user manual and corresponding website describe the theoretical background in detail as well as model input and applications (Kroes et al., 2009). SWAP is developed and maintained by Wageningen University and Research centre.

4.2.2 WOFOST

The underlying principles of WOFOST have been discussed by van Keulen & Wolf (1986). The initial version was developed by the Centre for World Food Studies in Wageningen (van Diepen et al., 1989). The basic processes simulated by WOFOST are phenological development, biomass growth, its partitioning over plant organs, root growth and the soil water balance. The most important external drivers are daily weather data. Other external drivers are initial soil and crop conditions. The most important internal driver is the leaf area index (LAI) which is the result of the leaf area dynamics controlled by photosynthesis, allocation of biomass to leaves, leaf age and development stage. In turn, LAI controls the daily rates of photosynthesis and evapotranspiration.

Currently, WOFOST as described by Boogaard et al. (1998) and Kroes et al. (2009) is able to simulate potential production as governed by atmospheric conditions and plant characteristics, and limited production due to water, oxygen and/or salinity stress. Figure 4.4 shows the processes and relations incorporated in WOFOST. The radiation energy absorbed by the canopy is a function of incoming radiation and crop leaf area. Using the absorbed radiation and taking into account photosynthetic leaf characteristics, the potential photosynthesis is calculated. The latter is reduced due to water, oxygen and/or salinity stress, as quantified by the relative transpiration (T_a/T_p), and yields the actual photosynthesis.

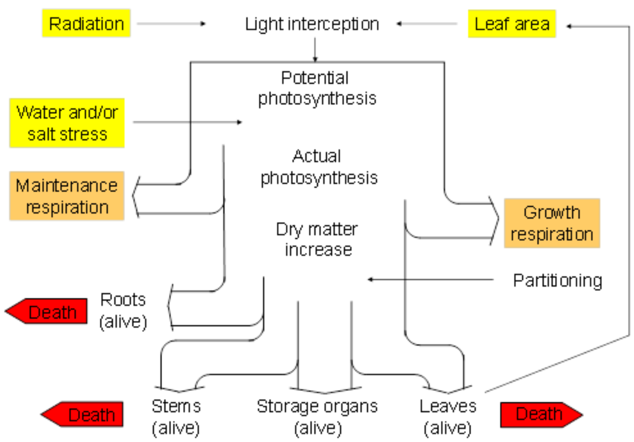

Figure 4.4 *Flow chart of crop growth processes included in WOFOST.*

Part of the carbohydrates (CH_2O) produced are used to provide energy for the maintenance of the living biomass (maintenance respiration). The remaining carbohydrates are converted into structural matter. In this conversion, some of the weight is lost as growth respiration. The dry matter produced is partitioned among roots, leaves, stems and storage organs. This is simulated using partitioning factors that are a function of the crop development stage. The amount partitioned to the leaves determines leaf area development and hence the capacity of light interception. This interaction of light interception and leaf area growth is a very important positive feedback in WOFOST. The dry weights of the various plant organs are predicted by integrating their growth rates over time. During the development of the crop, part of the living biomass dies due to senescence.

Changes in CO_2 directly affect photosynthesis. Rising levels of CO_2 will result in higher CO_2 uptake but also in closing of the stomata which then reduces CO_2 uptake. The net effect, however, is increase in crop growth. Kroes & Supit (2011) simulated grassland growth with SWAP for several climate scenarios and found that the increase of CO_2 concentration is more important than the predicted increase in temperature for both potential and actual yield.

In relation to climate change, heat stress may become just as important as drought stress for limiting crop production. It is well known that short episodes of high temperatures during the flowering period can drastically reduce the productivity of many field crops. However, the version of the WOFOST crop simulation model currently integrated in SWAP does not consider the direct impact of heat stress on grassland or maize productivity. For the moderate ocean climate of the Netherlands it is not expected that the direct impact of heat stress will lead to considerable yield losses in the coming decades (Teixeira et al., 2013). Furthermore, the amount of experimental data to parametrize such relationships is limited, which has hampered adding such algorithms to WOFOST. It is only recently within the framework of the AgMIP project that the systematic testing of models against dedicated heat stress experiments is taking place (Liu et al., 2016).

4.2.3 Linked models and model testing

We have linked both simulation models SWAP and WOFOST on a daily basis to ensure realistic interaction between water in the root zone and crop growth. This interaction allows for dynamic root growth as a function of weather and soil conditions, dynamic crop growth as a function of weather, crop characteristics and water availability, as well as a more realistic calculation of transpiration as a function of dynamic crop cover and leaf area simulations. Because both models are process-based, the linkage of these models enables to assess the effects of future climate on the interaction between hydrology and crop growth (Bartholomeus et al., 2012; Guisan & Zimmermann, 2000). In the current SWAP version 4, two production situations are simulated: the potential and water-limited situation. The potential crop production situation is defined by temperature, day length, solar radiation, atmospheric CO_2 content and crop characteristics. Optimum nutrient and moisture levels are assumed. The water-limited situation is defined by the abovementioned factors in combination with water or oxygen shortages and salinity excess.

For testing the performance of the combined SWAP model we needed data from experiments where both hydrological parameters and crop growth were measured and where no other limitations for crop growth occurred than water-related limitations, i.e. drought or too wet conditions. Kroes et al (2015) described how for this purpose three datasets remained for grassland and two datasets for silage maize. For grassland, data from a sandy soil (*Ruurlo*) and a peat soil (*Zegveld)* were available and for silage maize we had access to data from two different experiments on sandy soils, one of which in a relatively dry situation (*Cranendonck)* and the other with higher groundwater levels and a more loamy texture (*Dijkgraaf).* The Ruurlo data were available for 1980-1984 (two different fields) and the Zegveld data for 2003-2005. Then the Cranendonck data for silage maize were measured in the years 1974-1982 and the Dijkgraaf data were more recent (2007-2008).

The grassland composition of the experimental sites that were used for calibrating SWAP mainly consists of varieties of English ryegrass (*Lolium perenne*) which is the dominant type of grassland in the Netherlands and Western Europe. See also Schapendonk et al. (1998) for a description of similar sites that were used for the related LINGRA model.

The crop files for silage maize are based on the standard WOFOST crop files for maize that are calibrated for the Netherlands and Germany. These crop files are based on field trials executed in Belgium, United Kingdom and the Netherlands and on research executed in the framework of the MARS project (https://ec.europa.eu/jrc/en/mars). Typical heat sums for silage maize are 750 °C.d for emergence to flowering and 850 °C.d for the period from flowering to ripeness with a baseline temperature of 8 °C.

4.2.4 Meta-model

In WaterVision Agriculture, a meta-model is defined as a model derived from another more complex model. In the case of the linked SWAP model, the meta-model of SWAP must be able to simulate crop growth as if it was directly calculated using SWAP. A meta-model thus models the model results from another model (the original model).

A meta-model is usually a lot less complex than the original model, as it only describes a small part of the original model. In the case of WaterVision Agriculture we are looking for a meta-model that can reproduce the annual average crop yield reduction as a function of drought, too wet or too saline conditions. All other model results simulated by SWAP, like water content in the root zone or daily biomass production, will not be addressed by the meta-model.

The advantage of having a meta-model is that it requires a lower amount of input data than the original model. For SWAP simulations for instance we need a soil profile description with hydraulic characteristics and a large number of crop characteristics. The developed meta-model only requires soil type and crop type. This makes the meta-model easier to use and is requiring less computation time. So, based on the complex process-based model SWAP, easily applicable statistical relationships have been derived between groundwater characteristics and crop yield. These relationships, the meta-model, mimic the relevant processes involved and generate roughly the same model results as the SWAP model under the prescribed boundary conditions.

The meta-models we use for WaterVision Agriculture are so called random forest models (Breiman, 2001). Random forest models consist of many (usually several hundreds of) classifications or regression trees (CART-models). In our case, we have grown forests with regression trees. Each regression tree predicts crop growth given a set of explanatory variables like crop type, soil type, meteorological district, climate scenario, and several groundwater characteristics (e.g. mean groundwater level, mean highest groundwater level, mean lowest groundwater level, average spring groundwater level). Starting at the trunk of a regression tree, the data are recursively split into smaller parts based on simple rules like “IF soil type is sand THEN follow the left branch up the tree ELSE follow the right branch up the tree”. Each branch of the tree is split in turn until a terminal leaf is reached. This leaf contains a prediction (in our case crop growth). Instead of a single tree, random forests employ an entire ensemble of regression trees (forest of trees) to improve prediction accuracy by averaging the predictions of all individual regression trees.

4.2.5 Input data for deriving the meta-model

For deriving the meta-model, the SWAP model was run approximately 360,000 times. This number is a result of simulation runs for two crops (grassland and silage maize), 72 soil units of the Dutch soil physical database, five weather stations, current weather and four climate scenarios. As lower boundary condition for the SWAP model we used the $q_b(h)$-relation (Kroes et al., 2009). This relation assumes that the vertical flux (q_b) is related to groundwater level (h) according to:

$$q_b = A\,e^{(Bh)} + C \qquad 4.4$$

where *A, B* and *C* are coefficients. For deriving the meta-model we allow *A* to vary between -10 to 0, *B* between -0.10 to -0.01 and finally *C* is related to the boundary of drainage (z_d):

$$C = A\,e^{(B|z_d|)} \qquad 4.5$$

Where z_d can vary between 250 to 25 cm below soil surface.

Meteorological data were available from the Dutch meteorological institute KNMI. This involves daily global radiation, minimum and maximum temperature, air humidity, wind speed, rainfall amounts and duration for five weather stations in the Netherlands for 30-year periods. KNMI provides current weather data for the period 1981-2010 as well as projected data for 30-year periods around 2050 for different climate scenarios (KNMI, 2014). Crop yield reduction has been simulated for two crops: grassland and silage maize.

Soil profile information was obtained from the BOFEK 2012 data-base (Wösten et al., 2013a). It contains soil physical data for 72 representative soil profiles covering the whole of the Netherlands. For each combination of crop (2x), soil profile (72x), weather station (5x), and climate scenario (5x), 100 sets of bottom boundary conditions have been drawn by means of Latin hypercube sampling (Iman & Conover, 1982). This sampling method enforces an efficient coverage of the parameter space.

4.2.5.1 Soil physical data BOFEK

Soil water transport in the unsaturated zone is largely affected by the soil hydraulic characteristics (water retention curve pF and hydraulic conductivity $k(h)$). Such data are available for the whole of the Netherlands from the national soil physical database BOFEK (Wösten et al., 2013a). This database has 72 soil profiles with a vertical soil layer schematization that is characterised by 36 different soil physical relations for different soil layers.

Using these soil characteristics, tests were carried out with the SWAP model for these 72 soil physical units and different types of land use using different input options (tabular input of pF- and *K(h)*-functions or using Mualem-Van Genuchten-parameters (Mualem, 1976; Van Genuchten, 1980)). This resulted in small adjustments in the numerical solutions of the SWAP model to increase calculation speed and in small changes in the database to eliminate minor errors. An improved version of the database was made available on the website (http://www.wageningenur.nl/nl/show/Bodemfysische-Eenhedenkaart-BOFEK2012.htm).

4.3 Results

4.3.1 Test results linked SWAP-WOFOST

The linked SWAP-WOFOST model was evaluated using five experimental datasets with observations for grassland and silage maize (Table 4.1). These sets were selected because the experiments had a focus on stress due to drought or wet conditions; other stresses, like nutrient shortage or pests and diseases hardly occurred at these experiments which allowed an evaluation of the SWAP-WOFOST model for water stress situations. The experimental data of these five sets originated from a range of studies, performed in different years and different parts of the Netherlands. For all these sets, simulation studies have been performed before with the SWAP model and we assume calibration has taken place. The SWAP-related input data and parameters that were used before have also been used now. A detailed analysis of the hydrological conditions and crop parameterisation is given by Kroes et al. (2015); in this paragraph a summary of the crop yield results is presented because we regard crop production as the most relevant indicator for the performance of the linked SWAP-WOFOST model.

Table 4.1 *Testsets for SWAP-WOFOST.*

Nr	*Crop*	*Location*	*Period*	*Soil type*	*Reference*
1	*Grassland*	*Ruurlo16*	*1980-1984*	*Cambic Podzol*	*Kroes & Supit (2011)*
2	*Grassland*	*Ruurlo48*	*1980-1984*	*Cambic Podzol*	*Kroes & Supit (2011)*
3	*Grassland*	*Zegveld03*	*2003-2005*	*Terric Histosol*	*Hendriks et al. (2011)*
4	*Silage maize*	*Cranendonck16*	*1974-1982*	*Cumulic Anthrosol*	*Schröder (1985)*
5	*Silage maize*	*Dijkgraaf*	*2007-2008*	*Umbric Gleysol*	*Elbers et al. (2009)*

For the grassland sites, the predicted yields of the different grassland cuts were compared with the observed values (Figure 4.5). The mean error between annual observed and simulated yield for the three grassland sites is respectively 2.8, 2.7 and 0.2 t ha^{-1} dry matter. We think that the agreement between observations and simulations is rather satisfactory. Annual simulated grassland yields were generally higher than the observed annual yields. That is especially true for the year 1982 at the two Ruurlo experiments, where actual and observed results of the years 1980, 1981 and 1984 compare well and the results of the year 1982 shows the largest difference between simulated and observed. A more detailed analysis explained this overestimation as an effect of simplifications in model approaches and also the impact of the cold spring seems to be simulated not accurately enough. At the Ruurlo site only drought stress occurs; there is hardly ever excess of water in this sandy soil. At the organic soils of Zegveld, both too dry and too wet conditions may occur. Especially 2003 was a dry year.

The two sites with experimental data for silage maize were used for evaluating SWAP-WOFOST by comparing the simulated and observed total aboveground biomass at harvest (Figure 4.6). The mean error between annual observed and simulated yield shows an underestimation of respectively 2.8 and 3.6 t ha^{-1} dry matter. We regarded the simulated yields in the different years at the Cranendonck site and the single experiment at Dijkgraaf as satisfactory given the uncertainties and simplifications of the model approaches. At Cranendonck, drought stress is the main factor influencing productivity. At Dijkgraaf, both too dry and too wet conditions may occur, but for this site only data for one year were available. Both types of stress occurred in that year with a dry spring and relatively wet summer months. The effects of drought stress in the extremely dry year of 1976 at Cranendonck were simulated relatively well, which may be regarded as an indicator of the ability of the combination of SWAP and WOFOST to enable the simulation of extreme events.

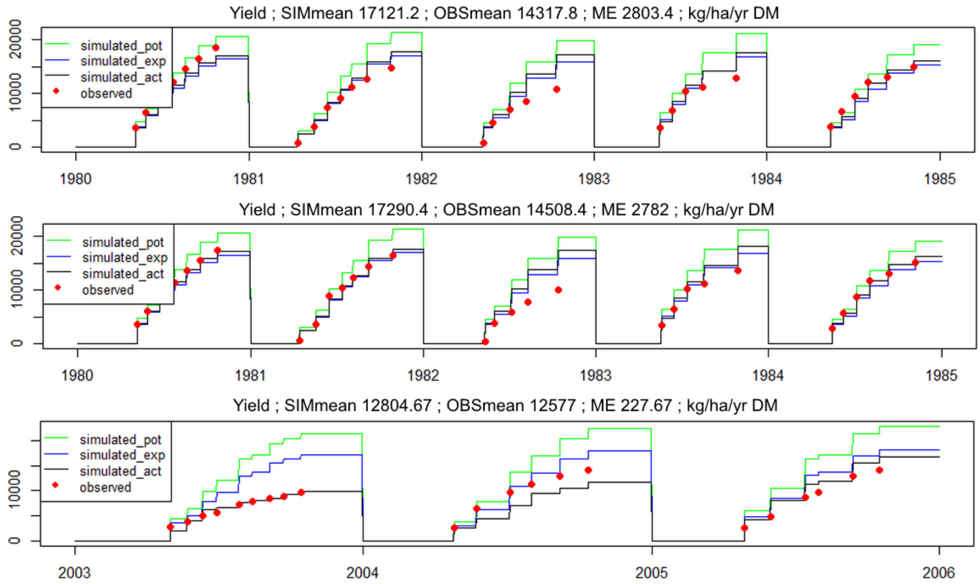

Figure 4.5 *Results of simulated and observed yields of grassland for three locations: Ruurlo16 (upper figure), Ruurlo48 (middle figure), and Zegveld03 (lower figure). The green lines correspond to simulated potential yield; blue to the simulated exploitable yield; black to the simulated actual yield. The red dots indicate the observed yield of a grassland cut. SIMmean, OBSmean and ME are annual mean values for simulated actual yield, observed yield and the difference (maximum error ME), respectively.*

4.3.2 Examples for the application of SWAP

SWAP generates insight in the variation in relative transpiration and in crop yield on different time scales and for different climate scenarios, each relevant for different user questions. Figure 4.7 (A and C) shows annual variation in transpiration reduction due to either too dry or too wet conditions for both current (A) and future climatic conditions (C). Based on these simulations climate average (30-year) values can be derived, which are relevant for quantifying the direction of changes as related to long-term changes in climate conditions or in water management. Figure 4.7 A illustrates that the climate-average drought stress can be relatively minor, but that peaks in stress can occur in specific years, like in the year 2003. SWAP allows to analyse such years in more detail, with a focus on extreme events (Figure 4.7 B). Due to climate change, drought stress may increase significantly (Figure 4.7 C and D), while oxygen stress shows only a minor increase. Figure 4.7 D also shows that even in a very dry year, an abundant rainfall event may occur in some period of the year which also results in reduced crop growth. The different levels of application serve different needs, from policy making (long-term averages) to operational water management (daily values).

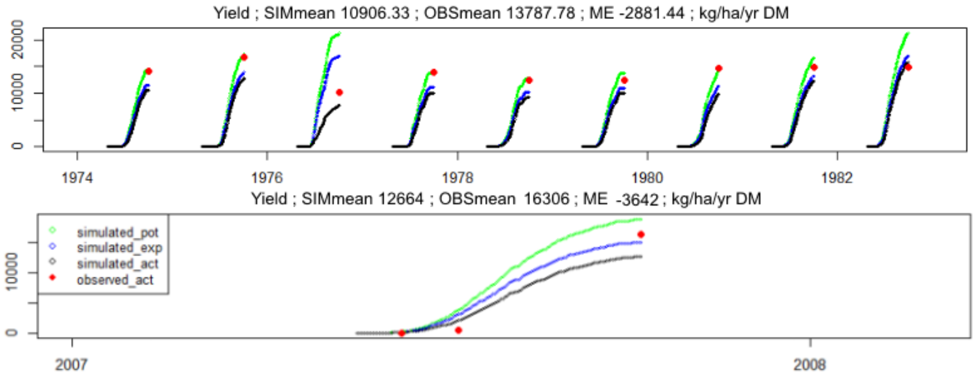

Figure 4.6 *Results of simulated and observed yields of silage maize: Cranendonck 16 (upper figure) and Dijkgraaf (lower figure). The green lines correspond to the simulated potential yield; blue to the simulated exploitable yield; black to the simulated actual yield; red dots indicate the observed dry matter yield. SIMmean, OBSmean and ME are annual mean values for simulated actual yield, observed yield and the difference (maximum error ME).*

4.3.3 Examples of the meta-model WaterVision Agriculture

Figure 4.8 shows examples of meta-model results for 9 different soil types of the BOFEK database, for grassland and the current climate in De Bilt, with the mean highest groundwater level (MHG) on the y-axis and the mean lowest groundwater level (MLG) on the x-axis. Red dots represent crop yield reduction due to drought and blue dots are the result of situations with too wet conditions for crop growth. The size of the dots indicates the average annual amount of crop yield reduction.

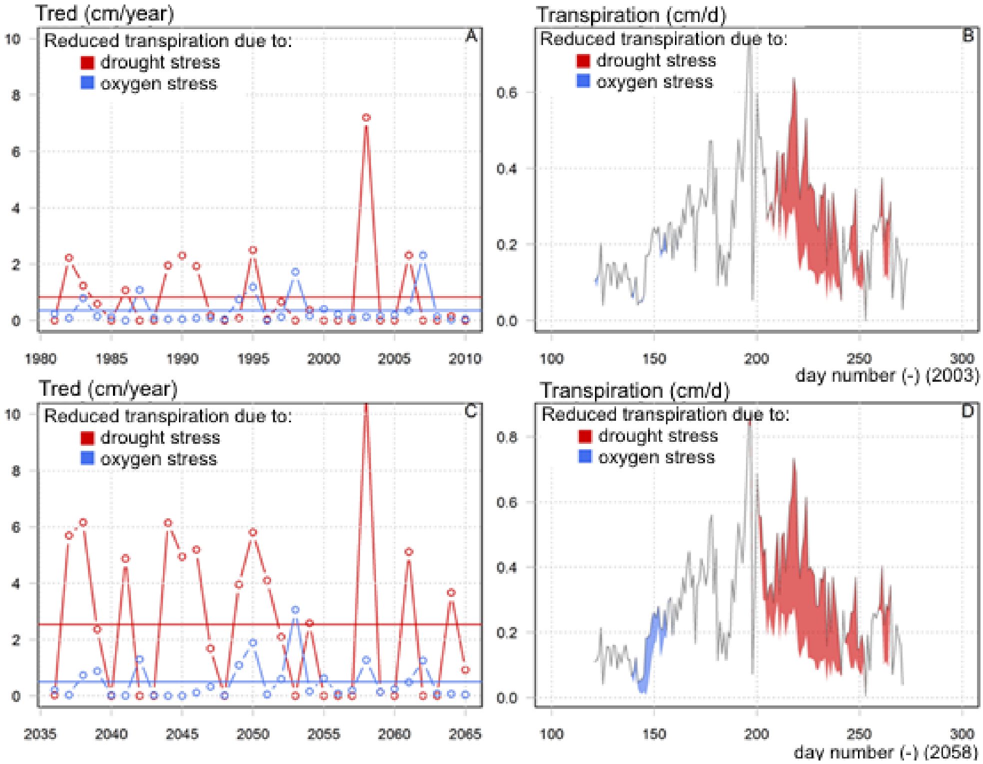

Figure 4.7 *SWAP simulations of transpiration reduction (Tred) due to drought stress and oxygen stress for a silage maize crop on a fictitious sandy soil. The panels show both the different causes of stress and the different time scales the model can be used for. A: yearly cumulative transpiration reduction due to drought stress and oxygen stress and the climate-average (30-year) stresses (horizontal lines). B: potential and actual transpiration for 2003. The red and blue polygons, representing the difference between potential and actual transpiration, demonstrate the period and level of drought stress and oxygen stress. C-D: same as A-B, but for future climate conditions instead of current climate, using climate scenario Wh of the KNMI, representing 2°C global temperature rise and a high value for change in air circulation patterns (KNMI, 2014).*

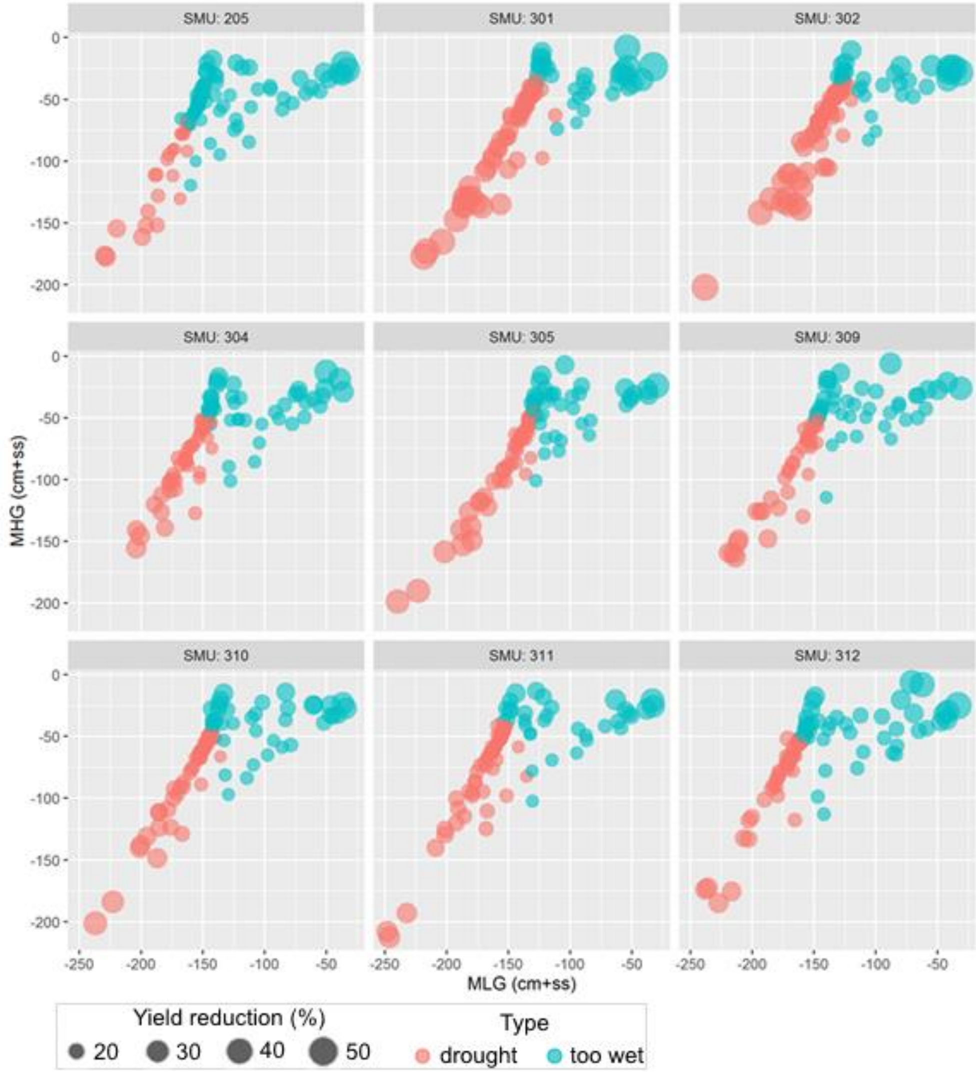

__Figure 4.8__ Meta-model WaterVision Agriculture: examples for 9 different soil types of the BOFEK database (SMU=Soil Mapping Unit) for grassland and the current climate in De Bilt, with the mean highest groundwater level (MHG) on the y-axis and the mean lowest groundwater level (MLG) on the x-axis. Red dots represent crop yield reduction due to drought and blue dots represent crop yield reduction as a result of too wet conditions (oxygen stress).

An important goal of the WaterVision Agriculture project is enabling the application of the meta-model to any area in the Netherlands. As an example we applied the meta-model to an area in the south of the Netherlands (Vierlingsbeek) with mainly sandy soils. The location of this area is shown in Figure 4.9. This example area is an area where drinking water is pumped up and the influenced area is considered to be almost circular. Figure 4.10 shows the effect on crop yield resulting from the lowering of the groundwater levels as annual average percentage (as the sum of dry and wet conditions). The differences on the map are mainly caused by differences in soil type. The changes in crop growth are largest near the drinking water well.

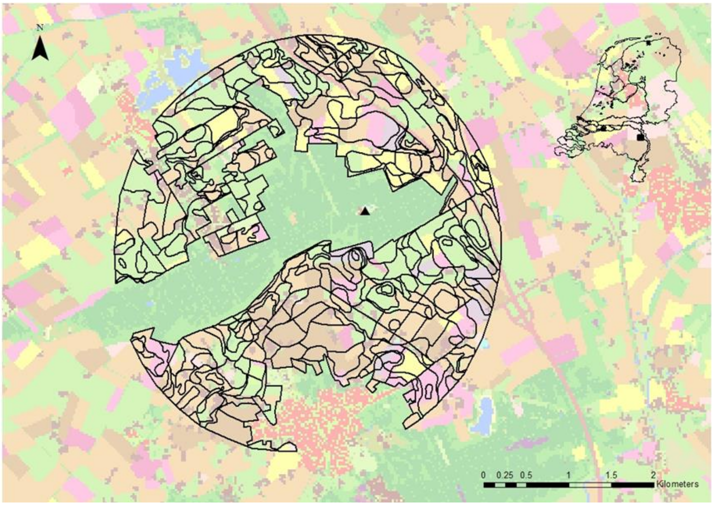

Figure 4.9 *Location and topography of the Vierlingsbeek area in the Netherlands. The black triangle is the location of the drinking water well.*

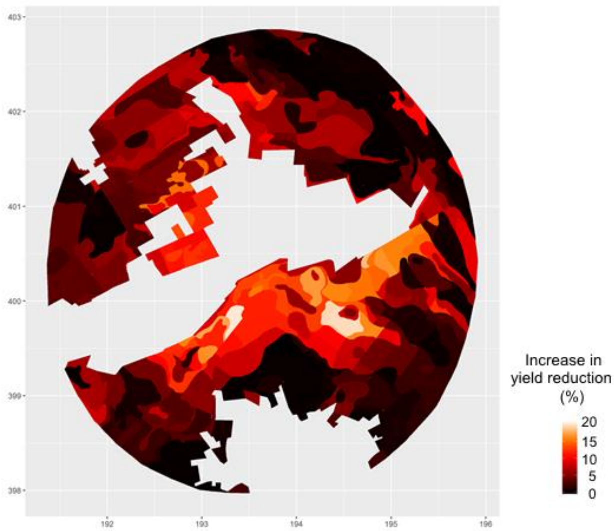

Figure 4.10 *Application of the meta-model WaterVision Agriculture to the Vierlingsbeek area in the Netherlands. The effect on crop yield resulting from the lowering of the groundwater levels is shown as annual average increase in yield reduction compared to a situation without changes in groundwater levels.*

4.4 Discussion

The project Watervision Agriculture aims at a climate-proof instrument that can determine crop yield effects as a result of drought, too wet or too saline conditions, based on process-based models. Furthermore, the instrument should be applicable to various crop and water management situations as required by the end users. It can be used at field level and for evaluating crop yield as a function of current weather as well as of extreme weather events as described in section 4.3.2 and the meta-model allows a quick application on regional level showing long term effects of hydrological measures in section 4.3.3. With these different components of WaterVision Agriculture we have made a toolbox for different applications as requested by the end users.

In the next phase of the project similar work for other crops than grassland and silage maize is scheduled as well as a method to add farm economic effects to the evaluation tools. Furthermore, in the coming year the indirect effects of drought and oxygen stress will be addressed. This includes for instance the effect of too wet conditions for harvest, resulting in yield losses or damage to the soil structure when harvest takes place anyway. Indirect effects are also related to crop quality or postponing grazing or cutting of grassland. It is expected that new information will become available on salt tolerance levels of different crops. This information should then also be included in WaterVision Agriculture. For the future some issues remain that may get attention in a following project. Many users would like to include nutrient effects on crops, which also allows an evaluation of fertilization and groundwater quality.

5. Groundwater salinity and its impact on grassland production in the Netherlands

The coupled SWAP-WOFOST model was used to study effects of increasing salinity of groundwater, drought and water excess on grass production in the Netherlands. WOFOST simulates crop growth and SWAP simulates transport of water, solutes and heat in the vadose zone. The model was tested using several datasets from field experiments. We applied the models at regional scale where we quantified the impact of various groundwater salinity levels on grass growth and production using historical weather data (1971-2000). The salt concentrations in the subsoil were derived from the National Hydrological Instrument. The results show that salinity effects on grass production are limited. In wet years the excess rainfall will infiltrate the soil and reduce salt water seepage. In a next step we used future weather data for the year 2050 derived from three Global Circulation Models. From each model we used data from two CO_2 emission scenarios. As expected higher temperatures increased drought stress, however, the production reduction due to salt water in the root zone is limited. Salt stress mainly occurred when irrigation was applied with saline water. The increased CO_2 concentration in combination with the limited drought stress resulted in increasing simulated actual and potential yields. Overall conclusion for grassland in the Netherlands is: drought stress is stronger than stress caused by water excess which on its turn is stronger than salinity stress. Future water demand for irrigation may increase by 11 – 19 % and result in drought stress if irrigation water of sufficient quality is limited or not available

Based on:

Kroes, J. G. & Supit, I., 2011. Impact analysis of drought, water excess and salinity on grass production in the Netherlands using historical and future climate data. Agriculture, Ecosystems & Environment, 144(1), 370–381.

5.1 Introduction

Grassland is the most common land use type in the Netherlands. About 40% of the agricultural land is occupied by grass. Of the grassland about 90% is permanent, the remaining 10% is temporary grassland. Grass is the most common forage crop grown in the Netherlands (Aarts, 2003). Because of the economic importance, the functioning and structure of grass ecosystems have been studied intensively the last decades in temperate regions (Clark et al., 1997). Due to their large extent grasslands play a major role in environmental issues that are related to agricultural activities, climate change, water balance studies, etc. (Conijn, 2005).

The IPCC (2007) predicts large climate changes which may have large implications on water resources and consequently as well as on water management and agricultural production. Climate change causes a chain of problems which require integrated approaches. In coastal areas for example, sea level rise will exacerbate water resource constraints due to increased salinization of groundwater supplies (IPCC, 2007).

Water management in the Netherlands is a dynamic process with shallow water tables and a strong interaction between groundwater and surface water. An integrated approach is required to model yield-limiting factors, which are likely to have a large impact on overall crop production (Hansen et al., 2006). Van den Hurk et al. (2006) predicted a climate change for the Netherlands that will cause a rising temperature, increasing potential evaporation and precipitation during winter. There is little doubt about the fact that these changes will require land use and water management adaptations on short and long term.

In this study we investigate the impact of future climate on the grass production in the Netherlands accounting for an increased CO_2 concentration, rising temperatures as well as groundwater salinization. We compare future climate impact with results using recent weather (1971-2000). In this way we quantify the expected climate change effects on the grass production.

Impact analyses are preferably carried out using a hydrological model that has a physical base and responds to strong fluctuations of shallow groundwater levels which will occur and have a large impact on vertical fluxes in the vadose zone. We selected the SWAP model (Kroes et al., 2000; Van Dam et al., 2008) for its solid physical base and its stable numerical solutions of the Richards equation for water flow and the convection-dispersion equation for solute flow. WOFOST (van Keulen & Wolf, 1986; Van Diepen et al., 1989; Supit et al., 1994; Boogaard et al., 1998) was chosen because it includes the photosynthesis approach which allows to introduce increased CO_2 concentrations without making large changes to the modelled system.

The SWAP and WOFOST models were coupled in the late 90's (Van Dam et al., 1997). Information between the soil and crop growth components is exchanged on a daily base. SWAP-WOFOST was applied in several studies (e.g. Singh et al., 2006, Bessembinder et al., 2005) but never for grass in the Netherlands. In this study we established the SWAP-WOFOST parameters for grass using experimental data from three sites in the Netherlands. Subsequently these parameters were used to simulate grass yields for the areas in the Netherlands that have been classified as grass, using weather data from the period 1971-2000. The results were used to assess drought, water excess and salt stress resulting from the present climate. In a next step the impact of future climate on grass yields was analysed using 6 climate scenarios for the year 2050. To investigate the influence of the increased CO_2 concentration on grass growth and production, two scenarios were simulated, one where the increased CO_2 concentration is accounted for, another one without increase.

5.2 Materials and methods

5.2.1 Model

This study uses the agrohydrological model SWAP (Soil-Water-Plant-Atmosphere) and the crop growth submodel WOFOST (WOrld FOod STudies). Both models are coupled and exchange information with a time-interval of one day. SWAP 3.2.26 (Van Dam et al., 2008, Kroes et al., 2009) was applied to simulate water and salt flow in the unsaturated and saturated upper part of the soil system. Water flow is described with the Richards equation, including sink terms for root water extraction and sink/source terms for lateral exchange with surface water. The Mualem-Van Genuchten relations are applied to describe the soil hydraulic functions. The top boundary is located above the canopy and daily meteorological data were input to the model. The Penman-Monteith equation (Allen et al., 1998) was used to calculate the potential evapotranspiration. The bottom boundary interacts with a regional groundwater system using data supplied by a separate regional hydrological model. The lateral boundary interacts with surface water systems through drainage and infiltration. A simplified, weir controlled, water balance of the surface water system is simulated which resulted in surface water levels that in turn were imposed to interact with groundwater levels. SWAP describes the salt flow with the convection-dispersion equation; water and salinity stress are related to root water uptake according to Feddes et al. (1978) and Maas & Hoffman (1977). The actual root water flux is achieved by multiplying the potential root water uptake with stress factors for water and salinity stress:

$$S_a = \alpha_{rd}\, \alpha_{rw}\, \alpha_{rs}\, S_p \qquad (5.1)$$

Where: S_a and S_p are the actual and potential root water uptake for each model compartment (d^{-1}), α_{rd} (-), α_{rw} (-), α_{rs} (-) are the reduction or stress factors for the impact of drought, water excess and salinity. Integration of S_a over the root layer yielded the actual transpiration rate T_a. SWAP has been tested in many locations with different boundary conditions. A recent overview has been given by Van Dam et al. (2008) and is available at http://www.swap.alterra.nl.

The WOFOST principles have been discussed by Van Keulen & Wolf (1986) and Van Diepen et al. (1989). It has been modified and applied for many purposes (e.g. De Koning & Van Diepen, 1992; Rötter, 1993; Supit, 1997). The crop growth submodel calculates daily crop photosynthesis on the basis of the radiation absorbed by the canopy and water and/or salinity stress. After substraction of the maintenance respiration, the remainder of the photosynthesis products are partitioned over leaves, stems, roots and reproductive organs. For the grass crop constant partitioning factors are assumed. The dry weights of the plant organs are obtained by integrating the differences between growth and senescence rates. WOFOST, as incorporated in SWAP, accounts for different environmental stress factors. The effects of water and salinity stress are accounted for by the hydrological part of the model (see eq 1). Additional growth reduction may result from influence of temperatures, deviating CO_2 levels, a lack of nutrients or unknown residual stress caused by diseases, pests and/or weeds. Taking all these separate environmental stress factors into account, the daily gross assimilation growth rate (A_{gross} in kg ha^{-1} d^{-1} dry matter) is determined as follows:

$$A_{gross} = f_{Trel}\; f_{CFET}\; f_{nut}\; f_{res}\; A_p \qquad (5.2)$$

Where: f_{Trel} is a transpiration reduction factor (-) determined by salinity, drought and water excess (eq. 1), f_{CFET} is a correction factor for potential transpiration introduced to account for changing atmospheric CO_2 levels that influence stomata and water vapour exchange (-), f_{nutl} is the influence of nutrients (-), f_{res} is the residual factor for unknown environmental impact (see next section) (-), A_p is the potential gross assimilation growth rate (kg ha^{-1} d^{-1} dry matter). In this study we simulate two situations, one where no stress occurs: the potential situation. In the second situation the abovementioned stress factors occur, which will be referred to as the actual situation.

5.2.2 Model parameters

5.2.2.1 Field experiments

The SWAP-WOFOST model was tested for three grassland sites in the Netherlands. Note that grass is the predominant land use type in the Netherlands. Model results were compared to observed grass yields. Figure 5.1 gives the location of the fields; the main field characteristics are summarized in Table 5.1. All three experiments were carried out on permanent grass fields and had several cuttings per year. The observations included yields of different cutting regimes and different fertilizer levels.

Table 5.1 *Main characteristics of the grassland field experiments used to test the model.*

Characteristic	*Ruurlo*	*Zegveld*	*Cranendonck*
Soil type	*Sandy loam*	*Peat*	*Sandy*
Monitoring period	*1980-1985*	*2003-2006*	*1997-2002*
Grassland management	*permanent grassland; 3 fertilizer levels; 5-7 cuttings per year*	*permanent grassland; 5-8 cuttings per year*	*permanent grassland; 5-8 cuttings per year*
Groundwater levels (m-soil)	*1.5 – 0.5*	*0.8 – 0.2*	*1.5 – 0.5*
Reference	*Snijders et al., 1987*	*Van den Akker et al., 2007*	*Van der Salm et al., 2000*

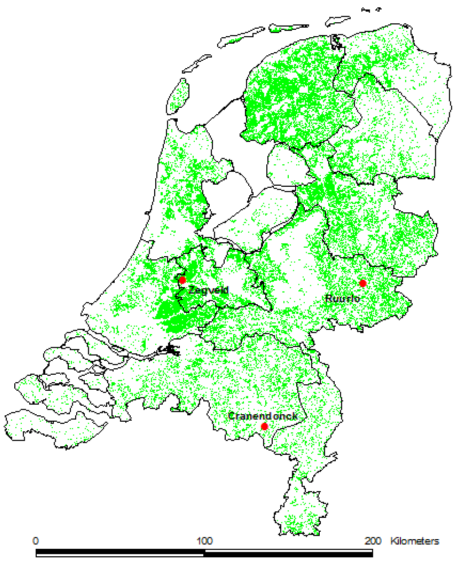

Figure 5.1 *Location of the three grassland field experiments (Ruurlo, Zegveld and Cranendonck) and spatial distribution of grassland in the Netherlands (green).*

The Ruurlo field experiment was carried out in the years 1980-1985 on small field plots (37.5 m^2) without grazing. The plots received various fertilizer treatments. The Zegveld field experiment was recently (2003-2006) carried out on peat soils with very shallow water tables. The field experiment in Cranendonck was carried out during the years 1977-2002. Some of the experiments lasted for a longer period, but we selected those years for which at least yields and groundwater levels were monitored. Meteorological data were taken from local observations or from the nearest weather station which supplied sufficient data to apply the Penman-Monteith equation. Crop growth and yields were simulated for all fields. Cutting and regrowth were accounted for.

One Ruurlo field experiment was assumed to have no nutrient stress (see Table 5.2, fertilizer treatment of 600 kg ha^{-1} yr^{-1} N) and was used to determine the residual stress factor (f_{res}). An automatic calibration was performed using the PEST package (Doherty, 2004) with the yearly yields as target values and the residual stress factor as calibration parameter. All 4 other field experiments were used to validate the residual stress factor.

To account for nutrient stress, a nutrient reduction factor f_{nut} was derived from relations between nitrogen supply and yield given by Van der Meer et al. (1986). This resulted in values of 0.7 and 0.8 for the fields with low fertilizer treatments (see Table 5.2). Field experiments were simulated with observed groundwater levels as lower boundary condition (see Figure 5.2).

Table 5.2 Factors for nutrient stress.

Field experiment	*Fertilizer treatment (kg ha^{-1} yr^{-1} N)*	*Nutrient stress factor f_{nut} (-)*
Ruurlo low fertilizer	*200*	*0.7*
Ruurlo high fertilizer	*600*	*1.0*
Ruurlo very high fertilizer	*800*	*1.0*
Zegveld	*300*	*0.8*
Cranendonck	*200*	*0.7*

5.2.2.2 Regional scale experiment

In previous studies (Wolf et al., 2003 and Tiktak et al., 2002) hydrological rate and state variables were generated for 6405 units, which were characterized by a unique combination of soil type, land use, average groundwater level, flux at the lower boundary, geohydrological structure of deeper soil layers, classes of drainage resistances, and chemical status of the subsoil (Kroes et al., 2002; Kroon et al., 2001).

The top boundary of each unit is the soil surface where rain water, snow melt, and irrigation infiltrate into the soil and water is lost by transpiration, interception, soil evaporation and surface runoff. The lateral boundary is used to simulate the interaction (drainage or infiltration) with surface water systems. The bottom boundary is situated in a saturated soil layer and determines the interaction with a regional groundwater system (Van Bakel et al., 2008). Results of the deep groundwater NAGROM model were used as lower boundary for SWAP.

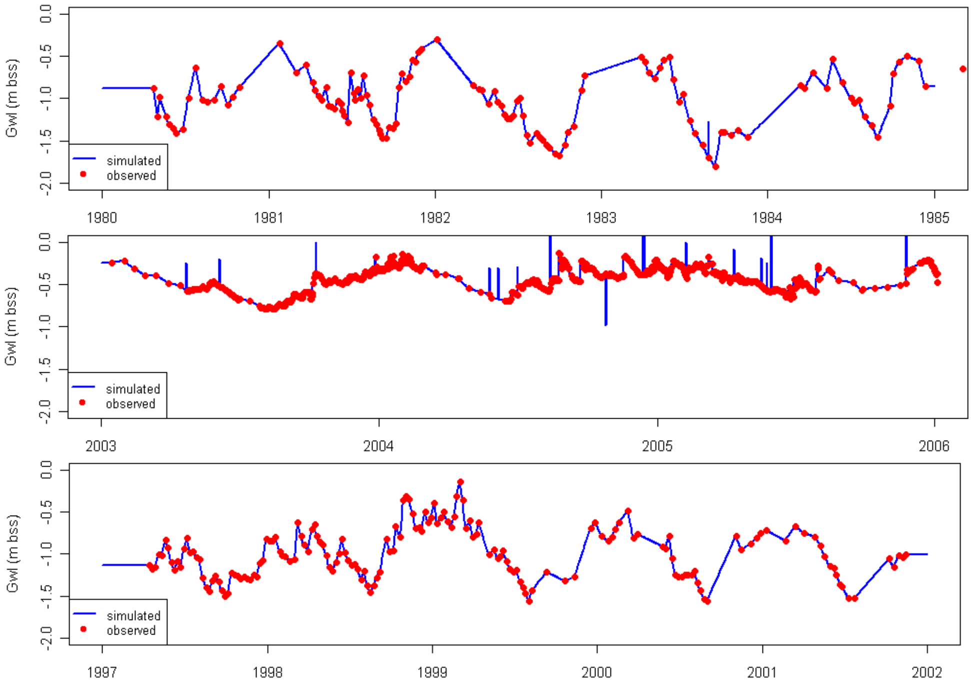

Figure 5.2 *Observed (dots) and simulated (lines) groundwater levels (m below soil surface) of three grassland field experiments Ruurlo (top), Zegveld (middle) and Cranendonck (bottom).*

Our experiment used data from 2121 grassland units, covering about 40% of the agricultural land use (see Figure 5.1). The grassland submodel includes the following adaptations:

a) The Penman-Monteith equation for potential evaporation was applied using an extended dataset from Sluijter & Nellestijn (2002), which includes a climate serie of 30 years.
b) The parameterization of the grass crop parameters (Kroes et al., 2009) was taken from the field experiments. We assumed that mowing took place when the grass dry matter production reached 4.2 t ha^{-1}.
c) Salt entered the soil profile as chloride originating from three different sources: i) the lower boundary, ii) irrigation water and iii) infiltrated from surface water;
d) Chloride concentrations for the lower boundary of the soil profiles were derived from simulations results with the National Hydrological Instrument (see Figure 5.3; De Lange et al., 2014) at the bottom of the Holocene aquitard (Oude Essink et al., 2005). The bottom of the Holocene aquitard varies from a depth of 20 m below sea

level near the coast to a depth of 35 m above sea level in eastern and southern parts of the Netherlands.

e) Chloride concentration levels of the irrigation and surface water are the same as the concentrations for the lower boundary.

f) The conversion from chloride concentration to electrical conductivity (EC_{sat} in dS m^{-1}) was described by:

$$EC_{sat} = a\left[c_{act}\frac{\theta_{act}}{f\theta_{sat}}\right]^{b} \quad (5.3)$$

Where c_{act} is the solute concentration in the liquid phase at saturated volumic soil moisture content (mg cm^{-3}), θ_{act} is the actual volumic soil water content (cm^3 cm^{-3}), θ_{sat} is the saturated volumic soil moisture content (cm^3 cm^{-3}) and *a*, *b* and *f* are empirical constants. In this study we used *a* = 4.21, *b* = 0.763 and *f* = 1.7

g) The parameters values for salinity stress were based on Maas & Hoffman (1977) and Maas (1990);

h) A long-term initialisation (30 years) was carried out to obtain equilibrium salinity conditions in the soil profile.

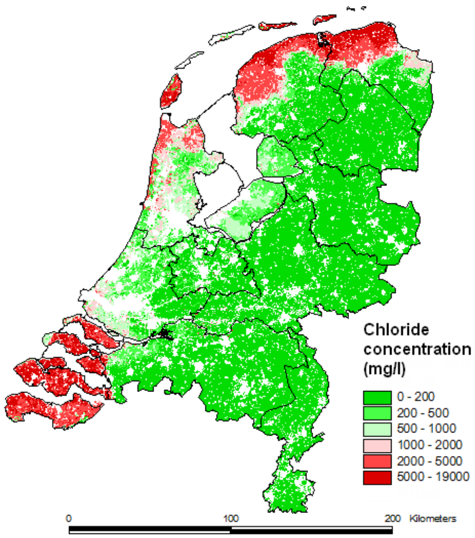

Figure 5.3 *Spatial distribution of salinity (Cl^-) concentrations (mg l^{-1}) in the subsoil of the Netherlands.*

The areas equipped for irrigation were taken from regional inventories. Within these areas irrigation events were simulated when a critical pressure head of -316 cm was reached at 20 cm depth. A supply of irrigation water was simulated to reach field capacity. Furthermore, we assumed that irrigation water is taken from the surface water.

5.2.2.3 Regional scale scenarios input

To assess climate change impacts on grass production, salt and water stress we used the IPCC AR4 Global Circulation Model (GCM) results. Note that the range of these results is large and regionally dependent (NRC 2003; Giorgi & Bi 2005). Therefore we used data from three GCMs. From each GCM we used the A2 and the B1 scenario from the Special Report on Emissions Scenarios (Nakićenović et al., 2000). Each scenario represents different mixes of changes in population, economic output, land use, and energy and technology use, among others, but can be generally characterized by maximum atmospheric CO_2 concentrations (Sheffield & Wood, 2007). A2 represents the worst-case scenario. As a result of continuously increasing global population and limited technological change, CO_2 emissions in the period 2000–2099 are predicted to increase 4-5 times and, as a result, the atmospheric CO_2 concentrations will increase from about 350 to 850 ppm (Table 5.3).

Table 5.3 *Global Circulation Models used in this study.*

Model name	*Modeling group*	*Country*	*References*
IPSL-CM4	*Institute Pierre Laplace*	*France*	*Dufresne, 2007a,b,c*
MICRO3.2	*Center for Climate System Research*	*Japan*	*Nozawa, 2005a,b,c*
ECHAM5/MPI-OM	*Max-Planck Institute for Meteorology*	*Germany*	*Roeckner, 2006a,b,c*

The B1 scenario emphasizes environmental protection and a relatively slow increase of world population. In this scenario, the atmospheric CO_2 concentrations is predicted to stabilize at 550 ppm by the end of the century. We also used data from the twentieth century simulations (20C3M). These simulations are dictated by historical greenhouse gas and sulphate-aerosol concentrations and other forcings since the start of the industrial revolution (Sheffield & Wood, 2007). Rainfall occurrence is generated similar to the LARS weather generator (Semenov & Barrow, 1997). Rainfall amounts are modelled on a monthly basis with a mixed Weibull distribution (Suhaila & Jemian, 2007). Similar to Jaramillo & Borja (2004) and Carta & Ramírez (2007), we used a mixed Weibull distribution to represent wind regimes. We assume that wind speed is independent from the other parameters. Relative differences between the scenario results of year 2050 and 2000 are used to update the monthly parameters of the mixed Weibull distribution. Temperature, radiation and vapour pressure are generated according to the method described by Richardson (1981). Similar as for rainfall amounts and windspeed parameters, relative differences between the scenario results of year 2050 and 2000 are used to update the monthly parameters of the functions that describe temperature, vapour pressure and radiation. Table 5.4 presents the main characteristics of the climate in 2050 as it differs with respect to the average in the period 1971-2000.

***Table 5.4**. Main characteristics of future (2050) and present (1971-2000) climate. Characteristics of future climate are given as differences to the present situation. Future climate is based on 3 different GCM's and 2 emission scenarios (A2 and B1).*

Item	Present	IPSL-CM4		MICRO3.2		ECHAM5/MPI-OM	
		A2	B1	A2	B1	A2	B1
Rainfall (mm)	793.3	-40	-38	87	84	35	112
Radiation (kJ m^{-2})	9820.1	166	275	-36	622	171	171
T_{min} (°C)	6.1	2.4	2.3	2.2	2.0	2.1	1.7
T_{max} (°C)	13.2	2.6	2.5	2.1	1.9	1.9	1.5
Humidity (kPa)	1.0	0.2	0.1	0.2	0.2	0.1	0.1
Windspeed (m s^{-1})	4.7	0.1	0.0	0.3	0.1	0.3	0.3

Direct effects of increasing atmospheric CO_2 concentrations on the CO_2 assimilation and growth of C3 crops like grass, are incorporated via the maximum and initial angle of the CO_2 assimilation-light response and a limited decrease in transpiration rate. The changes in the WOFOST parameters that reflect these changes in plant behaviour at increasing CO_2 concentrations, are summarized in Table 5.5. These parameter adaptations are based on studies by Allen et al. (1990), Goudriaan et al. (1984), Goudriaan et al. (1985), Goudriaan (1990), Goudriaan & Unsworth (1990), Goudriaan & de Ruiter (1983) and Idso (1990), and on literature surveys on crop responses to CO_2 doubling by Cure (1985), Cure & Acock (1986), and Kimball (1983).

***Table 5.5** Changes in initial angle (EFF) and in maximum (AMAX) of the CO_2 assimilation - light response curve and in the reduction factor for potential transpiration (CFET) for adaptation of the WOFOST model to an increased CO_2 concentration. The relative figures are given in brackets (Source: J. Wolf personal communication).*

Variant	EFF (kg ha^{-1} h^{-1} / J m^{-2} s^{-1})	AMAX (kg ha^{-1} h^{-1})	CFET (-)
1985	0.50 (100 %)	40.0 (100 %)	1.00
2050_A2	0.53 (106 %)	52.0 (130 %)	0.95
2050_B1	0.52 (104 %)	49.2 (123 %)	0.96

Pot experiments demonstrated that a doubling of CO_2 concentrations results in yield increases of 40 to 60%. However, yield increases in free air CO_2 enrichment (FACE) studies are lower than for enclosure studies (Long et al. 2006) due to more plant interaction (e.g. shadowing in canopy). Yield increases of 25 to 40% for doubled CO_2 (De Temmerman et al., 2002; Wolf & Van Oijen, 2002; Wolf & Van Oijen, 2003; Wolf et al., 2002) were found in such circumstances. Hence, the change in the model parameters that determines the CO_2 assimilation (EFF, AMAX) due to CO_2 doubling have been multiplied with 60%.

5.3 Results

5.3.1 Field experiments

5.3.1.1 Calibration

The Ruurlo field experiment was calibrated with a high fertilization level resulting in an average actual yearly yield of 14.1 t ha^{-1} DM (dry matter) grass achieved during 5-7 cuttings (see Figure 5.4 and Table 5.6). Simulated potential yields varied between 20 and 23 t ha^{-1}, with the highest potential yield found in 1982, a year with a 10% higher radiation than the average radiation of the investigated years, and a 0.5 ^{0}C higher average air temperature calculated over the considered period. Actual simulated yield of this field was 0.2 t ha^{-1} lower than the observed value (see Table 5.6). The calibration resulted in a value of 0.66 for the residual stress factor f_{res}, implicating that 1/3 of the difference between potential and actual yield should be assigned to factors not accounted for by the model (such as diseases, pests and/or weeds, management, from lab to experimental field) as well as to structural errors in model and data.

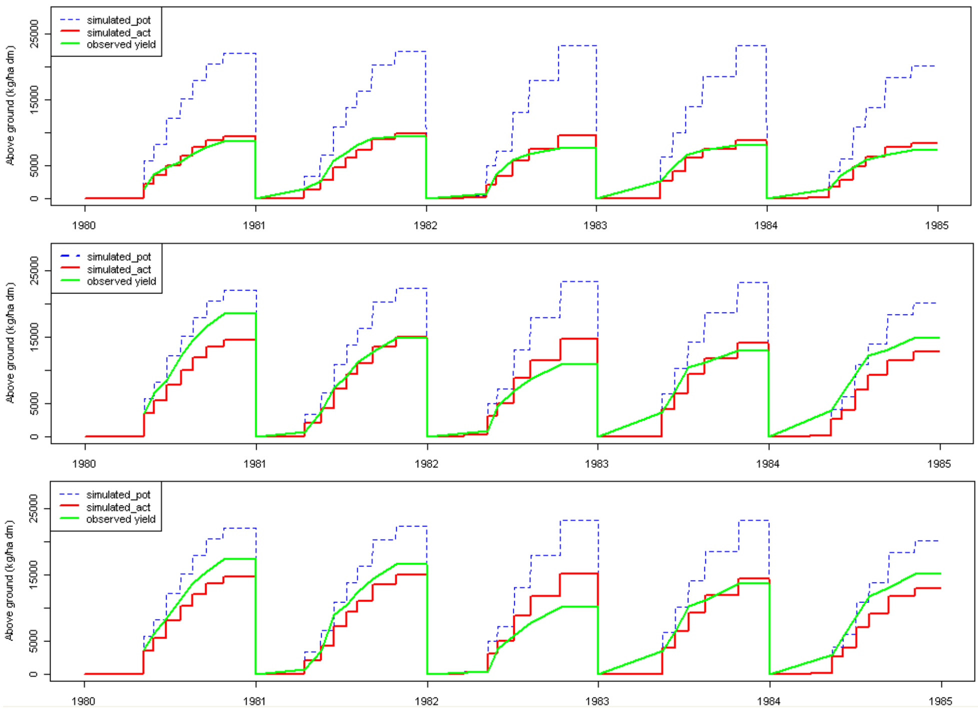

Figure 5.4 *Observed, potential simulated and actual simulated yields (kg ha^{-1}) of three grassland field experiments in Ruurlo: with fertilizer levels low (top), high (center) and very high (bottom).*

***Table 5.6** Yields of the experimental fields.*

Field experiment	*Yield (t ha^{-1} yr^{-1} as dry matter)*		
	Simulated	*Observed*	*Mean bias error*
Ruurlo low fertilizer	*9.1*	*8.2*	*0.97*
Ruurlo high fertilizer	*14.1*	*14.3*	*-0.19*
Ruurlo very high fertilizer	*14.4*	*14.5*	*-0.15*
Zegveld	*12.2*	*12.6*	*-0.38*
Cranendonck	*10.2*	*10.8*	*-0.56*

5.3.1.2 Validation

To verify the validity of the residual stress factor f_{res} = 0.66 for different situations, the other four experiments were simulated leaving f_{res} unchanged. The nutrient stress was accounted for using stress factors of 0.7 and 0.8 for the fields with low fertilizer treatments (see Table 5.2). The Ruurlo field experiments with a very high fertilization level showed a small underestimation of simulated versus observed yields. The field with low fertilization level showed the largest mean bias error of nearly 1 t ha^{-1}. The Zegveld and Cranendonck experiments performed well with a mean bias error of respectively 0.4 and 0.6 t ha^{-1} (see Table 5.6 and Figure 5.5). The average product of residual and nutrient factor of all experimental fields was 0.55.

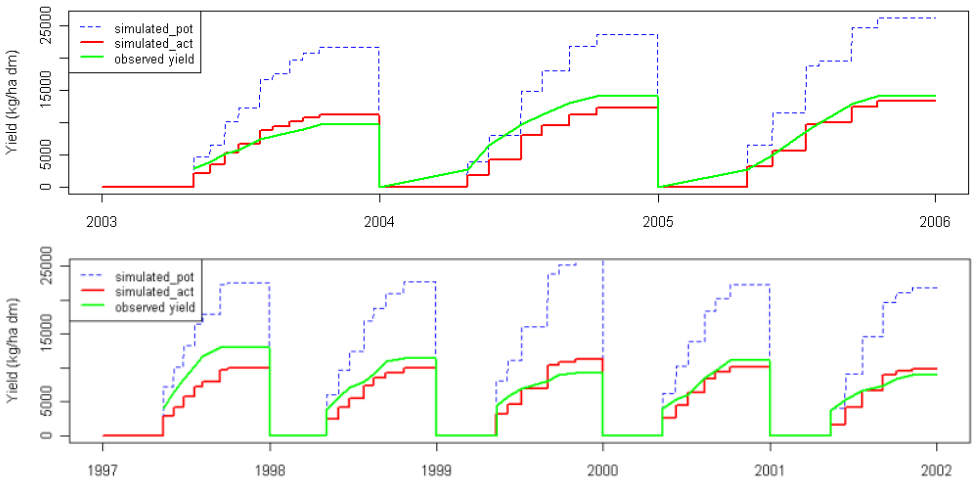

***Figure 5.5** Observed, potential simulated and actual simulated yields (kg ha^{-1}) of grassland field experiments in Zegveld (top) and in Cranendonck (bottom).*

5.3.2 Regional scale experiment

Average simulated potential and actual yields for the period 1971-2000 are respectively 21 and 10 t ha^{-1} yr^{-1} (see Table 5.7 and Figure 5.6). The gap between potential and actual yield is higher for those scenarios in which the drought stress increases in 2050 (Table 5.7). The simulated actual yields stagnate only for the IPSL A2 scenario. This can be attributed to limited rainfall in combination with increased drought stress in this scenario (see Table 5.4). For the other scenarios, the increasing temperature resulted in increasing yields (3.8–9.7%). The results including CO_2 increase show that for all scenarios the potential as well as the simulated actual yields increase.

Table 5.7 *Potential and actual yield (Y_{pot} and Y_{act} in t ha^{-1} yr^{-1} as dry matter), of current (mean of 1971-2000) and future (2050) climate; simulation results without and with adaptation according to Table 5.5.*

Adaptation to CO_2 increase	Yield	Current climate	IPSL-CM4		MICRO3.2		ECHAM5/ MPI-OM	
			A2	B1	A2	B1	A2	B1
No	Y_{pot}	21	23	23	22	22	23	23
	Y_{act}	10	10	11	11	11	11	12
Yes,	Y_{pot}		26	25	25	24	26	25
(see Table 5.5)	Y_{act}		13	13	13	13	14	13

Table 5.8 *Potential Evapotranspiration (ET_{pot}) and potential and actual Transpiration (T_{pot} and T_{act}), in mm yr^{-1}, of current (mean of 1971-2000) and future (2050) climate; simulation results without and with adaptation according to Table 5.5.*

Adaptation to CO_2 increase	Evapo-ration flux	Current climate	IPSL-CM4		MICRO3.2		ECHAM5/ MPI-OM	
			A2	B1	A2	B1	A2	B1
No	T_{pot}	426	514	508	466	478	478	458
	T_{act}	398	457	462	441	449	443	433
Yes,	T_{pot}		523	516	472	473	484	463
(see Table 5.5)	T_{act}		467	470	448	444	451	438

The results with and without CO_2 increase show that the contribution of the increased CO_2 concentration to the rising yields is much higher than the contribution of the increased temperature.

When future climate scenarios are considered ignoring the increased CO_2 concentration, the potential transpiration increases between 7.8% and 17.3% depending on the scenario (Table 5.8). As the temperature increases, the respiration losses increase as well, however, these losses are more than compensated as the period in which the ambient temperature remains in the optimum temperature range for maximum assimilation increases in 2050. This results in potential yield increases in 2050 between 2.9% and 6.3%.

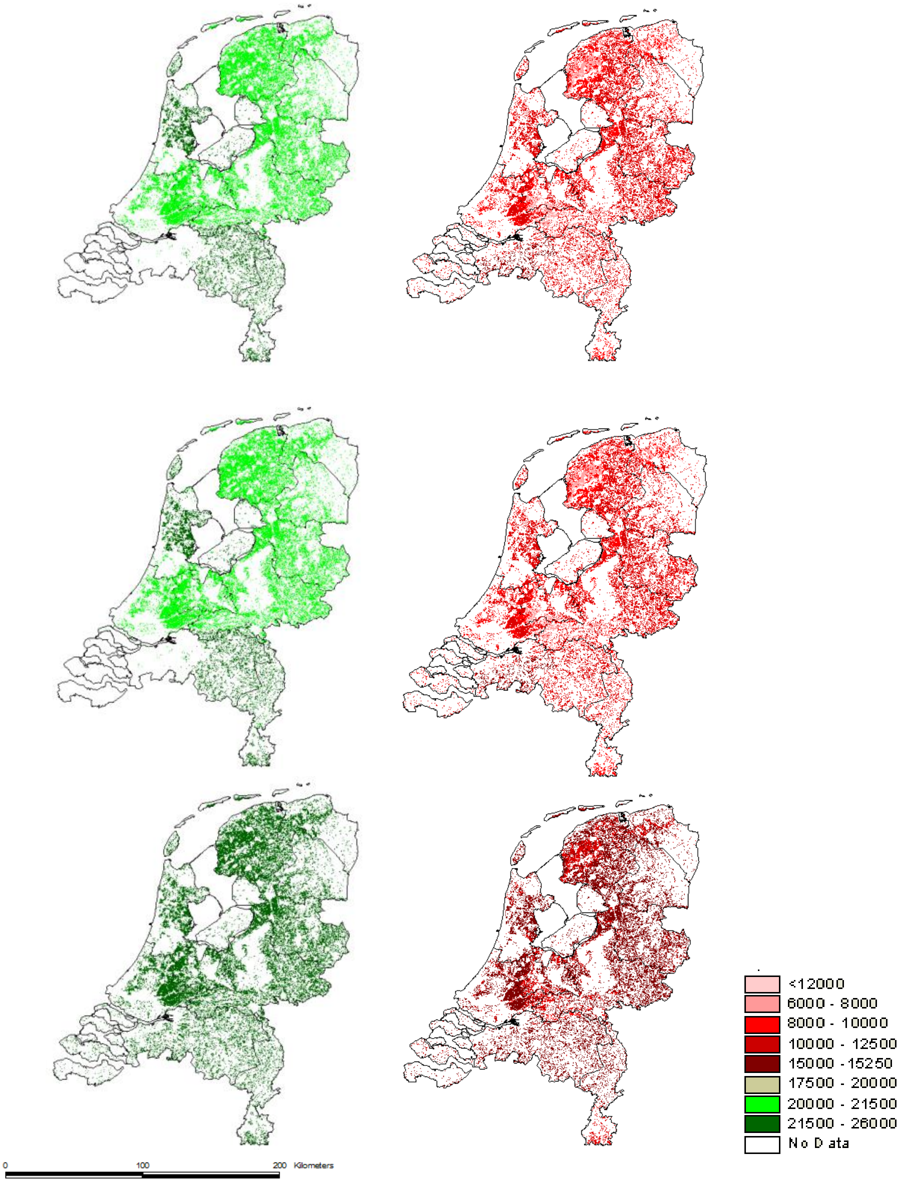

Figure 5.6 *Spatial distribution of grassland yields: potential simulated (left) and actual simulated (right); all yields in kg ha*$^{-1}$ *yr*$^{-1}$ *dry matter; actual yields include water and salinity limitations. Top figures: long term average (1971-2000), Middle figures: scenario IPSL-CM4-A2, Bottom figures: scenario ECHAM-B1.*

The actual transpiration increases for all scenarios (Table 5.8); the difference between actual and potential transpiration is scenarios dependent and is mainly caused by drought (Table 5.9). For the IPSL scenarios drought stress is highest and shows a strong increase with respect to the current climate situation.

Comparison among the scenarios shows that the yield increases are highest when the A2 scenarios are applied. This can be mainly attributed to the higher CO_2 concentration in these scenarios. The actual and potential transpiration levels show a limited increase as the CO_2 concentration increases, suggesting that the grass production efficiency increases. This is confirmed by Wand et al. (1999) who mention a significant closure of the stomata and increased leaf water efficiency. These authors also mention an increasing leaf carbohydrate status and a decreasing leaf nitrogen concentration. According to Ryle et al. (1992) elevated CO_2 concentration reduces tissue nitrogen contents of expanded leaves, but has no effect on the nitrogen contents of unexpanded leaves, sheaths or roots. Note that to obtain optimal yields under increased CO_2 concentrations, higher fertilizer regimes are needed.

Table 5.9 *Stress part of difference between potential and actual transpiration, in mm yr^{-1}, of current (mean of 1971-2000) and future (2050) climate; simulation results without and with adaptation according to Table 5.5.*

Adaptation to CO_2 increase	*Stress part of Evaporation flux*	*Current climate*	*IPSL-CM4*		*MICRO3.2*		*ECHAM5/ MPI-OM*	
			A2	*B1*	*A2*	*B1*	*A2*	*B1*
No	*Water excess*	*4*	*3*	*3*	*6*	*5*	*4*	*5*
	Drought	*24*	*54*	*44*	*19*	*24*	*31*	*20*
	Salinity	*0.03*	*0.10*	*0.05*	*0.01*	*0.02*	*0.04*	*0.03*
Yes,	*Water excess*		*3*	*3*	*6*	*6*	*4*	*5*
(see Table 5.5)	*Drought*		*54*	*43*	*18*	*23*	*29*	*20*
	Salinity		*0.10*	*0.05*	*0.01*	*0.02*	*0.04*	*0.03*

Figure 5.7 presents the simulated irrigation amounts in the current situation and in 2050 as a result of the considered scenarios. The simulated irrigation amounts increase for both the IPSL scenarios and for the ECHAM5 A2 scenario. The strongest increase (>50%) occurs with the IPSL scenarios as the temperature increase in these scenarios is highest in combination with a rainfall reduction (Table 5.4). For both the MICRO3.2 scenarios and the ECHAM5 B1 scenario, the simulated irrigation amounts decrease due to increasing rainfall. However, for MICRO3.2 B1 this decrease is largely compensated by an increased radiation. In the ECHAM5 A2 scenario the rainfall increases slightly, but not enough to compensate for the increasing temperatures, making irrigation amounts to increase. The differences among the scenarios A2 and B1 are very small, so the changes in irrigation amounts can be mainly attributed to changes in rainfall-distribution and temperature. Note that 18% of the grassland area is irrigated. We assumed that this irrigated area does not change over time.

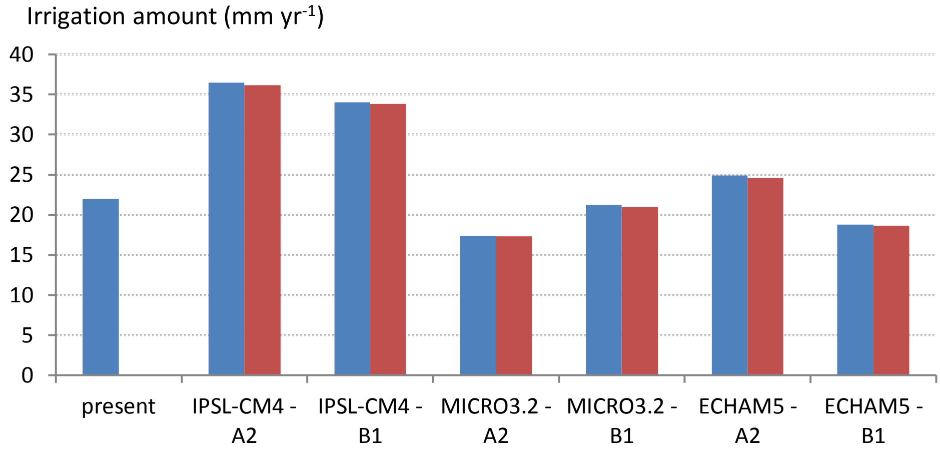

Figure 5.7 *Simulated irrigation amounts (mm yr^{-1}); without (left bar) and with (right bar) impact of CO_2-increase.*

In the present and 2050 scenarios, salinity and water excess hardly affect actual or potential grass yields (Table 5.9). One should bear in mind that the presented data are on a national level and the given stress factors may be obscured by the averaging process. To test if salt stress or water excess effects are notably higher in the lower areas, we separately analysed the areas with a Cl^- concentration of 2000 mg l^{-1} or higher in the subsoil (Figure 5.3). Salt stress and water excess increase, but remain small when compared to the drought stress (Table 5.10). Analysis of individual plots and individual years demonstrates that salt stress occurs in dry years such as 1976 on those plots irrigated with saline water. In wet years, excessive rainfall pushes the salt water influx down and water excess may occur. However, the presence of drainage systems may reduce the effects of water excess.

Table 5.10 *For the part of the Netherlands with [Cl^-] >2000 mg l^{-1}: Stress part of difference between potential and actual Transpiration, in mm yr^{-1}, of current (mean of 1971-2000) and future (2050) climate; simulation results without and with adaptation according to Table 5.5.*

Adaptation to CO_2 increase	*Stress part of Evaporation flux*	*Current climate*	*IPSL-CM4*		*MICRO3.2*		*ECHAM5/ MPI-OM*	
			A2	*B1*	*A2*	*B1*	*A2*	*B1*
No	*Water excess*	*3*	*2*	*2*	*4*	*4*	*3*	*4*
	Drought	*35*	*78*	*56*	*25*	*27*	*45*	*33*
	Salinity	*0.37*	*1.28*	*0.69*	*0.17*	*0.23*	*0.51*	*0.34*
Yes, (see Table 5.5)	*Water excess*		*2*	*2*	*4*	*4*	*3*	*4*
	Drought		*79*	*55*	*23*	*27*	*43*	*31*
	Salinity		*1.25*	*0.68*	*0.17*	*0.24*	*0.48*	*0.34*

5.4 Discussion

Simulation of grass growth and production is complex and influenced by many factors, such as: temperature, radiation, drought, water excess, nutrient status, plagues, diseases, soil structure and management. In some studies that deal with grass production, whole farm approaches are applied to address the complex interaction of grassland and farm management (Schils et al., 2007). We selected a process-based crop growth model based on photosynthesis and a simplified approach for management. This may not be suitable for a farm study but is acceptable for our purpose to assess the impact of climate change and salinity on grass yields. This study shows the limited impact of water excess and salinity on grass yields, even when salinity levels increase or groundwater tables rise and evaporation decreases.

Droughts are more important. We assumed that hydrological and salinity boundary conditions from 1971-2000 can be applied to the year 2050. This assumption implies that there will be no sea level rise, which seems unrealistic. According to Oude Essink et al. (2010), a rise of about 2 m is to be expected in 2100, which may increase hydraulic heads in a limited zone of about 10 km from the coastline. According to these authors, 5 km from the coast the effect of sea level rise on the hydraulic head is reduced to about 40%, further inland the hydraulic head may decrease to a maximum of 1 m as a result of land subsidence and declining recharge. Following the statements of Oude Essink et al. (2010), an estimated 1 m sea level rise in 2050, will cause a hydraulic head increase of 40 cm about 5 km from the coastline and decline further inland. This means that close to the coast our study underestimates groundwater seepage and consequently the effects of salt stress and water excess may therefore be higher. However, as can be seen in Figure 5.1 grasslands in the Netherlands generally are located further inland, where the hydraulic head increase is less and consequently the impact on groundwater tables is small; an effect that will be further reduced by increasing evapotranspiration and increased drainage by higher pumping rates.

Note that the climate change impact on bottom boundary conditions remains largely unknown and this lack of information may affect our results. For example, our study does not account for the effects of increasing autonomous salinization, a consequence of draining lakes and developing polders over the past 500 years, which have caused deeper and more saline groundwater to flow upward toward the deep polders (Oude Essink et al., 2010). Furthermore, the effect of sea level rise and climate change may be larger on salinity levels than on groundwater tables. Groundwater salinity may increase due to increasing head differences between sea water and groundwater and due to increasing evaporation. To account for these impacts a regional hydrological model could be applied. In spite of these shortcomings we believe that overall results remain valid since grass is salt tolerant and generally has a shallow rooting system.

Simulated potential and actual yields for the period 1971-2000 are respectively 21 and 10 t ha^{-1} yr^{-1}. Smit et al. (2008) reported actual grass yields of 10-11 t ha^{-1} yr^{-1} based on statistical analyses of production figures for the Netherlands. Potential grass yields reported in literature are 24-30 t ha^{-1} yr^{-1} (Gordon, 1988), 19.9 t ha^{-1} yr^{-1} (Schapendonk et al., 1998). Based on these data it seems that the simulated yield difference between potential and actual yield (Y_{pot} - Y_{act}) is realistic and about 50%. We explained part of this gap by introducing a so-called residual stress factor which we assumed to be 0.66 based on field experiments. The calibration of the residual stress factor was carried out in a simplified way ignoring several uncertainties. This implies that the resulting factor accounts for unknown environmental impacts, impacts caused by diseases, pests, weeds, structural model errors and errors caused by erroneous parameterisation of soil physics and plant characteristics. This may also imply that the spatial and temporal variation is underestimated. However, in spite of all these uncertainties, we found that the validation results were good enough to proceed with a regional application.

We found that grass yields increased as a results of the changing climate, however, one should bear in mind that the grass quality in terms of nutritional content may not remain constant. More fertilizers may be needed to reach the same nutritional quality. As grass production is not at its maximum, water shortages are less severe or hardly occur in the current situation. However as production levels increase the effects of droughts may also increase, i.e. the relative yield reduction becomes stronger. If it is desired to improve the current grass production level, one should expect larger impacts of droughts.

In this study saline water was simulated to enter the rootzone via 3 routes: i) upward seepage of groundwater from deeper soil layers, ii) irrigation water entering the soil surface, iii) infiltration water originating from surface water that laterally enters the soil. We assumed that irrigation and infiltration water have the same concentration as the groundwater, which implies a worst case approach without fresh water supply. Even in the Netherlands the irrigation route should be considered, because irrigation occurs in periods with a high evaporative demand, when soil moisture contents are low and salinity levels are high.

We regarded the chloride ion, because the relation between chloride and electrical conductivity is given and related to the Maas & Hoffman (1977) values, but for plant physiologically aspects the sodium ion is most important. The impact of high salinity on soil structure is not accounted for; high sodium levels will cause soil aggregates to disaggregate and disperse and lower soil structure; this should be accounted for especially in flooding situations where it may have a larger impact on yields then the stress factors we regarded in this study.

The Maas & Hoffman (1977) approach was developed using data from many different places, which introduces extra uncertainty because the circumstances to derive the model parameters differ from place to place with respect to irrigation water composition and climate and soil conditions. For grass the impact may not be very large, but as Van Bakel et al. (2009) suggest it is strongly recommended to carry out field experiments under Dutch conditions. It is also recommended to compare the Maas & Hoffman (1977) approach with an approach that uses the osmotic potential as driving force such as suggested by De Jong van Lier et al. (2009). The overall stress is calculated in a multiplicative way (eq 5.1 and 5.2), a method which is disputable (see e.g. Šimůnek & Hopmans, 2009).

The impact analyses are only valid for grass. Other crops may show other results. The impact of increased salinity levels on other crops such as seed potatoes and tulip bulbs may be different and should be analysed using the same model instrument. Another logical next step will be an analysis of the impact of changing hydrological boundary conditions due to interaction between regional systems (deep groundwater, surface water) with one or more high value crops. The approach we tested and applied enables estimates of stress factors and supports climate impact analyses on our eco-system in stress-like conditions.

5.5 Conclusion

Increasing salt concentrations and water excess have a limited effect on grass production. In non-irrigated areas (about 82% of total grassland) droughts have a much larger impact than excess of water and salinity.

In the irrigated areas the water requirement to obtain maximum yields increases and may generate water scarcity, especially if groundwater is not available and surface water supply is limited. Future water requirement for maximal production increases with respectively 19 and 11% for the A2 and B1 scenarios.

The applied methodology provides a tool to search for the optimal production as dictated by the climatic boundary condition. In case of reduced rainfall, a slight reduction of the simulated actual yield is predicted for the year 2050. Increasing CO_2 concentrations and temperatures stimulate grass growth and yields as long as water (rainfall) doesn't become a limiting factor. The future scenarios generally show increasing simulated potential and actual yields. Irrigation will compensate water deficit and contribute to increasing yields but only in those parts of the Netherlands where enough irrigation water of sufficient quality is available.

6. Agrohydrological analysis of groundwater recharge and land use changes in the Pampas of Argentina

This paper studies the changes of groundwater, climate and land use in the Pampas of Argentina. These changes offer opportunities and threats. Lowering groundwater without irrigation causes drought and successive crop and yield damage. Rising groundwater may alleviate drought as capillary rise supports root water uptake, crop growth and narrows the difference between potential and actual yields. However rising groundwater may also limit soil water storage, cause flooding in metropolitan areas and have a negative impact on crop yields. Changing land use from continuous soy bean into crop rotations or natural vegetation may decrease groundwater recharge and thus decrease groundwater levels. However in case of crop rotation leaching of nutrients like nitrate may increase.

We quantified these impacts using integrated dynamic crop growth and soil hydrology modelling. The models were tested at field scale using a local dataset from Argentina. We applied distributed modelling at regional scale to evaluate impacts on groundwater recharge and crop yields using long term weather data.

The experiments showed that threats arise from continuous monotone land use. Opportunities are created when a proper balance is found between supply and demand of soil water using a larger differentiation of land use. Increasing the areas of land use types with higher evapotranspiration, like permanent grassland and trees, will contribute to a more stable hydrologic system with more water storage capacities in the soil system and lower groundwater levels.

Modelling tools clearly support the evaluation of the impact of land use and climate change.

Based on:

Kroes, J., van Dam J., Supit, I., De Abelleyra, D., Verón, S., De Wit, A., Boogaard, H., Angelini, M., Damiano, F., Groenendijk, P., Wesseling, J., Veldhuizen. A., 2018. Agrohydrological analysis of groundwater recharge and land use changes in the Pampas of Argentina. Submitted to: Agricultural Water Management.

6.1 Introduction

Groundwater recharge results from the dynamic interaction between climate, land use and soil hydrology as it occurs in the critical zone, a thin portion of the biosphere connecting the lithosphere, atmosphere and hydrosphere (Amundson et al., 2007). The variation of this interaction in space and time can be very large and is influenced by human and natural activities. Especially in flat, poorly drained sub-humid plains, such as the Argentine Pampas, the Brazilian Pantanal, the Canadian plains of Manitoba and Saskatchewan and the Great Plains of Hungary and Western Siberia groundwater rise may cause large episodic floods (Aragón et al., 2010). The dynamic interaction has a large uncertainty which one wishes to minimize especially to predict effects of climate change and land use on groundwater recharge conditions (Smerdon, 2017). To improve the accuracy of model outputs, proper evapotranspiration data as upper boundary condition and the use of remote sensing information is recommended (Doble & Crosbie, 2017).

Mercau et al. (2016) analysed the impact of climate, topography and crop choice on the dynamics of water table levels for five years on a typical farm in the Western Pampas of Argentina. They concluded that crops with a higher capacity to reduce groundwater recharge magnify the effects of land use on the dynamics of water tables.

Vazquez-Amabile et al. (2013) applied the field-scale hydrological model DrainMod (Skaggs et al., 2012) at 12 farms fields within a radius of 100 km in western Buenos Aires Province. They observed water table depths generally within 3 meter below the soil surface and concluded that leaching of nitrate should be considered since 52% of the observations exceeded the threshold of 10 mg/L NO_3-N. A significant proportion of the leached nitrate originates from mineralization of organic matter (Vazquez-Amabile et al., 2017).

Viglizzo et al. (2009) found correlations between groundwater level and flooding in 12.4 million hectare of the Pampas in Argentina with highly significant relations in the highlands. They also stated that land use could be steered to minimize the impact of floods.

A better understanding of the underlying processes by which crops influence groundwater is essential for the evaluation of different measures to influence groundwater recharge. Garcia et al. (2017) applied the regional MIKE-SHE model to a sub-basin in Argentina and concluded that land use has strong effects on groundwater levels and remarked that land use decisions to control groundwater should have a broad consensus regarding social and physical aspects to minimize negative effects on agricultural production. The water contribution from a water table located approximately 1.5 to 2 m deep can represent up to 30% of the water requirements of soybeans in the flooding sandy Pampas, thus stabilizing the inter-annual variability of soybean yields (Videla Mensegue et al., 2015). Sainato et al. (2003) reported increasing salinity values in groundwater for the region around Pergamino where the aquifer shows an increase in water salinity to the West.

Groundwater tables rapidly rise and fall depending strongly on the interaction with climate, crop and soil. Aragón et al. (2010) used satellite data and groundwater monitoring wells to analyse the changes of groundwater depths and surface water amounts of the Western Pampas of Argentina during the flooding cycle of 1996-2006. They showed that mean regional groundwater levels rose by 2.5 m in 5 years, which decreased the average vadose zone from 3.7 m to 1.2 m. In the same period, the regional surface water coverage (ponds, rivers, lakes) increased from 3% to 28% primarily by the development of new water bodies. This had a huge impact on hydrological connectivity throughout the landscape transport and flooding risks. Kuppel et al. (2015) extended the hydrologic analysis of the Pampas to the period 2000-2013 and included the eastern lower part of the Pampas. They investigated three responses of the Pampas to periods with increased rainfall: (i) increased water storage leading to rising water tables and floods, (ii) higher evapotranspiration losses favoured by higher soil moisture contents and capillary rise and, at very high levels of water storage, (iii) enhanced surface water outflows favoured by the surface water connectivity. They concluded that in the Pampas the first two responses are dominant: rising water tables and higher evapotranspiration losses.

A better understanding of the complex interactions between crops and shallow groundwater is therefore recommended and will help to stabilize yields and balance opportunities and risks caused by the 'labile hydrology' of the Pampas (Nosetto et al., 2009).

With this paper we intend to contribute to a better understanding of the complex interactions between soil hydrology and crop growth within the critical zone. We analysed the impact of different groundwater tables and different land use types on groundwater recharge and agricultural production. An analysis of the distribution of water over crops, vadose zone and groundwater is necessary to consider processes like soil moisture redistribution, root water uptake and capillary rise of groundwater. We developed a toolbox consisting of a state-of-the-art dynamic simulation model for agricultural crop growth and a Richards equation-based model for soil water flow.

We used local observations of crop and soil parameters with special attention to a detailed determination of soil hydraulic properties. Furthermore we analysed the sensitivity of soil hydraulic parameters with respect to vertical water flow and yields. This is essential to support model and calibration improvement (De Jong van Lier et al., 2015). After calibration

and evaluation we analysed the impact of changes of land use and rising groundwater level on regional agricultural production using long term climate data.
This study resulted from a case study that was carried out within an EU-project and reported by De Wit et al. (2017) and Kroes et al. (2017b).

6.2 Method and materials

6.2.1 Study Area

The Pampas of Argentina cover a wide plain of about 54 million ha of fertile lands (Viglizzo et al., 2003). Based on soil and rainfall patterns, the region can be divided into different agro-ecological areas (Viglizzo et al, 2003): i) Rolling Pampas in the centre of the area, ii) Sub-humid Eastern Pampas, iii) Semiarid Western Pampas, iv) Southern Pampas, v) North-Eastern Flooding Pampas, and vi) Mesopotamian Eastern Pampas. Dominating crops are soybean and rotations of the crops maize, wheat and soybean.

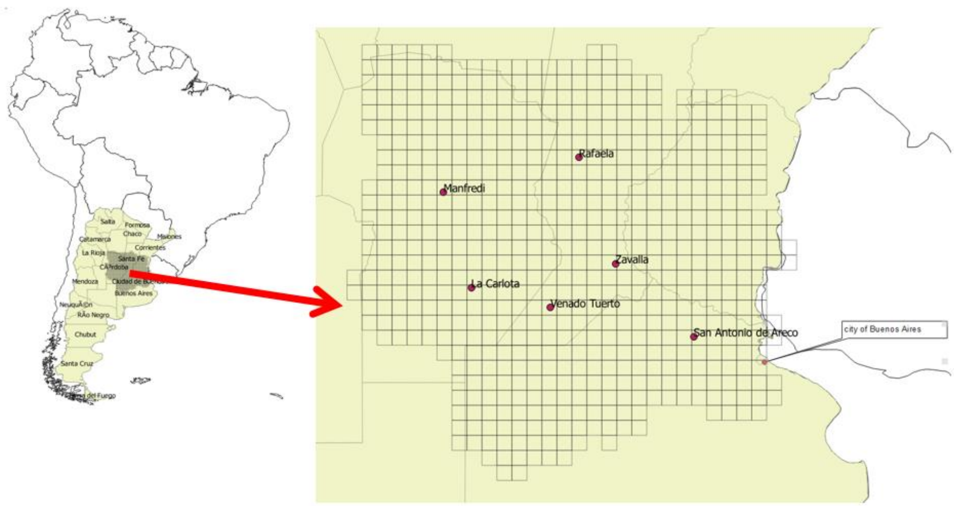

Figure 6.1 *The study area and location of 6 selected sites in the Argentina Pampas. The grid lines delimit the grid cells applied in the simulation at regional scale.*

We analysed the relation between groundwater and land use in a study area of about 40 million ha or 75% of the Pampas of Argentina (Figure 6.1). The grid lines indicate the boundaries of the grid cells applied in the simulation at regional scale. Within the study area we selected 6 sites for the calibration of soybean parameters.

6.2.2 Modelling Tools

We merged different modules for crop, soil water and atmosphere and integrated the two dynamic models SWAP (acronym for Soil Water Atmosphere Plant) and WOFOST (WOrld FOod STudies). SWAP is a dynamic soil hydrological model solving soil water pressure head differences using the Richard's equation (Van Dam et al., 2008; Kroes et al., 2017a) that has been applied in many studies (http://swap.wur.nl/References.htm). WOFOST is a generic crop growth simulation model, of which the principles are explained by Van Keulen & Wolf (1986) and Boogaard et al. (2014). WOFOST has been applied in many studies (e.g. Supit et al., 2012; De Wit et al., 2012, Asseng et al., 2013) at different spatial scales in many regions across the world. In order to simulate the soil carbon and soil nitrogen influence, we added also the module Soil-N (Groenendijk et al., 2016).

The integrated model (Figure 6.2) is distributed on Internet as version 4 of the open-source model SWAP (http://swap.wur.nl).

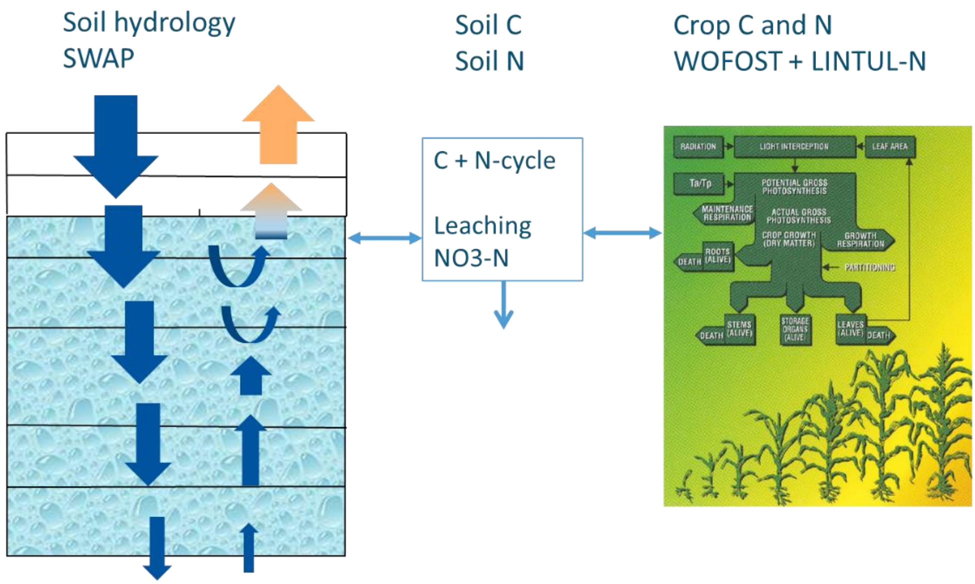

Figure 6.2 *Set of dynamic modelling tools integrated in SWAP version 4.*

The integrated model describes a one-dimensional system that ranges from the top of the soil or vegetation, to the bottom of the unsaturated or saturated part of the relevant soil system. In this study we simulated a soil column of 5.5 m.

SWAP numerically solves the one-dimensional Richards equation for the unsaturated-saturated zone:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_a(h) \quad (6.1)$$

where θ is the volumetric water content ($cm^3\ cm^{-3}$), t is time (d), K is the hydraulic conductivity ($cm\ d^{-1}$), S_a is soil water extraction rate by plant roots ($cm^3\ cm^{-3}\ d^{-1}$) and h is the soil water pressure head (cm).

To solve this equation, specified boundary conditions and soil hydraulic relations between θ, h and K are required. The upper boundary is defined by meteorological conditions which are input to the model and by a cultivation which can be a static or a dynamic type of crop (Kroes et al., 2017a). In this study we used the static sub-model for grassland and the dynamic sub-model WOFOST for both the growth of soybeans and for a crop rotation of soy-wheat-maize.

With these meteorological data, runoff is calculated when the rainfall intensities supersede the soil infiltration capacity or when the soil profile becomes saturated.

The lower boundary defines the interaction with a regional groundwater flow system. In this study we applied two types of bottom boundary conditions: a) free-drainage and b) Cauchy bottom boundary condition. For the Cauchy condition, the flux through the bottom boundary (q_{bot}) is defined by the difference of the hydraulic head (h+z) at the column bottom and the hydraulic head ϕ (cm) of the regional groundwater below the flow domain described by the model, divided by a hydraulic resistance c (d).

$$q_{bot} = \frac{[h+z]_{z=bot} - \phi}{c} \quad (6.2)$$

We used a constant hydraulic resistance of 500 days and varied the head of the regional groundwater (ϕ) to achieve the desired average depth of the fluctuating groundwater level.

As an alternative for the commonly used soil hydraulic functions of Mualem – Van Genuchten, the possibility to supply $\Theta(h)$ and $K(h)$ relationships as tabulated input is implemented. In that way any shape of the relationships can be considered. In this study, the tabular option is used.

The reduction of root water uptake due to too dry or too wet conditions is described according to Feddes et al. (1978). Sometimes only some parts of the root zone are stressed and show reduction of root water uptake, while other parts have favourable conditions for root water uptake. In these conditions the reduction in the stressed parts might be compensated by extra root water uptake in the parts with favourable conditions. Therefore we extended the Feddes concept with the compensation concept of Jarvis (2011).

To simulate soybean growth, the sequential phenological development pattern in WOFOST had to be adapted. This sequential pattern is typical for cereals and is appropriate for tuber crops (potato, sugar beet), which are crops with a relative simple development pattern. For soybean a hybrid phenological development model was developed taking elements from established models for soybean phenology (Setiyono et al., 2007) but still applying the sequential development stage logic that is needed for WOFOST. Adjustments have been described in detail by De Wit et al. (2017) and were implemented in SWAP 4.

We also implemented a soil nitrogen module and used the RothC-26.3 model (Coleman et al., 1997) for an organic matter module. Both nitrogen supplied to the soil by fertilizer applications and nitrogen obtained from mineralization of organic bounded nitrogen are stored in the soil. Mineralization rates of NH_4 and NO_3 control the nitrogen mineralization and immobilization in relation to the processes in the organic matter cycle.

Ammonium and nitrate balances were calculated on a daily basis. The leaching of nitrate and ammonium was simulated to be controlled by the stock of mineral N present and the water fluxes leaching through the root zone.

The nitrogen distribution within a crop is predicted in SWAP 4 based on the method described by Shibu et al. (2010). The N-contents of crop residues are calculated in the dynamic crop module and passed to the Soil-N module.

For soybean, the description of nitrogen fixation was based on a simple approach, assuming that N_2 fixation from the air is unlimited. If we assume for this case study that other factors, especially phosphorus supply, are not limiting this apporach is plausible and seems in agreement with Giller (2001) who states that "*The main environmental factors that constrain N2-fixation in the tropics include limitations of water, nutrients (particularly phosphorus) and toxicities*".
The soybean crop defines the demand for nitrogen and a user-defined fraction indicates the amount of nitrogen demand which is met by N-fixation from air and soil. We assumed that 80% of the required nitrogen comes from N-fixation, a value close to the default input value of 75% mentioned by Boons-Prins et al. (1993). The remaining demand was assumed to originate from mineralisation of the organic soil matter. For soybean in this study it implies that nutrient stress can be neglected. The adaptions for soybean and soil nitrogen in SWAP 4 have been described in detail by Groenendijk et al. (2016).

Using this integrated model we intended to account for different feedbacks between atmosphere, plants, soil characteristics, soil water and nitrogen limited crop growth. This allowed us to analyse in detail the impact of different land uses on groundwater recharge.

6.2.3 Field scale

6.2.3.1 Soil physical properties

A large number of soil layers in Argentina was analysed by (Damiano 2018). He developed a pedotransfer function to obtain the soil moisture retention and hydraulic conductivity function based on soil texture data from the Argentina Pampas. The results of this analysis are the parameters of the Uni-parametric Hutson & Cass (Uni-HC) equations which was processed by Damiano (2018) to determine the soil data for 8 locations in Argentina (Table 6.1). The equations of the applied soil moisture retention and hydraulic conductivity functions are given by Damiano (2018).

We created input tables for the SWAP model with these data and it appeared that some parameter combinations caused a discontinuity in the soil moisture retention curve near the inflection point which we adjusted by smoothing. This required an additional parameter *f* (Table 6.1) which we used to multiply the pressure head in the wet part of the soil moisture retention curve.

Table 6.1 *Parameters for the Argentinian soils (after Damiano, 2018) used to create the input tables. See Damiano (2018) for units and explanation.*

Code	Location	b	ψ_e	ψ_i	θ_i	D	K_s	f
Ar	Arrecifes	6.94	10.8	17.5	0.451	0.026	0.045	0.849
AD	Arroyo Dulce	6.98	11.0	17.9	0.449	0.027	0.046	0.872
Go	Gouin	7.52	13.3	21.5	0.472	0.024	0.045	0.959
Pe	Pergamino	7.52	14.6	23.7	0.456	0.024	0.058	0.874
Ra	Ramallo	7.75	16.8	27.2	0.462	0.023	0.026	0.860
Ro	Rojas	7.38	15.7	25.5	0.435	0.025	0.081	0.759
SL	Santa Lucia	7.61	14.4	23.4	0.467	0.024	0.037	0.938
VT	Venado Tuerto	7.42	13.1	21.3	0.446	0.024	0.063	0.914

To verify the procedure we used a data set, obtained from Damiano (Damiano, 2018, personal communication) with measured values of the retention curves (n =78) of the Pergamino soils (typical Argiudoll, silty loam; Soil Survey Staff, 2010). Through these data we calculated the optimal parameters of the equations presented by Damiano (2018). Results are presented in Figure 6.3.

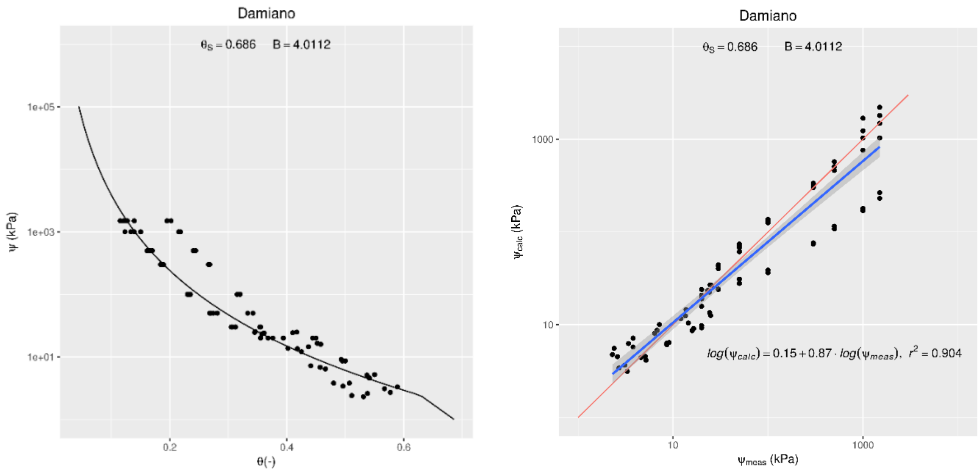

***Figure 6.3**. The curve fitted through the points of the measured water retention data of the Pergamino soil (left) and the correlation between the measured and computed pressure heads (right).*

The left-hand part of Figure 6.3 shows the fitted line and the measured points of the soil moisture retention curve. In the right-hand part of Figure 6.3 the measured and computed values are plotted against each other, showing a rather good agreement.

6.2.3.2 Parameter calibration for soybean

Observed field data from soybean field tests originated from RECSO (Red Nacional de Evaluación de Cultivares de Soja) and UNR (National University of Rosario) (De Wit et al., 2017). The observations consisted of data from 1259 experiments over the period 2011-2013 (sowing year) for five different sites: Zavalla, Venado Tuerto, Rafaela, Manfredi and La Carlotta (Table 6.2 and Figure 6.1).

Calibration procedures resulted in a set of parameter for WOFOST under optimal conditions. Procedure and results are extensively described by De Wit et al. (2017). This set was applied in the integrated SWAP-WOFOST model to allow more detailed analyses of groundwater impact.

Since the purpose of the simulations with the integrated model had a focus on the water balance it was necessary to simulate actual yields. This required an additional calibration where we used a so-called management factor to minimize the yield gap, the difference between simulated and observed actual yields. Such a management factor accounts for pests, diseases and farm management, not explicitly accounted for in the model. Our aim was to achieve a single representative value for the management factor which could then also be applied at a regional scale.

Table 6.2 *Properties of selected sites to test model results at field scale. Sites 2-6 were used for calibration with local field observations and for a 25 year comparison with actual yields from official statistics at county level.*

Site Nr	Site Name	Meteo station	Longitude	Latitude	CaseNr	Sowing date
1	San Antonio de Areco	San Antonio de Areco	-59.58	-34.23	2317	1-nov
2	Zavalla	Zavalla UNR WS	-60.88	-33.02	1626	14-nov
3	VenadoTuerto	Venado Tuerto Aero	-61.95	-33.75	2030	14-nov
4	Rafaela	Rafaela INTA WS	-61.55	-31.18	806	24-nov
5	Manfredi	Manfredi INTA WS	-63.77	-31.82	1000	14-nov
6	La Carlota	Rio Cuarto Aero WS	-64.23	-33.12	1881	14-nov

6.2.3.3 Verification of predicted soybean yields at county level

To verify the results of the calibration we simulated a longer time series using the boundary conditions from the regional simulations. Results of the 6 sites were compared to official statistics at county level for 6 cases that are located in the same region as the sites with experiments (Table 6.2). For the 6 cases we varied sowing dates (Table 6.2) and we assumed a harvest date of 05-April or at maturity, whichever was earlier. Official soybean yield statistics at county level (Min. AGPA, 2016) were converted to dry matter weight, assuming an average 13% moisture content

6.2.3.4 Parameter calibration for maize and wheat

To be able to analyse a crop rotation scheme that consisted of soybean, maize and wheat we tested maize and wheat for a long time series using official statistics at county level and meteorological data for the site San Antonio de Areco (Table 6.2 and Figure 6.1).

We calibrated the maize and wheat input files. For both crops we started with default data sets for the model WOFOST7.1.7 (WofostControlCentre, 2018). We then applied artificial fertilizer (50% NH_4-N and 50% NO_3-N) at a level of 200 kg/ha N, using a fertilization scheme based on data obtained from field visits in Argentina (Table 6.3). We calibrated the crop parameters using official yield statistics at county level (Min. AGPA, 2016).

Table 6.3 *Fertilization scheme for maize and wheat.*

Crop	Date of application	Dosage (kg ha-1)
Maize	03 October	50
Maize	15 November	150
Wheat	01 June	125
Wheat	01 August	75

6.2.3.5 Sensitivity analyses

To demonstrate the interaction of input parameter on various output values, impact response surfaces (IRS) are commonly used in crop modelling (Fronzek et al., 2018). We investigated the influence of the soil physical properties of the top soil layer (20 cm) on the flux through the bottom of the root zone, which may have positive (upward) or negative (downward) values. We focused on the soybean crop because it is the predominant crop in the region and in our analysis.

We used the results of the calibrated soybean simulation in Zavalla, including meteorological data for four years (2011-2014). Because it was expected that the depth of the groundwater table had a large influence on the results, we performed this exercise for eight different groundwater regimes varying from -500 to -150 cm. The influence of the soil physics of the top layer was investigated by changing saturated moisture content and saturated conductivity input values with a specified percentage. These percentages varied between -50% and +50% with 2% steps.

6.2.4 Regional scale

An analysis of time and space variations of actual yields and groundwater recharge was carried out using a distributed modelling approach. We introduced five different groundwater conditions and three different land use types which we analysed for their impact on crop yield and groundwater recharge.

6.2.4.1 Spatial schematization using soil, climate and land use

Spatial schematization was similar to the work by De Wit et al. (2017).

Overlays of maps from different gridded data sets for soil, climate and Gyga-ED zonation were made (De Wit et al., 2017). We used the detailed ISRIC WISE30sec soil map (Batjes, 2015), gridded datasets with meteorological information and a resolution of 0.25 degrees (Figure 6.1). The overlays resulted in 2842 unique calculation units which were used for distributed simulations. We used the same local weather data for the 6 selected sites (Table 6.2) and for the distributed modelling. To evaluate the accuracy an independent evaluation set was constructed and made available by INTA using daily data of 178 stations. For each station the most nearby grid cell was selected for each different data source. Minimum and maximum temperature, radiation and precipitation were included. In the vegetation and drought monitoring domain data are usually available at decadal time steps. Finally, it was decided to use different sources of meteorological data for precipitation and global radiation (De Wit et al., 2017).

The rainfall amounts show large temporal differences (Figure 6.4) with dry years like 1989 and 2008 that have a low median rainfall of 700 mm yr^{-1} and wet years like 2003 and 2012 that have a median rainfall of about 1200 mm. Years with most rainfall are 2002 and 2012 with values of more than 1600 mm yr^{-1}.

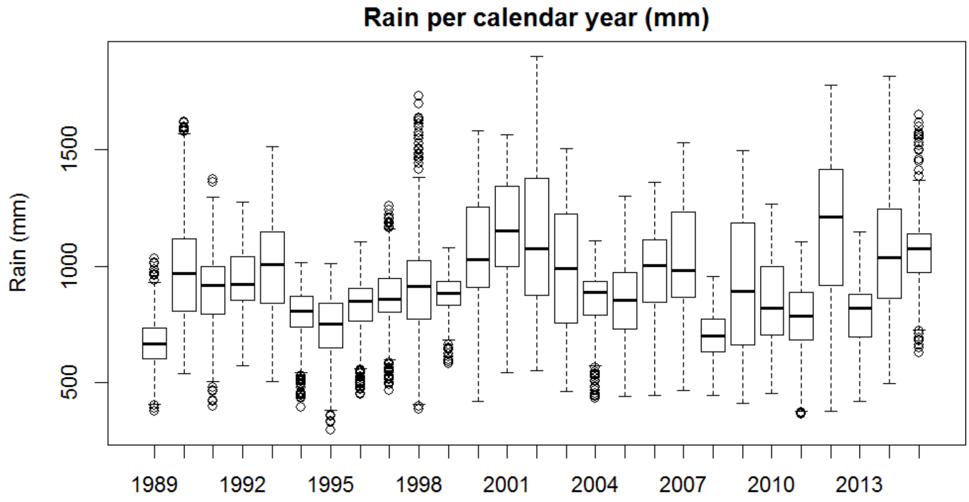

Figure 6.4 *Rainfall (mm yr^{-1}) in the Pampas for the years 1989 – 2015; values are given with a spatial variation as boxplots with median, quartile and extreme rainfall within all grids applied for the distributed modelling.*

The spatial differences are large (Figure 6.5), especially in the wet years 2002 and 2012. Rainfall increases from northwest to southeast.

For the evaluation of land use changes it was assumed that all grids have a dominant land use of either soybean, a crop rotation of soybean-wheat-maize or permanent grassland.

6.2.4.2 Soil physical parameters

Hydrologic analyses usually involve the evaluation of soil water infiltration, redistribution, percolation, capillary rise and plant-water relationships. To define the hydrologic soil water effects, knowledge of soil water characteristics for water potential and hydraulic conductivity is required. Although measuring these relationships in the field or laboratory is advised to obtain the best results, these measurements are time-consuming and expensive, especially if they have to be done for a large area. Statistical correlations can be found between these soil properties and other, more easily measurable soil variables such as texture, organic matter (OM), and structure. These pedotransfer functions (ptf) can provide estimates sufficiently accurate for many regional analyses and decisions (Saxton and Rawls 2006). For European soils the HYPRES database of pedotransfer functions (ptf's) has been developed (Wosten et al. 1999). For ptf's of soils from all over the world, another database has been created (Batjes, 2015). The main advantage of these databases is that they enable a direct link between the soil map and the soil physical characteristics. Recently, a review of the present state of ptf's has been published (Van Looy et al., 2017).

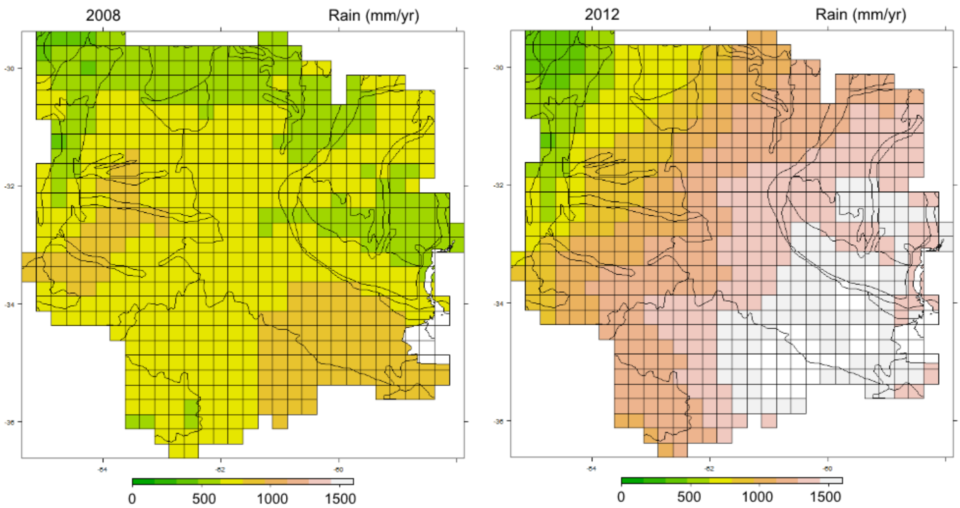

Figure 6.5 *Rainfall (mm yr^{-1}) in the dry year 2008 (left) and in the wet year 2012 (right).*

For Argentina Damiano (2018) developed and calibrated ptf's using local data. We applied these ptf's to generate soil physical input parameters which we applied in our regional analyses. Soil texture parameters for the ptf's were taken from Batjes (2015).

6.2.4.3 Increasing groundwater levels

We approached different groundwater levels using a Cauchy bottom boundary condition. This condition was preferred instead of using a fixed groundwater level, because it generates more realistic fluctuations of groundwater levels and especially more realistic fluxes across the bottom boundary.

This becomes especially relevant when simulating transport of several solutes simultaneously, like we did for salinity and nitrate.

We analysed 5 different bottom boundary conditions (BBC) using a vertical hydraulic resistance of 500 days and 5 different regional hydraulic heads (Table 6.4) in the groundwater aquifer below the simulated soil column of 5.5 m.

Table 6.4 Different bottom boundary conditions (BBC) applied in the regional analyses.

BBC nr	Regional groundwater head (m below soil surface)
1	>5.5 (Free drainage)
2	4
3	3
4	2
5	1

6.2.4.4 Land use evaluation with a crop rotation scheme and permanent grassland

We analysed the impact of land use changes by changing land use from soybean to i) crop rotations and ii) permanent grassland. These land use changes may well be introduced in practice and occurred in past and present as was described by (Viglizzo et al., 2009; Nosetto et al., 2013; Garcia et al, 2017).

For 3 crops, used in a rotation (soybean, wheat and maize), a preliminary test was executed to obtain realistic yields and phenology (paragraph 6.2.3.3 and 6.2.3.4). Subsequently a 25 year period was simulated using a 5-year crop rotation block consisting of the crop rotation sequence listed in Table 6.5 and fertilizer levels the same as at field scale (Table 6.3). We introduced a 5-year rotation to allow an introduction of 2 types of early soybean that are characterised by different dates for sowing and harvest (Table 6.5).

Table 6.5 A 5-year crop rotation sequence applied in the regional analyses.

Crop	Date Sowing	Date Harvest
Maize	01 October year 1	15 April year 2
Early Soybean	01 November year 2	25 April year 3
Wheat	01 July year 3	30 November year 3
Late Soybean	01 December year 3	01 August year 4
Maize	01 October year 4	15 April year 5
Early Soybean	01 October year 5	15 April year 6

For permanent grassland we used the static modelling option, which implies a fixed development of leaf area index and rooting depth, independent of climatic conditions and no simulation of crop yields. The leaf area index was fixed at a low value of 1.0 and the rooting depth at 30 cm. With these values a low productive permanent grassland with limited transpiration is simulated.

We applied free-drainage as bottom boundary condition for the evaluation of land use (Table 6.4, BBC nr 1).

6.3 Results

6.3.1 Field scale

6.3.1.1 Soybean calibration

Results of observed and simulated actual yields for the site in Zavalla (Figure 6.6) showed a good fit for the harvest-years 2012-2014. Calibration of the crop parameters resulted in an average potential yield of 5.9 t ha^{-1}. There is a relatively large difference between the simulated potential and simulated actual yields. The difference between potential and attainable yield was reduced by a management factor which was manually calibrated to a value of 0.88 and resulted in an average yield reduction of 0.7 t ha^{-1}. The management factor of 0.88 accounts for crop yield reduction processes, such as weeds, pests and diseases, which are not explained/described by our model. This value was regarded acceptable to explain difference between potential and attainable yield as discussed by Van Ittersum et al. (2013), who mentioned values ranging from 0.75 to 0.85. The remaining difference between potential and actual yield was largely caused by drought during the three years. Finally a mean actual yield of 3.2 t ha^{-1}. was simulated and regarded as a good result given the small difference of about 0.2 t ha^{-1} between simulated and observed actual yields.

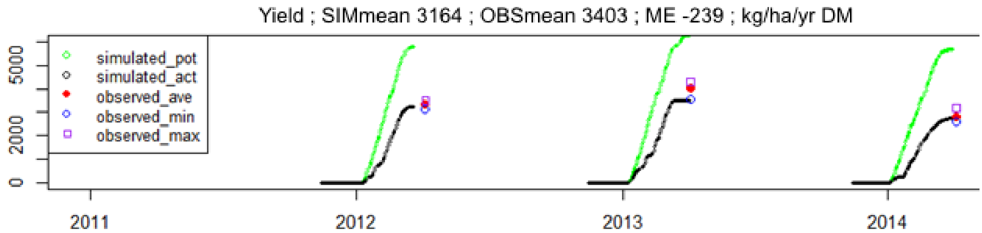

Figure 6.6 *Results for soybean at the Zavalla site: simulated and observed harvested yield of soybeans (kg ha^{-1} dry matter) for the calibration years 2011-2014.*

6.3.1.2 Actual soybean at six sites compared with official statistics at county level

We extended the simulations in space and time using 6 locations for a comparison with official statistics at county level.

A result of the comparison for Zavalla is given in Figure 6.7 showing simulated and observed yields for the period 1990-2010, a period for which statistics and model results were available. Simulated yields are higher than observed ones, indicating that we are not able to simulate all stress accurately. Our simulations for the Zavalla field neglect differences caused by variation in soil type, drainage condition and management. The statistics we used for comparison do have this variation in space and time. Given these differences in variation we think a long term yield difference of 856 kg ha^{-1} crop $season^{-1}$ is acceptable (Figure 6.7.)

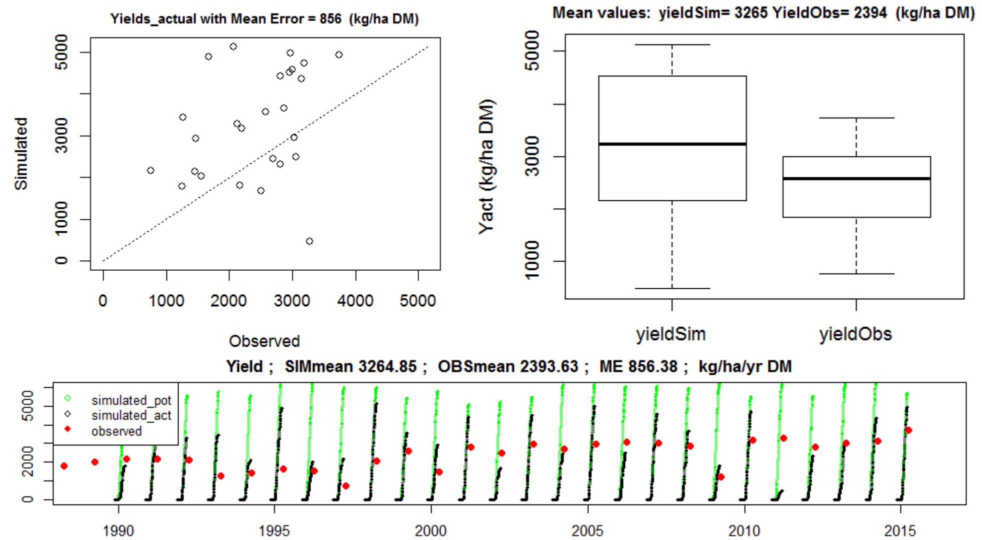

Figure 6.7 *Results for soybeans at the Zavalla site: Top left graph shows simulated and observed yields (kg ha^{-1} DM) from official statistics at county level for the period 1990-2015. Top right shows boxplot with median, quartile and extreme values. Lower graph shows the actual yields (kg ha^{-1} DM) during the period 1990-2015.*

The average of simulated and observed (official statistics at county level) values show that simulated results show differences similar to the statistics. The largest statistical differences (mean error ME and root mean square error RMSE) occur for Manfredi Rafaela (Table 6.6).

Table 6.6 *Observed and simulated soybean yields (kg ha^{-1} DM); Actual and potential simulated yield (Y_{act} en Y_{pot}) and observed yield (Y_{obs}) and the difference between actual yield and observed yield (Y_{diff}) given as average values for the period 1990-2015. Simulated values result from the integrated model SWAP. Observations result from official statistics at county level.*

Location	Y_{pot}	Y_{act}	Y_{obs}	Y_{diff}
SanAntonio	*5813*	*3064*	*2408*	*656*
Zavalla	*5853*	*3265*	*2408*	*856*
VenadoTuerto	*5907*	*2775*	*2537*	*238*
Rafaela	*5527*	*3185*	*2264*	*921*
Manfredi	*5799*	*3164*	*2003*	*1161*
LaCarlota	*5874*	*2659*	*1908*	*751*
Average	*2255*	*3019*	*764*	*764*

6.3.1.3 Maize and wheat

A result of the comparison for San Antonio de Areco for grain maize (Figure 6.8a and 6.8b) and wheat (Figure 6.8c and 6.8d) showed simulated and observed yields for the period 1990-2010, a period for which statistics and model results were available.

Resulting mean yields are within acceptable ranges. The differences within the statistical observations are larger than the differences within simulation results because the official statistics at county level include all spatial differences, while the simulations results are based on one soil type, drainage condition and management factor. Furthermore the simulated yields of both maize and wheat show much less variation than the observed yields which may also be caused by the use of one cultivar and less variation in soil types and drainage conditions than occurs within the region.

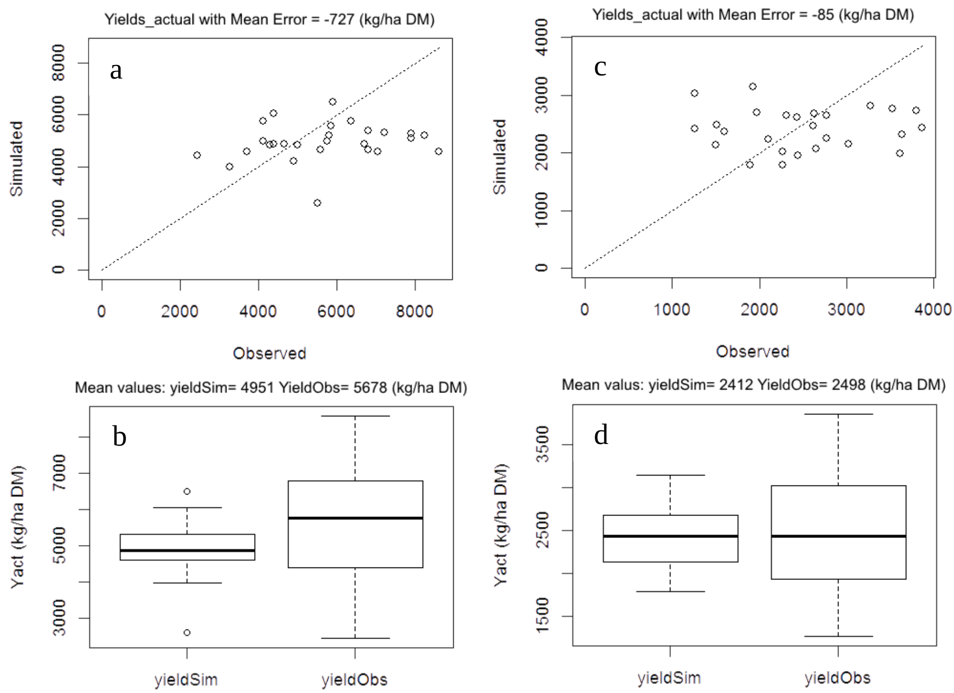

Figure 6.8 *Results for grain maize (a and b) and wheat (c and d) in San Antonio: Upper graphs simulated and observed yields (kg ha*$^{-1}$ *DM) from official statistics at county level for the period 1990-2015. Lower graph shows boxplot with median, quartile and extreme values.*

6.3.1.4 Sensitivity analysis

The impact of changes of hydraulic conductivity and moisture content on yield, groundwater recharge, vertical water flow to/from the root zone and runoff was analysed and results for the largest impacts are given as IRS-charts of the yearly average values in Figure 6.9.

Results show that both changing conductivity and moisture content influence the resulting yield and groundwater recharge. Crop yields are especially affected by a low hydraulic conductivity and moisture content (Figure 6.9a and 6.9b). The analyses of the effect of soil physical parameters on groundwater recharge (Figures 6.9c and 6.9d) show a larger sensitivity for hydraulic conductivity then for saturated moisture content. A more detailed analysis will be given by Wesseling et al (in prep).

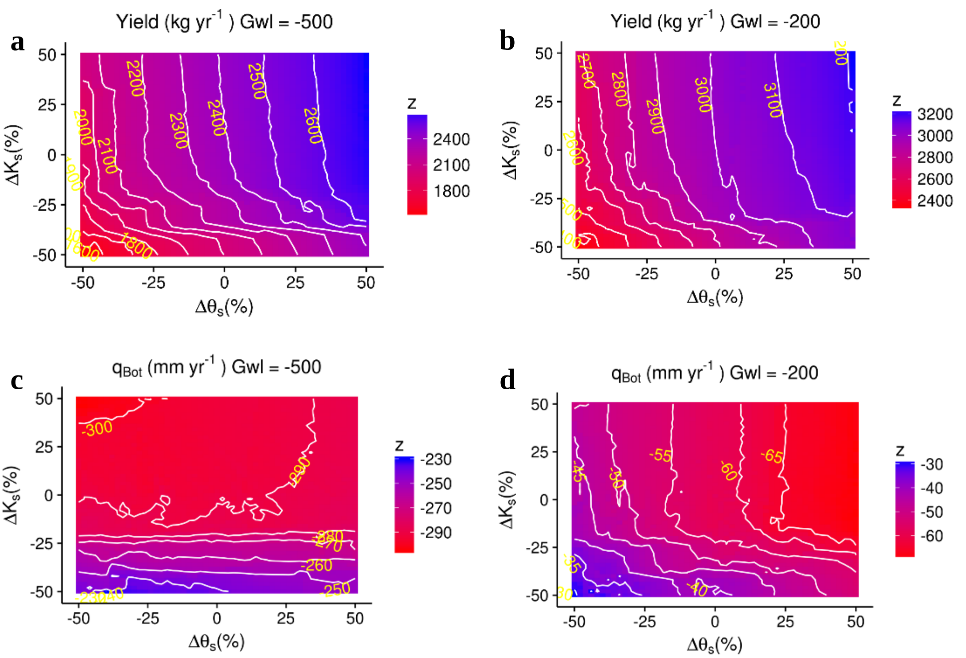

Figure 6.9 *Results of the sensitivity analysis: Impact on yield (kg ha^{-1} yr^{-1}) of K_s and $Θ_s$ using a groundwater level at an average depth of 500 cm (a) and 200 cm (b), and impact on groundwater recharge or bottom boundary flux (q_{bot} in mm yr^{-1}) using a groundwater level at an average depth of 500 cm (c) and 200 cm (d).*

6.3.2 Regional scale

6.3.2.1 Historical situation from 1990-2015

A soil hydrological scenario with deep groundwater (>5.5 m below the soil surface) was assumed. This scenario was simulated with the model SWAP using a hydrological bottom boundary condition of free-drainage (Table 6.4, BBC nr 1).

The average results of the spatially distributed simulations for the period 1990-2015 show an actual soybean yield (Y_{act}) of 2.8 t ha^{-1} DM (Dry Matter) and an upward and downward flux across the bottom of the root zone of respectively 99 and 72 mm crop season^{-1} (Table 6.7). The average downward flux across the bottom of the soil profile (groundwater recharge) is 209 mm yr^{-1}.

The actual yields and the groundwater recharge in dry 2008 and wet 2012 are presented in Figure 6.10 and 6.11. Soil types can be recognised in the spatial patterns of yield and groundwater recharge.

The groundwater recharge has relatively low median values, but shows a large spatial and temporal variation. In the wet year 2012 groundwater recharge is highest with values of more than 150 mm yr^{-1} in the soils in the NE part of the area.

6.3.2.2 Changes of groundwater levels

Five different drainage conditions were assumed in the simulations (Table 6.4) which resulted in groundwater levels fluctuating between depths of more than 5 meter to 1 m below soil surface. We analysed the impact of drainage conditions on yields and groundwater recharge.

Actual yields of soybean generally benefit when non-saline groundwater gets closer to the root zone. This was similarly predicted by our calculations showing a yield increase from 2.8 to 4.4 t ha^{-1} with increasing groundwater levels (Table 6.7). The upward flux to the root zone is 99 mm even in the case of free-drainage and increases to 249 mm when the groundwater level becomes shallow. This upward flux can be partitioned over a recirculation flux and capillary rise (Kroes et al., 2018). In free-drainage scenarios the upward flux is due to recirculation of percolation water and in the other scenarios with groundwater this upward flux is the sum of recirculation and capillary rise.

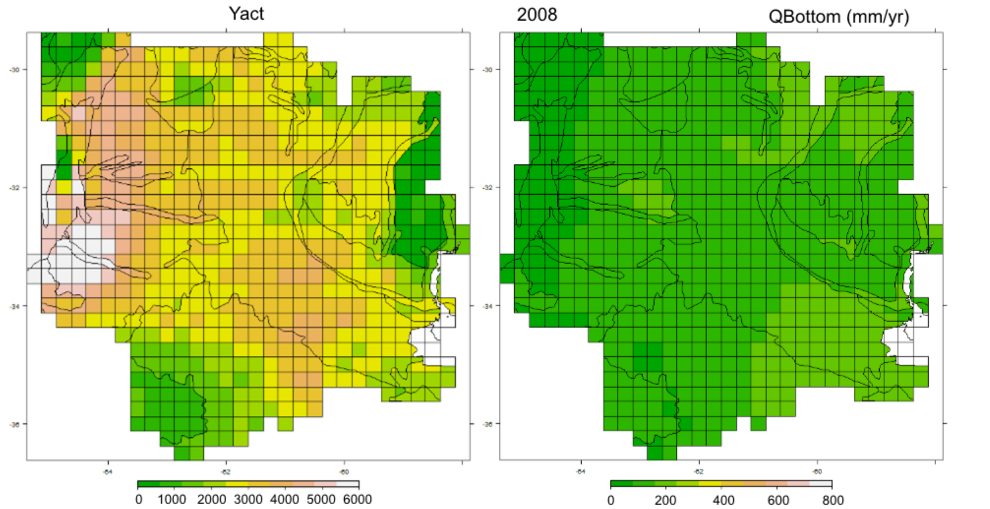

Figure 6.10 *Dry year 2008: Actual yields (kg ha^{-1} DM) (left) and groundwater recharge (mm yr^{-1}).*

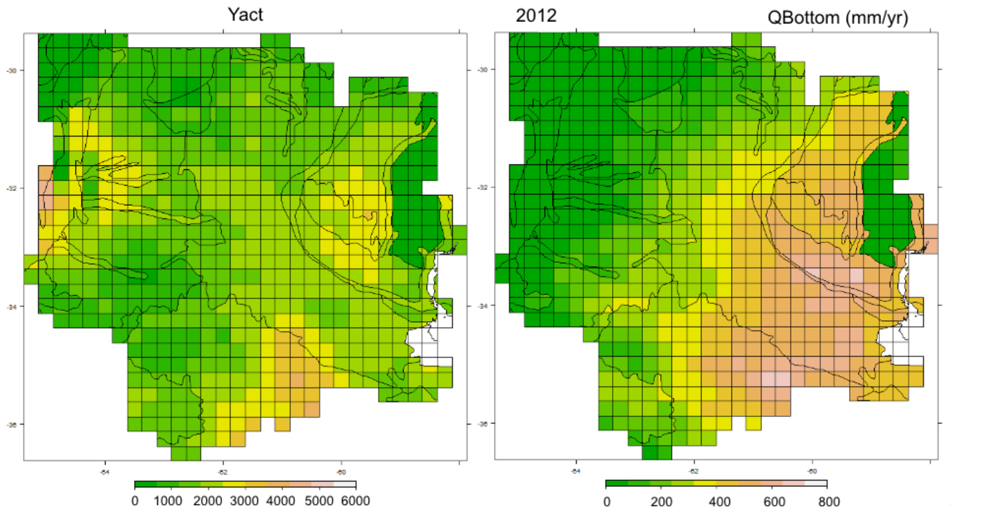

Figure 6.11 *Wet year 2012: Actual yields (kg ha^{-1} DM) (left) and groundwater recharge (mm yr^{-1}).*

Simulated crop transpiration increases from 421 to 530 mm during the cultivation period due to upward water fluxes caused by capillary rise and recirculation (Table 6.7). The average rainfall is 928 mm yr^{-1}; runoff increases and is highest in years with shallow groundwater. As groundwater levels increase, the downward flux across the bottom of the soil profile decreases from 209 mm yr^{-1} to an upward flux of 110 mm yr^{-1} under conditions with shallow groundwater.

The simulated flux across the root zone shows positive (upward) values (capillary rise) which increases as groundwater rises and a downward flux which is low and constant (Figure 6.12).

The increase is caused by the demand of the crop, which is refelected in an increasing yield as function of the upward flux across the bottom of the root zone (Figure 6.13). The net flux across the bottom of the root zone increases with a rising groundwater level (Figure 6.14), but the net flux across the bottom of the soil profile changes from a downward recharge to an upward extraction which will result in a lowering of the shallow groundwater (Figure 6.14).

Table 6.7 *Simulation results for soybean: average values for the period 1990-2015. Hydraulic head as bottom boundary condition and average groundwater level (Gwl), yield actual (Y_{act}) and potential (Y_{pot}), Actual transpiration (T_{act}), vertical flux across the bottom of the root zone during crop growth season, q_{RZ}^{up} is upward, q_{RZ}^{do} is downward flux, $q_{RZ}^{net} = q_{RZ}^{up} - q_{RZ}^{do}$, actual evapotranspiration from soil and crop (ET_{act}), and vertical flux across the bottom of the soil profile (q_{Bot}, positive values are upward, negative values are downward).*

Hydraulic head	Gwl	Y_{act}	Y_{pot}	T_{act}	q_{RZ}^{up}	q_{RZ}^{do}	q_{RZ}^{net}	Rain	Runoff	ET_{act}	q_{Bot}
(m -soil surface)		(kg ha^{-1} DM)		(mm season^{-1})				(mm yr^{-1})			
>5.5	6	2792	5753	421	99	72	27	928	18	692	-209
4	4	3127	5753	447	125	73	52	928	22	719	-180
3	3	3567	5753	479	159	74	85	928	34	755	-132
2	2	4085	5753	513	205	73	132	928	74	809	-41
1	1	4435	5753	530	248	60	188	928	163	871	110

6.3.2.3 Changes of land use

Three types of land use were simulated with free-drainage conditions: i) no tillage soybean, ii) rotation of maize-soybean-wheat, iii) permanent grassland.

The long term difference in average values of simulated groundwater recharge between crop rotation and soybean is about 1% (Table 6.8) which is small but has a large spatial and temporal variation with median changes of groundwater recharge that vary between 90% reduction and 55% increase.

Permanent grassland reduces long term average groundwater recharge with 72% from 209 to 59 mm yr^{-1} (Table 6.8) and has a similar large spatial and temporal variation with median changes of groundwater recharge that vary between 94% reduction and 6% increase.

Both the upward and downward vertical flux across the root zone is largest under permanent grassland due to the larger growing season. The downward flux across the bottom of the root zone is highest below grassland, but the bottom flux that contributes to groundwater recharge is lowest under permanent grassland due to its large recirculation flux (Table 6.8).

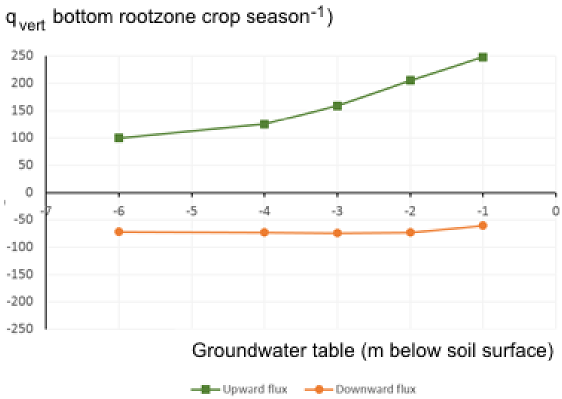

Figure 6.12 *Vertical water flux (q_{vert} in mm crop season^{-1}) across the lower boundary of the root zone as function of average groundwater level (m below soil surface); results for 5 different hydrological lower boundary condition; upward flux is positive, downward flux is negative.*

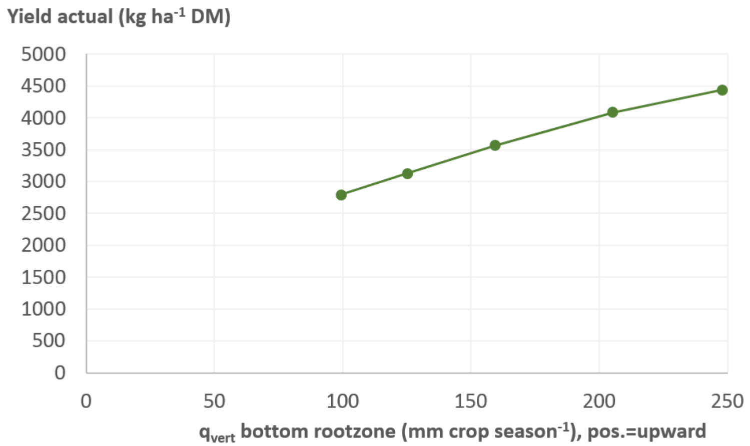

Figure 6.13 *Average actual yields (in kg ha^{-1} DM) as function of upward water flux (mm crop season^{-1}) across the lower boundary of the root zone.*

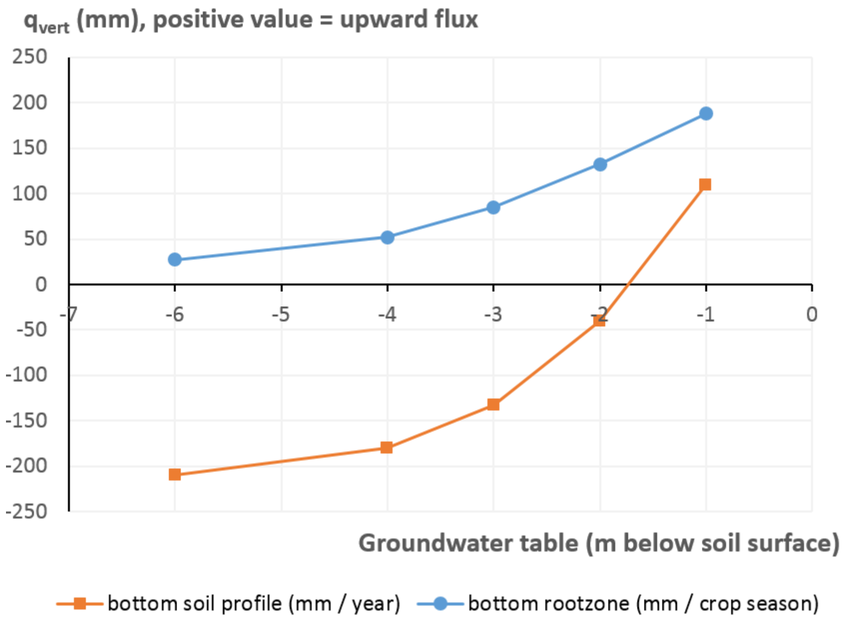

Figure 6.14 *Vertical water flux (mm) across the lower boundary of the root zone and across the lower boundary of the soil profile as function of average groundwater table (m below soil surface); results for 5 different hydrological lower boundary condition; upward flux is positive, downward flux is negative.*

Table 6.8 *Simulation results for soybean: average values for the period 1990-2015. Hydraulic head as bottom boundary condition and average groundwater level (Gwl), yield actual (Y_{act}) and potential (Ypot), actual transpiration (T_{act}), vertical flux across the bottom of the root zone during crop growth season, q_{RZ}^{up} is upward, q_{RZ}^{do} is downward flux, $q_{RZ}^{net} = q_{RZ}^{up} - q_{RZ}^{do}$, actual evapotranspiration from soil and crop (ET_{act}), and vertical flux across the bottom of the soil profile (q_{Bot}, positive values are upward, negative values are downward).*

Bottom Boundary Condition	Case Descr.	Y_{act}	Y_{pot}	T_{act}	q_{RZ}^{up}	q_{RZ}^{do}	q_{RZ}^{net}	Rain	Runoff	ET_{act}	q_{Bot}
		kg ha^{-1} DM		mm season^{-1}				mm yr^{-1}			
Free drainage	Soybean	2792	5753	421	99	72	27	928	18	692	-209
Free drainage	Crop rotation	2878	7439	345	70	66	5	924	17	695	-206
Free drainage	grassland			599	168	215	-47	924	20	832	-59

6.3.2.4 Changes of land use and nitrate leaching

A comparison was made for the nitrogen leaching under free-drainage conditions with soybean and the crop rotation. Results show that the nitrate leaching below a crop rotation is about 17% higher than the nitrate leaching below soybean (Figure 6.15a). Mean values of nitrate leaching for soybean and crop rotation are respectively 2.3 and 2.7 kg ha^{-1} yr^{-1} N. Mean values for ammonium are 0.2 and 0.3 kg ha^{-1} yr^{-1} N for respectively soybean and crop rotation. Leaching of ammonium hardly occurs because, if ammonium is produced by mineralisation of organic matter, it is rapidly transformed into nitrate by nitrification. The leaching of nitrate shows a large temporal and spatial variation with a larger variation for the crop rotation (Figure 6.16b) than for soybean (Figure 6.16a).

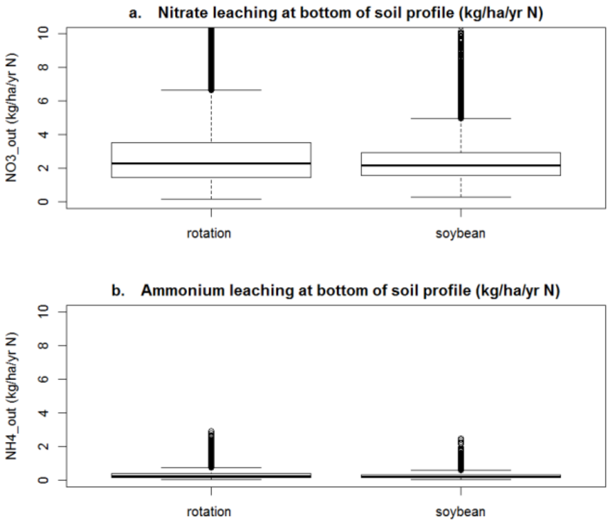

Figure 6.15 *Boxplots with simulated leaching of NO_3-N (figure a) and NH_4-N (figure b) influenced by crop rotation vs soybean under free-drainage conditions.*

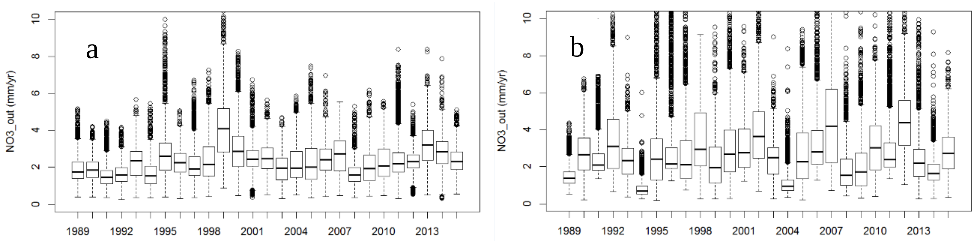

Figure 6.16 *Boxplots with simulated downward NO_3-N flux across bottom of soil profile (kg ha^{-1} yr^{-1} N). Figures (a) for soybean and (b) for crop rotation.*

When one divides the leaching of nitrate-N (2.7 kg ha^{-1} yr^{-1} N) over the groundwater recharge (q_{Bot} in Table 3.3) this results in an estimated yearly average level of nitrate leaching of about 1 mg/l NO_3-N. However if one regards the downward leaching of water from the rootzone (66 mm crop $season^{-1}$) the leaching of nitrate has a concentration of 4.1 mg/l NO3-N which is below the drinking water standard of 10 mg/l for NO3-N. In some regions higher values are found (Martínez et al., 2014) with large differences in space and time (Aparicio et al., 2008).

6.4 Discussion

Results for actual yields show a large variation for field sites within a region. Aramburu Merlos et al. (2015) estimated actual yields for a larger part of Argentina to be 2.65 t ha^{-1}, based on statistics. We simulated actual yields of 2.79 t ha^{-1} DM (Table 6.7). The relatively small difference can be caused by many reasons, such as other groundwater level fluctuations, a different soybean variety or a poor estimate of the management impact .

The calculated evapotranspiration for soybean shows a good agreement; Nosetto et al. (2012) determined 670 mm yr^{-1} which is close to the 692 mm yr^{-1} we calculated (Table 6.8) as long term average for a larger area and a long time series.

In order to lower groundwater levels and reduce the risk of flooding, groundwater recharge should be reduced. A minor reduction will be achieved by changing from monoculture soybean to crop rotations and a larger change will be achieved by changing to other types of land use like permanent grassland or trees. These land use systems will decrease groundwater recharge and contribute to the lowering of groundwater levels.
The recommendation for grassland and trees is in agreement with a study by Nosetto et al. (2012) who determined, for a region just north of our study region, high evapotranspiration of 1100 mm yr^{-1} for native forest and eucalyptus plantations compared to 670-800 mm yr^{-1} for herbaceous canopies.

Mercau et al. (2016) explored the impact of different crops on groundwater levels and concluded that crops do not have a substantial effect on the longer term dynamics of the water table. High groundwater levels offer an opportunity which should be carefully considered. It increases capillary rise, allows a more intensive use of irrigation and a higher variety of crops. Frequent on-farm and regional monitoring of groundwater levels should support cultivation strategies.

The simulations showed the sensitivity of yields, evapotranspiration and groundwater recharge for soil physical parameters. Soil physical properties play an important role in the distribution of the precipitation excess. We applied the ISRIC WISE30sec soil map (Batjes, 2015) with world soil property estimates and used it to transform soil texture into model parameters using so-called pedo-transfer (ptf) functions. Several datasets are available for different scales. Montzka et al. (2017) describe a global dataset based on ROSETTA (Schaap et al., 2001) applied to the SoilGrids1km data set of Hengl et al. (2014). Van Looy et al. (2007) give an overview of ptf's and recommend not to use ptf's beyond the region or soil type from which it was developed. The soils of the Pampas are very a-typical; therefore we refined the parameterisation using local and regional datasets. We used the ISRIC soil map in combination with local soil physical data from Damiano (2018). Further improvements can be achieved using more local soil information.

Long term NT (No Tillage) of soybean cultivation may cause a platy structure of soils in the Argentina Pampas (Sasal et al, 2017a and 2017b) which will have impact on the partitioning of the precipitation excess over surface and subsurface runoff and groundwater recharge. This impact is mainly caused by a reduction of rooting depth due to the poor permeability of the platy structured soils. We used a model experiment for the Zavalla site where we varied the maximum rooting depth to quantify the impact of platy soil structure on yield and groundwater recharge. Results show that the actual yields may be reduced from about 2.7 to 1.7 ton/ha DM and the groundwater recharge may increase from 246 to 331 mm (Figure 6.17).

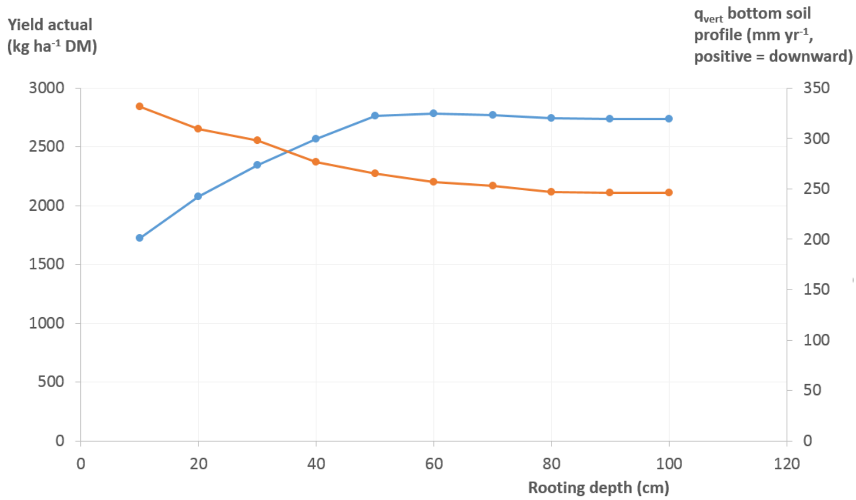

Figure 6.17 *Results of limited rooting depth on actual yield and on groundwater recharge q_{Bot}. Upper figure: actual yield (kg ha^{-1} DM) as function of maximum rooting depth (cm). Lower figure: Groundwater recharge (q_{Bot} in mm yr^{-1}) as flux across bottom of soil profile.*

Lowering groundwater without irrigation causes drought and successive crop and yield damage. In the Pampas of Argentina irrigation is marginal. However with the rising groundwater irrigation may increase which may contribute to increased evapotranspiration and, as a consequence, lower the groundwater again.

Salinity is an important issue when saline groundwater rises above critical levels (Nosetto et al. (2013). Salinity control measures were evaluated for the Mendoza area by Kupper et al. (2002) who applied the regional hydrological model SIMGRO and concluded that using more groundwater is an effective measure to control salinity in the root zone.

We carried out a regional scale analysis with salinity levels of 3 g l^{-1} in the upward seepage water flux across the bottom boundary for situations with average groundwater level at 2 and 1 meter below the soil surface. Results showed a very low impact on soybean yields. However this is not representative for the relation between land use and salinization which should be analysed in a broader perspective (Nosetto et al., 2013) because for more salt sensitive types of land use an increase of salinity may have a large impact.

The use of remote sensing was limited in this study, but future developments will facilitate increase of its use. Land use maps at field scale level like crop type (needed for rotations) are not easy to obtain for Argentina. New procedure are being developed at INTA to generating new land use maps and to facilitate the choice of meteorological data.

A regional analysis with real-time observations of groundwater levels was beyond the scope of this study. However several monitoring sites exist (Aragón et al., 2010; Kuppel et al., 2015) and intensification is under way. This may support early warning systems (Viglizzo et al., 2009) and enable a regional study using realistic groundwater levels as bottom boundary or as calibration in future studies.

Opportunities are created when a proper balance is found between supply and demand of soil water using a larger differentiation of land use. Increasing the areas of land use types with higher evapotranspiration, like permanent grassland and trees, will contribute to a more stable hydrologic system with more water storage capacities in the soil system and lower groundwater levels.

6.5 Conclusions and recommendations

Based on several modelling exercises the findings can be summarized as:

- Groundwater recharge from the unsaturated zone and from the root zone shows large differences and should be analysed separately
- Rising groundwater has an impact on agricultural production with large spatial and temporal differences
- Rising groundwater may reduce groundwater recharge (negative feedback)
- Crop rotations may increase risk of nitrogen leaching when compared to monoculture no-tillage soybean
- Multi-crop rotations may decrease groundwater recharge when compared to monoculture no-tillage soybean
- Platy soil structure under no-tillage soybean reduces yields and increases groundwater recharge

- Increasing the areas of land use types with higher evapotranspiration, like permanent grassland and trees, will contribute to a more stable hydrologic system with more water storage capacities in the soil system and lower groundwater levels
- Monitoring of groundwater levels at field and regional scale should be intensified to support early warnings systems and future studies
- Model analyses support the search to find a proper balance between positive and negative impacts of land use changes

7. Synthesis

7.1 Introduction

As indicated in the general introduction (chapter 1) of this thesis, water and its limitations in quantity and quality will require an increasing demand to analyse complex environmental problems in a sustainable way. The relations between soil water flow and crop growth are part of a complex system which needs multi-disciplinary approaches involving insight into soil physical and plant physiological processes. The interaction between soil and crop is often studied using large, even global, scale models that were developed at field scale. Modellin water limited crop growth under different land use and climate conditions is complex and often carried out using simplified approaches to quantify evapotranspiration flows and crop assimilation.
This research contributes to improved quantification of drought, aeration and salinity limited crop growth and yield predictions using new approaches for soil water flow and crop growth modelling with a focus on upward water flow to roots and transpiration as the essential link between soil water and crop growth. New methods developed in this thesis have been tested using data sets from several field experiments. Their upscaling resulted in methods and innovation at different spatial scales.

The main objective of this thesis is a contribution to achieve sustainability goals in the water-food domain using dynamic tools with a physical base that give insight into the cause of problems. This implies numerical modelling in a detailed, complex way that often raises the question: is this detail and complexity really necessary?

7.2 Major Findings

An answer to the research questions posed in the general introduction (chapter 1) will be given in this section. These findings are based on the results presented in the chapters 3 to 6.

7.2.1 The role of capillary rise and recirculated percolation water in the determination of crop yields

In regions with groundwater levels less than two meter below the soil surface, the impact of capillary rise and recirculated percolation water is important. Both contribute equally to the upward water flow to the root zone as shown in chapter 3. In 85% of the Netherlands groundwater is within 2 meters from the surface, whereas in some regions in the south and east of the Netherlands groundwater is deeper and capillary rise is irrelevant. However, in these regions the recirculation of percolation water occurs and should be taken into account.

Neglecting the impact of capillary rise and recirculated percolation water implies underestimating the production of dry matter and predicting lower yields. For grassland, maize and potatoes we simulated yields reductions of 26, 3 and 14 % corresponding to 3.7, 0.3 and 1.5 ton dry matter per ha.

7.2.2 Modelling drought, salinity and oxygen stress to predict crop yields

In chapter 4 we have shown that the impact of drought, salinity and oxygen on agricultural crop yields can be accurately quantified as demonstrated by an extensive comparison with field scale experiments. In order to achieve this we developed a new method that links dry, saline and wet conditions to an existing crop growth module. This new method can be used by farmers, regional governments, water boards and others to assess crop yield reductions due to surface water and groundwater changes.

7.2.3 Predicting the impact of different stresses on grassland production in the Netherlands

In non-irrigated areas, corresponding to about 82% of the Netherlands, droughts have a much larger impact on grass production than the excess of water and salinity. In chapter 5 we have modelled both current and future climate scenarios and generally found that increasing CO_2 concentrations and temperatures stimulate grass growth and yields as long as water (rainfall) is sufficient. Increasing salt concentrations and water excess have a limited effect on grass production. The considered future climate scenarios generally show increasing potential and actual yields as well as an increased demand for irrigation water of 11-19%. Irrigation will compensate water deficit and contribute to increasing yields but only in those parts of the Netherlands where enough irrigation water of sufficient quality is available.

7.2.4 Changes of groundwater levels and land use affect crop yields and groundwater recharge

Increasing groundwater levels generally benefit crop yields because the resulting increase in capillary flow decreases drought stress for the crops. In chapter 6 this is analysed for a soybean crop in the pampas of Argentina.
The long-term agricultural no-tillage management with soybean has a strong impact on the groundwater depth because of associated relatively low evapotranspiration. This results in increased groundwater recharge and increasing groundwater levels. Changing land use from soybean into crop rotations has a limited effect on the reduction of groundwater recharge and groundwater levels. However, in the case of crop rotation leaching of nutrients like nitrate may increase.

When groundwater levels get close to the soil surface flooding will occur. More variation and especially more continuous types of land use such as grassland and forest are therefore recommended as one of the options to lower groundwater levels and thereby increase storage capacity of the soil and reduce flooding risk.

7.3 Discussion

7.3.1 Key Issue 1: Physical base for interactions between soil hydrology and crop growth

The core of this thesis is about the relations between soil hydrology and crop growth. To establish a good understanding of these relations, the upward water flow can be modelled using hydraulic head gradients as driving force. The physical base for mathematical solutions of soil water flow, as formulated by Richards (1929 and 1931) and Richardson (1922), nowadays forms the foundation for numerical solutions applied by many in hydrological research of the critical zone.

Using a more process-oriented modelling approach provides a better insight into the cause of the problems that occur when one tries to model natural systems. This physics based

modelling approach is based on an extended version of the Richards equation as explained in more detail in chapter 2.
In particular, we have shown for modelling of crop yields in the Netherlands (chapters 3-5) that upward flow is an important part of water flow towards crop root systems as a result of the prevailing shallow groundwater condition. Similarly, when modelling saline groundwater (chapter 5), describing the upward flow of water and salts to the root zone is needed to accurately model crop yields and long-term salinization. In chapter 6, again, it is shown that a shallower groundwater level results in increased upward flow, decreasing crop drought stress.

The dynamic integration of a Richards based soil hydrology and generic crop growth modelling has reached an operational level which can be seen from the overview of applications on the page with References at the SWAP web site (http://swap.wur.nl/).
The dynamic coupling between soil hydrological processes and crop growth supports progress for some of the major challenges in hydrological modelling of the biosphere as proposed by Wada et al. (2017).

This type of modelling also supports the analysis of interaction between soil processes and crop growth (Vereecken et al., 2016), supports at least 7 of the 17 Sustainable Development Goals (SDGs) (Keesstra et al., 2016; Tóth et al., 2018) and supports analyses in the nexus between Water, Energy and Food (FAO, 2015b). Furthermore it contributes to more advanced research on process-oriented approaches as proposed recently by Vereecken et al. (2016) and Clark et al. (2017).

7.3.2 Key Issue 2: The importance of field experiments for multiscale applications

The demand from society and politics requires analysis of agricultural issues at different spatial scales such as field, regional, national and global scale. While the large scale is often most relevant to politics, the smaller scale is demanded by local participants such as farmers, researchers and extension agents. Taking land use at field scale as starting point has the advantage that we can deal with well-defined crop types, cultivation and management measures, soil profiles and properties and drainage conditions, for which geographic data are commonly available. At the same time, the smaller scale is also essential to test new model concepts and to analyse measures that are derived from large scale analyses but have to be applied at field/farm scale. A flexible modelling at different scales is also needed to analyse results at different scales: national statistics are generally a summation of field data and measures need to be translated to field scale.

Flexibility of modelling at different spatial scales is not common practice but, in my view, it should be a requirement. Increase of scale may increase uncertainty, especially when complexities in the system are simplified to achieve manageable modelling input (Oreskes, 1998).

In chapter 3, a new method was introduced to partition upward flow in a flow caused by capillary rise and a flow caused by recirculation. This new partitioning method was verified using six field experiments and in a next step it was applied to all soil units of the Netherlands.

Chapter 4 describes a new method to partition crop stress according to its causes (too dry, too wet or too saline) using dynamic coupling of soil water and crop growth. Tests were carried out at field level, then scaled to national level and a so-called meta-model was derived from the scaled results. The meta-model allows a quick application at regional level using key input data.

Chapter 5 describes a new method for dynamic grassland modelling: modelling the impact of saline groundwater on crop growth to quantify current and future grassland yields. The method was tested with three field experiments and scaled to national level of the Netherlands.

Chapter 6 describes a new method to model the crop soybean in Argentina using N-fixation and N-mineralisation and the upward water flow under different hydrological conditions. This new method was tested at field scale using local field and statistical data and was then extended to the pampas of Argentina.

The model approach in chapters 4 – 6 uses multiple spatial scales that range from field to region and is summarized in Figure 7.1. The core of this approach (A) has been tested for several experimental fields where water and crop growth data were available (B). For most cases Dutch field experiments were used, but the last case study also uses field experiments from Argentina.

For each case study the testing phase is succeeded by a period of data collection and analyses of farm management, soil information and weather data with an increasing importance of the role of remote sensing (C). Next follow GIS analyses like overlays (D) resulting in spatially unique units which serve as essential starting point for the regional analyses (E). The regional analyses may have several purposes, but generally they will result in policy measures that are to be applied at field scale. Besides, it is most likely they will generate new reseach questions and increase scientific knowledge.

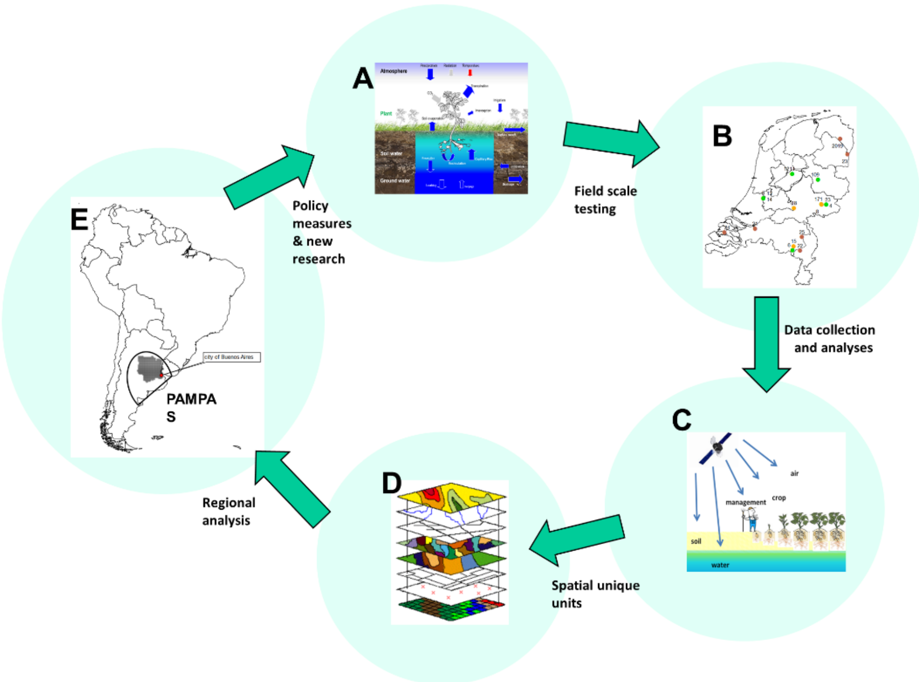

Figure 7.1 *Model approach at multiple scales.*

7.3.3 Key Issue 3: The search for sustainable agricultural systems to support global food production

Sub-optimal use of natural resources generally does not result in sustainable agricultural systems. Since the United Nations have defined sustainability goals in 2015 (UN, 2015) an increased pressure lies on policy makers to develop sustainable agricultural systems. To achieve this, the use of natural resources, especially fresh water, needs to be optimized.
When we quantify the gap between potential and actual yields and indicate where improvements can be made, this precisely serves the purpose of improving sustainability. In chapters 3-5 methods are presented and applied to quantify actual yields for the Netherlands. In chapter 6 a similar analysis for Argentina is performed with rising groundwater levels that threaten a sustainable system. We show that changes of land use can help alleviate this threat.

7.4 Implications and contribution to science

During the next decades food production should increase, putting pressure on fresh water demand. Water and food together with energy are essential resources for well-being, poverty reduction and sustainable development (FAO, 2015b) and are a common cause of competition and conflicts. Optimization of fresh water use will become increasingly important. With this thesis it is shown that a Richards equation-based simulation of water flow to the root zone and crops contributes to improved estimates of crop yield. Neglecting the flow of water under the rooted zone implies in subestimating crop yield by as much as 20% (Chapter 3) and may therefore have a drastic effect on economic models and derived policies. Similarly, neglecting this flow will overestimate the groundwater recharge. As a result of this, the availability of drinking water and the risk of flooding may be overestimated.

Dynamic interaction between hydrology and dry matter production is simulated at multiple scales with models and tools that are developed at field scale. Only a few crop models have the water balance as core and link crop growth to detailed soil moisture flow. The integration of SWAP and WOFOST into SWAP4 is a model which combines a physical approach for water flow with a generic approach for crop growth. Different approaches are compared and explicit attention is given to modelling at multiple scales. The outcome of this thesis will also contribute to improved simulations of inter-annual changes of crop yields. This thesis resulted in improved tools which are available as public domain and disseminated in publications and through distribution via internet (swap.wur.nl).

7.5 Limitations and recommendations

7.5.1 Parameters

The modelling approach applied in this thesis certainly has limitations. Accurate modelling requires knowledge of soil physical data, especially the relation between water content, pressure head en hydraulic conductivity. While these data are sometimes difficult to obtain on smaller scales they are needed with increasing demand (Vereecken et al., 2016). Use of pedotransfer functions may be an alternative to estimate soil hydraulic functions. Soil hydraulic functions are generally based on laboratory conditions which differ from actual field conditions. This implies in the fact that these functions should be applied with care for field conditions. Soil hydraulic functions valid for redistribution of stored water may not generally be applicable to infiltration due to hysteresis in the water retention function

(Norman, 2013). Collecting soil physical parameters under field conditions is recommended but not common practice.

The partition of precipitation into soil surface infiltration and runoff is strongly determined by soil physical parameters. In chapter 6 we used local data to model the surface runoff. Despite the inclusion of accurate data based on local crop variations and soil physical data, our simulated surface runoff is generally too low. This may be improved in several ways such as: i) use empirical data and subtract them from rainfall to lower surface infiltration, ii) adjust soil physical data to the platy structure of soils, iii) adjust the parameters of the surface runoff sub model in SWAP to fit an experimental field data set, iv) use actual rain durations/intensities instead of daily rainfall amounts.

Crop parameters are sometimes hard to get. We integrated the soil hydrological modelling therefore with the generic crop growth model WOFOST which has been applied extensively in many parts of the world. Calibration is often required for specific locations/regions but default settings are available as well as calibration procedures (see e.g. Akkermans et al., 2008).

Root water uptake can be improved using better parameters describing the relationships between root biomass, rooting depth, root distribution and root functions with land-use type, soil type, soil texture, topography and climate (Feddes & Raats, 2004). One new method to improve modelling of drought stress with SWAP4 simulates microscopic water flow to roots, including radial and axial hydraulic resistances within the plant system from root surface to leaf stomata (De Jong van Lier et al., 2013). However, this method needs further testing at field scale to find proper parameter sets.

7.5.2 Processes

Some processes have been implemented in the model but not used in this thesis: soil compaction, hysteresis and macropore flow. In the Argentina study (chapter 6) we could have simulated soil compaction by changing soil physics, but limited ourselves to reducing rooting depth in a discussion section because that would have most impact on crop yields. Additional processes require more local data and analyses which went beyond the scope of our study.

The partitioning of evapotranspiration over crop and soil has been modelled but could not be verified using field experiments. This verification is difficult because the fluxes are not directly observable. Isotopes are increasingly used, and may provide a mean to verify this partitioning method.

Not all processes that occur in nature have been modelled; for instance preferential flow, dual porosity, and ozone variation have not been implemented. Furthermore we applied a 1D approach whereas for some crops or processes (intercropping, drip irrigation) a 2D- or 3D-approach is recommended. Yet other processes are modelled incompletely. For instance, the types of crop stress implemented in the model are drought, oxygen, salinity and nitrogen deficit. Other crop growth factors that may be taken into other account are availability of other nutrients (phosphorus, potassium), and management of weeds, pests and diseases. Improvement and extension of these growth factors is needed to enlarge the modelling domain.

7.5.3 Model approach

The Richards equation itself has its intrinsic limitations. It is valid for variably saturated, heterogeneous, isotropic, rigid, isothermal porous media and incompressible water (Heinen, 1997).

We implemented and applied a nitrogen extension for the WOFOST crop module using an approach based on Shibu et al. (2010). The implementation in SWAP4 was tested on a few fields, but needs further verification using different fertilizer levels. We applied the carbon and nitrogen cycle of the soil for the root zone as one reservoir, but it is recommended to extend this using a multi-layer approach, especially if more reactive elements like phosphorus will be implemented. For a relation with nutrient stress the phosphorus is missing and should also be implemented both in crop and soil. Its importance will increase as the global phosphorus availability increases.

In the past, applications of the Richards equation have been criticized for being computationally too expensive for operational use (Short et al., 1995). Nowadays however, this is no longer an issue. For example, our simulations for the Argentina pampas (2842 calculation units, 27 years each) required less than 30 minutes when a grid of computing facilities (100 cores) are used, commonly available at low costs.

The dynamic integration of a Richards equation-based soil hydrology and dynamic crop growth modelling has reached an operational level. This supports the closure of the gap between dynamics of soil processes and crop growth and contributes to more advanced research on process-oriented approaches as proposed recently by Vereecken et al. (2016) and Clark et al. (2017).

To reduce uncertainty it is recommended to carry out sensitivity analyses which give insight in the contribution of different sources of uncertainty to the model results. Such an analysis has been carried out by Wesseling et al. (1997) for the soil hydrological system. However, an extended analyses for the integrated soil hydrology – crop system is needed. While first steps have been made (Mulder et al., 2016), Stahn et al., 2017), these should be improved and extended. Modelling of complicated processes requires special attention to calibration and verification to avoid errors in models and observations (Oliver & Alfonzo, 2018)
The additional description of soil carbon and nitrogen cycle processes to the SWAP model opens new fields of applications which are recommended for future studies. Examples include i) modelling biomass as an ecosystem service (Vereecken et al. 2016), ii) the possibility to include phosphorous cycle, and iii) improved groundwater recharge.

In conclusion, I hope this work will convince the reader that complex modelling is necessary and provides valuable insight into the processes underlying the interaction between soil hydrology and crop growth.

Literature cited

Aarts, H.F.M., 2003. Strategies to meet requirements of the EU-nitrate directive on intensive dairy farms. Proceedings No. 518, International Fertiliser Society, York, UK. 28 pp. Available at http://fertiliser-society.org/Proceedings/US/Prc518.HTM , accessed last on 5 June 2018.

Ahuja, L.R., Ma, L., Lascano, R.J., Saseendran, S.A., Fang, Q.X., Nielsen, D.C., Wang, E., Colaizzi, P.D., 2014. Syntheses of the Current Model Applications for Managing Water and Needs for Experimental Data and Model Improvements to Enhance these Applications, in: Practical Applications of Agricultural System Models to Optimize the Use of Limited Water. pp. 399–437. Available at http://doi.org/10.2134/advagricsystmodel5.c15 , accessed last on 5 June 2018.

Akkermans, W., Te Roller, J., Boogaard, H., De Wit, A., Wolf, J., Hessel, R. 2008. CALPLAT : platform for calibrating CGMS; ASEMARS report 5.2.1.

Allen, S.G., Idso, S.B., Kimball, B.A., Baker, J.T., Allen, L.H., Mauney, J.R., Radin, J.W., Anderson, M.G., 1990. Effects of air temperature on atmospheric CO2-plant growth relationships. Report TR048. U.S. Dep. of Energy/U.S. Dep. of Agriculture, Washington DC, USA.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation and Drainage Paper 56, FAO, Rome, Italy, 300 p. Retrieved from http://www.fao.org/docrep/X0490E/X0490E00.htm, accessed on 7 May 2018.

Amthor, J.F., 2000. The McCree–de Wit–Penning de Vries–Thornley respiration paradigms: 30 Years Later, Ann Bot, 86, 1-20.

Amundson, R., Richter, D.D., Humphreys, G.S., Jobbágy, E.G., Gaillardet, J., 2007. Coupling between biota and earth materials in the critical zone. Elements, 3(5), 327–332. http://doi.org/10.2113/gselements.3.5.327

Aparicio, V., Costa, J.L., Zamora, M., 2008. Nitrate leaching assessment in a long-term experiment under supplementary irrigation in humid Argentina. Agricultural Water Management, 95(12), 1361–1372. http://doi.org/10.1016/j.agwat.2008.06.003

Aragón, R., Jobbágy, E.G., Viglizzo, E.F., 2010. Surface and groundwater dynamics in the sedimentary plains of the Western Pampas (Argentina). Ecohydrology, 4(3), 433–447.

Aramburu Merlos, F., Monzon, J.P., Mercau, J.L., Taboada, M., Andrade, F.H., Hall, A.J., Jobaggy, E., Cassman, K.G., Grassini, P., 2015. Potential for crop production increase in Argentina through closure of existing yield gaps. Field Crops Research, 184, 145–154. http://doi.org/10.1016/j.fcr.2015.10.001.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P.J., Rötter, R.P. Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P.K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A.J., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L.A., Ingwersen, J., Izaurralde, R.C., Kersebaum, K.C., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J.W., Williams, J.R., Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nature Climate Change, (June). 1–6. https://doi.org/10.1038/ncliamte1916

Awan, U.K., Tischbein, B., Martius, C., 2014. A GIS-based approach for up-scaling capillary rise from field to system level under soil-crop-groundwater mix. Irrigation Science, 32(6), 449–458. http://doi.org/10.1007/s00271-014-0441-5.

Babajimopoulos, C., Panoras, A., Georgoussis, H., Arampatzis, G., Hatzigiannakis, E., Papamichail, D., 2007. Contribution to irrigation from shallow water table under field conditions. Agricultural Water Management, 92(3), 205–210.

Bartholomeus, R.P., Witte, J.P.M., van Bodegom, P.M., van Dam, J.C., Aerts, R., 2008. Critical soil conditions for oxygen stress to plant roots: substituting the Feddes-function by a process-based model, Journal of Hydrology, 360, 147–165. https://doi.org/10.1016/j.jhydrol.2008.07.029

Bartholomeus, R.P., Witte, J.P.M., van Bodegom, P.M., van Dam, J.C., de Becker, P., Aerts, R., 2012. Process-based proxy of oxygen stress surpasses indirect ones in predicting vegetation characteristics. Ecohydrology, 5(6): 746-758. https://onlinelibrary.wiley.com/doi/epdf/10.1002/eco.261

Bastiaanssen, W.G.M., Allen, R.G., Droogers, P., D'Urso, G., Steduto, P., 2004. Inserting Man's Irrigation and Drainage Wisdom into Soil Water Flow Models and Bringing it Back Out: How Far Have We Progressed ? Unsaturated-Zone Model. Progress, Challenges Appl. 263–299. Available at https://library.wur.nl/ojs/index.php/frontis/issue/view/197, accessed last on 2 June 2018.

Bastiaanssen, W.G.M., Allen, R.G., Droogers, P., Urso, G.D., Steduto, P., 2007. Twenty-five years modeling irrigated and drained soils : State of the art. Agricultural Water Management, 92, 111–125. http://doi.org/10.1016/j.agwat.2007.05.013

Batjes, N.H., 2015. World soil property estimates for broad- scale modelling (WISE30sec). ISRIC Report 2015/01. Belmans, C., Wesseling JG, Feddes RA, 1983. Simulation of the water balance of a cropped soil: SWATRE. J. Hydrol., 63, 271-286.

Ben-Gal, A., Karlberg, L., Jansson, P.E., Shani, U., 2003. Temporal robustness of linear relationships between production and transpiration. Plant Soil 251, 211–218. https://doi.org/10.1023/A:1023004024653.

Bessembinder, J., Leffelaar, P., Dhindwal, A., Ponsioen, T., 2005. Which crop and which drop, and the scope for improvement of water productivity. Agricultural Water Management 73(2):113-130.

Bierhuizen, J.F., Slatyer, R.O., 1965. Effect of atmospheric concentration of water vapor and CO_2 in determining transpiration photosynthesis relationships of cotton leaves. Agricultural Meteorology, 2, 259 270.

Bigiarini, M.Z., 2013. Package " hydroGOF "; R-package from www.r-project.org/ (accessed on 7 May 2018).

Black, T.A., Gardner, W.R. , Thurtell, G.W. , 1969. The prediction of evaporation, drainage, and soil water storage for a bare soil. Soil Sci. Soc. Am. J., 33, 655-660.

Boesten, J.J.T.I., Stroosnijder, L. , 1986. Simple model for daily evaporation from fallow tilled soil under spring conditions in a temperate climate. Neth. J. Agric. Sci., 34, 75-90.

Boesten, J.J.T.I., van der Linden, A.M.A., 1991. Modeling the influence of sorption and transformation on pesticide leaching and persistence. J. Environ. Qual., 20, 425-435.

Bonfante, A., Basile, A., Acutis, M., Mascellis, R. De, Manna, P., Perego, A., Terribile, F., De Mascellis, R., Manna, P., Perego, A., Terribile, F., 2010. SWAP, CropSyst and MACRO comparison in two contrasting soils cropped with maize in Northern Italy. Agric. Water Manag. 97, 1051–1062. https://doi.org/10.1016/j.agwat.2010.02.010

Bonfante, A., Basile, A., Manna, P., Terribile, F., 2011. Use of Physically Based Models to Evaluate USDA Soil Moisture Classes. Soil Sci. Soc. Am. J. 75, 181. https://doi.org/10.2136/sssaj2009.0403

Boogaard, H.L., van Diepen C.A., Rötter R.P., Cabrera, J.M.C.A., van Laar, H.H., 1998. WOFOST 7.1; user's guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Center 1.5. Wageningen, SC-DLO. Techn. Doc. 52.

Boogaard, H., Wolf, J., Supit, I., Niemeyer, S., Ittersum, M., 2013. A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union. Field Crops Research, vol143, 2013, p. 130-142.

Boogaard, H.L., Van Diepen, C.A., Rötter, R.P., Cabrera, J.M.C.., Van Laar, H.H., 2014. WOFOST Control Centre 2.1 and WOFOST 7.1.7 - User's guide for the WOFOST CONTROL CENTRE 2.1 and the crop growth simulation model WOFOST 7.1.7. Available at https://www.wur.nl/en/Research-Results/Research-Institutes/Environmental-Research /Facilities-Products/Software-and-models-WENR/WOFOST/Documentation-WOFOST.htm accessed last on 21 May 2018.

Boons-Prins, E.R., de Koning, G.H., van Diepen, C.A., Penning de Vries, F.W.T., 1993. Crop-specific simulation parameters for yield forecasting across the European Community. Reports CABO-TT, no 32.

Bouma, J., 1981. Soil morphology and preferential flow along macropores. Agricultural Water Management, 3(4), 235–250. http://doi.org/10.1016/0378-3774(81)90009-3

Bouman, B.A.M., van Keulen, H., van Laar, H.H., Rabbinge, R., 1996. The 'School of de Wit' crop growth simulation models: a pedigree and historical overview. Agric. Systems 56, 171-198.

Braden, H., 1985. Ein Energiehaushalts- und Verdunstungsmodell für Wasser und Stoffhaushaltsuntersuchungen landwirtschaftlich genützter Einzugsgebiete. Mittelungen Deutsche Bodenkundliche Gesellschaft, 42, 294-299.

Breiman, L., 2001. Random Forests, Machine Learning 45(1), 5-32.

Camargo, G.G.T.T., Kemanian, A.R., 2016. Six crop models differ in their simulation of water uptake. In: Agricultural and Forest Meteorology 220, 116–129. https://doi.org/10.1016 /j.agrformet.2016.01.013

Carta, J.A., Ramírez, P., 2007. Analysis of two-component mixture Weibull statistics for estimation of wind speed distributions. Renewable Energy 32:518–531.

Clark, H., Newton, P.C.D, Bell, C.C., Glasgow, E.M., 1997. Dry matter yield, leaf growth and population dynamics in Lolium perenne/Trifolium repens- dominanted pature turves exposed to two levels of elevated CO2. Journal of Applied Ecology, 34:304-316.

Clark, M.P., Bierkens, M.F.P., Samaniego, L., Woods, R.A., Uijlenhoet, R., Bennett, K.E., Pauwels, V.R.N., Cai, X., Wood, A.W., Peters-Lidard, C.D., 2017. The evolution of process-based hydrologic models: Historical challenges and the collective quest for physical realism. Hydrol. Earth Syst. Sci. 21, 3427–3440. https://doi.org/10.5194/hess-21-3427-2017

Coleman, K., Jenkinson, D.S., Crocker, G.J., Grace, P.R., Klir, J., Korschens, M., Poulton, P.R., Richter, D.D., 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma, 81(1-2), 5–28.

Conijn, J.G., 2005. A dynamic simulation model for grassland management and C and N flows at field scale. Report 107, Plant Research International. Wageningen.

Cure, J.D., 1985. Carbon dioxide doubling responses: a crop survey. p. 99-116. In: Strain, B.R. & J.D. Cure. Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238. U.S. Dep. of Energy, Washington D.C., USA.

Cure, J.D., Acock, B., 1986. Crop responses to carbon dioxide doubling; a literature survey. Agricultural and Forest Meteorology 38:127-145.

Damiano, F, 2018. Modelización de parámetros hidráulicos del suelo en una cuenca hidrográfica de la región pampeana. Journal of Soil Science, AACS, Argentina. In press

De Jong van Lier, Q., van Dam, J.C., Metselaar, K., 2009. Root Water Extraction under Combined Water and Osmotic Stress. Soil Science Society of America 73:862-875.

De Jong van Lier, Q., van Dam, J.C., Durigon, A., dos Santos, M.A., Metselaar, K., 2013. Modeling water potentials and flows in the soil-plant system comparing hydraulic resistances and transpiration reduction functions. Vadose Zone Journal, http://doi.org/10.2136/vzj2013.02.0039

De Jong van Lier, Q., Wendroth, O., van Dam, J.C., 2015. Prediction of winter wheat yield with the SWAP model using pedotransfer functions: an evaluation of sensitivity, parameterization and prediction accuracy. Agricultural Water Management, 154, 29-42.

De Koning, G.H.J., van Diepen, C.A., 1992. Crop production potential of rural areas within the European communities. IV. Potential, water-limited and actual crop production. Working document W68. Netherlands Scientific Council for Government Policy, The Hague, The Netherlands, pp. 83.

De Lange, W.J., Prinsen, G.F., Hoogewoud, J.C., Veldhuizen, A.A., Verkaik, J., Oude Essink, G.H.P., Van Walsum, P.E.V., Delsman, J.R., Hunink, J.C.,Kroon, T., 2014. An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument. Environmental Modelling and Software, 59, 98–108. http://doi.org/10.1016/j.envsoft.2014.05.009

De Temmerman, L., Wolf, J., Colls, J., Bindi, M., Fangmeier, A., Finnan, J., Ojanpera, K., Pleijel, H., 2002. Effect of climatic conditions on tuber yield (Solanum tuberosum L.) in the European 'CHIP' experiments. European Journal of Agronomy 17: 243-255.

De Vos, J.A., Sival, F.P., Clevering, O.A., van Kleef, J., 2006. Stikstof- en fosfaatverliezen naar grond- en oppervlaktewater bij vernatting van landbouwgronden. Veldexperimenten Vredepeel 2003-2005. Alterra, Wageningen & PPO-Akkerbouw, Groene Ruimte en vollegrondsgroente, Alterra-rapport 1392, Lelystad en Wageningen.

De Vries, J.J., 2007. Groundwater. In Theo Wong, Dick A.J. Batjens & Jan de Jager, KNAW, 2007 (Ed.), Geology of the Netherlands (pp. 295–315). Retrieved from http://www.hydrology.nl/key-publications/231-groundwater-geology-of-the-netherlands.html.

De Willigen, P., Janssen, B.H., Conijn, J.G., Velthof, G.J., Chardon, W.J., 2008. Decomposition and accumulation of organic matter in soil ; comparison of some models. Alterra Rapport, 1726., Wageningen

De Wit, C.T., 1958. Transpiration and crop yields, Versl. Landbouwk. Onderz. 64. 6. Wageningen. Available at http://library.wur.nl/WebQuery/wurpubs/fulltext/186445 accessed on 21 May 2018.

De Wit, C.T., 1965. *Photosynthesis of leaf canopies. Versl. Landbouwk. Onderz. (Agric. Res. Rep.) 663*. Wageningen. Available at http://edepot.wur.nl/187115 , accessed on 7 May 2018.

De Wit, C.T., 1978. Simulation of assimilation, respiration and transpiration of crops. Simulation Monographs. Available at https://edepot.wur.nl/167486 accessed on 18 May 2018

De Wit, A.J.W., van Diepen, C.A., 2008. Crop growth modelling and crop yield forecasting using satellite-derived meteorological inputs. International Journal of Applied Earth Observation and Geoinformation, 10(4): 414-425.

De Wit, A.J.W., Duveiller, G., Defourny, P., 2012. Estimating regional winter wheat yield with WOFOST through the assimilation of green area index retrieved from MODIS observations. Agricultural and Forest Meteorology, 164: 39-52.

De Wit, A., Abelleyra, D., Veron, S., Kroes, J., Supit, I., Boogaard, H, 2017. *Technical description of crop model (WOFOST) calibration and simulation activities for Argentina, pampas region.* EU-SIGMA report WP4.

De Wit, A.J.W., Boogaard, H., Fumagalli, D., Janssen, S., Knapen, R., Kraalingen, D. van, Supit, I., Wijngaart, R. van der, Diepen, K. van, 2018. 25 years of the WOFOST cropping systems model. Agricultural Systems. https://doi.org/10.1016/j.agsy.2018.06.018

DHI, 2017. MIKE SHE. Volume 2: Reference Guide. Available at http://manuals.mikepoweredbydhi.help/2017/Water_Resources/MIKE_SHE_Printed_V2.pdf Accessed last on 19 May 2018.

Dijkstra, J.P., Hack-ten Broeke, M.J.D., Wijnands, F.G., 1995. Stikstofemissie naar het grondwater van geintegreerde en gangbare bedrijfssystemen in de akkerbouw op de proefboerderijen Borgerswold en Vredepeel: simulatie van de vocht- en nitraathuishouding op de proefboerderij Vredepeel voor de jaren 1990-1993. DLO-Staring Centrum. Rapport 287.3, Wageningen.

Doble, R.C., Crosbie, R.S, 2017. Review: Current and emerging methods for catchment-scale modelling of recharge and evapotranspiration from shallow groundwater. *Hydrogeology Journal*, *25*(1), 3–23.

Doherty, 2004. PEST, Model-Independent Parameter Estimation. User Manual: 5th Edition. Watermark Numerical Computing. (http://www.pesthomepage.org/ , dd 20091003)

Dos Santos, M.A., de Jong van Lier, Q., van Dam, J.C., Freire Bezerra, A.H., 2017. Benchmarking test of empirical root water uptake models. Accepted by Hydrology and Earth System Science.

Ehlers W, Goss M., 2003. Water Dynamics in Plant Production. CABI Publishing: Cambridge, MA.

Eitzinger, J., Trnka, M., Hösch, J., Žalud, Z., Dubrovský, M., 2004. Comparison of CERES , WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. Ecol. Modell. 171, 223–246. https://doi.org/10.1016/j.ecolmodel.2003.08.012

Elbers, J.A., Moors, E.J., Jacobs, C.M.J., 2009. Gemeten actuele verdamping voor twaalf locaties in Nederland. Alterra-rapport 1920. Available at http://library.wur.nl/WebQuery/wurpubs/445274 , accessed on 8 May 2018.

Falkenmark, M., 1986. Fresh Water-Time: For A Modified Approach. *Ambio*, *15*(4), 192–200. http://doi.org/10.2307/4313251

Fan, Y., Li, H., Miguez-Macho, G., 2013. Global patterns of groundwater table depth. Science (80). 339, 940–943. https://doi.org/http://dx.doi.org/10.1126/science.1229881

FAO-UNESCO, 1980. Soil Map of the World. Paris, UNESCO. Available at http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/. Last accessed at 05 June 2018.

FAO, 2015a. Status of the World's Soil Resources. Main report. Available at http://www.fao.org/documents/card/en/c/c6814873-efc3-41db-b7d3-2081a10ede50/

FAO, 2015b. The Water-Energy-Food Nexus. A new approach in support of food security and sustainable agriculture. Review of Environment, Energy and Economics **19**. Available at http://www.fao.org/3/a-bl496e.pdf , accessed last on 17 May 2018.

Feddes, R.A., 1988. Modelling and Simulation in Hydrologic Systems related to Agricultural Development: State of the Art. Agric. Water Manag. 13, 235–248. https://doi.org/10.1016/0378-3774(88)90157-6

Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc. Wageningen. 189 pp. Available at http://edepot.wur.nl/168026 accessed last on 19 May 2018.

Feddes, R.A., Kabat, P., Bakel, P.J.T. Van, Bronswijk, J., Halbertsma, J., 1988. Modelling soil water dynamics in the unsaturated zone - state of the art. Journal of Hydrology, 100, 69–111. https://doi.org/10.1016/0022-1694(88)90182-5

Feddes, R.A., Raats, P.A.C., 2004. Parameterizing the soil-water-plant-root system. In: Feddes, R.A., de Rooij, G.H. and van Dam, J.C. (eds). Unsaturated zone modelling: progress, challenges and applications. Kluwer Academic, Dordrecht. pp. 95-141. Available at https://library.wur.nl/ojs/index.php/frontis/issue/view/197, accessed last on 2 June 2018.

Feodoroff, A., 1969. Redistribution of moisture after infiltration in dry soils. Influence of gravity. p.385-389. In: Rijtema, P.E., & Wassink, H., 1969. Water in the unsaturated zone; L'eau dans la zone non saturée (Vol. I, II, p. 1–525 (I) and 526–995 (II)). Proceedings of the Wageningen Symposium by UNESCO - IASH. Retrieved from http://unesdoc.unesco.org/images/0001/000143/014319mo.pdf .

Fronzek, S., Pirttioja, N., Carter, T.R., Bindi, M., Hoffmann, H., Palosuo, T., Ruiz-Ramos, M., Tao, F., Trnka, M., Acutis, M., Asseng, S., Baranowski, P., Basso, B., Bodin, P., Buis, S., Cammarano, D., Deligios, P., Destain, M., Dumont, B., Ewert, F., Ferrise, R., François L.,Gaiser, T., Hlavinka, P., Jacquemin, I., Kersebaum, K.C., Kollas, C., Krzyszczak, J., Lorite, I.J., Minet, J., Ines M., Montesino, M., Moriondo, M., Müller, C., Nendel, C., Öztürk, I., Perego, A., Rodríguez, A., Ruane, A.C., Ruget, F., Sanna, M.,Semenov, M.A., Slawinski, C., Pierre Stratonovitch, P., Iwan Supit, I., Waha, K., Wang, E., Wu, L., Zhao, Z., 2018. Classifying multi-model wheat yield impact response surfaces showing sensitivity to temperature and precipitation change. Agricultural Systems, 159, 209–224. http://doi.org/10.1016/j.agsy.2017.08.004

FutureWater, 2011. Middle-East and Northern Africa Water Outlook. Commissioned by World Bank. Available at: http://www.futurewater.nl/wp-content/uploads/2011/04/Final_Report_v11.pdf , accessed last on 5 June 2018

García, Pablo E., Menénendez, Angel N., Podestá Guillermo, Bert, Federico, Arora, Poonam, Jobbágy, Esteban, 2017. Land use as possible strategy for managing water table depth in flat basins with shallow groundwater, International Journal of River Basin Management, 16:1, 79-92.

Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Quarterly Journal of the Royal Meteorological Society 105, 43-55.

Gash, J.H.C., Lloyd, C.R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. Journal of Hydrology 170 (1995) 79-86.

Geerts, S., Raes, D., Garcia, M., Condori, O., Mamani, J., Miranda, R., Cusicanqui, J., Taboada, C,, Yucra, E., Vacher, J., 2008. Could deficit irrigation be a sustainable practice for quinoa (Chenopodium quinoa Willd.) in the Southern Bolivian Altiplano? Agricultural Water Management, 95(8), 909–917. http://doi.org/10.1016/j.agwat.2008.02.012 .

Giorgi, F., Bi, X., 2005. Updated regional precipitation and temperature changes for the 21st century from ensembles of recent AOGCM simulations. Geophysical Research Letters 32:4. doi:10.1029/2005GL024288.

Giller, K.E., 2001. Nitrogen fixation in tropical cropping systems. 2nd Edition. CABI Publishing. Field Crops Research (Vol. 34). CABI Publishing. http://doi.org/10.1016/0378-4290(93)90012-C

Goode, D.J., 1996. Direct simulation of groundwater age. Water Resources Research, 32(2), 289–296.

Gordon, 1988. Grass and grass products in the eighties. Proceedings of the Nutrition Society 39:249-256.

Goudriaan, J., 1977. Crop meteorology: a simulation study. Simulation monographs, Pudoc, Wageningen.

Goudriaan, J., 1990. Primary productivity and CO2. p. 23-25. In: Goudriaan, J., H. van Keulen & H.H. van Laar (Eds.). The greenhouse effect and primary productivity in European agro-ecosystems. Pudoc, Wageningen, Netherlands. Goudriaan, J. & van Laar, H.H., 1978. Calculation of daily totals of the gross CO2 assimilation of leaf canopies. Netherlands Journal of Agricultural Science 26:373-382.

Goudriaan, J., de Ruiter, H.E., 1983. Plant growth in response to CO2 enrichment, at two levels of nitrogen and phosphorus supply. 1. Dry matter, leaf area and development. Netherlands Journal of Agricultural Science 31:157-169.

Goudriaan, J., van Laar, H.H., van Keulen, H., Louwerse, W., 1984. Simulation of the effect of increased atmospheric CO2 on assimilation and transpiration of a closed crop canopy. Wissenschaftliche Zeitschrift der Humboldt-Universität zu Berlin,Math.-Nat. R.33: 352-356.

Goudriaan J., van Laar, H.H. , van Keulen, H., Louwerse, W., 1985. Photosynthesis, CO2 and plant production. p. 107-122. In: Day, W. & R.K. Atkins (Eds.). Wheat growth and modeling. NATO ASI Series. Serie A: Life sciences Vol. 86. Plenum Publishing, New York, USA.

Goudriaan, J., Unsworth, M.H., 1990. Implications of increasing carbon dioxide and climate change for agricultural productivity and water resources. p. 111-130. In: Impact of carbon dioxide, trace gasses, and climate change on global agriculture. ASA Special Publication no. 53. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, USA.

Groenendijk, P., and van den Eertwegh, G.A.P.H., 2004. Drainage-water travel times as a key factor for surface water contamination. p. 145–178. In R.A. Feddes et al. (ed.) Unsaturated zone modeling. Progress, challenges and applications. Wageningen UR Frontis Ser. 6. Kluwer, Dordrecht, the Netherlands

Groenendijk, P., Renaud, L.V., Roelsma, J., 2005. Prediction of nitrogen and phosphorus leaching to groundwater and surface waters; process descriptions of the ANIMO4.0 model, Wageningen, Alterra, Report 983.

Groenendijk, P., Heinen, M., Klammler, G., Fank, J., Kupfersberger, H., Pisinaras, V., Gemitzi, A., Peña-Haro, S., García-Prats, A., Pulido-Velazquez, M., Perego, A., Acutis, M., Trevisan, M., 2014. Performance assessment of nitrate leaching models for highly vulnerable soils used in low-input farming based on lysimeter data. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2014.07.002

Groenendijk, P., Boogaard, H., Heinen, M., Kroes, J., Supit, I., Wit, A. De., 2016. Simulation of nitrogen-limited crop growth with SWAP / WOFOST. Report 2721. Alterra Rapport, 2721.

Groot, J.J.R., 1987. Simulation of nitrogen balance in a system of winter wheat and soil. Simulation Reports CABO-TT, No. 13. Wageningen, the Netherlands, 69 pp

Guderle, M., Hildebrandt, A., 2015. Using measured soil water contents to estimate evapotranspiration and root water uptake profiles – a comparative study. Hydrology and Earth System Sciences, 19(1), 409–425. http://doi.org/10.5194/hess-19-409-2015.

Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecol Model, 135: 147-186.

Hack-ten Broeke, M.J.D., Hegmans, J.H.B.M., 1996. Use of soil physical characteristics from laboratory measurements or standard series for modelling unsaturated water flow. Agricultural Water Management 29: 201-213.

Hack-ten-Broeke, M.J.D., Kroes, J.G., Bartholomeus, R.P., Dam, J.C. Van, Wit, A.J.W. De, Supit, I., Walvoort, D.J.J., Bakel, P.J.T. van, Ruijtenberg, R., 2016. Quantification of the impact of hydrology on agricultural production as a result of too dry, too wet or too saline conditions. In: SOIL, 2, 391–402.

Han, M., Zhao, C., Šimůnek, J., Feng, G., 2015. Evaluating the impact of groundwater on cotton growth and root zone water balance using Hydrus-1D coupled with a crop growth model. Agricultural Water Management, 160, 64–75. http://doi.org/10.1016/j.agwat.2015.06.028.

Hansen, J.W., Challinor, A., Ines, A., Wheeler, T., Moron, T., 2006. Translating climate forecasts into agricultural: advances and challenges. Climate Research 33:27-41.

Hansen, S., Abrahamsen, P., Petersen, C.T., Styczen, M., 2012. Daisy: model use, calibration and validation. Trans. ASABE 55, 1315–1333. Available via https://daisy.ku.dk/publications/

Harter, T., Hopmans, J.W., 2004. Role of vadose-zone flow processes in regional-scale hydrology: review, opportunities and challenges, in: Unsaturated-Zone Modeling: Progress, Challenges and Applications. pp. 179–208. Available at https://library.wur.nl/ojs/index.php/frontis/issue/view/197, accessed last on 2 June 2018.

Heinen, M., 1997. Dynamics of water and nutrients in closed, recirculating cropping systems in glasshouse horticulture: with special attention to lettuce grown in irrigated sand. Wageningen. Available at http://edepot.wur.nl/210124, accessed on 3 June 2018.

Heinen, M., 2001. FUSSIM2: brief description of the simulation model and application to fertigation scenarios. Agronomie, 21(4), 285–296. http://doi.org/10.1051/agro:2001124

Heinen, M., de Willigen, P., 2005. Vergelijking van de organische stofmodellen MOTOR en MINIP. Alterra Rapport, 1260. Wageningen

Heinen, M., 2013. Compensation in Root Water Uptake Models Combined with Three-Dimensional Root Length Density Distribution. Vadose Zone Journal, 13(2), http://doi.org/10.2136/vzj2013.08.0149

Hendriks, R.F.A., Jacobs, C.M.J., Duyzer, J., Moors, E.J., Kroon, P.S., Veenendaal, E.M., Kabat, P., 2011. Simulation of Daily Nitrous Oxide Emissions from Managed Peat Soils. Vadose Zone Journal, 10, 156–168.

Hengl, T., de Jesus, J.M., MacMillan, R.A, Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samul-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalez, M.R, 2014. SoilGrids1km - Global Soil Information Based on Automated Mapping. PloS One, 9.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proceedings of the National Academy of Sciences of the USA, 109: 3232–3237.

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G.K, Chenu, G.E, van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, .FY., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G.G, MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., Keating, B.A., 2014. APSIM - Evolution towards a new generation of agricultural systems simulation. Environmental Modelling and Software, 62, 327–350. http://doi.org/10.1016/j.envsoft.2014.07.009

Hooghoudt, S.B., 1937. Contributions to the Knowledge of Some Physical Soil Properties. No. 43 (13) B, p. 461-676. Determination of the Conductivity of Soils of the Second Kind (In Dutch: Verslagen van Landbouwkundige Onderzoekingen, no. 43(13) B, Dep. van Economische Zaken, Directie van den Landbouw. Algemeene Landsdrukkerij), The Hague.

Hrachowitz, M., Clark, M.P., 2017. Integrated assessment and modelling: Overview and synthesis of salient dimensions. Hydrol. Earth Syst. Sci. https://doi.org/10.5194/hess-21-3953-2017

Huo, Z., Feng, S., Huang, G., Zheng, Y., Wang, Y., Guo, P., 2012. Effect of groundwater level depth and irrigation amount on water fluxes at the groundwater table and water use of wheat. Irrigation and Drainage, 61(3), 348–356. http://doi.org/10.1002/ird.685.

Idso, S.B., 1990. Interactive effects of carbon dioxide and climate variables on plant growth. p. 61-69. In: Impact of carbon dioxide, trace gasses, and climate change on global agriculture. ASA Special Publication no. 53. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, USA.

Iman, R.L., Conover, W.J., 1982. A distribution-free approach to inducing rank correlation among input variables. Commun. Statist.-Simula. Computa. 11, 311-334.

IPCC, 2007. Climate Change 2007: Synthesis Report. The final part of the IPCC's Fourth Assessment Report (AR4). http://www.ipcc.ch/pdf/assessment-report/ar4/syr/

Jamieson, P.D., Semenov, M.A., Brooking, I.R., Francis, G.S., 1998. Sirius: a mechanistic model of wheat response to environmental variation. In: European Journal of Agronomy 8, 161–179.

Jansen, M.J.W, 1999. Analysis of variance designs for model output. Computer Physics Communications, 117(1), 35–43.

Janssen, G.M.C.M., Fraters, B., Boumans, L.J.M., Vrijhoef, A., 2013. Onderzoek naar vervangend rekenmodel om weersinvloeden op nitraatconcentraties te berekenen. Vergelijking van de modellen ONZAT, HYDRUS-1D en SWAP. https://doi.org/RIVM Rapport 680717033/2013

Jaramillo, O.A., Borja, M.A., 2004. Wind speed analysis in La Ventosa, Mexico: a bimodal probability distribution case. Renewable Energy 29:1613–30.

Jarvis, N.J., 1989. A simple empirical model of root water uptake. J. Hydrol., 107, 57-72.

Jarvis, N.J., 2011. Simple physics-based models of compensatory plant water uptake: concepts and eco-hydrological consequences. Hydrology and Earth System Sciences, 15(11), 3431–3446. http://doi.org/10.5194/hess-15-3431-2011.

Jenkinson, D.S., 1990. The turnover of organic carbon and nitrogen in soil. Philosophical Transactions of the Royal Society, B. 329(1255), 361–368.

Jones, A., Panagos, P., Barcelo, S., Bouraoui, F., Bosco, C., Dewitte, O., Gardi, C., Erhard, M., Hervás, J., Hiederer, R., Jeffery, S., Lükewille, A., Marmo, L., Montanarella, L., Olazábal, C., Petersen, J.-E., Penizek, V., Strassburger, T., Tóth, G., van den Eeckhaut, M., van Liedekerke, M., Verheijen, F., Viestova, E., Yigini, Y., 2012. The State of Soil in Europe. JRC Report 25186.

Kabat, P., Broek, van den, B.J., Feddes, R.A., 1992. SWACROP: A water management and crop production simulation model. ICID Bulletin 92, vol. 41 No. 2, 61-84.

Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., van der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O., 2016. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. The Soil, 2(2), 111–128. https://doi.org/10.5194/soil-2-111-2016

Kersebaum, K.C., Hecker, J.M., Mirschel, W., Wegehenkel, M., 2007. Modelling water and nutrient dynamics in soil – crop systems : a comparison of simulation models applied on common data sets, in: K.C. Kersebaum et al. (Eds.), Modelling Water and Nutrient Dynamics in Soil–Crop Systems, SPRINGER-VERLAG, pp. 1–17. https://doi.org/10.1007/978-1-4020-4479-3_1

Kimball, B.A., 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agronomy Journal 75:779-788.

KNMI, 2014. KNMI'14: Climate Change scenarios for the 21st Century – A Netherlands perspective. Scientific Report WR2014-01, KNMI, De Bilt, the Netherlands (www.climatescenarios.nl)

KNMI, 2016. Royal Netherlands Meteorologica l Institute (KNMI), DeBilt, http://www.knmi.nl/, accessed on 8 May 2018.

Kollet, S.J., Maxwell, R.M., 2006. Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. Advances in Water Resources, 29(7), 945–958. http://doi.org/10.1016/j.advwatres.2005.08.006

Konikow, L., Bredehoeft, J., 1992. Groundwater models cannot be validated. Advances in Water Resources, 15(1), 75–83. http://doi.org/10.1016/0309-1708(92)90033-X

Kowalik, P.J., 2006. Drainage and capillary rise components in water balance of alluvial soils. Agricultural Water Management, 86(1-2), 206–211. http://doi.org/10.1016 /j.agwat.2006.08.003

Kramers, G., Van Dam, J.C., Ritsema, C.J., Stagnitti, F., Oostindie, K., Dekker, L.W., 2005. A new modelling approach to simulate preferential flow and transport in water repellent porous media: Parameter sensitivity, and effects on crop growth and solute leaching. Aust. J. Soil Res. 43, 371–382. https://doi.org/10.1071/SR04098

Kroes, J.G., Wesseling, J.G., Van Dam, J.C., 2000. Integrated modelling of the soil-water-atmosphere-plant system using the model SWAP 2.0 an overview of theory and an application. Hydrological Processes 14:1993-2002.

Kroes, J.G., Bakel, P.J.T. van, Huygen, J., Kroon, T., H.Th.L.Massop, Pastoors, R., 2002. Regional validation of a nation wide application of a comprehensive 1D hydrological model. In Accuracy 2002 (pp. 10–12). Melbourne.

Kroes, J.G., van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Jacobs, C.M.J., 2009. SWAP version 3.2. Theory description and user manual. Alterra report 1649 update 02, Wageningen University and Research centre, Wageningen. Available at http://edepot.wur.nl/39776 , accessed on 17 May 2018.

Kroes, J.G., Supit, I., 2011. Impact analysis of drought, water excess and salinity on grass production in The Netherlands using historical and future climate data. Agriculture, Ecosystems & Environment, 144(1), 370–381. https://doi.org/10.1016 /j.agee.2011.09.008

Kroes, J.G., Bartholomeus, R., van Dam, J., Hack-ten Broeke, M., Supit, I., Hendriks, R., de Wit, A., van der Bolt, F., Walvoort, D., Hoving, I., Van Bakel, J., 2015. Waterwijzer Landbouw, fase 2. Modellering van het bodem-water-plantsysteem met het gekoppelde instrumentarium SWAP-WOFOST (Eng: Watervision Agriculture, phase 2. Modeling of the soil-water-plant system with SWAP-WOFOST), Rapport 2015- 16, STOWA, Amersfoort. https://library.wur.nl/WebQuery/titel/2093940, accessed on 7 May, 2018.

Kroes, J.G., Van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R.F.A., Mulder, H.M., Supit, I., Van Walsum, P.E.V., 2017a. SWAP version 4, Theory description and user manual. Wageningen Environmental Research, ESG Report 2780. http://library.wur.nl/WebQuery/wurpubs/fulltext/416321, accessed on 7 May, 2018

Kroes, J.G., Groenendijk, P., Abelleyra, D. de, Verón, S.R., Plotnikov, D., Bartalev, S., Yan, N, Wu, B., Kussul, N., Fritz, S, 2017b. Environmental Impact Assessment of Agricultural Land Use Changes. EU-SIGMA report WP5.1. version 2.0, 14-04-2017. https://library.wur.nl/WebQuery/wurpubs/fulltext/445875

Kroes, J., Supit, I., Van Dam, J., Van Walsum, P., Mulder, M., 2018. Impact of capillary rise and recirculation on simulated crop yields. Hydrol. Earth Syst. Sci., 22, 2937-2951. https://doi.org/10.5194/hess-22-2937-2018

Kroon, T., Finke, P.A., Peereboom, I., Beusen, A.H.W., 2001. Redesign STONE. The new schematization for STONE: the spatial partitioning of land based on hydrological and soil chemical characteristics (in Dutch). RIZA report 2001.017. RIZA, Lelystad, the Netherlands

Kuppel, S., Houspanossian, J., Nosetto, M.D., Jobbagy, E.G, 2015. What does it take to flood the Pampas?: Lessons from a decade of strong hydrological fluctuations. Water Resour. Res., 51(4), 2937-2950

Kupper, E., Querner, E.P., Morábito, J.A., Menenti, M., 2002. Using the SIMGRO regional hydrological model to evaluate salinity control measures in an irrigation area. Agricultural Water Management, 56(1), 1–15.

Lemieux, J.M., Sudicky, E.A., 2010. Simulation of groundwater age evolution during the Wisconsinian glaciation over the Canadian landscape. Environ. Fluid Mech 10, 91-102.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J., Ort, D.R., 2006. Food for thought: Lower than expected crop yield stimulation with rising CO2 concentrations. Science 312:1918-1921.

Liu, B., Asseng, S., Liu, L., Tang, L., Cao, W., Zhu, Y., 2016. Testing the responses of four wheat crop models to heat stress at anthesis and grain filling. Global Change Biology, 22: 1890–1903.

Ma, Y., Feng, S., Song, X., 2015. Evaluation of optimal irrigation scheduling and groundwater recharge at representative sites in the North China Plain with SWAP model and field experiments. Computers and Electronics in Agriculture, 116, 125–136. http://doi.org/10.1016/j.compag.2015.06.015

Maas, E.V., Hoffman, G.J., 1977. Crop salt tolerance - current assessment. J. Irrigation and Drainage Division ASCE 103 (IRI): 115-134. Proceeding Paper 12993.

Maas, E.V., 1990. Crop salt tolerance. In: 'Agricultural salinity assessment and management', K.K. Tanji (Ed.), ASCE Manuals and Reports on Engineering practice, No 71, New York, USA.

Martens, B., Miralles, D.G., Lievens, H., Van Der Schalie, R., De Jeu, R.A.M., Fernández-Prieto, D., Beck, H.E., Dorigo, W.A., Verhoest, N.E.C., 2017. GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. Geoscientific Model Development, 10(5), 1903–1925. http://doi.org/10.5194/gmd-10-1903-2017

Martínez, D., Moschione, E., Bocanegra, E., Glok Galli, M., Aravena, R., 2014. Distribution and origin of nitrate in groundwater in an urban and suburban aquifer in Mar del Plata, Argentina. Environmental Earth Sciences, 72(6), 1877–1886. http://doi.org/10.1007/s12665-014-3096-x

Mercau, J.L., Nosetto, M.D., Bert, F., Giménez, R., Jobbágy, E.G, 2016. Shallow groundwater dynamics in the Pampas: Climate, landscape and crop choice effects. Agricultural Water Management, 163, 159–168.

Min. AGPA, 2016. Ministerio de Agricultura Ganaderia Pesca y Alimentacion - Estimaciones Agricolas (http://www.siia.gov.ar/sst_pcias/estima/estima.php , accessed on 4-Oct-2016)

Mollerup, M., 2010. Daisy 2D Numerics. Web page http://code.google.com/p/daisy-model/wiki/Num2D

Montzka, C., Herbst, M., Weihermüller, L., Verhoef, A., Vereecken, H, 2017. A global data set of soil hydraulic properties and sub-grid variability of soil water retention and hydraulic conductivity curves. Earth System Science Data Discussions, 1–25.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res., 12, 513-522.

Mueller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Folberth, C., Glotter, M., Hoek, S., Iizumi, T., Izaurralde, R.C., Jones, C., Khabarov, N., Lawrence, P., Liu, W., Olin, S., Pugh, T.A.M.M., Ray, D.K., Reddy, A., Rosenzweig, C., Ruane, A.C., Sakurai, G., Schmid, E., Skalsky, R., Song, C.X., Wang, X., De Wit, A., Yang, H., Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Folberth, C., Glotter, M., Hoek, S., Iizumi, T., Izaurralde, R.C., Jones, C., Khabarov, N., Lawrence, P., Liu, W., Olin, S., Pugh, T.A.M.M., Ray, D.K., Reddy, A., Rosenzweig, C., Ruane, A.C., Sakurai, G., Schmid, E., Skalsky, R., Song, C.X., Wang, X., De Wit, A., Yang, H., 2017. Global gridded crop model evaluation: Benchmarking, skills, deficiencies and implications. Geosci. Model Dev. 10, 1403–1422. https://doi.org /10.5194/gmd-10-1403-2017

Mulder, M.H., Kroes, J.G., Supit, I., 2016. Uncertainty and global sensitivity analysis of actual evapotranspiration and crop Yield using SWAP-WOFOST. In proceedings from: iCROPM2016. Crop Modelling for Agriculture and Food Security under Global Change. 15-17 March 2016, Berlin, Germany (pp. 294–295). http://doi.org/doi.org/10.1017/CBO9781107415324.004

Nakićenović, N., Davidson, O., Davis, G., Grübler, A., Kram, T., Rovere, E.L.L., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R., Dadi, Z., 2000. Emissions scenarios—summary for policymakers. Intergovernmental Panel on Climate Change, Geneva.

Nielsen, D.R., van Genuchten, M.Th., Biggar, J.W., 1986. Water flow and solute transport in the unsaturated zone. Water Resour. Res., 22, supplement, 89S-108S.

Niswonger, R.G., Prudic, D.E., Regan, S.R., 2006. Documentation of the Unsaturated-Zone Flow (UZF1) Package for Modeling Unsaturated Flow Between the Land Surface and the Water Table with MODFLOW-2005. U.S. Geological Survey Techniques and Methods, 71.

Norman, J.M., 2013. Fifty Years of Study of S-P-A Systems: Past Limitations and a Future Direction. Procedia Environmental Sciences, 19, 15–25. http://doi.org/10.1016 /j.proenv.2013.06.003

Nosetto, M.D., Jobbágy, E.G., Jackson, R.B., Sznaider, G.A., 2009. Reciprocal influence of crops and shallow ground water in sandy landscapes of the Inland Pampas. Field Crops Research, 113(2), 138–148.

Nosetto, M.D., Jobbágy, E.G., Brizuela, A.B., Jackson, R.B, 2012. The hydrologic consequences of land cover change in central Argentina. Agriculture, Ecosystems and Environment, 154, 2–11.

Nosetto, M.D., Acosta, A.M., Jayawickreme, D.H., Ballesteros, S.I., Jackson, R.B., Jobbágy, E.G, 2013. Land-use and topography shape soil and groundwater salinity in central Argentina. Agricultural Water Management, 129, 120–129.

NRC, 2003. Understanding climate change feedbacks. Report of the Panel on Climate Change Feedbacks, National Research Council. National Academies Press, Washinhton, 166pp.

Oliver, D.S., Alfonzo, M., 2018. Calibration of imperfect models to biased observations. Comput. Geosci. 22, 145–161. https://doi.org/10.1007/s10596-017-9678-4

Oreskes, N., 1998. Evaluation (Not Validation) of Quantitative Models. Environ. Health Perspect. 106, 1453–1460.

Oreskes, N., Belitz, K. 2001. Philosophical Issues in Model Assessment. Model Valid. Perspect. Hydrol. Sci.

Oster, J.D., Letey, J., Vaughan, P., Wu, L., Qadir, M., 2012. Comparison of transient state models that include salinity and matric stress effects on plant yield. Agric. Water Manag. 103, 167–175. https://doi.org/10.1016/j.agwat.2011.11.011

Oude Essink, G.H.P., van Baaren, E.S., de Louw, P.G.B., 2010. Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands. Water Resources Research 46:1-16.

Oude Essink, G.H.P., Houtman, H., Goes, B.J.M., 2005. Chloride concentration at the bottom of the Holocene aquitard in the Netherlands (in Dutch), Rep. NITG05-056-A, 17 pp. TNO, Utrecht, The Netherlands.

Pachepsky, Y., Smettem, K., Vanderborght, J., Herbst, M., Vereecken, H., Wösten, J.H.M., 2004. Reality and fiction of models and data in soil hydrology. Unsaturated-zone Model. progress, challenges Appl. 231–260. Available at https://library.wur.nl/ojs/index.php /frontis/issue/view/197, accessed last on 2 June 2018.

Passioura, J.B., 1996. Simulation Models: Science, Snake Oil, Education, or Engineering? Agron. J. 88, 690–694.

PBL, 2018. The geography of future water challenges. http://www.pbl.nl/sites/default /files/cms/publicaties/pbl-2018-the-geography-of-future-water-challenges-2920.pdf , accessed last on 1-June-2018.

Peña-Haro, S., Zhou, J., Zhang, G.F., Chen, C., Stauffer, F., Kinzelbach, W., 2012. A Multi-Approach Framework to Couple Independent Models for Simulating the Interaction between Crop Growth and Unsaturated-Saturated Flow Processes. Proceedings of 2012 Congr. IEMSS Sixth Biennial Meeting, Leipzig, Germany, Available at http://www.iemss.org/iemss2012/proceedings/D3_1_0957_PenaHaro_et_al.pdf accessed last on 19 May 2018.

Penning de Vries, F.W.T., van Laar, H.H., 1982. Simulation of growth processes and the model BACROS. In Penning de Vries, F.W.T. & H.H. van Laar (Eds.) Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, the

Netherlands. p. 114-135. Available at http://library.wur.nl/WebQuery /wurpubs/fulltext/172216 accessed last on 21 May 2018.

Popper, K.R., 1934. The Logic of Scientific Discovery, New Yorker, The. https://doi.org/10.1016/S0016-0032(59)90407-7

Porter, J.R., 1993. AFRCWHEAT2: a model of the growth and development of wheat incorporating responses to water and nitrogen. In: Eur. J. Agron. 2, 69–82.

Rallo, G., Agnese, C., Minacapilli, M., Provenzano, G., 2012. Comparison of SWAP and FAO Agro-Hydrological Models to Schedule Irrigation of Wine Grapes. J. Irrig. Drain. Eng. 138, 581–591. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000435.

Refsgaard, J.C., 1997. Parameterisation, calibration and validation of distributed hydrological models. J. Hydrol. 198, 69–97. https://doi.org/10.1016/S0022-1694(96)03329-X

Richards, L.A., 1929. The usefulness of capillary potential to soil-moisture and plant investigators. Journal of Agricultural Research, 37(12), 719–742.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics 1 (1931), 1(May), 318–333.

Richardson, L.F., 1922. Weather prediction by numerical process. Cambridge, The University press. p. 262.

Richardson, C.W., 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. Water Resources Research, 17:182–190.

Rijtema, P.E., 1971. Een berekeningsmethode voor de benadering van de landbouwschade ten gevolge van grondwateronttrekking. ICW-Nota 587, Wageningen. http://library.wur.nl/WebQuery/wurpubs/advanced/422164 , accessed on 7 May, 2018

Rijtema, P.E., Groenendijk, P., Kroes, J.G., 1999. Environmental impact of Land Use in Rural Regions. Development, validation and application of model tools for management and policy analysis. Imperial Press.

Romano, N., Palladino, M., Chirico, G.B., 2011. Parameterization of a bucket model for soil-vegetation-atmosphere modeling under seasonal climatic regimes. Hydrology and Earth System Sciences, 15(12), 3877–3893. http://doi.org/10.5194/hess-15-3877-2011

Rossiter, D.G., 2017. Maps and models are never valid, but they can be evaluated 501. https://doi.org/10.1038/501027a

Rötter, R., 1993. Simulation of the biophysical limitations to maize production under rainfed conditions in Kenya. Evaluation and application of the Model WOFOST. Materiel zur Ost-Afrika vorschung, Heft 12, pp. 261 + Annexes.

Rötter, R.P., Palosuo, T., Kersebaum, K.C., Angulo, C., Bindi, M., Ewert, F., Ferrise, R., Hlavinka, P., Moriondo, M., Nendel, C., Olesen, J.E., Patil, R.H., Ruget, F., Takáč, J., Trnka, M., 2012. Simulation of spring barley yield in different climatic zones of Northern and

Central Europe: A comparison of nine crop models. F. Crop. Res. 133, 23–36. https://doi.org/10.1016/j.fcr.2012.03.016

Rötter, R.P, 2018. Classifying multi-model wheat yield impact response surfaces showing sensitivity to temperature and precipitation change. Agricultural Systems, 159, 209–224.

Ryle, G.J.A., Powell, C.E., Tewson, V., 1992. Effect of Elevated CO2 on the Photosynthesis, Respiration and Growth of Perennial Ryegrass. Journal of Experimental Botany 43(6):881-818.

Sainato, C., Galindo, G., Pomposiello, C., Malleville, H., de Abelleyra, D., Losinno, B, 2003. Electrical conductivity and depth of groundwater at the Pergamino zone (Buenos Aires Province, Argentina) through vertical electrical soundings and geostatistical analysis. Journal of South American Earth Sciences, 16(2), 177–186.

Sasal, M.C., Léonard, J., Andriulo, A., Boizard, H, 2017a. A contribution to understanding the origin of platy structure in silty soils under no tillage. Soil and Tillage Research, 173, 42–48.

Sasal, M.C., Boizard, H., Andriulo, A.E., Wilson, M.G., Léonard, J, 2017b. Platy structure development under no-tillage in the northern humid Pampas of Argentina and its impact on runoff. Soil and Tillage Research, 173, 33–41.

Saxton, K., Rawls, W, 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Science Society of America Journal, 70, 1569–1578.

Schaap, M.G., Leij, F.J., Van Genuchten, M.T., 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology, 251, 163–176.

Schapendonk, A.H.C.M., Stol, W., van de Geijn, S.C., Wijnands, J.H.M., Bunte, F., Hoogeveen, M.W., 1998. Effecten van klimaatverandering op fysieke en economische opbrengst van een aantal landbouwgewassen. AB-DLO, Nota 71. Wageningen. http://www.plant-dynamics.nl/UserFiles/File/pdf/klimaat-economie.pdf

Schapendonk, A.H.C.M., Stol, W., van Kraalingen, D.W.G., Bouman, B.A.M., 1998. LINGRA, a sink/source model to simulate grassland productivity in Europe, European Journal of Agronomy, Volume 9, Issues 2–3, November 1998, Pages 87-100, ISSN 1161-0301, http://doi.org/10.1016/S1161-0301(98)00027-6

Schils, R.L.M., de Haan, M.H.A, Hemmer, J.G.A., Pol-van Dasselaar, A. van den, Boer, J.A. de, Evers, A.G., Holshof, G., Middelkoop, J.C. van, Zom, R.L.G., 2007. DairyWise, A Whole-Farm Dairy Model. Journal of Dairy Science 90: 5334-5346.

Scholten, H., Kassahun, A., Refsgaard, J.C., Kargas, T., Gavardinas, C., Beulens, A.J.M., 2007. A methodology to support multidisciplinary model-based water management. Environ. Model. Softw. 22, 743–759. https://doi.org/10.1016/j.envsoft.2005.12.025

Schröder, J.J., 1985. De invloed van grote giften runderdrijfmest op de groei, opbrengst en kwaliteit van snijmais en op de bodemvruchtbaarheid en waterverontreiniging; Maarheze (zandgrond) 1974-1982. Verslag nr. 31, PAGV, Lelystad (in Dutch)

Semenov M.A., Barrow E.M., 1997. Use of a stochastic weather generator in the development of climate change scenarios. Climatic Change 35:397-414.

Setiyono, T.D., Weiss, A., Specht, J., Bastidas, A.M., Cassman, K.G., Dobermann, A, 2007. Understanding and modeling the effect of temperature and daylength on soybean phenology under high-yield conditions. Field Crops Research, 100(2–3), 257–271.

Seo, H., Šimůnek, J., Poeter, E., 2007. Documentation of the HYDRUS package for MODFLOW-2000, the US Geological Survey modular ground-water model. GWMI 2007-01. Int. Ground Water Modeling Ctr., Colorado School of Mines, Golden, (1980), 1–98.

Sheffield, J., Wood, E.F., 2007. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Climate Dynamics 31:79–105. DOI 10.1007/s00382-007-0340-z.

Shibu, M.E., Leffelaar, P.A., van Keulen, H., Aggarwal, P.K., 2010. LINTUL3, a simulation model for nitrogen-limited situations: Application to rice. European Journal of Agronomy, 32(4), 255–271. http://doi.org/10.1016/j.eja.2010.01.003

Short, D., Dawes, W.R., White, I., 1995. The practicability of using Richards' equation for general purpose soil-water dynamics models. Environment International, 21(5), 723–730. http://doi.org/10.1016/0160-4120(95)00065-S

Šimůnek, J., Sejna, M., Saito, H., Sakai, M., van Genuchten, M.T.., 2008. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, Version 4.0 April 2008. Environmental Sciences. Riverside, California.

Šimůnek, J., Hopmans, J.W., 2009. Modeling compensated root water and nutrient uptake. Ecological modelling 220:505-521.

Šimůnek, J., van Genuchten, M.T., Šejna, M., 2016. Recent Developments and Applications of the HYDRUS Computer Software Pac. Vadose Zone Journal, 15(7), 25. http://doi.org/10.2136/vzj2016.04.0033

Sinclair, T.R., Amir, J., 1992. A model to assess nitrogen limitations on the growth and yield of spring wheat. Field Crops Res. 30, 63–78.

Singh R., Kroes J.G., van Dam, J.C., Feddes, R.A., 2006. Distributed ecohydrological modelling to evaluate irrigation system performance in Sirsa district India : I- Current water management and its productivity. Journal of Hydrology 329(3-4): 692-713 .

Skaggs, R.W., Youssef, M.A., Chescheir, G.M., 2012. Drainmod: model use, calibration and validation. Transactions of the ASABE, 55(4), 1509–1522.

Smerdon, B.D., 2017. A synopsis of climate change effects on groundwater recharge. Journal of Hydrology, 555, 125–128.

Smit, H.J., Metzger, M.J., Ewert, F., 2008. Spatial distribution of grassland productivity and land use in Europe. Agricultural Systems, 98(3), 208-219.

Snijders, P.J.M., Woldring, J.J., Geurink, J.H., van der Meer, H.G., 1987. Stikstofwerking van geïnjecteerde runderdrijfmest op grasland [Utilization of nitrogen from injected or surface spread cattle slurry to grassland], Report 103, Research Station for Cattle, Sheep and Horse Husbandry, Lelystad.

Sluijter, R., Nellestijn, J., 2002. Atlas of Climate in The Netherlands – time period 1971-2000. Royal Netherlands Meterological Institute (publised in Dutch: Klimaatatlas van Nederland - tijdvak 1971 – 2000). www.knmi.nl., published by: Elmar, Rijswijk, ISBN 90-389-1191-2.

Soil Survey Staff, 2010. Claves para la Taxonomía de suelos. USDA, Dpto de Agricultura USA. Traducción, Ortiz, C & MC Gutiérrez. 331p.

SSSA, 2008. Glossary of Soil Science Terms 2008. Soil Science Society of America. Soil Science. Retrieved from https://www.soils.org/publications/soils-glossary, accessed on 7 May, 2018.

Stahn, P., Busch, S., Salzmann, T., Eichler-Löbermann, B., Miegel, K., 2017. Combining global sensitivity analysis and multiobjective optimisation to estimate soil hydraulic properties and representations of various sole and mixed crops for the agro-hydrological SWAP model. Environmental Earth Sciences, 76(10). http://doi.org/10.1007/s12665-017-6701-y

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. European Journal of Agronomy, 18(3–4), 289–307. http://doi.org/10.1016 /S1161-0301(02)00109-0

Sun, M., Zhang, X., Huo, Z., Feng, S., Huang, G., Mao, X., 2016. Uncertainty and sensitivity assessments of an agricultural-hydrological model (RZWQM2) using the GLUE method. J. Hydrol. 534, 19–30. https://doi.org/10.1016/j.jhydrol.2015.12.045

Supit I., A.A. Hooijer, van Diepen, C.A. (eds.), 1994. System description of the WOFOST 6.0 crop simulation model implemented in CGMS. Volume 1: Theory and Algorithms, EUR 15956, Office for Official Publications of the European Communities, Luxembourg.1994-146 pp. catno: CL-NA-15956-EN-C.

Supit, I., 1997. Predicting national wheat yields using a crop simulation and trend models. Agricultural and Forest Meteorology 88:199-214.

Supit, I., 2000. An exploratory study to improve the predictive capacity of the Crop Growth Monitoring Systems as applied by the European Commission. Doctoraal thesis, Wageningen University, Wageningen, the Netherlands, available at: http://library.wur.nl/WebQuery/wurpubs/fulltext/196579 , accessed on 7 May 2018.

Supit, I., van Diepen, C.A., de Wit, A.J.W., Wolf, J., Kabat, P., Baruth, B., Ludwig, F., 2012. Assessing climate change effects on European crop yields using the Crop Growth

Monitoring System and a weather generator. Agricultural and Forest Meteorology, 164, 96–111.

Suhaila, J., Jemian, A.A., 2007. Fitting daily rainfall amount in peninsular Malaysia using several types of exponential distributions. Journal of Applied Scienes Research 3:1027-1036.

Talebnejad, R., Sepaskhah, A.R., 2015. Effect of different saline groundwater depths and irrigation water salinities on yield and water use of quinoa in lysimeter. Agricultural Water Management, 148, 177–188. http://doi.org/10.1016/j.agwat.2014.10.005

Teixeira, Edmar I., Fischer, Günther, van Velthuizen, Harry, Walter, Christof, Ewert, Frank, 2013. Global hot-spots of heat stress on agricultural crops due to climate change, Agricultural and Forest Meteorology, Volume 170, 15 March 2013, Pages 206-215, ISSN 0168-1923, http://doi.org/10.1016/j.agrformet.2011.09.002

Tiktak, A., De Nie, D.S., van der Linden, A.M.A., Kruijne, R., 2002. Modelling the leaching and drainage of pesticides in the Netherlands: The GeoPEARL model. Agronomie 22:373–387.

Tóth, G., Hermann, T., da Silva, M.R., Montanarella, L., 2018. Monitoring soil for sustainable development and land degradation neutrality. Environ. Monit. Assess. 190. http://doi.org/10.1007/s10661-017-6415-3

UN Water, 2013. Water Security & the Global Water Agenda. A UN-water Analytical Brief. Hamilton, Ontario: United Nations University, Institute for Water, Environment & Health (UNU-INWEH). http://www.unwater.org/ publications/water-security-global-water-agenda/ , accessed last on 1-June-2018

UN, 2015. Sustainable Development Goals; 17 goals to transform our world. https://www.un.org/sustainabledevelopment/sustainable-development-goals/, accessed last on 29-April-2018:

UNEP, 1992. Proceedings of the Ad-hoc Expert Group Meeting to Discuss Global Soil Databases and Appraisal of GLASOD/SOTER, February 24-28. Nairobi, UNEP.

Van Bakel, P.J.T., Massop, H.Th.L., Kroes, J.G., Hoogewoud, J., Pastoors, R., Kroon, T., 2008. Actualisatie Hydrologie voor STONE 2.3; Aanpassing randvoorwaarden en parameters, koppeling tussen NAGROM en SWAP, en plausibiliteitstoets. (Eng: Updating the hydrology component in STONE 2.3; Adjusting boundary conditions and parameters, linking NAGROM and SWAP, and plausibility test). WOt-rapport 57. Wettelijke Onderzoekstaken Natuur & Milieu (MNP), Alterra, Wageningen, the Netherlands.

Van Bakel, P.J.T., Kselik, R.A.L., Roest, C.W.J., Smit, A.A.M.F.R., 2009. Review of crop salt tolerance in the Netherlands. Report 1926, Alterra, Wageningen.

Van Dam, J.C., Huygen, J., Wesseling, J.G., Feddes, R.A., Kabat, P., van Walsum, P.E.V., Groenendijk, P., van Diepen, C.A., 1997. Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Wageningen University and Research. Technical Document 45, available at http://library.wur.nl/WebQuery/wurpubs/fulltext/222782, accessed on 17 May 2018.

Van Dam, J.C., Feddes, R.A., 2000. Simulation of infiltration, evaporation and shallow groundwater levels with the Richards equation. J. of Hydrol., 233, 72-85.

Van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Kroes, J.G., 2008. Advances of Modeling Water Flow in Variably Saturated Soils with SWAP. Vadose Zone Journal, 7(2), 640–653. http://doi.org/10.2136/vzj2007.0060

Van den Akker, J.J.H., Hendriks, R.F.A., Mulder, J.R., 2007. Invloed van infiltratiewater via onderwaterdrains op de afbraak van veengrond. Helpdeskvraag HD2057_onderwaterdrains_vanDrunen_1106. Alterra rapport 1597. Wageningen, the Netherlands. Online: htttp://www.alterra.wur.nl/

Van den Brande, M., 2013. Remote sensing beelden van NDVI en hydrologisch modelleren. BSc thesis Wageningen UR. Wageningen.

Van den Hurk, B.J.J.M., KLein Tank, A.M.G., Lenderink, G., van Ulden, A.P., van Oldenborgh, G.J., Katsman, C.A., van den Brink, H.W., Keller, F., Bessembinder, J.J.F., Burgers, G., Komen, G.J., Hazeleger, W., Drijfhout, S.S., 2006. KNMI Climate Change Scenarios 2006 for the Netherlands. KNMI publication WR-2006-01. KNMI, De Bilt, Netherlands.

Van der Gaast, J.W., Massop, H.T.L., Vroon, H.R.J., 2009. Effecten van klimaatverandering op de watervraag in de Nederlandse groene ruimte. Alterra-rapport 1791. Wageningen. available at: http://edepot.wur.nl/7870 , accessed on 7 May 2018.

Van der Meer, H.G., Ryden, J.C., Ennik, G.C., 1986. Nitrogen fluxes in intensive grassland systems. Martinus Nijhoff Pub. Boston, MA.

Van der Ploeg, M.J., Teuling, A.J., 2013. Going Back to the Roots: The Need to Link Plant Functional Biology with Vadose Zone Processes. Procedia Environmental Sciences, 19, 379–383. http://doi.org/10.1016/j.proenv.2013.06.043.

Van der Salm, C., Schoumans, O.F., 2000. Phosphate losses on four grassland plots used for dairy farming. Measured phosphate losses and calibration of the model ANIMO. Report 083, Alterra, Wageningen, the Netherlands.

Van Diepen, C.A., Wolf, J., Keulen, H., Rappoldt, C., 1989. WOFOST: a simulation model of crop production Soil Use and Management. 5, 16–24. https://doi.org/10.1111/j.1475-2743.1989.tb00755.x

Van Dobben, W.H., 1962. Influence of temperature and light conditions on dry matter distribution, development rate and yield in arable crops. Netherlands Journal of Agricultural Science 10, 377-389.

Van Gaelen, H., Vanuytrecht, E., Willems, P., Diels, J., Raes, D., 2017. Bridging rigorous assessment of water availability from field to catchment scale with a parsimonious agro-hydrological model. Environmental Modelling and Software, 94, 140–156. http://doi.org/10.1016/j.envsoft.2017.02.014

Van Genuchten, M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44, 892-898.

Van Genuchten, M.Th., Cleary, R.W., 1979. Movement of solutes in soil : computer simulated and laboratory results. In: G.H. Bolt (Ed.), Soil Chemistry B, Physico-Chemical Models. Elsevier, Amsterdam, pp. 349-386.

Van Heemst, H.D.J., 1986a. The distribution of dry matter during growth of a potato crop. Potato Research 29, 55-66.

Van Heemst, H.D.J., 1986b. Crop phenology and dry matter distribution. In: H. van Keulen & J. Wolf (Eds.). Modelling of agricultural production: soil, weather and crops. p. 13-60.

Van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. European Journal of Agronomy, 18, 201-234.

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z, 2013. Yield gap analysis with local to global relevance-A review. Field Crops Research, 143, 4–17.

Van Keulen, H., Wolf, J., (Eds), 1986. Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc Wageningen, the Netherlands, 479p. Available at https://edepot.wur.nl/168025 accessed on 17 May 2018.

Van Keulen, H., Seligman, N.G., 1987. Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Simulation Monographs. Pudoc, Wageningen, the Netherlands. 310 pp.

Van Looy, K., Bouma, J., Herbst, M., Koestel, J., Minasny, B., Mishra, U., Montzka, C., Nemes, A., Pachepsky, Y., Padarian, J., Schaap, M., Tóth, B., Verhoef, A., Vanderborght, J., van der Ploeg, M., Weihermüller, L., Zacharias, S., Zhang, Y., Vereecken, H, 2017. Pedotransfer functions in Earth system science: challenges and perspectives. Reviews of Geophysics, 1–58.

Van Walsum, P.E.V., Supit, I., 2012. Influence of ecohydrologic feedbacks from simulated crop growth on integrated regional hydrologic simulations under climate scenarios. Hydrol. Earth Syst. Sci. 16, 1577-1593.

Van Walsum, P.E.V., van der Bolt, F.J.E., 2013. “Sensitivity of the Delta Model to Evapotranspiration Exploring Structural Uncertainties due to Evapotranspiration Concepts. Alterra Report 2481.”

Van Wijk, A.L.M., Feddes, R.A., Wesseling, J.G., Buitendijk, J., 1988. “Effecten van Grondsoort En Ontwatering Op de Opbrengst van Akkerbouwgewassen”. ICW Rapporten nieuwe serie 31. Wageningen.

Vanderborght, J., Kasteel, R., Herbst, M., Javaux, M., Thiéry, D., Vanclooster, M., Mouvet, C., Vereecken, H., Thiery, D., Vanclooster, M., Mouvet, C., Vereecken, H., 2005. A Set of Analytical Benchmarks to Test Numerical Models of Flow and Transport in Soils. Vadose Zo. J. 4, 206. https://doi.org/10.2136/vzj2005.0206

Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., Heng, L.K., Garcia Villa, M., Mejias Moreno, P., 2014. AquaCrop: FAO's crop water productivity and yield response model. Environmental Modelling and Software, 62, 351–360. http://doi.org/10.1016/j.envsoft.2014.08.005

Vazquez-Amabile, G., Bosch, N., Ricca, A.P., Ortiz-de-Zarate, M.L., Rojas, D., Lascombes, J., Parra, V., Duarte, G., Feiguin, M.F, 2013. Evaluation of DRAINMOD model to study groundwater table dynamics and N load in Western Pampas, Argentina. American Society of Agricultural and Biological Engineers Annual International Meeting 2013, ASABE 2013, 3(131595082), 0–13.

Vázquez-Amabile, G.G., Bosch, N., Ricca, A.P., Rojas, D.E., Zárate, M.L.O. De, Lascombes, J., Feigun, M.F., Cristos, D., 2017. Napa freática: dinámica, variables de control y contenido de nitratos en suelos de pampa arenosa. Ciencia Del Suelo, 35(1041), 117–134.

Vereecken, H., Schnepf, A., Hopmans, J.W., Javaux, M., Or, D., Roose, T., Vanderborght, J., Young, M.H., Amelung, W., Aitkenhead, M., Allison, S.D., Assouline, S., Baveye, P., Berli, M., Brüggemann, N., Finke, P., Flury, M., Gaiser, T., Govers, G., Ghezzehei, T., Hallett, P., Hendricks Franssen, H.J., Heppell, J., Horn, R., Huisman, J.A., Jacques, D., Jonard, F., Kollet, S., Lafolie, F., Lamorski, K., Leitner, D., McBratney, A., Minasny, B., Montzka, C., Nowak, W., Pachepsky, Y., Padarian, J., Romano, N., Roth, K., Rothfuss, Y., Rowe, E.C., Schwen, A., Šimůnek, J., Tiktak, A., Van Dam, J., van der Zee, S.E.A.T.M., Vogel, H.J., Vrugt, J.A., Wöhling, T., Young, I.M., 2016. Modeling Soil Processes: Review, Key Challenges, and New Perspectives. Vadose Zo. J. 15. http://doi.org/10.2136/vzj2015.09.0131

Verloop, J., Hilhorst, G.J., Oenema, J., Van Keulen, H., Sebek, L.B.J., Van Ittersum, M.K., 2014. Soil N mineralization in a dairy production system with grass and forage crops. Nutrient Cycling in Agroecosystems, 98(3), 267–280. http://doi.org/10.1007/s10705-014-9610-4

Videla Mensegue, H., Degioanni, A., Cisneros, J, 2015. Estimating shallow water table contribution to soybean water use in Argentina. Eur. Sci. J., 11(14), 23–40.

Viglizzo, E.F., Pordomingo, A.J., Castro, M.G., Lertora, F.A., 2003. Environmental assessment of agriculture at a regional scale in the Pampas of Argentina, 2003.

Viglizzo, E.F., Jobbagy, E.G., Carreño, L.V., Frank, F.C., Aragón, R., De Oro, L., Salvador, V.S, 2009. The dynamics of cultivation and floods in arable lands of central Argentina. Hydrology and Earth System Sciences Discussions, 5(4), 2319–2345.

Von Hoyningen-Hüne, J., 1983. Die Interception des Niederschlags in landwirtschaftlichen Beständen. Schriftenreihe des DVWK 57, 1-53.

Wada, Y., Bierkens, M.F.P., De Roo, A., Dirmeyer, P.A., Famiglietti, J.S., Hanasaki, N., Konar, M., Liu, J., Schmied, H.M., 2017. Human–water interface in hydrological modelling: current status and future directions. Hydrol. Earth Syst. Sci, 21, 4169–4193. http://doi.org/10.5194/hess-21-4169-2017

Wand, S.J.E., Midgley, G.Y.F., Jones, M.H., Curtis, P.S., 1999. Responses of wild C4 and C3 grass (Poaceae) species to elevated atmospheric CO2 concentration: a meta-analytic test of current theories and perceptions. Global Change Biology 5(6):723-741.

Wesseling, J.G., 1991. CAPSEV: steady state moisture flow theory. Program description, user manual. Wageningen, Staring Centre. Report 37. available at: http://edepot.wur.nl/360382 , accessed at 7 May 2018.

Wesseling, J.G., Kroes, J.G., Metselaar, K., 1997. Global sensitivity analysis of the Soil-Water-Atmosphere-Plant (SWAP) model.

Wesseling, J.G., Feddes, R.A., 2006. Assessing crop water productivity from field to regional scale. Agricultural Water Management, 86(1–2), 30–39. http://doi.org /10.1016/j.agwat.2006.06.011

Wesseling, J.G., Kroes, J.G., Campos Oliveira, T., Damiano, F., in prep. Sensitivity and uncertainty analyses of models: much easier than expected!. Paper submitted to the 2nd International Soil Modelling Conference, 5-7 November 2018, Wageningen

WofostControlCentre, 2018. WOFOST Control Centre, available at https://www.wur.nl /en/Expertise-Services/Research-Institutes/Environmental-Research/Facilities-Products/Software-and-models/WOFOST/Downloads-WOFOST.htm , last access on 14 May 2018.

Wolf, J., 2002. Comparison of two potato simulation models under climate change. II. Application of climate change scenarios. Clim. Res. 21, 187–198. https://doi.org /10.3354/cr021187

Wolf, J., van Oijen, M., 2002. Modelling the dependence of European potato yields on changes in climate and CO2. Agricutural and Forest Meteorology 112:217-231.

Wolf, J., van Oijen, M., Kempenaar, C., 2002. Analysis of the experimental variability in wheat responses to elevated CO2 and temperature. Agriculture, Ecosystems and Environment 93:227-247.

Wolf, J., Beusen, A.H.W., Groenendijk, P., Kroon, T., Rötter, R., van Zeijts, H., 2003. The integrated modeling system STONE for calculating emissions from agriculture in the Netherlands. Environmental Modeling & Software 18:597–617.

Wolf, J., van Oijen, M., 2003. Model simulation of effects of changes in climate and atmospheric CO2 and O3 on tuber yield potential of potato (cv. Bintje) in the European Union. Agriculture, Ecosystems & Environment 94:141-157.

Wösten, J.H.M., Lilly, A., Nemes, A., Bas, C. Le, 1999. Development and use of a database of hydraulic properties of European soils. Geoderma, 90, 169–185.

Wösten, J.H.M., de Vries, F., Hoogland, T., Massop, H., Veldhuizen, A., Vroon, H., Wesseling, J, Heijkers, Joost, Bolman, A., 2013a. BOFEK2012, the new soil physical schematisation of the Netherlands, (in Dutch: BOFEK2012, de nieuwe, bodemfysische schematisatie van Nederland); Alterra-rapport 2387, Wageningen.

Wösten, J.H.M., Verzandvoort, S.J.E., Leenaars, J.G.B., Hoogland, T., Wesseling, J.G., 2013b. Soil hydraulic information for river basin studies in semi-arid regions. Geoderma, 195-196, 79–86.

Wu, Y., Liu, T., Paredes, P., Duan, L., Pereira, L.S., 2015. Water use by a groundwater dependent maize in a semi-arid region of Inner Mongolia: Evapotranspiration partitioning and capillary rise. Agricultural Water Management, 152, 222–232. http://doi.org/10.1016/j.agwat.2015.01.016.

Xu, X., Huang, G., Sun, C., Pereira, L.S., Ramos, T.B., Huang, Q., Hao, Y., 2013. Assessing the effects of water table depth on water use, soil salinity and wheat yield: Searching for a target depth for irrigated areas in the upper Yellow River basin. Agricultural Water Management, 125, 46–60. http://doi.org/10.1016/j.agwat.2013.04.004.

Zhou, J., Cheng, G., Li, X., Hu, B.X., Wang, G., 2012. Numerical Modeling of Wheat Irrigation using Coupled HYDRUS and WOFOST Models. SSSAJ Soil Water Manag. Conserv. **76,** 575–585. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.725.6726&rep=rep1&type=pdf, last access on 17 May 2018.

Zipper, S.C., Soylu, M.E., Booth, E.G., Loheide, S.P., 2015. Untangling the Effect of Shallow Groundwater and Soil Texture as Drivers of Subfield-Scale Yield Variability. Water Resources R, 51, 1–21. http://doi.org/10.1002/2015WR017522.

Summary

With only 2.5% of the water on Earth available as fresh water, the security of its supply to feed a growing poplation will become increasingly uncertain. Global institutes try to find means to improve the distribution and security of water and food. Agriculture uses 70% of available fresh water which makes it by far the largest consumer of the limited amounts of fresh water. Water resources are finite and there is a need for new approaches to deal with increasingly complex water and food issues. Land and water management can contribute significantly to a sustainable increase of food security when based on modelling and monitoring in the soil water and plant domain.

Field scale experiments are needed to test new theories for their correctness and added predictive value with the soil water balance as a central core to explain impacts and changes of crop growth. Contribution of upward vertical water flow to roots is an essential part of the water balance and an important driver for transpiration of crops. A physical approach to quantify this vertical water flow should therefore be compared with more simplified approaches and be quantified using field experimental data.

The focus of this thesis is on vertical water flows. To be able to produce sound water balances actual yields have to be modelled, because actual transpiration is directly related to actual dry matter production. This in turn requires the ability to simulate actual crop growth and the need to account for actual water and crop management.

Nowadays modelling is common practice to analyse experiments at different scales, ranging from field to global scale. The natural domains described in this thesis require extensive field tests and verifications at different scales.

This thesis contributes to a better understanding of soil-water-plant interactions and to more advanced modelling of process-oriented approaches. It intends to provide an answer to four research questions :

1. What is the role of the vertical water flows capillary rise and recirculated percolation water in the determination of crop yields?
2. How can we model drought, salinity and oxygen crop stress to predict actual yields?
3. Can we predict the impact of different stresses on actual grassland production in the Netherlands?
4. How do changes of groundwater levels and land use affect actual crop yields and groundwater recharge?

This thesis starts in chapter 2 with a description of the agro-hydrological modelling tool SWAP 4 as it was applied in this thesis. A historical overview of 40 years modelling history is given followed by a brief description of Richards-based equations for soil water flow and a description of dynamic crop growth modelling. Solute transport is described as it was used in chapter 5 to simulate capillary rise of saline groundwater. Soil organic matter, soil nitrogen and crop nitrogen are described because these options are applied in chapter 6 to simulate nitrogen flows in soybean and soils in Argentina. Additional options are summarized with references to publications with detailed descriptions of the underlying processes.

SWAP 4 integrates modelling tools for Richards equation-based soil hydrology (SWAP) and process-oriented crop growth (WOFOST). This allows new ways to analyse the interaction of the two domains which is shown in the cases that are described in the chapters 3 – 6 of this thesis.

Chapter 3 quantifies the contribution of upward flow as capillary rise and separately as recirculated water to crop yield and groundwater recharge. Therefore we performed impact analyses of various soil water flow regimes on grass, maize and potato yields in the Dutch delta. The impact is clearly present in situations with relatively shallow groundwater levels (85% of the Netherlands), where capillary rise is a well-known source of upward flow; but also in free-draining situations the impact of upward flow is considerable. In the latter case recirculated percolation water is the flow source. To make this impact explicit we implemented a synthetic modelling option that stops upward flow from reaching the root zone, without inhibiting percolation. Such a hypothetically moisture-stressed situation compared to a natural one in the presence of shallow groundwater shows mean yield reductions for grassland, maize and potatoes of respectively 26, 3 and 14 % or respectively about 3.7, 0.3 and 1.5 ton dry matter per hectare. About half of the withheld water behind these yield effects originates from recirculated percolation water as occurs in free-drainage conditions and the other half comes from increased upward capillary rise. Soil water and crop growth modelling should consider both capillary rise from groundwater and recirculation of percolation water as this improves the accuracy of yield simulations. This also improves the accuracy of the simulated groundwater recharge: neglecting these processes causes overestimates of 17% for grassland and 46% for potatoes, or 63 and 34 mm yr^{-1}, respectively.

Chapter 4 describes a general method to quantify the effects of hydrological measures on agricultural production in the Netherlands. The method is based on the hydrological simulation model SWAP and the crop growth model WOFOST. SWAP simulates water transport in the unsaturated zone using meteorological data, boundary conditions (like groundwater level or drainage) and soil parameters. WOFOST simulates crop growth as a function of meteorological conditions and crop parameters. The method allows a source-partitioning of stress-causes and results are illustrated for grassland and maize. The approach is tested using field scale experiments. The combination of these process-based models is also used to derive a meta-model, i.e. a set of easily applicable simplified relations for assessing crop growth as a function of soil type and groundwater level. These relations are based on multiple model runs for at least 72 soil units and the possible groundwater regimes in the Netherlands

Chapter 5 describes the impact of future increasing salinity of groundwater, drought and water excess on grass production in the Netherlands. Models were first tested using datasets from field experiments and then applied at regional scale where we quantified the impact of various groundwater salinity levels on grass growth and production using a climate set of historical weather data. The results show that salinity effects on grass production are limited because the excess rainfall will infiltrate the soil and reduce salt water seepage. In a next step we used future weather data for the year 2050, derived from three Global Circulation Models and two CO_2 emission scenarios. Salt stress mainly occurred when irrigation was applied with saline water. The increased CO_2 concentration in combination with the limited drought stress resulted in increasing simulated actual and potential yields. Overall conclusion for grassland in the Netherlands is: drought stress is stronger than stress caused by water excess which on its turn is stronger than salinity stress. Future water demand for irrigation may increase by 11 – 19 % and results in water scarcity if water supply is insufficient.

Chapter 6 studies the changes of groundwater, climate and land use in the Pampas of Argentina. These changes offer opportunities and threats. Lowering groundwater without irrigation causes drought and successive crop and yield damage. Rising groundwater may alleviate drought as capillary rise supports root water uptake and improves crop growth. However rising groundwater may also limit soil water storage, cause flooding in metropolitan areas and have a negative impact on crop yields. Changing land use from continuous soy bean into crop rotations or natural vegetation may decrease groundwater recharge and thus decrease groundwater levels. However in case of crop rotation leaching of nutrients like nitrate may increase. We quantified these impacts using integrated dynamic crop growth and soil hydrology modelling. The models were tested at field scale using local dataset from Argentina. We applied distributed modelling at regional scale to evaluate impacts on groundwater recharge and crop yields using long term weather data. The experiments showed that threats come from continuous monotone land use with low evapotranspiration. Opportunities are created when a proper balance is found between supply and demand of soil water using a larger differentiation of land use. Increasing the areas of land use types with higher evapotranspiration, like permanent grassland and trees, will contribute to a more stable hydrology.

In the final chapter 7 answers to the 4 research questions are given:

1. What is the role of the vertical water flows?

In regions with groundwater levels less than two meters below the soil surface, the impact of capillary rise and recirculated percolation water is important. Both contribute equally to the upward water flow to the root zone as shown in chapter 3. In 85% of the Netherlands groundwater is within 2 meters depth, whereas in regions in the south and east of the Netherlands groundwater levels are deeper and capillary rise does not occur, but the process of recirculated percolation water occurs and should be taken into account. Neglecting the impact of capillary rise and recirculated percolation water implies neglecting production of dry matter and results in lower yields. For grassland, maize and potatoes we simulated yields reductions of 26, 3 and 14 % corresponding to 3.7, 0.3 and 1.5 ton dry matter per ha.

2. How to model stress to predict actual yields?

The impact of drought, salinity and oxygen on agricultural crop yields can be accurately quantified as demonstrated by an extensive comparison with field scale experiments. In order to achieve this we developed a new method that links dry, saline and wet conditions to an existing crop growth module. This new method can be used by farmers, regional governments, water boards and others to assess crop yield reductions due to groundwater changes.

3. How do different stresses affect actual grassland production?

In non-irrigated areas, which applies to about 82% of the Netherlands, droughts have a much larger impact on grass production than the excess of water and salinity. In chapter 5 we have modelled both current and future climate scenarios and generally found that increasing CO_2 concentrations and temperatures stimulate grass growth and yields as long as water (rainfall) is sufficient. Increasing salt concentrations and water excess have a limited effect on grass production. The considered future climate scenarios generally show increasing potential and actual yields as well as an increased demand for irrigation water of 11-19%. Irrigation will compensate water deficit and contribute to increasing yields but only in those parts of the Netherlands where enough irrigation water of sufficient quality is available.

4. How do groundwater levels and land use affect actual crop yields and groundwater recharge?

Increasing groundwater levels generally benefit crop yields because capillary rise decreases drought stress in the root zone. This was analysed for soybean growth in the pampas of Argentina. The long-term agricultural land use of no-tillage growth of soybean has a strong impact on groundwater levels because of its relatively low evapotranspiration. This results in reduced groundwater recharge and increasing groundwater levels. Changing land use from soybean into crop rotations has a limited effect on the reduction of groundwater recharge and groundwater levels. In the case of crop rotation leaching of nutrients like nitrate may increase. When groundwater levels get close to the soil surface flooding will occur. More variation and especially more continuous types of land use such as grassland and forest are therefore recommended as one of the options to lower groundwater levels and thereby increase storage capacity of the soil and reduce flooding risk.

Complex modelling is often necessary and provides valuable insight into the processes underlying the interaction between soil hydrology and crop growth. With this thesis it is shown that a Richards equation-based simulation of water flow to root zone and crops contributes to improved estimates of crop yield. Neglecting these processes will overestimate the groundwater recharge. As a result of this, the availability of drinking water and the risk of flooding may be overestimated.

Samenvatting

Om de groeiende wereldbevolking te voeden is er steeds meer zoet water nodig. Omdat slechts 2,5% van al het water op aarde zoet water is, zal de beschikbaarheid van zoet water steeds minder zeker worden. Diverse instituten over de hele wereld proberen manieren te vinden om de distributie en zekerheid van zoet water en voedsel te verbeteren. Van de beschikbare hoeveelheid zoet water wordt 70% door de landbouw gebruikt. Watervoorraden zijn eindig en er is dringend behoefte aan nieuwe methoden om met de steeds complexer wordende water- en voedselproblemen om te gaan. Land- en waterbeheer op basis van modellering en monitoring in het bodemwater- en gewasdomein kan een aanzienlijke bijdrage leveren aan een duurzame toename van de voedselzekerheid.

Veld-experimenten zijn nodig om nieuwe theorieën te testen op hun juistheid en toegevoegde voorspellende waarde. De waterbalans van de bodem moet daarbij centraal staan om effecten en veranderingen in gewasgroei te verklaren. Een essentieel onderdeel van de waterbalans en een belangrijke aanjager voor transpiratie van gewassen is de bijdrage van opwaartse verticale waterstroming vanuit het grondwater naar de wortelzone.

De focus van dit proefschrift ligt op verticale waterstromen als onderdeel van de waterbalans van de ondiepe bodem. Voor deze waterbalans moet een realistische gewasverdamping worden berekend. Omdat er een direct verband is tussen gewasverdamping en gewasgroei moet er ook een realistische gewasgroei worden gemodelleerd. Het modelleren van realistische gewasgroei is geen sinicure omdat veel processen die de groei beinvloeden niet gemodelleerd kunnen worden..

Tegenwoordig is modellering een gangbare praktijk om experimenten op verschillende schaalniveaus te analyseren, van veldschaal tot mondiale schaal. Een gedegen analyse van de natuurlijke domeinen die in dit proefschrift worden beschreven, vereist uitgebreide veldtests en verificaties op verschillende schalen.

Dit proefschrift draagt bij tot een beter begrip van de interacties tussen de bodem-water-plant systemen en tot meer geavanceerde procesgerichte modelmatige benaderingen. Bovendien wordt antwoord gegeven op vier onderzoeksvragen:

1. Wat is de rol van de verticale waterstromen zoals capillaire opstijging en recirculerend percolatiewater op de gewasopbrengsten?
2. Hoe kunnen we droogte-, zout- en zuurstof-stress modelleren en wat is hun invloed op de gewasopbrengsten?

3. Kunnen we de impact van verschillende stress-vormen op de graslandproductie in Nederland voorspellen?
4. Wat is de invloed van veranderingen in grondwaterstanden en landgebruik op gewasopbrengsten en grondwateraanvulling?

Dit proefschrift begint in hoofdstuk 2 met een beschrijving van het agro-hydrologische model SWAP 4 zoals dat in dit proefschrift is toegepast. Een historisch overzicht van 40 jaar modelleringsgeschiedenis wordt gegeven, gevolgd door een korte beschrijving van de toegepaste vergelijkingen voor dynamische modellering van bodemwaterstroming en gewasgroei. Het transport van opgeloste stoffen wordt beschreven zoals dat in hoofdstuk 5 is gebruikt om de vertikale opstijging van zout grondwater te simuleren. Hoofdstuk 2 beschrijft tevens de modellering van organische stof en stikstof in bodem en gewas zoals deze is toegepast in hoofdstuk 6 voor de simulatie van stikstofstromen in soja en bodems in Argentinië. Aanvullende model-opties zijn samengevat met verwijzingen naar publicaties voor gedetailleerde beschrijvingen van de processen.
SWAP 4 integreert modelleertools voor de op de Richards' vergelijking gebaseerde bodemhydrologie (SWAP) en procesgerichte gewasgroei (WOFOST). Daarmee zijn nieuwe manieren gerealiseerd om de interactie tussen de domeinen bodem en gewas te analyseren. Daarvan worden voorbeelden beschreven in de hoofdstukken 3 - 6 van dit proefschrift.

Hoofdstuk 3 beschrijft een modelmatige kwantificering van de bijdrage aan de gewasopbrengst van twee vormen van vertikale opwaartse grondwaterstroming: i) capillaire opstijging van bodemvocht bij contact met grondwater en ii) recirculerend percolatiewater dat ontstaat door drukverschillen, ook bij de afwezigheid van grondwater. Tevens is het effect van deze stroming op de grondwateraanvulling gemodelleerd. Daarvoor zijn analyses uitgevoerd van verschillende grondwaterstromingsregimes op de opbrengsten van grasland, snijmaïs en aardappelen in Nederland. De invloed van de vertikale opwaartse grondwaterstroming is niet alleen duidelijk aanwezig in situaties met relatief ondiepe grondwaterstanden (85% van Nederland) waar capillaire stijging een bekende bron van opwaartse stroming is, ook in gebieden met zeer diep grondwater is de impact van opwaartse stroming aanzienlijk. In het laatste geval is recirculerend percolatiewater de bron. Om deze impact te kunnen kwantificeren is een synthetische modelleringsoptie geïmplementeerd die ervoor zorgt dat de opwaartse stroming de wortelzone niet bereikt, terwijl neerwaartse percolatie niet wordt belemmerd. Een dergelijke hypothetische situatie toont gemiddelde opbrengstreducties voor grasland, maïs en aardappelen van respectievelijk 26, 3 en 14% of respectievelijk ongeveer 3,7, 0,3 en 1,5 ton droge stof per hectare in vergelijking met een natuurlijke situatie met ondiep grondwater. Ongeveer de helft van de bijdrage van bodemwater aan deze opbrengstseffecten is te wijten aan recirculerend percolatiewater en de andere helft komt van een verhoogde opwaartse capillaire stijging. Bij het modelleren van bodemwater en gewasgroei moeten zowel de capillaire opstijging van het grondwater als de recirculatie van percolatiewater in overweging worden genomen, omdat dit de nauwkeurigheid van de simulaties verhoogt. Ook de nauwkeurigheid van de gesimuleerde grondwateraanvulling wordt vergroot. Verwaarlozing van deze processen resulteert in overschattingen van de aanvulling met 17% voor grasland en 46% voor aardappelen, ofwel respectievelijk 63 en 34 mm jr^{-1}.

Hoofdstuk 4 beschrijft een algemene methode om de effecten van hydrologische maatregelen op de landbouwproductie in Nederland te kwantificeren. De methode is gebaseerd op het hydrologische model SWAP en het gewasgroeimodel WOFOST. De methode maakt bronverdelingen van stress-oorzaken mogelijk. De aanpak is getest met experimenten op veldschaal waarbij resultaten worden geïllustreerd voor grasland en maïs. De combinatie van deze procesgebaseerde modellen is ook gebruikt om een zogenaamd metamodel af te leiden, d.w.z. een reeks gemakkelijk toepasbare vereenvoudigde relaties voor het beoordelen van gewasgroei als functie van grondsoort en grondwaterstand. Deze relaties zijn gebaseerd op modelruns voor 72 bodemeenheden en diverse grondwaterregimes in Nederland.

Hoofdstuk 5 beschrijft een modelanalyse van de impact van historisch en toekomstig zout grondwater, droogte en wateroverlast op de opbrengsten van grasland in Nederland. Modellen zijn getest met datasets uit veldexperimenten en vervolgens toegepast op regionale schaal. Daarbij is de impact van verschillende zoutgehaltes van het grondwater op grasgroei en -productie gekwantificeerd met behulp van historische weergegevens. De resultaten laten zien dat de effecten van zoutgehaltes op de grasproductie beperkt zijn omdat het neerslagoverschot ervoor zorgt dat het zoute water in de ondergrond blijft. Vervolgens zijn scenario’s doorgerekend met toekomstige weergegevens voor het jaar 2050, afgeleid van drie Global Circulation Models en twee CO_2-emissiescenario's. Opbrengstderving door zoutstress trad voornamelijk op wanneer er werd beregend met zout water. De verhoogde CO_2-concentraties in combinatie met de beperkte droogtestress resulteerden in verhoogde gesimuleerde opbrengsten. Algemene conclusie voor grasland in Nederland is: droogtestress is groter dan stress veroorzaakt door wateroverlast die op zijn beurt sterker is dan zoutstress. De toekomstige vraag naar water voor beregening kan met 11 - 19% toenemen en resulteren in droogtestress als de wateraanvoer onvoldoende is.

Hoofdstuk 6 beschrijft een analyse van de veranderingen in grondwater, klimaat en landgebruik in de Pampa's van Argentinië. Deze veranderingen bieden zowel kansen als bedreigingen. Het verlagen van grondwater zonder irrigatie veroorzaakt droogte en dus gewasschade. Stijgend grondwater kan de schade door droogte beperken, omdat capillaire opstijging de wateropname door plantenwortels ondersteunt en daarmee de gewasgroei verbetert. Stijgend grondwater beperkt echter ook de bergingscapaciteit van grondwater in bodems waardoor de kansen op overstromingen in grootstedelijke gebieden kunnen toenemen en gewasopbrengsten kunnen dalen. Veranderend landgebruik van monoculturen van soja naar meer vruchtwisselingen per jaar en meerjarige natuurlijke vegetaties kan de verdamping doen toenemen, de aanvulling van het grondwater verminderen en dus de grondwaterstanden verlagen. In het geval van gewasrotatie kan uitspoeling van voedingsstoffen zoals nitraat echter toenemen. Deze effecten zijn gekwantificeerd met behulp van modellen voor geïntegreerde dynamische gewasgroei en bodemhydrologie. De modellen werden getest op veldschaal met behulp van lokale datasets uit Argentinië. Op regionale schaal is een gedistribueerde modellering toegepast om de effecten op de aanvulling van het grondwater en de gewasopbrengsten te evalueren met behulp van lange-termijn weergegevens. Deze rekenexperimenten lieten zien dat bedreigingen voortkomen uit continu monotoon landgebruik met lage verdamping. Kansen ontstaan wanneer een goed evenwicht wordt gevonden tussen vraag en aanbod van grondwater met behulp van een grotere differentiatie van landgebruik. Het vergroten van het aantal landgebruikstypen met hogere verdamping, zoals blijvend grasland en bomen, zal bijdragen aan een meer stabiele hydrologie.

In het laatste hoofdstuk 7 wordt antwoord gegeven op de 4 onderzoeksvragen:

1. Wat is de rol van verticale waterstromen zoals capillaire opstijging en recirculerend percolatiewater op de gewasopbrengsten?

In gebieden met grondwaterstanden die minder dan twee meter beneden maaiveld liggen, is de impact van capillaire opstijging en gerecirculeerd percolatiewater belangrijk. Beide vormen van verticale grondwaterstroming dragen in dezelfde mate bij tot de opwaartse waterstroom naar de wortelzone zoals blijkt uit de resutlaten van hoofdstuk 3. In 85% van het oppervlakte van Nederland ligt het grondwater binnen 2 meter diepte, terwijl in het zuiden en oosten van Nederland de grondwaterstanden dieper zijn en er vrijwel geen capillaire stijging voorkomt maar wel recirculerend percolatiewater. Het verwaarlozen van de impact van capillaire opkomst en recirculerend percolatiewater leidt tot een verminderde productie van droge stof en resulteert in lagere opbrengsten. Voor grasland, maïs en aardappelen simuleerden we opbrengstreducties van 26, 3 en 14% overeenkomend met 3,7, 0,3 en 1,5 ton droge stof per ha.

2. Hoe kunnen we droogte-, zout- en zuurstof-stress modelleren en wat is hun invloed op de voorspelling van werkelijke opbrengsten?

De impact van droogte, zout en zuurstoftekort op de opbrengst van een landbouwgewas kan goed worden gekwantificeerd, zoals blijkt uit een uitgebreide vergelijking met experimenten op veldschaal. Om dit te bereiken hebben we een nieuwe methode ontwikkeld die droge, zoute en natte omstandigheden koppelt aan een bestaande module voor gewasgroei. Deze nieuwe methode kan worden gebruikt door boeren, regionale overheden, waterschappen en anderen om de reducties van gewasopbrengsten te berekenen die het gevolg zijn van veranderingen in grondwaterstanden.

3. Kunnen we de impact van verschillende stress-vormen op de graslandproductie in Nederland voorspellen?

In gebieden waar niet beregend wordt, ca. 82% van Nederland, heeft droogte een veel grotere impact op de graslandproductie dan wateroverlast en hoge zoutgehaltes. Uit een modelmatige analyse van huidige en toekomstige klimaatscenario's blijkt dat stijgende CO2-concentraties en -temperaturen de grasgroei en opbrengsten stimuleren zolang water (neerslag) voldoende aanwezig is. Stijgende zoutconcentraties en wateroverlast hebben een beperkt effect op de graslandproductie. De toekomstige klimaatscenario's laten over het algemeen toenemende opbrengsten zien, evenals een toegenomen vraag naar beregeningswater van 11-19%. Beregening compenseert het watertekort en draagt bij aan het verhogen van de opbrengst, maar alleen in die delen van Nederland waar voldoende irrigatiewater van goede kwaliteit beschikbaar is.

4. Wat is de invloed van veranderingen in grondwaterstanden en landgebruik op gewasopbrengsten en grondwateraanvulling?

Stijgende grondwaterstanden zijn in het algemeen gunstig voor gewasopbrengsten omdat capillaire opstijging de droogtestress in de wortelzone vermindert. Dit is geanalyseerd voor de groei van soja in de pampa's van Argentinië. De langjarige teelt van soja heeft een sterke invloed op de grondwaterstanden vanwege de relatief lage evapotranspiratie. Dit heeft geresulteerd in een toename van de grondwateraanvulling en stijgende grondwaterstanden. Veranderend landgebruik van soja naar gewasrotaties heeft een beperkt effect op de reductie van grondwateraanvoer- en grondwaterstanden. Door gewasrotaties kan uitloging van voedingsstoffen zoals nitraat toenemen. Wanneer grondwaterstanden dichtbij het maaiveld komen neemt de kans op overstroming toe. Meer variatie en vooral meer continue soorten landgebruik zoals grasland en bos worden daarom aanbevolen als een van de opties om grondwaterstanden te verlagen, de opslagcapaciteit van de bodem te vergroten en het overstromingsrisico te verminderen.

Complexe modellering is vaak nodig en biedt waardevol inzicht in de processen die ten grondslag liggen aan de interactie tussen bodemhydrologie en gewasgroei. Met dit proefschrift wordt aangetoond dat een fysische (Richards vergelijking) basis voor simulaties van de stroming van grondwater naar de wortelzone en het gewas bijdraagt aan verbeterde schattingen van de gewasopbrengst. Door de vertikale opwaartse grondwaterstroming te verwaarlozen, wordt de aanvulling van het grondwater overschat. Als gevolg hiervan kan de beschikbaarheid van drinkwater en het risico van overstromingen worden overschat.

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With this thesis a 15 years old wish comes true. But as it goes, when working at an Institute where projects with limited financial budgets govern daily plans, writing a report was more important than writing a paper. So the plans were delayed again and again. It was in 2003 that Jos van Dam helped me to make more specific plans and from 2011-2015 discussions with Jos and Sjoerd van der Zee helped me to turn plans into a table of content. Parallel to that, around 2011, Piet Groenendijk en Ab Veldhuizen helped me to initiate projects within the so-called 'Kennisbasis'. Within these projects I could work on the integration of soil hydrology (SWAP) and crop growth (WOFOST) during the years 2011-2015. The focus was on the Netherlands so we had to be able to deal with grassland which occupies more than 40% of the land use. With Iwan Supit I revitalized the grassland modules in the SWAP model, tested them and published a paper in 2011 which became a basic starting point for this thesis. We continued with other crops and laid the base for the current project Watervision. For the first article of this thesis the support from Paul van Walsum was indispensable; the article was accepted by HESS but only after 9 reviews.

The modelling tools were applied in an EU-project (SIGMA) which gave me the oppertunity to apply them in several countries, one of them was Argentina. That resulted in a paper which became the final chapter of this thesis; it also resulted in excellent contacts in Argentina.

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About the author

Johannes Gerhardus (Joop) Kroes was born on July 21, 1952 in Amsterdam. He obtained his bachelor's degree in 1984 at the Van Hall Larenstein University of Applied Sciences in Velp, the Netherlands. In 1995 he received his master's degree in hydrology and soil science at the Wageningen University.

He worked as researcher at Wageningen University and Research centre since December 1, 1984 where he started working with dr P.E. Rijtema on nutrient leaching issues for about 10 years. After receiving hist master's degree in 1995 he specialized in soil hydrology and worked on the development, testing and applications of the agro-hydrological model SWAP. Next to this he developed, together with a team, several methods and models for water, nutrients and pesticides which are used extensively in the Netherlands and abroad. The last ten years of his carreer he worked on the integration of model tools for soil hydrology and crop growth which has lead to the publication of this thesis.

His research activities range from the study of processes at field scale level to applications at regional scale. He published papers and reports describing studies that deal with modelling as a tool to analyse and interpret experiments and future situations as influenced by water management, land use management and climate change and variability. He has a large experience in transfer and dissemination of knowledge within several projects and as a lecturer in several courses. He was leader of a workpackage to enhance Environmental Impact Assessments in an EU-SIGMA project where Argentina became a focus country. He was a very active contributor to the project Watervision, a project supported by Dutch waterboards to quantify effects of hydrological measures on agricultural yields, based on simulation models for water management and crop growth. Projects like the two just mentioned form the base of his career and were the base for this thesis.

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- Organizer of Final EURO-AGRIWAT conference Water Footprint of agricultural products : progress , challenges and solutions, 07-09 March 2016 ,Wageningen, The Netherlands
- Leader of a WorkPackage on Environmental Impact Assessment in the EU –SIGMA project (2013-2017)

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- Lecturer in the course 'Modelling water flow and solute transport for agricultural and environmental management', Wageningen University. (1997-2003),
- Lecturer in course 'Environment impact assessment', project SIGMA, April 2014.
- Lecturer in the BSc. course 'Atmosphere-vegetation-soil interactions' (2015-2018), Wageningen University

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- "Some WUR-activities in Argentina". Netherlands Water Partnership, 09 May 2017, The Hague, The Netherlands
- *Salinity risk in Argentina"*, Science Exchange, 04 September 2017, Wageningen, The Netherlands
- *Agrohydrological analysis of groundwater and land use in the Pampas of Argentina.* Aapresid Congress, 9 August 2018. Cordoba, Argentina

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