Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-598, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 29 November 2016

Title:

Capillary rise affecting crop yields under different environmental conditions

Joop Kroes[1], Iwan Supit[1,2], Martin Mulder[1], Jos Van Dam[3], Paul Van Walsum[1]

[1] *Wageningen University & Research - Environmental Research (Alterra)*

[2] *Wageningen University & Research – Chair Water Systems and Global Change*

[3] *Wageningen University & Research – Chair Soil Physics and Land Management*

Abstract

This paper describes analyses of different soil water flow regimes on growth and yields of grass, maize and potato crops in the Dutch delta, with a focus on the role of capillary rise. Different flow regimes are characterised by differences in soil composition and structure are derived from a national soil database. Capillary rise and its influence on crop growth and resulting yields is simulated using Swap-Wofost with different boundary conditions. Case studies and model experiments are used to illustrate the impact of capillary rise. This impact is clearly present in situations where a groundwater level is present (85% of NL) but also in other situations the impact of capillary rise on crop growth and production is considerable. When one compares situations with average groundwater levels with free drainage conditions without capillary rise yield-reductions of grassland, maize and potatoes are respectively 25, 4 and 15 % or respectively about 3.2, 0.5 and 1.6 ton dry Matter per ha. Neglecting capillary rise also has impact on the downward leaching water flux, the groundwater recharge. Impact can be considerable; for grassland and potatoes the reduction is 17 and 46% or 64 and 34 mm. Modelling of soil water flow should consider capillary rise of soil water which will results in improved yield and downward leaching simulations.

1. Introduction

Crop growth strongly depends on soil moisture conditions. Climate conditions determine these conditions through rain that penetrates directly into the root zone or comes available via lateral flow. The distribution of soil moisture strongly depends on soil physical properties that determine vertical flow. The upward capillary flow, capillary rise, becomes a vital supply term to a crop when it manages to bridge the distance between groundwater level and crop roots. The contribution of this capillary flow to the total water budget can be significant. For example Kowalik (2006) mentions that during the growing season, for grass the capillary rise was equal to 90–150 mm for Aquepts Inceptisols and 60–130 mm for Aquepts Histosols. In dry years the capillary supply can be 40–50% of the total supply for Histosols, but close to zero for some Inceptisols (Kowalik, 2006). Babajimopoulos et al. (2007) found that under the specific field conditions about 3.6 mm/day of the water in the root zone originated from the shallow water table, which amounts to about 18% of the transpired water 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 7 to 17% of this area has a water table or its capillary fringe within 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 landuse.

Wu et al. (2015) showed that capillary rise plays a main role in supplying the vegetation throughout the season, hence a strong dependence of vegetation upon groundwater. According to Geerts et al. (2008) the contribution of water from capillary rise to the quinoa production in the Irpani region (Peru), 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.

In the Pampeana region of Argentina, more than 6 million hectares are subject to the influence of a water table that oscillates at depths reached by the roots of the plants (Martini and Baigorri, 2002). 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 environments representative of the flooding sandy pampas, thus stabilizing the inter-annual variability of grain yield (Videla Mensegue et al., 2015).

In The Netherlands the average groundwater table is less than 2 meter below the soil surface in 85% of the area (De Vries, 2007) where capillary rise will reach the root zone. But also in the remaining 15% of the area with deep groundwater levels the effect of capillary rise is present, albeit to a more limited extent: in those areas the capillary rise is limited to moisture that has percolated to just below the root zone during a wet period, and which is then drawn back into the root zone as internal recirculation during an ensuing dry period as a result of capillary suction.

Wesseling and Feddes (2006) report that in summer when the evapotranspiration demand is high, crops partially depend on water supply from soil profile storage and capillary rise from the groundwater table in the Netherlands. Van der Gaast et al. (2009) applying the method of Wesseling (1991) found for the Netherlands a maximum capillary flow of 2 mm/d 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 driving force for capillary rise is the difference in soil water potential, referred to as heads. There are several models available that solve these head differences in a numerical way, e.g. HYDRUS (Šimůnek et al., 2008) and SWAP (Feddes et al., 1988, Van Dam et al., 2008).

We applied the integrated model SWAP-WOFOST to solve head differences and crop yield simulations. Kroes and Supit (2011) applied the same model for grassland and recommended further analyses using different boundary conditions. We now apply this model with different boundary conditions using 45 years of observed weather climate weather and three different crops. For the lower boundary we using different hydrologic conditions that influence the vertical flow. For the soil system itself we will 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 field scale.

This paper quantifies the effects of capillary rise on crop growth under different conditions of soil hydrology, soil type and weather. We hypothesize that neglecting capillary rise 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 capillary rise modelling for crop growth modelling.
Our main research questions are: i) What is the impact of capillary rise on crop yield and downward leaching of water ? ii) What is the impact of soil types on capillary rise ?

2. Materials and methods

2.1 Modelling approach

We applied the coupled SWAP and WOFOST modeling system, using a one day time step. SWAP (Van Dam et al., 2008; Kroes et al., 2009) 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). SWAP simulates the unsaturated and saturated water flow in the upper part of the soil system, using the Richards' equation. Root water extraction and lateral exchange with surface water are accounted for. The soil hydraulics are described by the Mualem–Van Genuchten relations and the potential evapotranspiration is calculated with the Penman–Monteith equation (Allen et al., 1998). Hydraulic heads supplied by a separate regional hydrological model are used to simulate the interaction between the bottom boundary and the groundwater. Drainage and infiltration through the lateral boundary account for the flow to the surface water. The surface water system is simulated using a simplified, weir controlled, water balance. Note that the surface water system in its turn interact with the ground water 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://www.swap.alterra.nl. Eitzinger et al. (2004), Bonfante et al. (2010), Oster et al. (2012), Rallo et al. (2012) and Ahuja et al. (2014) amongst others tested the model performance.

Van Keulen and Wolf (1986) explained the principles and Van Diepen et al. (1989) presented the first WOFOST version. WOFOST has been adapted and applied in many studies (e.g Rötter, 1993; Van Ittersum et al., 2003; de Wit and Van Diepen, 2008; Supit et al., 2012; De Wit et al., 2012). In WOFOST the crop assimilation is a function of the absorbed radiation and temperature. The assimilation is reduced in case water or nutrient stress occur. Subsequently, the maintenance respiration is subtracted and the remaining assimilates are partitioned over 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-WOFOST, crop assimilation depends on the ambient CO2 concentration as well (see: Kroes and Supit, 2011; Supit et al., 2012). To account for unknown residual stress caused by diseases, pests and/or weeds an additional assimilation reduction factor is introduced. The rooting density decreases exponential with depth. To withdraw water for crop uptake from deeper soil layers if the upper part of the soil is very dry, a form of compensation root uptake (hydraulic lift) is used (Jarvis, 2011). The increasing atmospheric CO_2 concentrations during relatively long historical simulation periods (>20years) is accounted for.

2.2 Case studies

SWAP-WOFOST is validated using results of 7 case studies at 6 locations in The Netherlands (Figure 1) where grassland, maize and potatoes is grown and using hydrological, soil and crop observations. The main characteristics of the 7 cases are summarized in Table 1. The soil texture ranged from sand to clay. The observations included parameters, such as groundwater levels, yields and in some cases soil moisture contents, soil pressure head and evapotranspiration. The weather data were collected from nearby weather stations or from onsite measurements. Observations for case 1 and 3 (location De Marke) were available for a period of 22 years (1992-2013) from one field where grassland and maize was grown for respectively 7 and 15 years.

Calibration resulted in parameter values for drought and management which are given in table 2. Planting and harvest dates were given. Oxygen stress was parameterised identic to Hack et al. (2016). For all cases a so-called management factor was used to close the gap between observed and actual yield. Management factors were relatively high because the cases describe field studies that generally have a good management with limited yield losses. The input crop parameters for maize only differed with respect to the management factor (MF) which ranges from 0.85-0.95. For potatoes the input crop parameters were kept the same for all 3 cases. 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). 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/). Observed groundwater levels were used as lower boundary condition for Borgerswold (crop: potato). In 2 cases a lateral boundary condition was applied with drainage to a surface water system (Table 3). The simulation results were analysed using an R-package (Bigiarini, 2013) and the statistics are presented in Table 5.

2.3 Soil crop experiment

To analyse the impact of soil type on capillary rise we used 72 soils derived from a national soil data base (Wösten et al., 2013a).

These 72 soils were aggregated from 315 soil units of the 1:50000 Dutch Soil Map (Figure 2) using hydraulic clustering methods and considering 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, the available water in the root zone, etc. These soil hydraulic properties were subsequently used as input in SWAP-WOFOST.

We calculated capillary rise as the upward flux at the bottom of the root zone. Root zone extension as a result of root growth is accounted for. For each soil we applied 3 hydrological boundary conditions: a) free drainage without capillary rise, b) free drainage with capillary rise and c) an average fluctuating groundwater level (Table 4).

Conditions a) and b) were simulated using free drainage at the bottom of the soil profile. Since the applied model for water flow solves the Richard equation in a numerical way this implies that shortages of water below the root zone will automatically be compensated by using stored water or water from deeper soil layers and thereby generating an upward capillary flux. Since we wanted to analyse the impact of capillary rise, we adjusted the model

SWAP in such a way that capillary rise could be switched on and off. Without capillary rise the hydraulic conductivity was minimized for upward flow in the soil layers just below the root zone. Condition c) approaches an average groundwater level by using conditions that were derived from a national study (Van Bakel et al., 2007). This national study used simulation units with are unique in groundwater dynamics and land use. We selected three large simulation units with long term average groundwater levels between 40 and 120 cm below the soil surface (Dutch groundwater class IV, units 2245, 3859 and 621 for grassland, maize and potato, covering respectively 1806, 794 and 58102 ha, data from Van Bakel et al., 2007). See also the supplementary material of Kroes and Supit (2011) for an additional explanation of the study from Van Bakel et al (2007).

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 was exceeded, iii) for maize and potatoes the planting dates were respectively 25-Oct and 15-Oct.

The 3 crops and 3 lower boundary conditions resulted in 9 combinations. Each combination was simulated with 72 soils for a period of 45 years (1971-2015) with meteorological conditions from the station De Bilt (KNMI, 2016). In a subsequent analysis we grouped the results of these 72 soils to 5 main soil groups clay, loam, peat, peat-moor and sand to be able to analyse impact on grouped soil types.

3 Results

3.1 Case studies

The first 2 case studies are from one location (De Marke) where a grassland-maize rotation was practised. The results show that the hydrological conditions (Figure 3 and Table 5) were simulated accurately for those years for which observed data was available (1991-1995). From 1995-1997 the groundwater levels drop as a result of low precipitation (about 700 mm/year). The fall of the year 1998 shows rising groundwater levels that correspond well with very wet conditions at that moment. The simulated grassland yields are overestimated and the simulated maize yields are underestimated however they are well within acceptable ranges (Figure 4 and Table 5).

For the maize case studies 3 and 4 groundwater level and soil moisture are well simulated (Figure 5 and Table 5). The simulated maize yields (Figure 6, Table 5) are less acceptable for case 3 as is indicated by a zero or negative Nash-Sutcliffe efficiency (NS) which suggests that the observed mean is a better predictor than the model. In 1976, a very dry year, the soil hydrology dynamics and the resulting yield were well captured. The yield of case study 4 has a small bias of about 300 kg.ha^{-1} DM between observed and simulated.

The simulated hydrological conditions for the 3 fields of the potato-cases 6 and 7 show a good fit with the observed (Figure 7, Tabel 5). The simulated yields (Figure 8) show the largest deviation from the observed for case 5 (location Borgerswold). The more recent experiments of cases studies 6 and 7 (Rusthoeve and Vredepeel) show differences between simulated and observed yields of respectively 1400 and 300 kg.ha^{-1} DM. These case studies unfortunately cover only one year. The Rusthoeve performs less due to the complex situation in the subsoil with drainage conditions that require more observations to improve the simulations.

Even though some yields are not accurate enough to satisfy statistical criteria for good model performance, we think that the global overall picture is acceptable. With more field information and calibration a better result may be achieved but we think that especially the good hydrological model performance allows an application at a larger scale with different hydrological boundary conditions.

Before carrying out an analyses at a larger scale we analysed the impact of capillary rise for the case studies. To analyse this impact we carried out new simulations without capillary rise towards the root zone for a grassland, maize and potato case. Results of these 3 cases are given in Table 6 for the situation with and without capillary rise. This shows that suppressing capillary rise lowers yields by 5, 2 and 22% respectively for a grassland, maize and potato case. The downward leaching of water of water from the root zone was reduced with respectively 3, 5 and 94% (Table 6). A larger scale experiment was then carried out to analyse this impact for different soil conditions.

3.2 Soil crop experiment

The 3 crops from the case studies were simulated with 72 soils from the national database using 3 different lower boundary conditions and 45 years with weather from 1970-2015. The capillary rise shows large variations among crops and bottom boundary conditions (Tables 7). The highest values for capillary rise were found for average groundwater conditions (Ave) with median for grassland, maize and potatoes of respectively 191, 79 and 115 mm/year. Differences among the lower boundary conditions are caused by differences in weather, growing season, dynamic position of the root zone and demand root water uptake. Even in free drainage situations (FD$_{cr}$) the capillary rise caused by the internal recirculation can be considerable, ranging from 20 – 78 mm long term average (Table 7).

Results of simulated capillary rise of 45 years weather, 72 soils and 2 lower boundary conditions (FB$_{cr}$ and Ave) are presented in Figures 9, 10, 11 (upper part) and for 5 grouped soils (Figure 9, 10, 11, lower part). The differences in capillary rise between soils are relatively small compared to the differences among years and within one grouped soil type.

For grassland the variation of capillary rise within years is larger than those of maize and potatoes because of the differences in rooting depth which is shortest for grassland and the continuous soil cover of grassland. The downward leaching of grassland is highest for grassland for the same reasons (Table 7).

The highest median yields are simulated when average groundwater situations including capillary rise are considered (Table 7, Ave)

Results of the simulations with 3 different lower boundary conditions (FD_{nc}, FD_{cr} and Ave) are also compared by subtraction. Results of the subtraction are given for capillary rise (Figures 12-14) and for yields (Figures 15-17) and summarized (Table 8). The elimination of capillary rise to the root zone in free drainage conditions reduces grassland, maize and potatoes yields with respectively 13, 1 and 8 % (Table 8). A comparison between situations with average groundwater levels and free drainage situations shows a similar yield reduction: respectively. 13, 3 and 8 %. When one compares situations with average groundwater levels with free drainage conditions without capillary rice yield-reductions of grassland, maize and potatoes are respectively 25, 4 and 15 % (Table 8) or respectively about 3.2, 0.5 and 1.6 ton.ha^{-1} Dry Matter (Table 7).

The impact of neglecting capillary rise on downward leaching flux, the groundwater recharge, is highest for potatoes and lowest for maize. For grassland, maize and potatoes differences were calculated of respectively 17, -6 and 46% (Table 8) or 64, -3 and 34 mm (Table 7). Low values for maize are caused by the deeper rooting systems which reduces the impact of relative differences because the groundwater level will be close to the bottom of the root zone.

4. Discussion

The case studies and soil-crop experiments in this paper clearly state the importance of capillary rise for simulations regarding impact of groundwater on crop yields. This impact is clearly present in situations where a groundwater level is present (85% of NL) but also in other situations the impact of capillary rise is considerable. According to our simulation experiments the impact of capillary rise on yield is about 50% due to internal recycling as occurs in free drainage conditions, another 50% of yield reduction is caused by direct upward capillary flow.

According to Supit & Van Der Goot (1999) water limited results are seldom chosen as predictors which suggests a minor contribution of the soil. Our analysis shows that the soil is important. Several items can be addressed that have a high impact on capillary rise. The depth of the groundwater directly influences the size of the gap that the capillary flux has to bridge to reach to be able to reach the root zone. The vertical soil profile is important because differences in hydraulic properties influence vertical water flow.

Modelling concepts should consider upward capillary flow, variable rooting depth and a dynamic interactions between soil water and crop growth.

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 management of soil and water, items like ploughing and irrigation, are not considered. Furthermore pattern of rooting needs a more detailed analyses; we applied an exponential decrease of rooting patterns and compensation of root uptake as hydraulic lift according to Jarvis (2011) but the actual rooting distributions is still simple and requires a more detailed analyses. Another item we neglected is the preferential flow of water by the occurrence of non-capillary sized macropores (Bouma,, 1961, Feddes, 1988), which is relevant in especially clay soils. Hysteresis is also not considered. An additional analysis of these issues is recommended, preferably about the impact of different rooting patterns on capillary rise.

5. Conclusions

We quantified the impact of capillary rise in layered soils on crop yields of grassland, maize and potatoes. We compared situations with average groundwater levels with free drainage conditions with and without capillary rice. The largest difference was found when one compares situations with average groundwater levels with free drainage conditions without capillary rise. From these differences one may conclude that neglecting capillary rise has a large impact on simulated yields and water balance calculations especially in regions where shallow groundwater occurs.

The comparison shows yield-reductions of grassland, maize and potatoes of respectively 25, 4 and 15 % or respectively 3.2, 0.5 and 1.6 ton Dry Matter per ha (Table 7). Reduction on the downward leaching water flux, the groundwater recharge can be considerable; for grassland and potatoes the reduction is 17 and 46% or 70 and 34 mm.

Improved modelling of soil water flow should consider capillary rise of soil water which will results in improved yield and downward leaching predictions.

Acknowledgement

Part of the case studies has been used before (Hack et al., 2016). This project is related to the project WaterVision Agriculture (www.waterwijzer.nl) which is financed by a large group of financers: STOWA (Applied Research of the Water Boards), Ministry of Infrastructure and Environment, ACSG (Advisory Commission for Damage related to Groundwater), provinces Utrecht and Zuid-Holland, ZON (Zoetwatervoorziening Oost-Nederland), Water companies Vitens and Brabant Water, VEWIN, LTO and the Ministry of Economic Affairs (project KB-14-001-046).

References

Ahuja, L. R., Ma, L., Lascano, R. J., Saseendran, S. A., Fang, Q. X., Nielsen, D. C., … 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* (Vol. 5, pp. 399–437).

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.

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.

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

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

Bonfante, A., Basile, A., Acutis, M., 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. *Agricultural Water Management*, 97(7), 1051–1062. http://doi.org/10.1016/j.agwat.2010.02.010

De Vos, J.A., F.P. Sival, O.A. Clevering en J. van Kleef, 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 354 pp. Theo Wong, Dick A.J. Batjens and 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 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.JW., 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, C. T. (1978). *Simulation of assimilation , respiration and transpiration of crops. Simulation Monographs*.

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

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. *Ecological Modelling*, 171, 223–246. http://doi.org/10.1016/j.ecolmodel.2003.08.012

Fan, Y., Li, H., & Miguez-Macho, G. (2013). Global patterns of groundwater table depth. *Science*, *339*(6122), 940–943. http://doi.org/http://dx.doi.org/10.1126/science.1229881

Feddes, R.A., P.J. Kowalik and H. Zaradny, 1978. *Simulation of field water use and crop yield.* Simulation Monographs. Pudoc. Wageningen. 189 pp.

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.

Folberth, C., Skalský, R., Moltchanova, E., Balkovič, J., Azevedo, L. B., Obersteiner, M., & van der Velde, M. (2016). Uncertainty in soil data can outweigh climate impact signals in global crop yield simulations. *Nature Communications*, 7(May), 11872. http://doi.org/10.1038/ncomms11872

Hack-ten Broeke, M.J.D. and J.H.B.M. Hegmans, 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*.

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

KNMI, 2016. Royal Netherlands Meteorologica l Institute (KNMI), DeBilt, http://www.knmi.nl/

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

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. http://doi.org/10.1016/j.agee.2011.09.008

Liu, Y., Pereira, L. S., & Fernando, R. M. (2006). Fluxes through the bottom boundary of the root zone in silty soils: Parametric approaches to estimate groundwater contribution and percolation. *Agricultural Water Management*, 84(1-2), 27–40. http://doi.org/10.1016/j.agwat.2006.01.018

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

Marshall, B., Van den Broek, B.J., 1995. Field experiments and analysis of data in the case study. In: Kabat, P., Marshall, B., Van den Broek, B.J., Vos, J., Van Keulen, H. (Eds.), *Modelling and parameterization of the soil-plant-atmosphere system. A comparison of potato growth models*. Wageningen Press, Wageningen, Netherlands, pp. 179-210.

Martini, E., & Baigorri, H. (2002). Manejo del cultivo de soja en suelos con influencia de napa freática. In INTA (Ed.), Soja Actualización 2002, Vol. A- 9 - A-13, Marcos Juárez, Argentina.

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

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. *Agricultural Water Management*, 103, 167–175. http://doi.org/10.1016/j.agwat.2011.11.011

Rallo, G., Agnese, C., Minacapilli, M., & Provenzano, G. (2012). Comparison of SWAP and FAO Agro-Hydrological Models to Schedule Irrigation of Wine Grapes. *Journal of Irrigation and Drainage Engineering*, 138(7), 581–591. http://doi.org/10.1061/(ASCE)IR.1943-4774.0000435.

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

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.

Simunek, J., Sejna, M., Saito, H., Sakai, M., & Genuchten, M. T. Van. (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.

Supit, I., van der Goot, E. (1999). National wheat yield prediction of France as affected by the prediction level. *In: Ecological Modelling*, 116(2-3), 203–223. http://doi.org/10.1016/S0304-3800(98)00175-6

Supit, I. (2000). *An exploratory study to improve predictive capacity of the Crop Growth Monitoring System as applied by the European Commission*. *Treebook 4*. Treemail publishers. Retrieved from www.treemail.nl

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.

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 Diepen, C.A. van, Wolf, J., Keulen, H. van, 1989*. WOFOST: a simulation model of crop production. Soil Use and Management, 5:16-24*.

Van den Brande, M. (2013). *Remote sensing beelden van NDVI en hydrologisch modelleren*. BSc thesis Wageningen UR. Wageningen.

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. Retrieved from www.alterra.nl

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 Ittersum, M.K., P.A. Leffelaar, H. van Keulen, M.J. Kropff, L. Bastiaans and J. Goudriaan (2003). On approaches and applications of the Wageningen crop models. European Journal of Agronomy, 18, 201-234.

Van Keulen, H., Wolf J. (Eds), 1986. Modelling of agricultural production: weather, soils and crops. Simulation Monographs, Pudoc Wageningen, The Netherlands.\

Van Middelkoop, J. C., van der Salm, C., Ehlert, P. A. I., de Boer, I. J. M., & Oenema, O. (2016). Does balanced phosphorus fertilisation sustain high herbage yields and phosphorus contents in alternately grazed and mown pastures? *Nutrient Cycling in Agroecosystems*. http://doi.org/10.1007/s10705-016-9791-0

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.

Watanabe, K., Yamamoto, T., Yamada, T., Sakuratani, T., Nawata, E., Noichana, C., Sributtad A., Higuchi, H. (2004). Changes in seasonal evapotranspiration, soil water content, and crop coefficients in sugarcane, cassava, and maize fields in Northeast

Thailand. *Agricultural Water Management*, *67*(2), 133–143. http://doi.org/10.1016/j.agwat.2004.02.004

Wesseling, J.G., 1991. *CAPSEV: steady state moisture flow theory. Program description, user manual.* Wageningen, Staring Centre. Report 37. Retrieved from www.alterra.nl http://dx.doi.org/10.1016/j.agrformet.2012.04.01

Wösten, H., 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. http://doi.org/10.1016/j.geoderma.2012.11.021

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

Tables

Table 1 Main characteristics of case studies used to verify setup of model combination SWAP-WOFOST

Case study	Crop	Location	Period	Soil type	Observations*	Reference
1	Grassland	De Marke	1995-1996, 2005-2008, 2013	dry sandy soil	Gwl, Yield, Theta20cm	Hack et al. (1996)
2	Silage maize	De Marke	1992-1994, 1997-2003, 2009-2012	dry sandy soil	Gwl, Yield, Theta20cm	Hack et al. (1996)
3	Silage maize	Cranendonck	1974-1982	Cumulic Anthrosol	Gwl, Yield	Schröder (1985)
4	Silage maize	Dijkgraaf	2007	Umbric Gleysol	Gwl, Yield, ET,Theta20cm	Elbers et al. (2010)
5	Potato	Borgerswold	1992, 1994	Sandy loam	Gwl, Yield	Dijkstra et al., 1995
6	Potato	Rusthoeve	2013	lichte kleibodem	Gwl, Yield, Qdrain	Van Den Brande (2013)
7	Potato	Vredepeel	2002	Sandy loam	Gwl, Yield	De Vos et al., 2006

** Gwl = Ground water 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.*

Table 2 Important crop parameter for the 3 crops in the 7 case studies

Case study	Crop	Drought stress*	MF**	Maximum depth of root zone (cm)
1	Grassland	h3h = -200.0 cm h3l = -800.0 cm h4 = -8000.0 cm	0.8	40
2	Silage	h3h = -400.0 cm	0.90	100
3	maize	h3l = -500.0 cm	0.85	
4		h4 = -10000.0 cm	0.95	
5	Potato	h3h = -300.0 cm	0.8	50
6		h3l = -500.0 cm	0.8	
7		h4 = -10000.0 cm	0.8	

** 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; ** MF=Management Factor to account for imperfect management*

Table 3 Boundary conditions for vertical water flow at 6 locations

Case study	Location	Bottom boundary condition*	Lateral Boundary
1,2	De Marke	Cauchy	No Drainage
3	Cranendonck	Cauchy	No Drainage
4	Dijkgraaf	Cauchy	No Drainage
5	Borgerswold	Observed groundwater	No Drainage
6	Rusthoeve	Cauchy	Drainage, tube at -90 cm
7	Vredepeel	Closed	Drainage, ditch at -100 cm

** The Cauchy bottom boundary condition uses a hydraulic head based on piezometer observations from an open data portal (see text)*

Table 4 Characteristics of 3 different hydrological bottom boundary conditions

Condition	Bottom Boundary	Description
a	FD$_{nc}$	Free drainage without capillary rise towards root zone
b	FD$_{cr}$	Free drainage with capillary rise towards root zone
c	Ave	An average fluctuating groundwater level

Table 5 Results of Case studies: simulated and observed values

Case study	Name	unit	Simulated mean	Observed mean	ME[1]	RMSE[2]	NS[3]	d[4]	n[5]
1. Grassland	Yield	kg/ha/yr DM	11728	11049	679	1343	0.6	0.9	7
	Gwl	m-soil	-1.34	-1.30	-0.04	0.46	0.3	0.9	77
	Theta20cm	m3/m3	0.27	0.27	0.01	0.06	0.5	0.9	43
2. Maize	Yield	kg/ha/yr DM	11564	11850	-286	2825	-3.2	0.4	14
3. Maize	Yield	kg/ha/yr DM	14054	13788	266	2587	-1.1	0.7	9
	Gwl	m-soil	-1.42	-1.36	-0.05	0.25	0.4	0.9	61
4. Maize	Yield	kg/ha/yr DM	15974	16306	-332				1
	LAI	m2/m2	2.1	2.5	-0.3	0.6	0.7	0.9	10
	ETact	mm/yr	1.4	1.9	-0.6	0.9	0.5	0.9	232
	Gwl	m-soil	-1.03	-1.07	0.03	0.06	0.9	1.0	112
	Theta20cm	m3/m3	0.29	0.27	0.01	0.03	0.5	0.8	219
5. Potato	Yield	kg/ha/yr DM	10532	9246	1286	1350	-31.9	0.3	2
	Gwl	m-soil	-1.10	-1.10	0.00	0.03	1.0	1.0	123
6. Potato	Yield	kg/ha/yr DM	10019	8610	-1409				1
	Gwl	m-soil	-1.07	-1.10	0.02	0.19	0.6	0.9	887
	qDrain	mm	1.1	0.6	0.4	1.4	0.4	0.8	1084
7. Potato	Yield	kg/ha/yr DM	11071	11359	-288				1
	Gwl	m-soil	-1.04	-1.07	0.03	0.11	0.8	0.9	353

[1] *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*

[2] *RMSE: Root Mean Square Error between sim and obs, in the same units of sim and obs, with treatment of missing values. RMSE gives the standard deviation of the model prediction error. A smaller value indicates better model performance.*

[3] *NS: Nash-Sutcliffe efficiencies range from -Inf to 1. Essentially, the closer to 1, the more accurate the model is. NS = 1, corresponds to a perfect match of modelled to the observed data. NS = 0, indicates that the model predictions are as accurate as the mean of the observed data. -Inf < NS < 0, indicates that the observed mean is better predictor than the model.*

[4] *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. The index of agreement can detect additive and proportional differences in the observed and simulated means and variances; however, it is overly sensitive to extreme values due to the squared differences.;*

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

Table 6 Results of case studies: values and differences of yield, capillary rise and leaching fluxes, resulting from simulations with and without capillary rise

Case study***	Model Result	Condition A*	Condition B**	*Differences* A-B	Unit	*Differences* (%) 100*(A-B)/A
1. Grassland	Y_{act}	11904	11353	551	kg/ha/yr DM	5
	$q_{caprise}$	28	0	28	mm/yr	100
	$q_{leaching}$	314	306	9	mm/yr	3
2. Maize	Y_{act}	12504	12257	247	kg/ha/yr DM	2
	$q_{caprise}$	8	0	8	mm/yr	100
	$q_{leaching}$	81	77	4	mm/yr	5
7. Potato	Y_{act}	11071	8665	2406	kg/ha/yr DM	22
	$q_{caprise}$	105	0	105	mm/yr	100
	$q_{leaching}$	15	1	14	mm/yr	94

** Condition A has actual bottom boundary conditions (according to table 3); ** Condition B has actual bottom boundary conditions (table 3) but without capillary rise to root zone;*
**** Cases studies 1 and 2 were simulated for limited periods of respectively 2005-2008 and 1991-1994 to have a continuous sequence of years, Case study 7 was simulated for one year*

Table 7 Results of soil crop experiments: values of 5 parameters resulting from 3 different hydrological bottom boundary conditions (FD_{nc}, FD_{cr} and Average)

Crop	Model Result	FD_{nc}	FD_{cr}	Average	Unit
Grassland	Y_{act}	9781	11227	12978	kg/ha/yr DM
	$q_{caprise}$	0	78	191	mm
	$q_{leaching}$	318	340	382	mm
Maize	Y_{act}	12127	12239	12626	kg/ha/yr DM
	$q_{caprise}$	0	20	79	mm
	$q_{leaching}$	48	53	45	mm
Potato	Y_{act}	8764	9482	10342	kg/ha/yr DM
	$q_{caprise}$	0	44	115	mm
	$q_{leaching}$	39	50	73	mm

Table 8 Results of soil crop experiments: Differences (%) between results from hydrological bottom boundary conditions (FD_{nc}, FD_{cr} and Ave)

Crop	Model Result	Differences (%)		
		FD_{cr} - FD_{nc}	Ave- FD_{cr}	Ave- FD_{nc}
Grassland	Y_{act}	13	13	25
	$q_{caprise}$			
	$q_{leaching}$	6	11	17
Maize	Y_{act}	1	3	4
	$q_{caprise}$			
	$q_{leaching}$	10	-18	-6
Potato	Y_{act}	8	8	15
	$q_{caprise}$			
	$q_{leaching}$	22	32	46

Figures

Legend

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

Figure 1 Location of case studies for grassland, maize and potatoes; location De Marke has a rotation of grassland and maize on the same field.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-598, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 29 November 2016

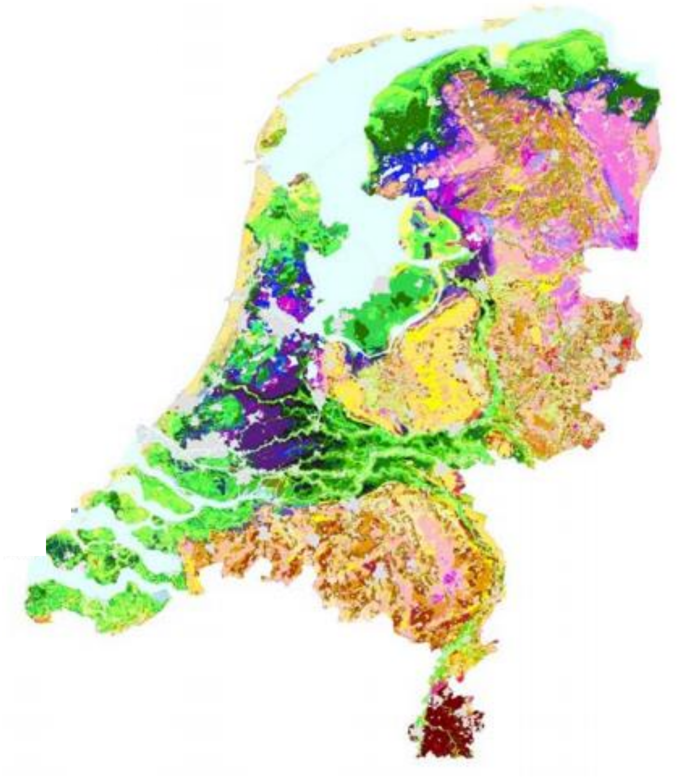

Figure 2 . 72 soils of the Soil Physical Map (Wösten et al., 2013)

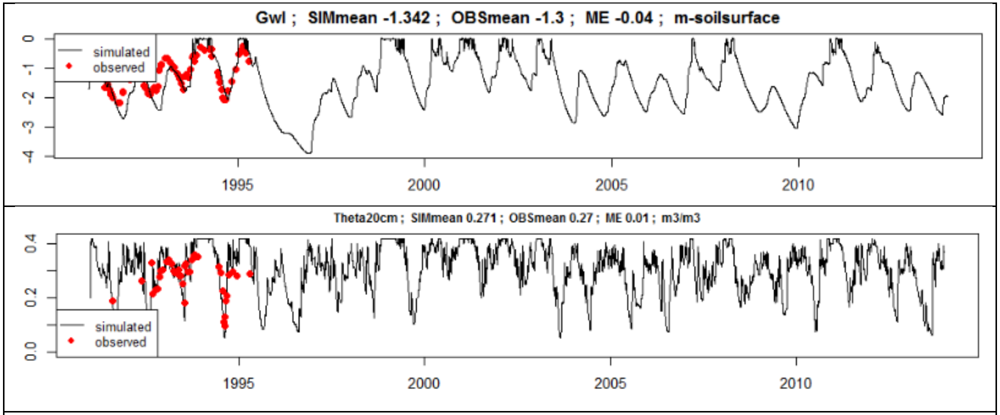

Figure 3 . Results of case studies at location 1 : simulated and observed groundwater level (m-soil surface) (top) and soil moisture content (-) at 20 cm below the soil surface (bottom)

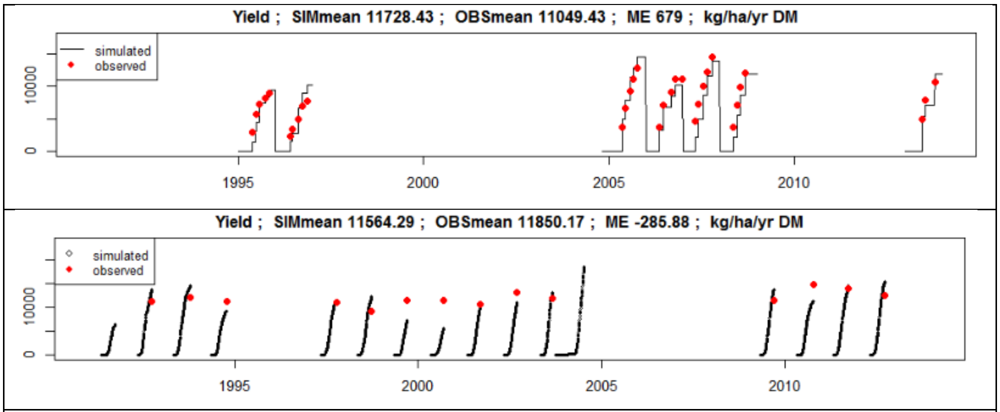

Figure 4 . Results of case studies at location 1 : simulated and observed yields (kg/ha DM) of grassland (top) and maize (bottom)

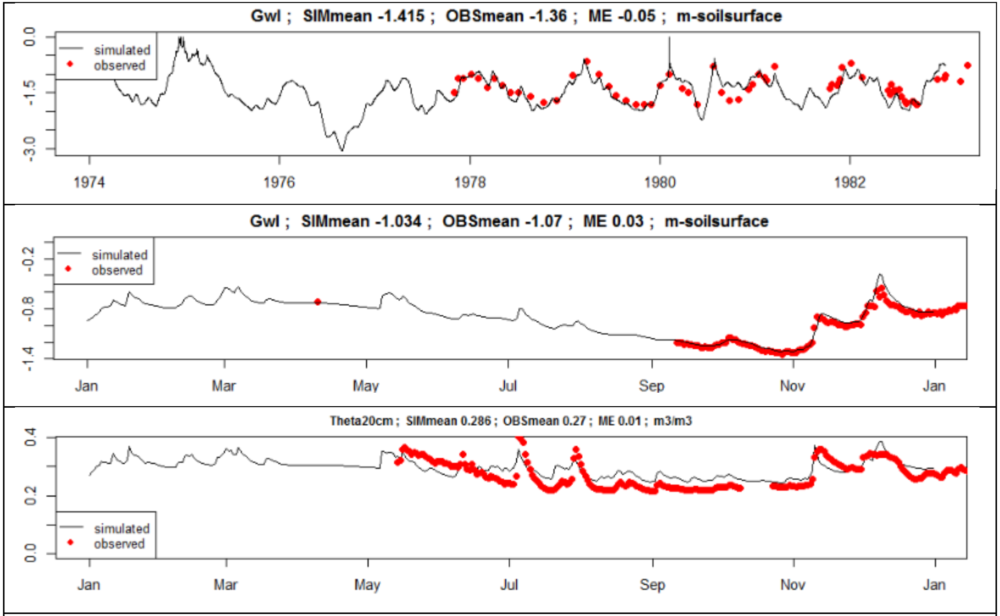

Figure 5. Results of case studies for silage maize (cases 3 and 4) : top fig = groundwater levels (m-soil surface) case 3; middle fig = groundwater levels (m-soil surface) case 4 and bottom fig = Theta (-) at a depth of 20 cm-soil surface case 4

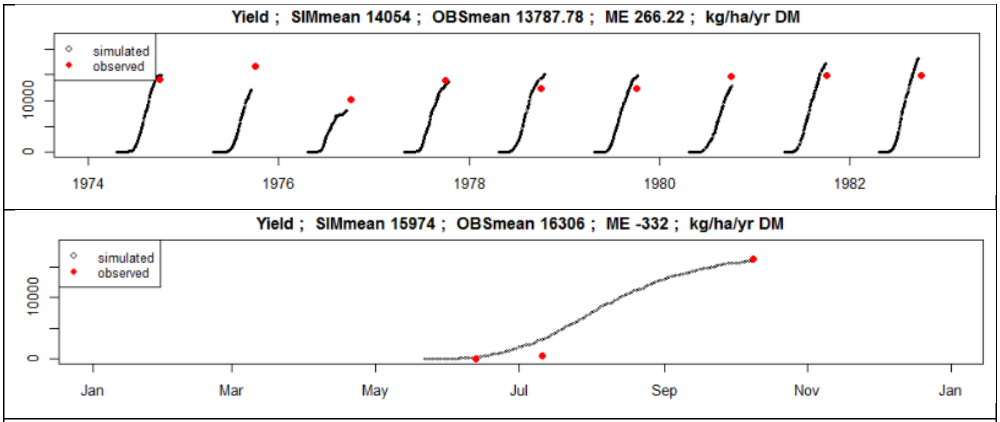

Figure 6 . Results of case studies for silage maize (cases 3 and 4): yields (kg/ha DM)

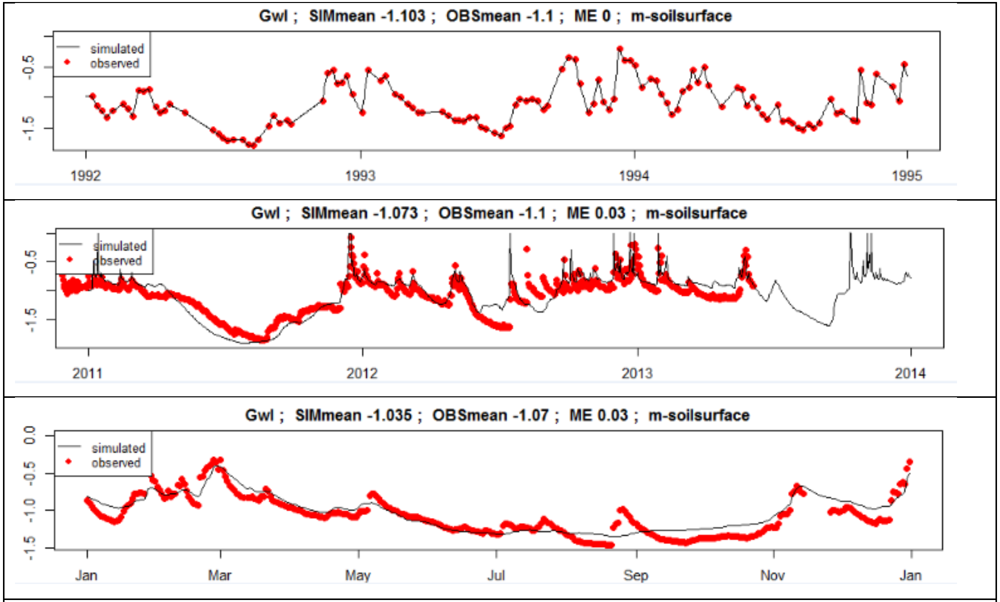

Figure 7 . Results of case studies for potato (case 5,6,7) : groundwater levels (m-soil surface)

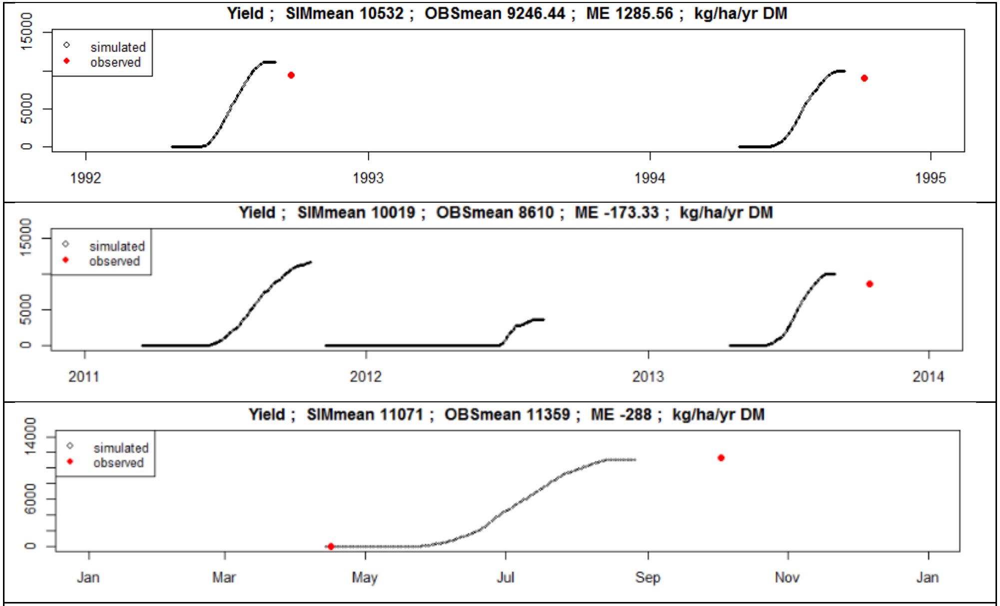

Figure 8 . Results of case studies for potato (cases 5,6,7) : yields (kg/ha DM)

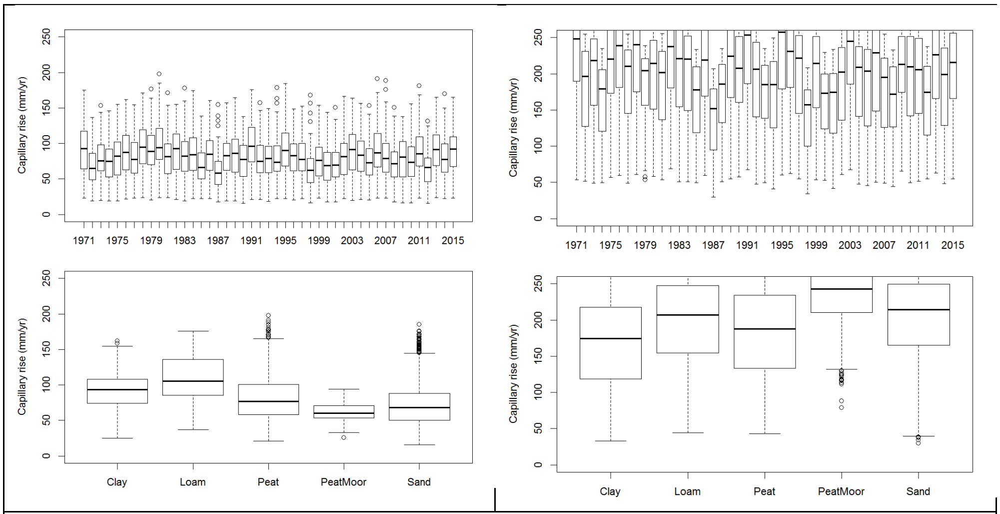

Figure 9 . Results of soil-crop experiment for grassland: Capillary rise (mm/yr) for conditions with free drainage (left) and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

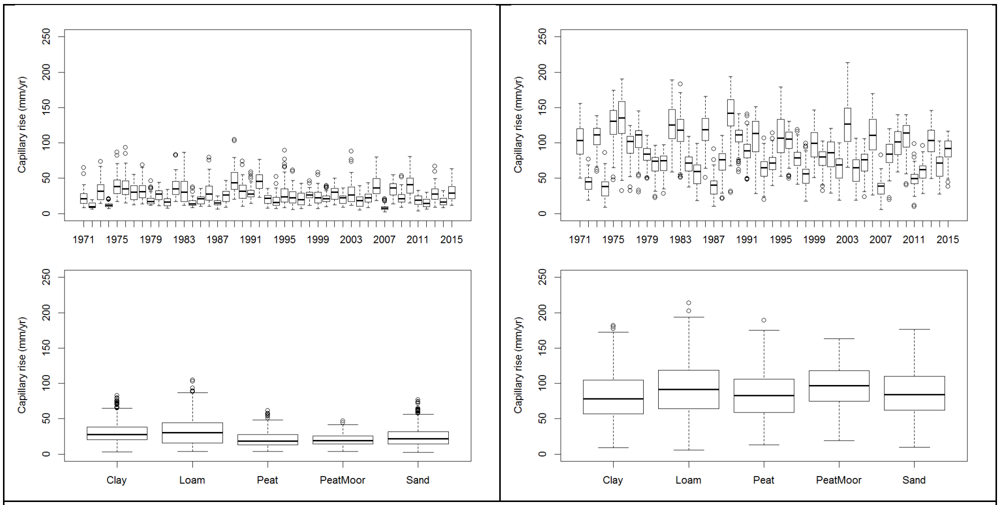

Figure 10 . Results of soil-crop experiment for silage maize: Capillary rise (mm/yr) for conditions with free drainage (left) and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

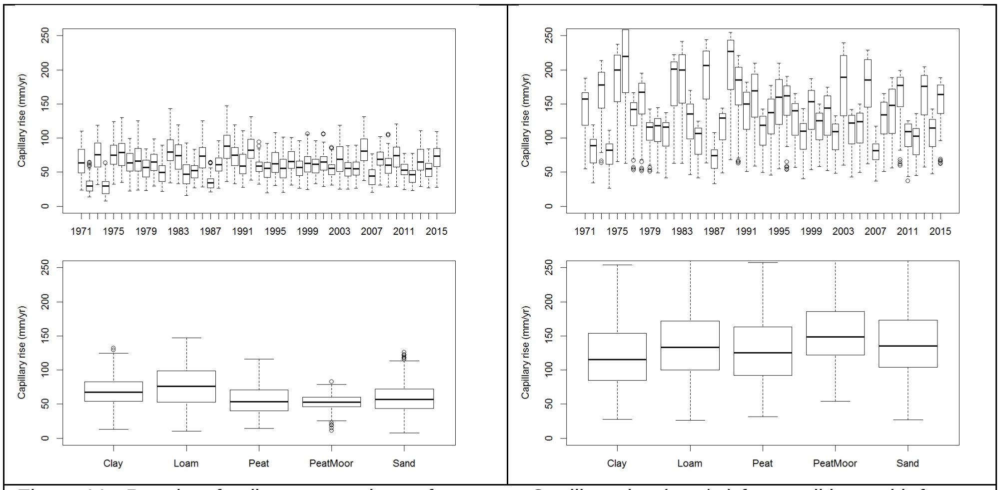

Figure 11 . Results of soil-crop experiment for potato: Capillary rise (mm/yr) for conditions with free drainage (left) and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

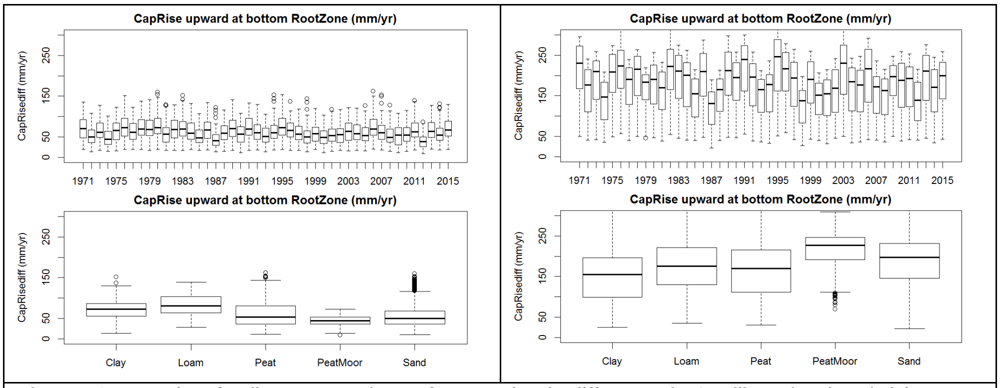

Figure 12 . Results of soil-crop experiment for grassland: difference in Capillary rise (mm/yr) between conditions with no capillary rise + free drainage and free drainage (left) and between conditions with no capillary rise + free drainage and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

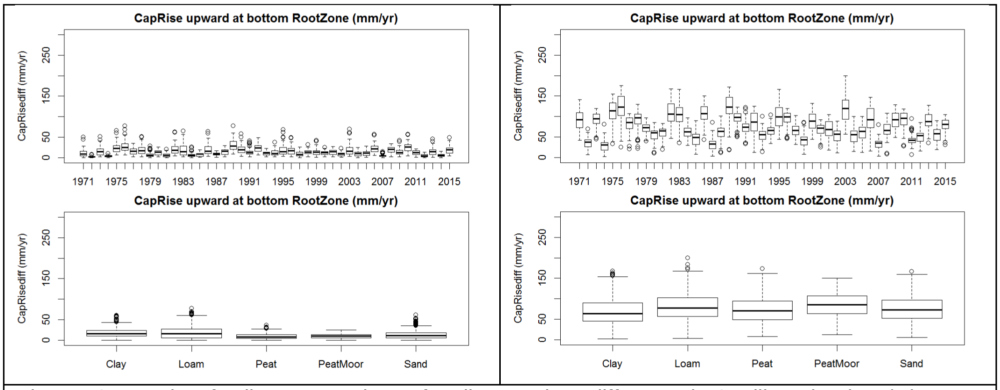

Figure 13. Results of soil-crop experiment for silage maize: difference in Capillary rise (mm/yr) between conditions with no capillary rise + free drainage and free drainage (left) and between conditions with no capillary rise + free drainage and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

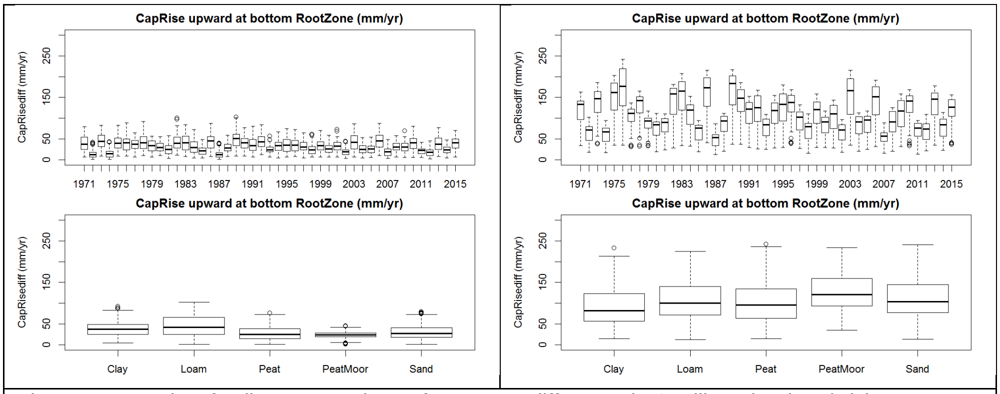

Figure 14. Results of soil-crop experiment for potato: difference in Capillary rise (mm/yr) between conditions with no capillary rise + free drainage and free drainage (left) and between conditions with no capillary rise + free drainage and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

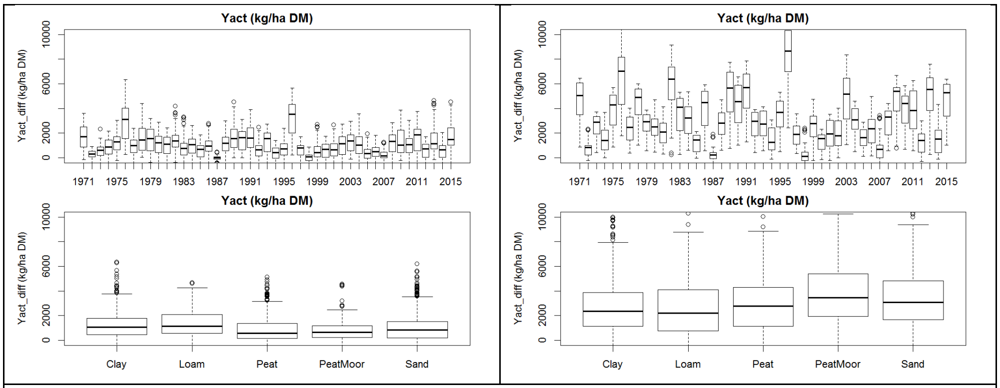

Figure 15. Results of soil-crop experiment for grassland: difference in Yield (kg/ha) between conditions with no capillary rise + free drainage and free drainage (left) and between conditions with no capillary rise + free drainage and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

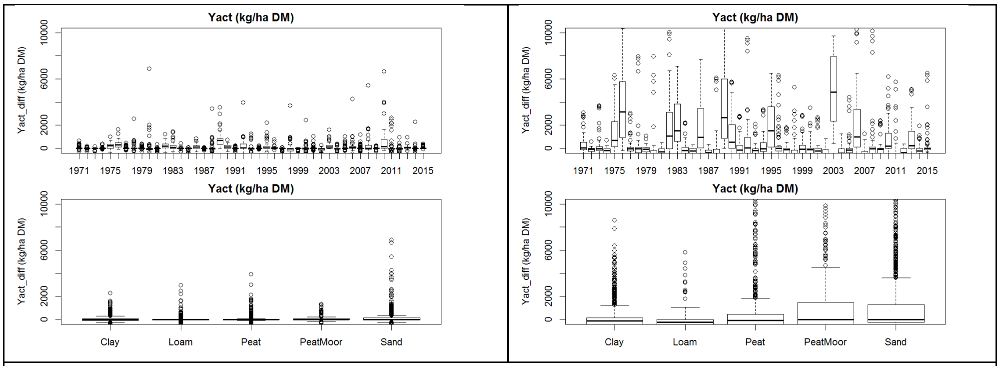

Figure 16. Results of soil-crop experiment for silage maize: difference in Yield (kg/ha) between conditions with no capillary rise + free drainage and free drainage (left) and between conditions with no capillary rise + free drainage and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types

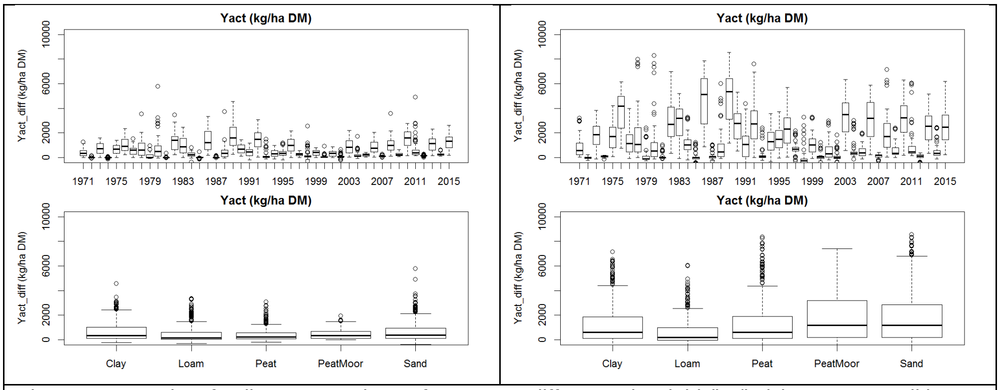

Figure 17. Results of soil-crop experiment for potato: difference in Yield (kg/ha) between conditions with no capillary rise + free drainage and free drainage (left) and between conditions with no capillary rise + free drainage and average groundwater levels (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types