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Impact of capillary rise and recirculation on simulated crop yields

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Abstract

Upward soil water flow is a vital supply of water to crops. The purpose of this study was 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 characterised 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 ha. 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 year^{-1}, respectively.

1. Introduction

Crop growth strongly depends on soil moisture conditions. Climate variables determine these conditions through rain 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 vertical 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 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 (Rijtema and Wassink, 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/day 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 and concluded for cotton in a north-western part of China that capillary rise from groundwater contributes almost to 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 (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. 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 meter below the soil surface in (De Vries, 2007), where root extraction can induce capillary rise from groundwater. Wesseling and 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 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 and 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, and 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 line we introduce the concept of soil moisture yield subsidy as additional 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, 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 more or less empirical options for capillary rise. Five models have the ability to numerically solve 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 and 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 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: 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?

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., 2017) 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 C.T. 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:

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

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) and *z* is the vertical coordinate (cm), taken positively upward, $S_a(h)$ is 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 of 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, 2017 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://www.swap.alterra.nl. 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 and 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 and Van Diepen, 2008; Supit et al., 2012; De Wit et al., 2012). Crop assimilation was 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 was reduced when water stress occurred. Subsequently, the maintenance respiration was subtracted and the remaining assimilates were partitioned over the plant organs (i.e. leaves, stems, roots and storage organs). For maize and potatoes the partitioning was development stage dependent. For perennial grass however, a constant partitioning factor was assumed. By integrating the difference between growth and senescence rates over time, dry weights of various plant organs were established.

In SWAP-WOFOST, crop assimilation depends on the ambient CO_2 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 was introduced. The rooting density decreased exponentially with depth. To withdraw water 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, 2011). The increasing atmospheric CO_2 concentrations during relatively long historical simulation periods (>20 years) was accounted for.

2.2 Case studies for validation

SWAP-WOFOST was validated using results of 7 case studies at 6 locations in the Netherlands (Figure 1) where grassland, maize and potatoes are grown and observations were available from hydrology, soil and crop. 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 studies 1 and 2 (DM-Grass and DM-Maize in Table 1) 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.

We used the model calibrations carried out by Kroes et al. (2015) and Hack et al. (2016) and limited our calibration efforts to parameter values for drought and management (Table 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 parameterised as described by Hack et al. (2016). Drought stress was parameterised 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 favorable soil moisture conditions (Jarvis, 1989).

For all cases a so-called management factor was used to close the gap between observed and actual yield. The input crop parameters for maize only differed with respect to the management factor which ranges from 0.85-0.95. 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 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 3 cases (Table 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 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/). 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 1). The simulation results were analysed using an R-package (Bigiarini, 2013) and the statistics are presented in Table 2.

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 schematization consisted of one or more soil horizons, each with different soil physical properties. The method was described in detail by Wösten et al. (2013a) and the data are available at http://www.wur.nl/nl/show/Bodemfysische-Eenhedenkaart-BOFEK2012.htm. 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-WOFOST 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 3 hydrological conditions (Figure 2), ranging from relatively dry (a) to relatively wet (c) 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 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 the supplementary material (S2) for more detail and the supplementary material of Kroes and 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 2, conditions a and b). Condition (a) has been included in this study to explicitly demonstrate the role of recirculation as 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 that 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 generally 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 2 conditions b and c). The capillary rise (Figure 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 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 presence of soil moisture.

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, iii) for maize and potatoes the harvesting dates were respectively set to 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 data 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 (Figure 3) to be able to analyse the impact at grouped soil types.

The implementation of the synthetic modelling option is explained in supplementary material (section S4) with references to open source model SWAP version 4.0.1 which was used to carry out all the simulations.

3 Results

3.1 Case studies for validation

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 4 and Table 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 low precipitation (about 700 mm/year). The fall of the year 1998 showed rising groundwater levels that corresponded well with very wet conditions at that moment. 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 which differences were well within acceptable ranges (Figure 5 and Table 2).

For the other 2 maize case studies (C-Maize and D-Maize) groundwater levels and soil moisture were well simulated (Table 2). The simulated maize yields (Table 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.

The simulated hydrological conditions for the 3 fields of the potato-cases R-Potato and V-Potato showed a good fit with the observed (Table 2). The simulated yields (Table 2) showed the largest deviation from the observed for case B-Potato. The more recent experiments of potato cases studies R-Potato and V-Potato showed differences between simulated and observed yields of respectively 1374 and -288 $kg.ha^{-1}$ DM (Table 2). These case studies unfortunately covered only one 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 was 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 weres 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 think 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-WOFOST for the 3 crops allowed 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 3 cases are given in

Table 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). Detailed results can be found in the supplementary material (S1). In supplementary material S4 input data for case 3 (V-Potato) can be found. In a next step we carried out a larger scale experiment to quantify this impact for different soil crop and climate conditions.

3.2 Soil crop experiment to analyse the role of capillary rise

The 3 crops from the case studies were simulated with 72 soils from the national database using 3 different bottom boundary conditions and 45 years with weather from 1970-2015.

Results of simulated upward flow of 45 years weather, 72 soils and 3 lower boundary conditions are summarized with mean values in Table 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/year. 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 – 78 mm long-term average (FD_{rc} in Table 4). In free-draining soils the variation of 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 (Figures 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 7, lower part).
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 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 4). These high values were largely due to the precipitation excess during winter in the Netherlands.

Upward seepage across the bottom boundary did not occur in the free-drainage conditions (Figure 2 a and b). Leaching was highest (Table 4) in the synthetic free-drainage condition without capillary rise (Figure 2 a). Note that the values in Table 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 of vertical fluxes close to the root zone during the remainder of the year. The leaching flux at 5.5 m depth (Table 4, $q_{leaching}$) increased when upward flow was suppressed (lower transpiration, more groundwater recharge), with respectively 44, 2 and 16 mm.year^{-1} for grassland, maize and potatoes. The shallow groundwater in Dutch conditions (Figure 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.year^{-1} for grassland, maize and potatoes (Table 4, $q_{seepage}$).

As can be expected, the synthetic condition without upward flow and without groundwater (Figure 2 a), had the lowest simulated mean yields for all crops (Table 4). The highest mean yields were simulated when average groundwater situations including capillary rise were considered (Table 4, Ave). The relative mean yield increase was lowest for maize and highest for grassland (Table 5) which was probably caused by the difference in rooting depth.

The simulation results with 3 different lower boundary conditions (Figure 2 conditions a, b and c) were also compared by subtraction. The subtraction enables a quantification of the contribution of the 2 different sources of upward flow: groundwater and recirculating percolation water.

The elimination of recirculating percolation water to the root zone in free drainage conditions (synthetic condition a compared to b, Figure 2) reduced grassland, maize and potato yields with respectively 14, 0 and 7 % (Table 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 2) with average groundwater levels (condition c, Figure 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 2) with average groundwater levels (condition c) yield-reductions of grassland, maize and potatoes were respectively 26, 3 and 14 % (Table 5) or respectively about 3.7, 0.3 and 1.5 ton.ha^{-1} dry matter (Table 4). These yield differences quantify the contribution of 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 2) of 3 hydrological conditions were calculated of respectively 17, -11 and 46 % ($q_{percolation}$ in Table 5) or 63, -5 and 34 mm ($q_{percolation}$ in Table 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 $ton.ha^{-1}$ dry matter in stress conditions (Table 6). The results are presented in more detail in the supplementary material (S3).

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 wass included (Table 5). This increase wass mainly caused by internal recirculation, i.e. a part of the downward flux past the root zone wass 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.

Crop models that apply tipping 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 and Hildebrand (2015) our simulation results show that a detailed vertical flow improves predictions of root water uptake. Tipping bucket models generally overestimate drought stress and groundwater recharge and subsequently underestimate crop yield. The irrigation demand may be overestimated as well. The high 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 allow proper statistical evaluation of the two approaches. The calibration of both model approaches had too much freedom with the available datasets, which upset a reliable validation. Therefore we used the measured data sets to illustrate that with common soil and crop input values SWAP-WOFOST yielded realistic and plausible results for the crops considered in this study. Further, crop growth and soil water flow were simulated by SWAP-WOFOST with state of the art 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 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. 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 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 support this process of recirculation in conditions where the vertical water fluxes across the root zone is relatively high. This will clearly be the case in delta regions where you have occasionally a precipitation excess.

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 about 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 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 6, min row). Comparing the minimum yield values it 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 (Ave) 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 of root density and compensation of root uptake according to Jarvis (2011) but the macroscopic root water uptake concept was still simple and may require a more detailed analyses (Dos Santos et al. 2017). 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 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 dryer; situations without groundwater and without recirculation had less yield and higher yield variation than situations where groundwater influenced capillary rise (For detailed information on results see the supplementary material S1 and S3).

5. Conclusions

We quantified the impact of upward flow on crop yields of grassland, maize and potatoes in layered soils. We compared situations with average groundwater levels with 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 of grassland, maize and potatoes of respectively 26, 3 and 14 % (Table 5) or respectively 3.7, 0.3 and 1.5 ton Dry Matter per ha (Table 4). Reduction of the percolation flux can be considerable; for grassland and potatoes the reduction was 17 and 46% (Table 5) or 63 and 34 mm (Table 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.

We think that the quantification of recirculation on 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.

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References

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 (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 CO_2-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.

Bartholomeus, R. P., Witte, J. P. M., van Bodegom, P. M., van Dam, J. C., and Aerts, R., (2008). Critical soil conditions for oxygen stress to plant roots: substituting the Feddes-function by a process-based model, J. Hydrol., 360, 147–165

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

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

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 *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

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

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.

Feodorof, 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

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

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

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

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.

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

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

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

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

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.

Kroes, J., Bartholomeus, R., van Dam, J., Hack-ten Broeke, M., Supit, I., Hendriks, R., de Wit, A., van der Bolt, F., Walvoort, D., Hoving, I., and 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. http://waterwijzer.stowa.nl/Upload/publicatie2014/STOWA%202015%2016%20WEB%20LR.pdf

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

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.

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

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

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.

Šimůnek, 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.

SSSA (2008). Glossary of Soil Science Terms 2008. Soil Science Society of America. Soil Science. Retrieved from https://www.soils.org/publications/soils-glossary#

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.

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

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 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 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 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.

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.

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

Wit, C. T. De. (1965). *Photosynthesis of leaf canopies. Versl. Landbouwk. Onderz. (Agric. Res. Rep.) 663*. Wageningen. Retrieved from http://www.osti.gov/servlets/purl/915469-OIrVN9/

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.

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

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

Tables

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

Case study[1]	Crop	Location	Period	Soil type	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. (2010)	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	lichte kleibodem	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

[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 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} DM	11183	11049	133	1347	0.6	0.9	7
	Gwl	m-soil	-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} DM	11593	11850	-257	2864	-3.3	0.4	14
C-Maize	Yield	kg.ha^{-1}.yr^{-1} DM	14097	13788	310	2595	-1.2	0.7	9
	Gwl	m-soil	-1.41	-1.36	-0.05	0.25	0.4	0.9	61
D-Maize	Yield	kg.ha^{-1}.yr^{-1} DM	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-soil	-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} DM	10543	9246	1297				2
	Gwl	m-soil	-1.10	-1.10	0.00	0.03	1.0	1.0	123
R-Potato	Yield	kg.ha^{-1}.yr^{-1} DM	9984	8610	1374				1
	Gwl	m-soil	-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} DM	11071	11359	-288				1
	Gwl	m-soil	-1.03	-1.07	0.04	0.12	0.8	0.9	353

[1] Gwl = Ground Water Level; 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. RMSE gives the standard deviation of the model prediction error. A smaller value indicates better model performance.

[4] 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.

[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. 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.;

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

Table 3. Results of case studies: values and differences of yield, capillary rise and percolation fluxes, resulting from simulations with and without capillary rise

Case study[1]	Model Result	Condition A[2]	B[3]	*Differences* A-B	Unit	*Differences* (%) 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 table 1);
[3] Condition B has actual bottom boundary conditions (table 1) but without capillary rise to root zone;

Table 4. Results of soil crop experiments: mean values of 6 model results from 3 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}

Table 5. Results of soil crop experiments: differences (%) between results from 3 different hydrological conditions: FD_{nc} (Free Drainage with No reCirculation), FD_{rc} (Free Drainage with Recirculation) and Ave (Average Drainage conditions)

crop	model Result	differences (%) 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

Table 6. Results for potatoes of soil crop experiments for each clustered soil type: capillary rise, recirculation and yield from 3 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

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.

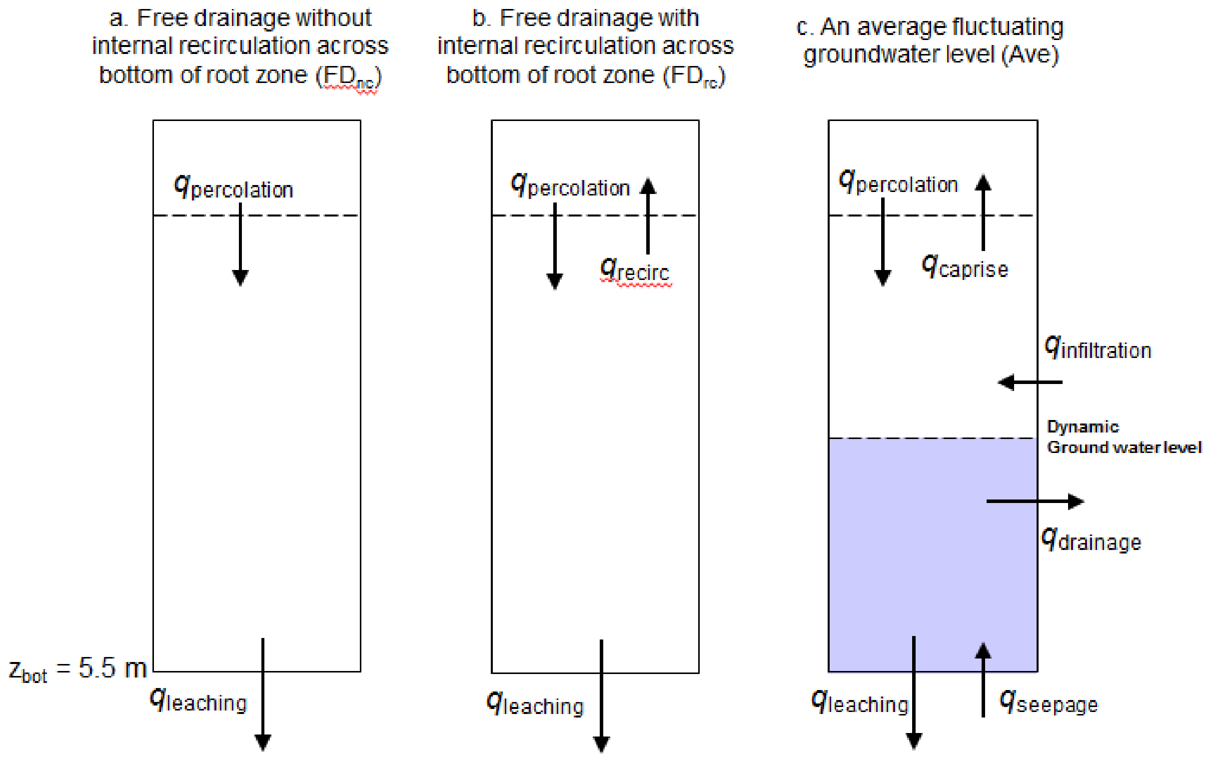

Figure 2. Schematization of 3 hydrological conditions: a. Free Drainage without recirculation across bottom of root zone (FD$_{nc}$), b. Free Drainage with recirculation across bottom of root zone (FD$_{rc}$) and c. Average fluctuating groundwater level (Ave).
Conditions a and b have free-draining bottom 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).

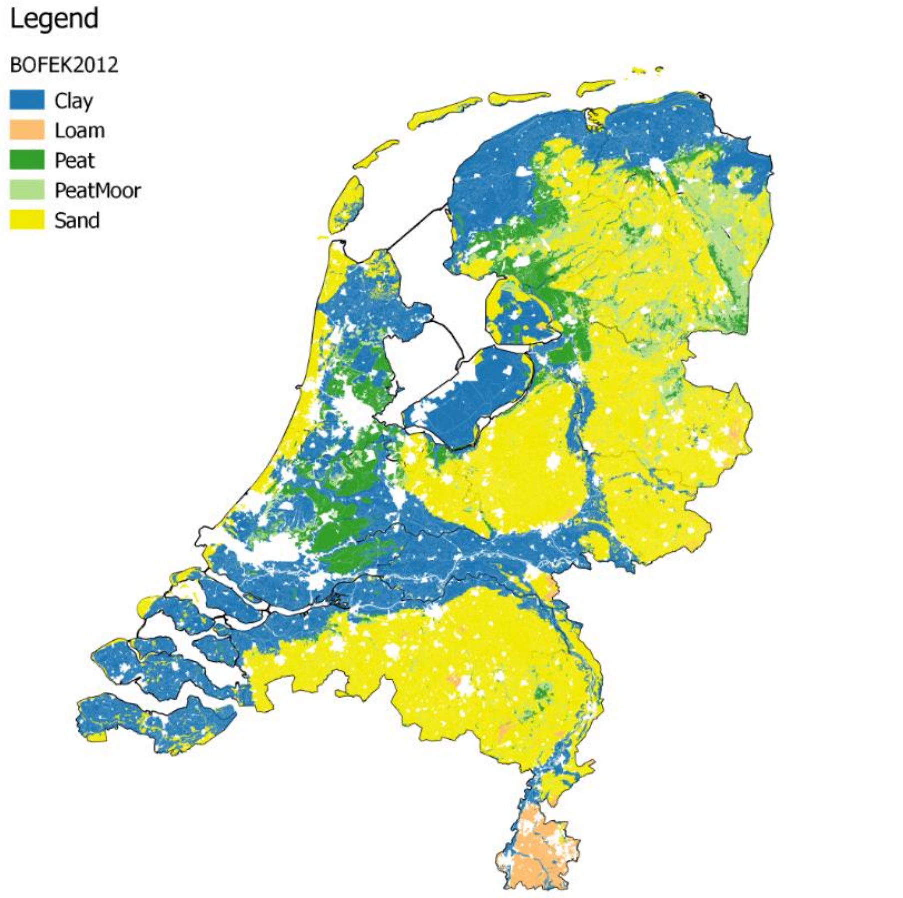

Figure 3. Five grouped soil types, based on 72 soils of the Soil Physical Map of the Netherlands (Wösten et al., 2013)

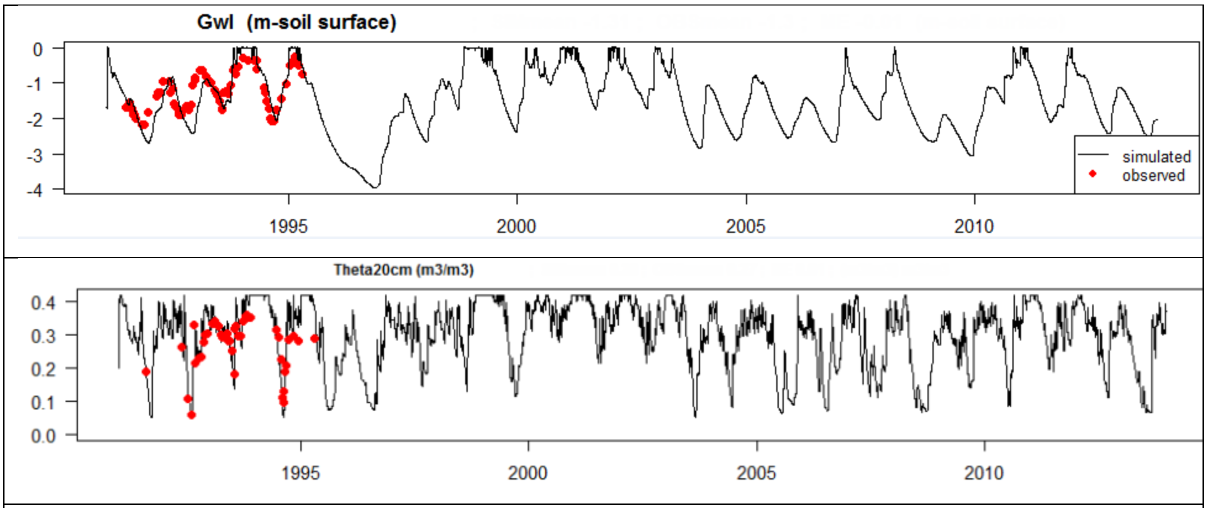

Figure 4. Results of case studies for grassland at location 1 (De Marke):
- *top figure = groundwater level (Gwl in m-soil surface):*
- *bottom figure = soil moisture content (Theta20cm in $m^3.m^{-3}$) at 20 cm below the soil surface*

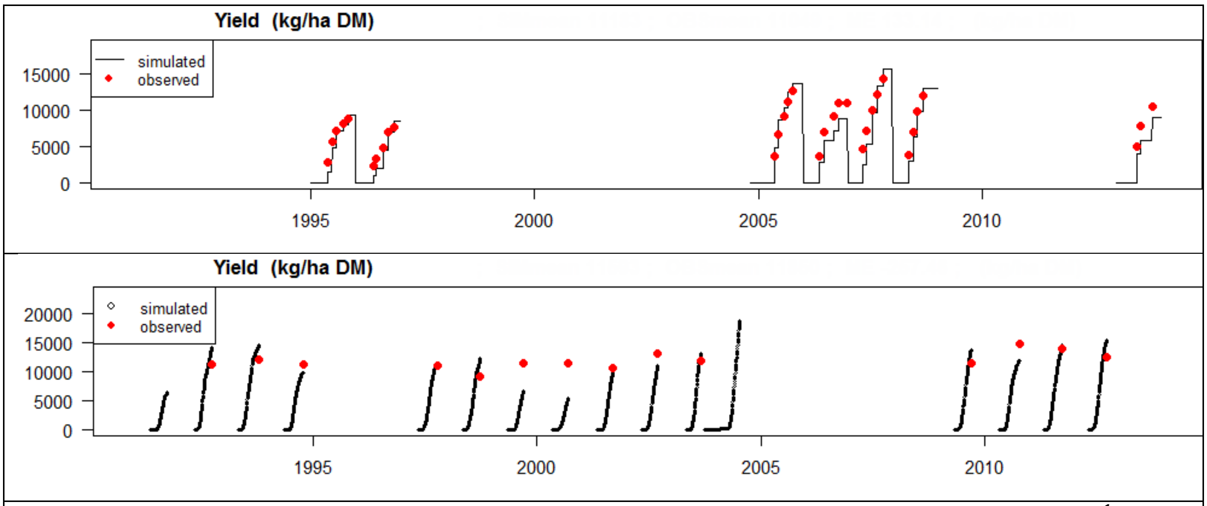

Figure 5. Results of case studies at location 1 (De Marke) : Observed Yields ($kg.ha^{-1}$DM) as red dots and Simulated above ground biomass as black lines or as black dots
- *top figure = yields ($kg.ha^{-1}$ DM) of grassland*
- *bottom figure = yields ($kg.ha^{-1}$ DM) of maize*

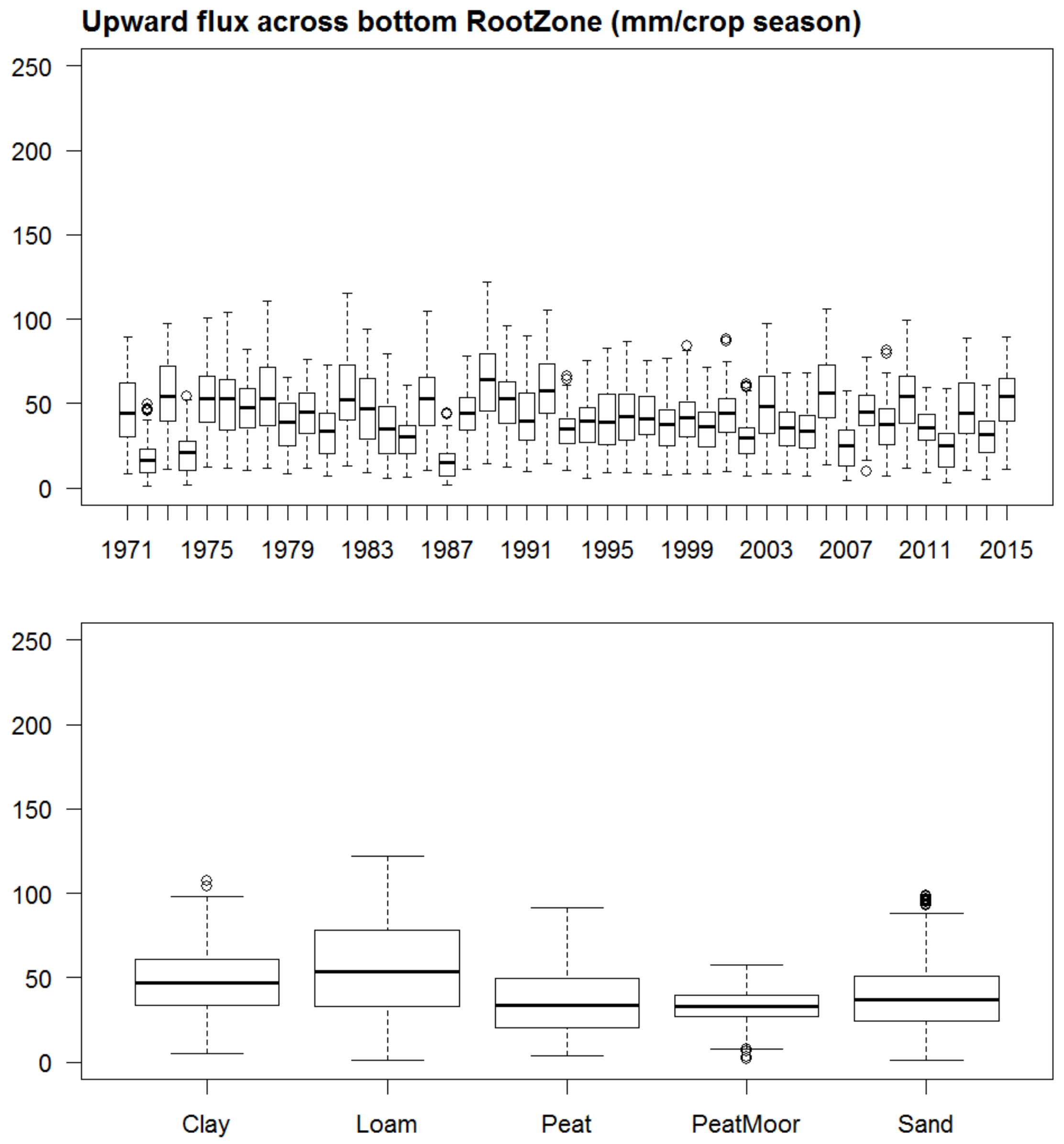

Figure 6. Results of soil-crop experiment for potato: Upward flux across the bottom of the root zone (q_{recirc} in mm.crop season $^{-1}$) for hydrological conditions with free drainage (FD_{rc});
Upper figures: results for all 72 soils for the period 1971-2015;
Lower figures: results as boxplots for clustered soil types.

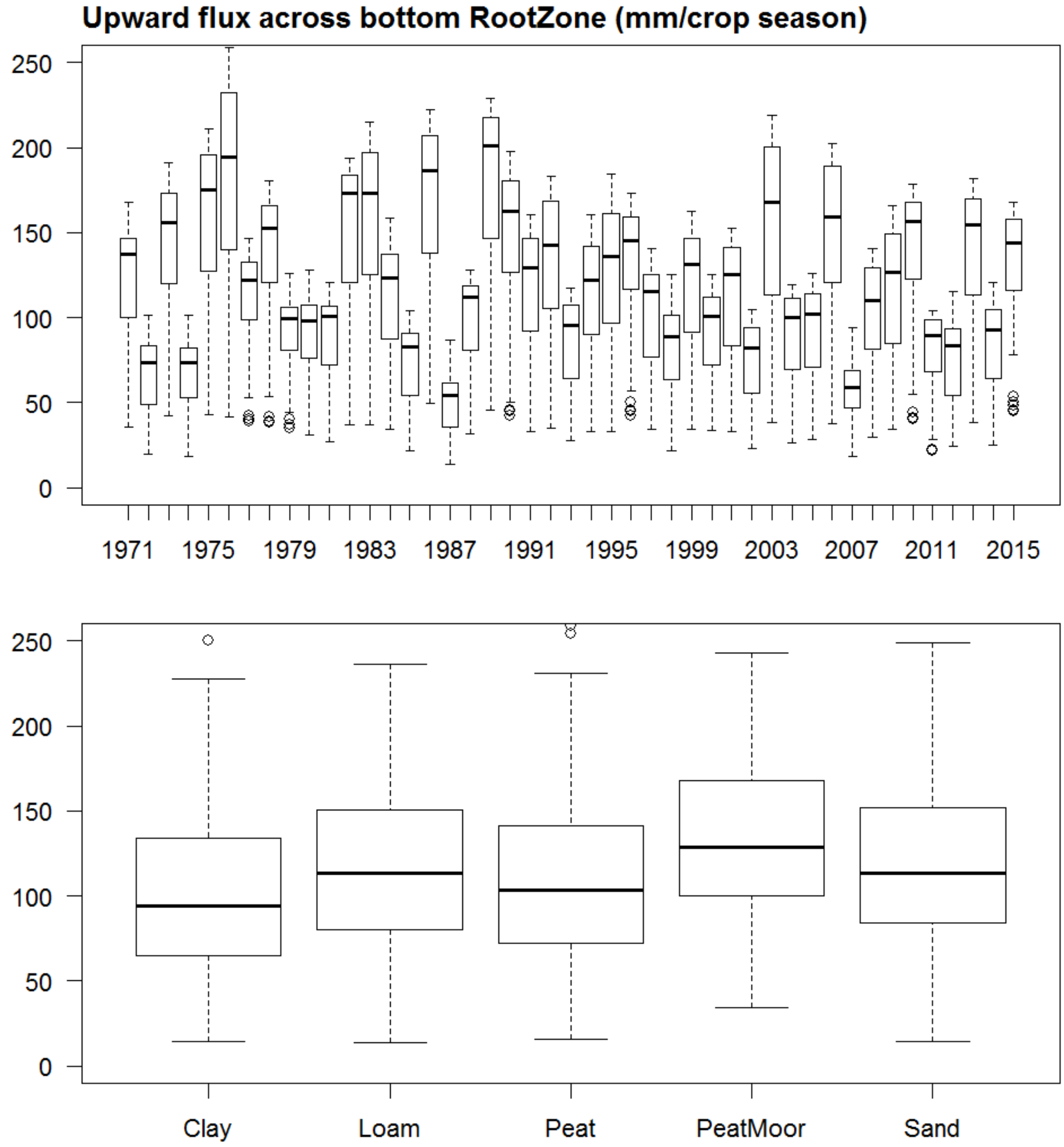

Figure 7. Results of soil-crop experiment for potato: Upward flux across the bottom of the root zone ($q_{caprise}$ in mm.crop season^{-1}) for hydrological conditions with average groundwater level (Ave); Upper figures: results for all 72 soils for the period 1971-2015; Lower figures: results as boxplots for clustered soil types.