**Supplementary material to**

**Impact of capillary rise and recirculation on simulated crop yields**

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This supplementary material has a content with 5 sections

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# S1: Additional results of field studies for validation

See the text of the article for an explanation of the references to the cases

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| Figure S1. Results of case studies for silage maize:   * top figure = groundwater levels (Gwl in m-soil surface) case C-Maize; * middle figure = groundwater levels (Gwl in m-soil surface) case D-Maize; * bottom figure = theta (Theta20cm in m3.m-3) at a depth of 20 cm-soil surface case D-Maize. |
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| Figure S2. Results of case studies for silage maize: Yields (kg.ha-1DM) Observed as red dots and Simulated above ground biomass as black dots.   * top figure = case C-Maize; * bottom figure = case D-Maize. |

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| Figure S3. Results of case studies for potato:   * top figure = groundwater levels (Gwl in m-soil surface) case R-potato; * bottom figure = groundwater levels (Gwl in m-soil surface) case V-Potato*.* |

# S2: Selection and validation of average hydrological condition “Ave”

This section describes how we found the average hydrological condition “Ave”.

We selected units from the National Study (Van Bakel et al., 2008) which has 3 types of land use (grassland, arable crops (potatoes) and forage maize) distributed over 12 groundwater classes (Gt in Table S1). From these groundwater classes the class IV may be regarded as an average class. From this average class IV we selected boundary conditions from large plot numbers 2245, 3859 and 621 for grassland, maize and potatoes (Table S2), which are units with sizes of respectively 1806, 794 and 5812 ha.

Resulting groundwater levels were verified for grassland (Figure S4), forage maize (Figure S5) and potatoes (Figure S6).

Table S1. Groundwater classes (Gt) on the national soil map 1:50.000 of The Netherlands with their mean highest (GHG) and mean lowest (GLG) groundwater levels (in cm below the soil surface) and their agricultural land areas (1000 ha) according to the soil map and the model system applied by Van Bakel, 2008).

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| Groundwater class | | | Agricultural land area (1000 ha) | | | |
| Gt | GHG (cm) | GLG (cm) | Grassland | Maize | Arable | Total |
| I | - | <50 | 52 | 0 | 1 | 54 |
| II | - | 50-80 | 155 | 6 | 7 | 168 |
| III | <40 | 80-120 | 125 | 16 | 15 | 157 |
| IV | >40 | 80-120 | 66 | 18 | 74 | 157 |
| V | <40 | >120 | 117 | 18 | 14 | 150 |
| VI | 40-80 | >121 | 286 | 72 | 275 | 633 |
| VII | >80 | >122 | 183 | 91 | 360 | 635 |
| Total |  |  | 984 | 221 | 746 | 1952 |

Table S2 Calculation units of which boundary conditions for the average situation were taken from the national study (Van Bakel et al., 2008).

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| Gt | landuse | plot nrs | area (ha) | soiltype |
| IV | grassland | 2245 | 1806 | sand |
| IV | silage maize | 3859 | 794 | sand |
| IV | potato | 621 | 5812 | sand |

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| Figure S4. Result of grassland: average groundwater levels (cm-soil surface) characterized for each soil unit by mean highest and lowest groundwater levels(left) and by groundwater class (right). | |

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| Figure S5. Result of forage maize: average groundwater levels (cm-soil surface) characterized for each soil unit by mean highest and lowest groundwater levels(left) and by groundwater class (right). | |

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| Figure S6. Result of potatoes: average groundwater levels (cm-soil surface) characterized for each soil unit by mean highest and lowest groundwater levels(left) and by groundwater class (right). | |

# S3: Additional results of soil crop experiments to analyse the role of upward flow

This section presents results of the 3 hydrological conditions:

* FDnc: Free Drainage without recirculation across bottom of root zone
* FDrc: Free Drainage with recirculation across bottom of root zone
* Ave: Average fluctuating groundwater level

Results are given in Figures:

* Figures S7-S9: The upward flux across the bottom of the root zone during crop season
* Figures S10-S12: Difference in upward flux by comparing hydrological conditions
* Figures S13-S15: Yields of 3 crop types and 3 hydrological conditions
* Figures S16-S18: Difference of Yields by comparing results of hydrological conditions

See the main text and figures for an explanation of hydrological conditions and corresponding fluxes.

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| Figure S7 . Results of soil-crop experiment for grassland: Upward flux (mm.crop season-1) for conditions FDrc (left) and Ave (right);  Upper figures: results for all 72 soils for the period 1971-2015;  Lower figures: results as boxplots for clustered soil types. | |

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| Figure S8. Results of soil-crop experiment for silage maize: Upward flux (mm.crop season-1) for conditions FDrc (left) and Ave (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types | |

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| Figure S9. Results of soil-crop experiment for potato: Upward flux (mm.crop season-1) for conditions FDrc (left) and Ave (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types | |

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| Figure S10. Results of soil-crop experiment for grassland: difference in Upward flux (mm.crop season-1) between conditions FDnc and FDrc (left) and between conditions FDnc and Ave (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types | |

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| Figure S11. Results of soil-crop experiment for silage maize: difference in Upward flux (mm.crop season-1) between conditions FDnc and FDrc (left) and between conditions FDnc and Ave (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types | |

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| *Figure S12. Results of soil-crop experiment for potato: difference in Upward flux (mm.crop season-1) between conditions FDnc and FDrc (left) and between conditions FDnc and Ave (right); Upper figures: results for all 72 soils for the period 1971-2015. Lower figures: results as boxplots for clustered soil types* | |

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| Figure 13. Results of soil-crop experiment for grassland: Yield (kg/ha) for hydrological conditions FDnc (left), FDrc (center) and Ave (right);  Upper figures: results for all 72 soils for the period 1971-2015;  Lower figures: results as boxplots for clustered soil types. | | |

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| *Figure S14. Results of soil-crop experiment for silage maize: Yield (kg/ha) for hydrological conditions FDnc (left), FDrc (center) and Ave (right);*  *Upper figures: results for all 72 soils for the period 1971-2015;*  *Lower figures: results as boxplots for clustered soil types.* | | |

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| Figure S15. Results of soil-crop experiment for potato: Yield (kg/ha) for hydrological conditions FDnc (left), FDrc (center) and Ave (right);  Upper figures: results for all 72 soils for the period 1971-2015;  Lower figures: results as boxplots for clustered soil types. | | |

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| Figure S16. Results of soil-crop experiment for grassland: difference in Yield (kg/ha) between conditions (FDrc – FDnc) (left) and conditions (Ave– FDnc) (right);  Upper figures: results for all 72 soils for the period 1971-2015;  Lower figures: results as boxplots for clustered soil types. | |

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| Figure S17. Results of soil-crop experiment for silage maize: difference in Yield (kg/ha) between conditions b – a (FDCR – FDNC) (left) and conditions c – a (Ave– FDNC) (right);  Upper figures: results for all 72 soils for the period 1971-2015;  Lower figures: results as boxplots for clustered soil types. | |

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| Figure S18. Results of soil-crop experiment for potato: difference in Yield (kg/ha) between conditions b–a (FDCR – FDNC) (left) and conditions c–a (Ave– FDNC) (right);  Upper figures: results for all 72 soils for the period 1971-2015;  Lower figures: results as boxplots for clustered soil types. | |

# S4: How to simulate water fluxes without recirculation and capillary rise

An option was implemented in the agro-hydrological model SWAP4 to minimize the vertical upward flux in the 2 compartments below the root zone by setting the hydraulic conductivity for upward flow to a very small value (10-10 cm.d-1) using an implicit scheme for the conductivity in situations where the flow is upward. This results in a strong reduction of the upward flow from compartments below the root zone towards the root zone.

The option is activated when the input file with extension “swp” contains the line:

SWCAPRISE = .true.

An output file with vertical water fluxes across the bottom of the rootzone is generated when the input file with extension “swp” contains the line:

SWCAPRISEOUTPUT=.true.

This output file gets the extension “crz”.

This was implemented in Swap4 (Kroes et al., 2017) and can be downloaded from [www.swap.alterra.nl](http://www.swap.alterra.nl)

An example can be simulated with Swap4.0.1 and results must be identic to the results presented in table 3 of the main test. Two simulations can be executed: with and without upward flow towards the root zone, using the synthetic model option. Results shows that suppressing upward flow lowers yields by 20% for potato . The groundwater recharge was reduced with 94%. (Table 3, case 3 (V-Potato).

The example can be simulated using the following steps:

* Download Swap4.0.1 from [www.swap.alterra.nl](http://www.swap.alterra.nl) as InstallPackageSwap401.zip
* Unzip the file InstallPackageSwap401.zip
* Verify that you have the folder cases
* Download the example as a zip-file from :

http://[www.swap.alterra.nl/Documents/Swap401Case7CapRiseArticle.zi](http://www.swap.alterra.nl/Documents/Swap401Case7CapRiseArticle.zip)p

* Unzip the file as a subfolder “7.CapRiseArticle” in the folder cases
* Simulate the example with capillary rise by double clicking RunSwap.cmd in the folder \cases\7.CapRiseArticle\7a.PotatoD(Vredepeel26)\_A\_withCaprise\
* Simulate the example without capillary rise by double clicking RunSwap.cmd in the folder

\cases\7.CapRiseArticle\ 7b.PotatoD(Vredepeel26)\_B\_withoutCaprise\

# S5: A case study to illustrate the process of recirculation: grassland De Marke field09

*Introduction*

To demonstrate and support our hypothesis that the process of recirculation makes crop modelling more accurate we added another case study.

We selected experiments from field 9 at location 1 (De Marke) with additional observations of soil water pressure heads and soil moisture contents at different depths during the years 1992-1995 (Hack-ten Broeke & Hegmans (1996). Land use was permanent grassland with observed yields.

*Method*

The field had relatively deep groundwater at an average level of 1.69 meter below the soil surface. With these groundwater levels capillary rise will be low, especially in summer when crops demand water for transpiration.

We used this field experiment to approach the 2 hydrological conditions (Figure 2 in main text):

* a) Free drainage without internal recirculation across bottom of root zone (FDnc)
* b) Free drainage with internal recirculation across bottom of root zone (FDrc)

We simulated the actual situation using SWAP 4.0.1 and tried to get a best approximation of the two hydrological conditions using the given groundwater level as lower boundary condition for both simulations (Fig. S19).

A calibration was followed using the management factor as calibration parameter (RELMF), resulting in a value of 0.7 for the management factor. This was done for the hydrological condition b) where internal recirculation was active.

All other conditions, including crop parameter parameters, were taken from case study DM-Grass (see Table 1, main text) for the same location De Marke.

The results of the simulation of condition b) showed an average upward flux of 49 mm/year (Fig. S21) and an average downward flux of 501 mm/year across the bottom of the root zone. Condition a) had no upward flux and an average downward flux of 485 mm/year.

*Results*

Condition b (with recirculation):

The resulting yield showed an average difference of 51 kg/ha DM between simulated and observed yearly yields (Fig. S20).

The resulting soil water pressure heads and soil moisture contents at depths of 10, 20, 30 and 40 cm were acceptable (Fig. S22 and S23).

Results for greater depths were left out of the analyses because they became saturated in the winter of the 1993-1994 and were less relevant for the flux across the bottom of the grassland root zone which varies between 20 and 40 cm below the soil surface..

Condition a (without recirculation):

The resulting yield showed an average difference of 660 kg/ha DM between simulated and observed yearly yields (Fig. S24).

The resulting soil moisture contents at depths of 10, 20, 30 and 40 cm were very similar to results from condition b) with an identic RMSE (Fig. S25).

The resulting soil water pressure heads at depths of 30 and 40 cm are quite similar to condition b) (Fig. S26). The soil water pressure heads in the upper parts of the root zone (10 and 20 cm depth) show the largest difference when compared to condition b): RMSE goes from 5153 to 7396 cm and soil water pressure heads incidentally goes down from about 500 to values of less than 20.000 cm (Fig S26, depth of 20 cm) causing severe drought conditions.

*Discussion*

The difference in soil water pressure head in the upper part of the root zone demonstrate drying of the soil due to a lack of recirculating water in the hydrological condition a).

This results 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.

It supports the hypothesis that it is recommended 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 a precipitation excess.

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| Figure S19. Observed and simulated groundwater level (Gwl). |

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| Figure S20. Results of hydrological condition b) with internal recirculation across bottom of root zone (FDnc): simulated and observed grassland yield (kg/ha DM) |

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| Figure S21. Simulated vertical upward flux (mm/year) across the bottom of the root zone in the simulation with recirculation |

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| Figure S22. Results of hydrological condition b) with internal recirculation across bottom of root zone (FDrc): simulated and observed soil moisture contents (-) at 4 depths: 10, 20, 30 and 40 cm below the soil surface vertical in the simulation with recirculation |

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| Figure S23. Results of hydrological condition b) with internal recirculation across bottom of root zone (FDnc): simulated and observed soil water pressure heads (cm) at 4 depths: 10, 20, 30 and 40 cm below the soil surface |

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| Figure S24. Results of hydrological condition a) without internal recirculation across bottom of root zone (FDnc): simulated and observed grassland yield (kg/ha DM) |

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| Figure S25. Results of hydrological condition a) without internal recirculation across bottom of root zone (FDrc): simulated and observed soil moisture contents (-) at 4 depths: 10, 20, 30 and 40 cm below the soil surface vertical in the simulation with recirculation |

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| Figure S26. Results of hydrological condition a) without internal recirculation across bottom of root zone (FDnc): simulated and observed soil water pressure heads (cm) at 4 depths: 10, 20, 30 and 40 cm below the soil surface |

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