Spatial crop-water variations in rainfed wheat systems

From simulation modelling to site-specific management

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Thesis research framework

The local rainfed wheat systems

- Local rainfed arable farming systems ⇒ *"Campiña del Guadalquivir"* ⇒ approx. 300.000 ha of **Vertisols**;
- ***Campiña soils*** ⇒ shrinking-swelling nature ⇒ **clay texture**, high bulk density, moderate-deep depth and **undulating topography**;

- **Wheat (mostly durum) is grown 1-2 times every four seasons**;
- Water shortage is frequently experienced (>80% of seasons);
- **Water is a major wheat yield determining factor**;

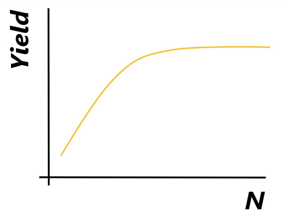
The spatial dilemma

- Crops are spatially heterogeneous;
- **Spatial crop-water variations cause yield variability**;
- Spatial variability brings risks to farmers;

$\boxed{\text{under- vs. over-use of fertilizer}}$

The spatial dilemma within rainfed crop systems modelling

Fertilization $\Leftarrow$ Crop yield benchmarks



Crop modelling $\Rightarrow$ benchmarking crop yields

Simulation of different yield-levels within a single field $\Rightarrow$ VAR

However, crop simulation models are not spatially distributed

Point-based $\Rightarrow$ averaging characteristics to model an area of interest

Thesis objectives

1. To investigate opportunities to simulate spatial water variations at crop field level;
2. To explore new data assimilation methods within crop modelling for determining crop yield variability at field level; [1]
3. To simulate water lateral inflows and to evaluate their net contribution to spatial variations of rainfed wheat yields in fields of undulating topography;
4. To analyse the economic relevance of site-specific management to deal with spatial crop-water variations;

[1] while keeping a point-based water-balance.

Crop-water modelling approaches and opportunities to simulate spatial water variations at crop field level

Water modelling approaches

12 different simulation models were selected [2] and their water modelling approaches were systematically reviewed.

Two model families:

1. **Crop models**: centered on crop growth and development as affected by the environment;
2. **Hydrological models**: emphasize mostly systems' water dynamics at multiple scales;

Main structural differences:

1. **'Point-based'** representation of the crop environment;
2. **Partial distribution over space** of water-related processes;

[2] **Crop models**: WOFOST, DSSAT, APSIM, DAISY, STICS, AquaCrop and MONICA // **Hydrological models**: HYDRUS-1D, HYDRUS-2D, SWAP, MIKE-SHE and SWIM

Water modelling approaches

Main computational differences:

1. **Discrete and empirical mathematical approaches**:
    - Lower time-frequency of simulation steps (daily steps);
    - Water transport follows typically a 'tipping bucket' approach (drainage is assumed to be a steady-flow);
    - Infiltration and surface run-off are estimated according to empirically based methods (e.g., USDA Curve-Number);
2. **Continuous and mechanistic mathematical approaches**:
    - Higher time-frequency of simulation steps (hourly steps, non-linear functions);
    - Water movement is mechanistically modelled (e.g., Richards' equation to compute the hydraulic behaviour of the soil as a function of the soil water content);

Opportunities to simulate spatial water variations

From the systematic review [3] of water modelling approaches, **TWO major water-related processes were identified** as determinant for the simulation of spatial water variations at crop field level:

1. Surface lateral inflow;
2. Sub-surface lateral inflow;

Each of these processes is covered by at least one model, but none of the models covers simultaneously the two processes.

[3] Tenreiro, et al. (2020). Water modelling approaches and opportunities to simulate spatial water variations at crop field level. Agricultural Water Management, 240, 106254

Opportunities to simulate spatial water variations

Two main opportunities for progress [4] $\Rightarrow$ Chapter 3:

1. Promoting synergism between both modelling families (using hydrological models to simulate mechanisms to be integrated into crop models;
2. Integrating of lateral flows in the simulation of discrete water movement approaches;

[4] Tenreiro, et al. (2020). Water modelling approaches and opportunities to simulate spatial water variations at crop field level. Agricultural Water Management, 240, 106254

Canopy-yield modelling: New data assimilation methods within crop modelling

Exploring new data assimilation methods within crop modelling

THE CONCEPT

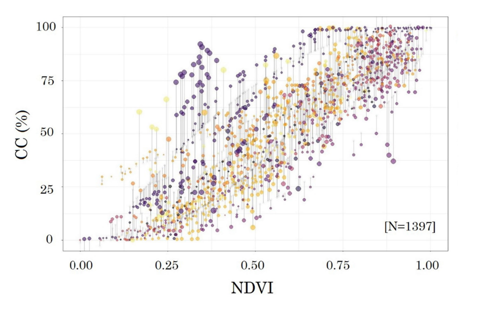
- Using **satellite imagery** for the assessment of **canopy cover (CC)** in agricultural crops;
- **Assimilation of satellite estimated CC** into the simulation modelling process;

HOW?

- **NDVI** (higher time and spatial resolution) ⇒ **CC estimates and CC-related parameters** (e.g., date of emergence, beginning of crop senescence) ⇒ **AquaCrop model**;
- **AquaCrop is a water-driven model** developed by FAO: *Y=f(CC,ET)*;
- Time-series of satellite imagery ⇒ **Temporal interpolation** of NDVI measures at each site ⇒ **Site-specific parameterization of the CC curve (and CC-related parameters) in AquaCrop**;

META-ANALYSIS (NDVI-CC relationships) [5]

- Data from 19 different studies;
- NDVI-CC relationships for 13 different agricultural crops;
- **Linear or quadratic** models;



[5] Tenreiro, et al. (2021). Using NDVI for the assessment of canopy cover in agricultural crops within modelling research. Computers and Electronics in Agriculture, 182, 106038.

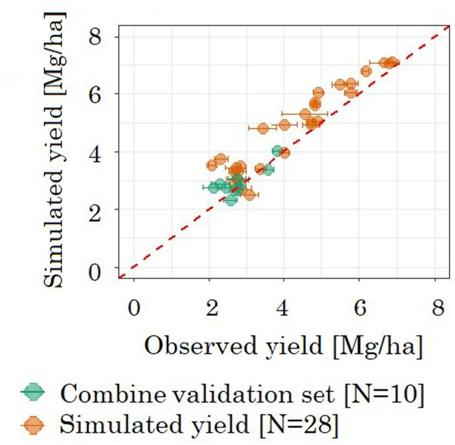
New data assimilation methods within crop modelling

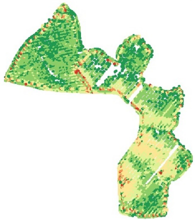
CASE-STUDY WITH WHEAT

1. Wheat NDVI-CC correlations used for AquaCrop parameterization at multiple locations within the same field;
2. **Simulations validated with field data** (combine harvester) collected from two different fields (three growing seasons);


CASE-STUDY OUTCOMES

- **Simulated yields' well correlated with observations** from yield-mapping (combine harvester) ⇒ comparable error ranges;





CASE-STUDY OUTCOMES

- The assimilation of NDVI-CC relationships into AquaCrop **captured 55% to 88% of the yield variation observed**;
- **We cannot rely solely on remote sensing to deal with spatial variation;**

Hypothesis: *Including spatial variations in water availability (e.g., lateral inflows) is likely to close the gap between simulated and observed yield variation.*

Water-yield modelling: Simulating water lateral inflow and its contribution to spatial variations of rainfed wheat yields

Field stage

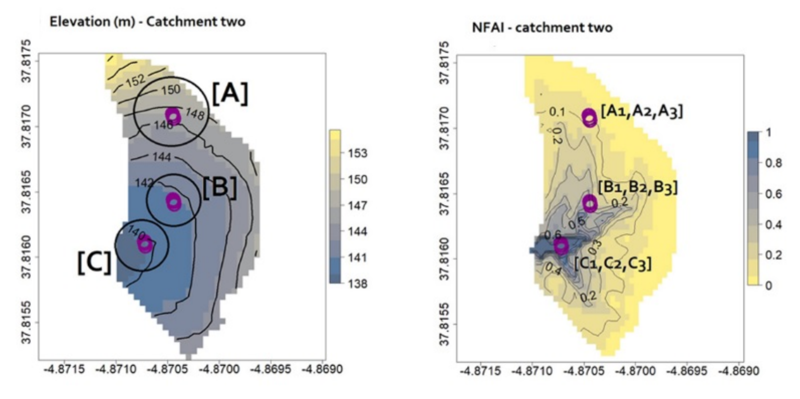
What is the net contribution of water lateral inflows to spatial variations of rainfed wheat yields in fields of undulating topography? [6]

- The magnitude and frequency of **lateral inflows (LIF)** were experimentally assessed;
- **Soil water content** $\Leftarrow$ high-frequency capacitance probes, at multiple locations within the same field (two seasons);
- Capacitance probes calibrated with neutron probe measurements.

[6] Tenreiro, et al. (2022). Simulating water lateral inflow and its contribution to spatial variations of rainfed wheat yields. European Journal of Agronomy, 137, 126515.

Field stage

- Sampling points defined according to hydrological-connectivity rules based on topography and a flow accumulation index;



Hydrological modelling stage

- LIF was inferred at daily time-steps from SWC observations and measured rainfall (with an autonomous rain gauge system) through a **water-balance approach**;

$$\boxed{\Delta SWC = P + LIF + CR - ET - SRn - D}$$

$$\boxed{LIF = \Delta SWC - P - CR + ET + SRn + D}$$

- Every time-step that SWC varied by an amount greater than the registered precipitation $\Rightarrow$ LIF assumed to take place;

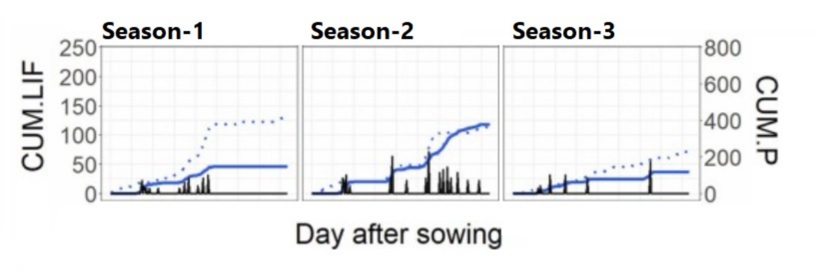
$$\boxed{LIF = [SWC_{increase} - rainfall_{amount}]}$$

Hydrological modelling stage

- The **HYDRUS-1D model** [7]was used to optimize soil hydraulic conductivity and surface run-off, at each observation point;
- The optimization procedure with HYDRUS was adjusted by means of SWC observations;
- The outputs of HYDRUS (surface run-off and K_{SAT}) + field experimental data (NFAI, daily CC and inferred LIF) $\Rightarrow$ input features to train and test a feed-forward **Artificial Neural Network (ANN)**;
- The ANN was used to upscale the analysis and to forecast LIF patterns over a period of 30 years;

[7]The HYDRUS-1D model is an hydrological model based on the Richards' equation, which was reviewed in the first research chapter of this thesis.

- ANN $\Rightarrow$ LIF computed at daily time-steps from sowing to harvesting dates (over a period of 30 years);



Crop modelling stage

The **AquaCrop model** was used to simulate **net yield responses to LIF** (NYR_{LIF}) over 30-Y:

- **LIF** daily calendars $\Rightarrow$ **AquaCrop simulations** (irrigation module);
- NYR_{LIF} = [Y_{LIF} - $Y_{No.LIF}$] $\sim$ [$Y_{downslope}$ - $Y_{upslope}$]
- LIF impact $\Leftarrow$ season rainfall amount and distribution;
- LIF $\in$ 10-38% of season rainfall (avr. 19%);
- Less rainfall $\Rightarrow$ water shortage $\Rightarrow$ LIF_{MWP} increases $\Rightarrow$ stronger impact of LIF $\Rightarrow$ higher NYR_{LIF};
- Lower potential yielding seasons $\Rightarrow$ higher yield variation;
- Great LIF impact in 1/3 of seasons (> 1 t ha^{-1} $\sim$ 25% CV);
- NYR_{LIF} **was on average 16% (400 kg ha^{-1})** in LIF zones; [8]

[8](15-20% of the total field area)

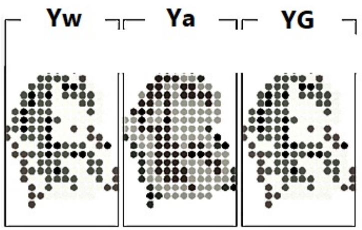
The economic relevance of site-specific management

Intra-plot spatial assessment of Yield Gaps

Distributing spatially the concept of yield gap (YG):

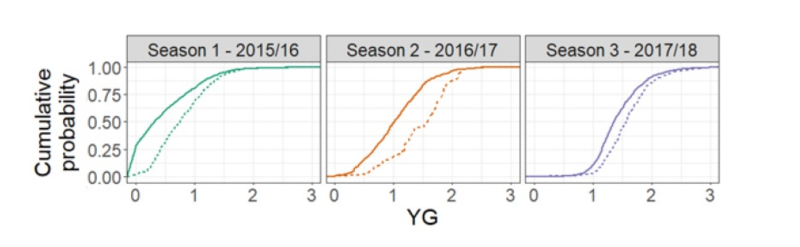
$YG_{(x,y)} = Yw_{(x,y)} - Ya_{(x,y)}$

1. $Yw_{(x,y)} \Leftarrow$ AquaCrop simulations;
2. $Ya_{(x,y)} \Leftarrow$ Combine harvester monitor;



The relative advantage of VAR adoption

- *Yw* ⇒ 'yield-N' benchmark & *Ya* ⇒ farmer's baseline;
- *The scope for improvement* ⇒ *YG* (considering full N-recovery in harvested grain);
- Technological shift ⇒ relative scope for improvement;
- *The relative scope for improvement?* ⇒ diff. between $YG_{(LIF)}$ and $YG_{(No-LIF)}$, considering the proportional relations between zones;



- $YG_{(LIF)} - YG_{(No-LIF)}$ = area between the two lines ⇒ diff. of the integrals of each cumulative probability curve ⇒ opportunity window for an additional margin in terms of yield gap closure;

The economics of VAR adoption - I

Differentiated cost-benefit analysis $\Rightarrow$ a differentiated N-rate (cost) and a differentiated yield gap closure (revenue);

1. Capital recovery of VAR adoption:
    - Net Present Value (NPV);
    - Internal Rate of Return (IRR);
    - Return-on-investment-time (ROI_t);
2. Multiple scenarios:
    - Same topographic structure vs. increased LIF area share;
    - Moderate vs. drastic prices increase;
    - Price supports vs. additional direct payment on crop area;
    - Support on VAR investment;

The economics of VAR adoption - II

- Important **trade-offs** for viability of VAR: ***area vs.*** $\boldsymbol{ROI_t}$;
- ROI_t < 10-Y ⇒ **annual sown area > 568 ha** (15x national mean);

- Current prices trends are likely to decrease the minimum area threshold for adoption (568 ha ⇒ 180 ha ⇒ 68 ha);

The economics of VAR adoption - III

- The 'additional revenue' had a stronger impact on margins than costs $\Rightarrow$ **strong effect of sown area and LIF area share (*'economies of scale'*)**;
- IRR < 0 for most levels of annual sown area $\Leftarrow$ tight NYR_{LIF} and minor LIF area share of experimental fields;
- The relative advantage $\Rightarrow$ average 'additional margin' $\Rightarrow$ highly variable from year to year and among different scenarios (-40 to 198 € ha^{-1});
- Prices' trends and an additional payment on sown area [9] are likely to decrease the minimum area threshold for adoption (30-60 ha $year^{-1}$);

[9] Introduction of an additional payment on sown area, equivalent to the existing supports, in Spain, on oilseeds and legume-crops ($\sim$45 € ha^{-1})

Conclusions

Obj. 1 - Opportunities to simulate spatial water variations

From the models' review [10]**, LIF were identified as determinant for the simulation of spatial water variations at crop field level**.

Two main opportunities for progress:

1. Promoting synergism between both modelling families (HYDRUS + AquaCrop);
2. Integrating LIF in the simulation of discrete water movement approaches (Experiments $\Rightarrow$ HYDRUS + ANN $\Rightarrow$ LIF $\Rightarrow$ AquaCrop);

[10] Tenreiro, et al. (2020).

Two main conclusions regarding the potential of assimilating NDVI-CC relationships into crop simulation: [11]

1. The assimilation of NDVI-CC relationships into AquaCrop is a valid strategy to simulate yield variations (capturing up to 88% of the observed variations);
2. Including spatial variations in water availability (e.g., LIF) is necessary to close the remaining gap between simulated and observed yield variation.

[11] Tenreiro, et al. (2021).

Obj. 3 - The net contribution of LIF to spatial variations of yields

- LIF contribute to yield variations in rainfed wheat systems;
- Years of maximum responsiveness were associated with low rainfall during the vegetative stages + LIF occurring at flowering and post-flowering stages; [12]
- **In LIF zones, the net contribution is on average 16% of grain yield**;
- **At field scale, NYR_{LIF} is lower than 5% due to the minor LIF area share within the entire field (i.e., 18-20%)**;

[12] Tenreiro, et al. (2022).

Obj. 4 - The economic relevance of VAR adoption

- There is a relative economic advantage of VAR in rainfed wheat systems of undulating topography. However, the economic viability of such a management system is profoundly affected by effects of scale.
- The minimum area required for amortization of VAR varies from 560 to 46 ha, depending on the N/grain prices, under the specific conditions analyzed in this thesis;
- In situations of different topography, where the LIF areas may be more important than those found here, VAR may be further applicable to farms smaller than the thresholds for adoption here presented;
- An additional payment on crop area, to promote the environmental benefits of N-VAR, could turn this technique viable for a much wider population of farmers.

Thank you for your attention

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