Optimal seasonal water allocation and model predictive control for precision irrigation

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Presentation Outline

- Motivation for Research
- Problem Formulation
- Two-level Controller
- Modelling
- Simulation Results
- Summary

Motivation – Freshwater Use

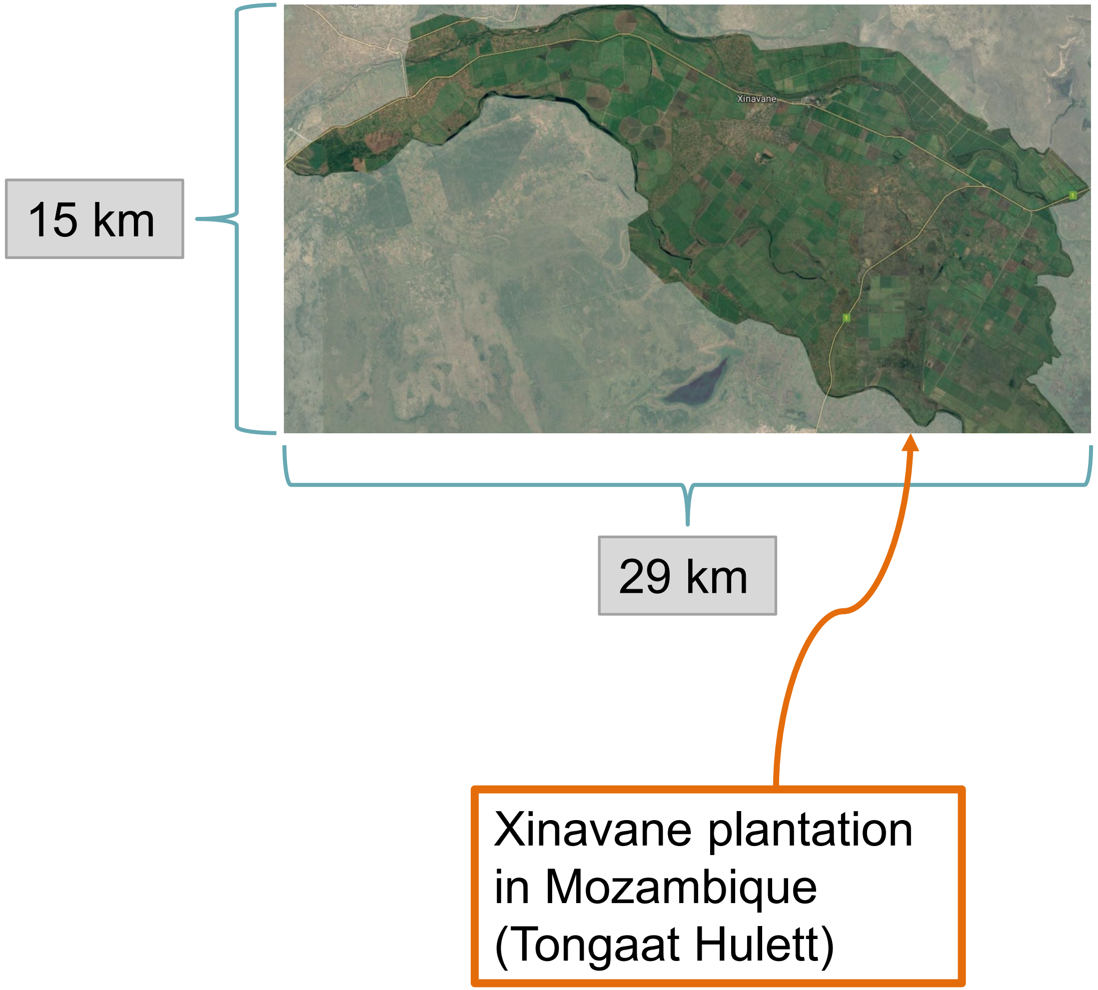
Agriculture is the largest global consumer of the available water resources, accounting for 69% of annual water withdrawals[1]

[1] *Water Energy Nexus: Excerpt from the World Energy Outlook 2016* (Tech. Rep.). 712 (2016). Paris, France.

Motivation – Large-scale plantations

Large plantations struggle with allocating water (spatially and temporally) when the water supply is limited (in times of drought) to maximize crop yield

- Multiple fields
- Resource constraints (human workers, water)



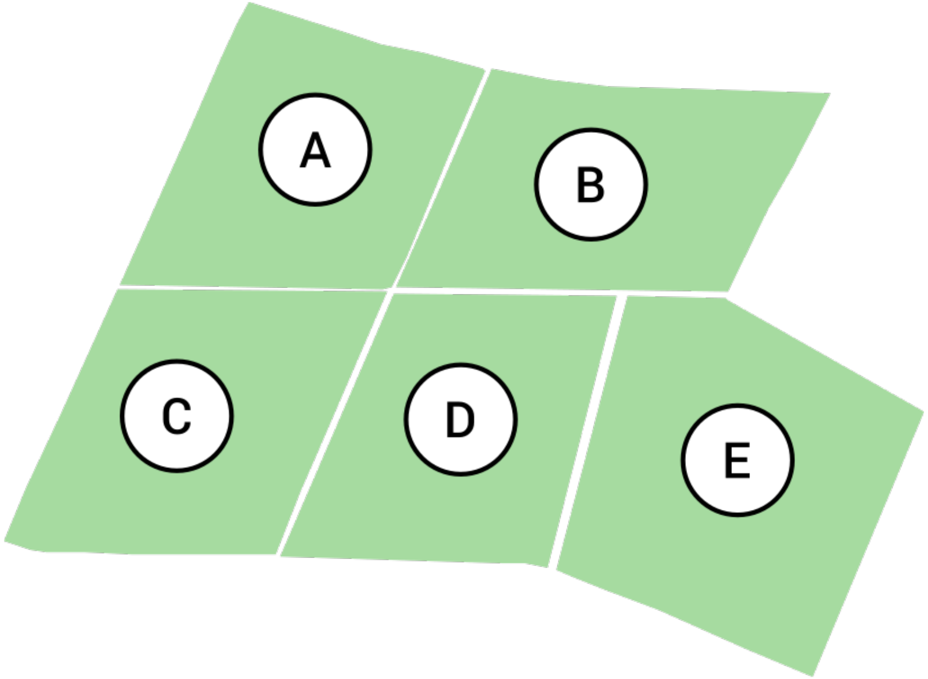
Problem formulation

Consider a plantation consisting of five fields.

The resource constraints/dynamics result in:

- Maximum number of fields that can be irrigated daily (for example max 50mm irrigation per day)
- Maximum water available (seasonal)
- Maximum amount of water that can be put on one field (for example 30mm)

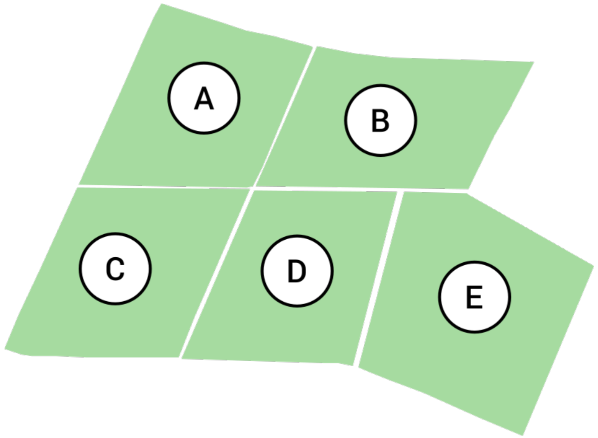
We assume the fields are homogenous and no lateral effects take place, thus each infield strategy can be accounted for using a water application efficiency (e.g. 60% for sprinkler irrigation)



Problem formulation

An example irrigation schedule would then be:

Day	Field A	Field B	Field C	Field D	Field E
1	20mm	30mm	-	-	-
2	-	-	20mm	10mm	20mm
3	30m	20mm	-	-	-
4	-	-	10mm	20mm	10mm

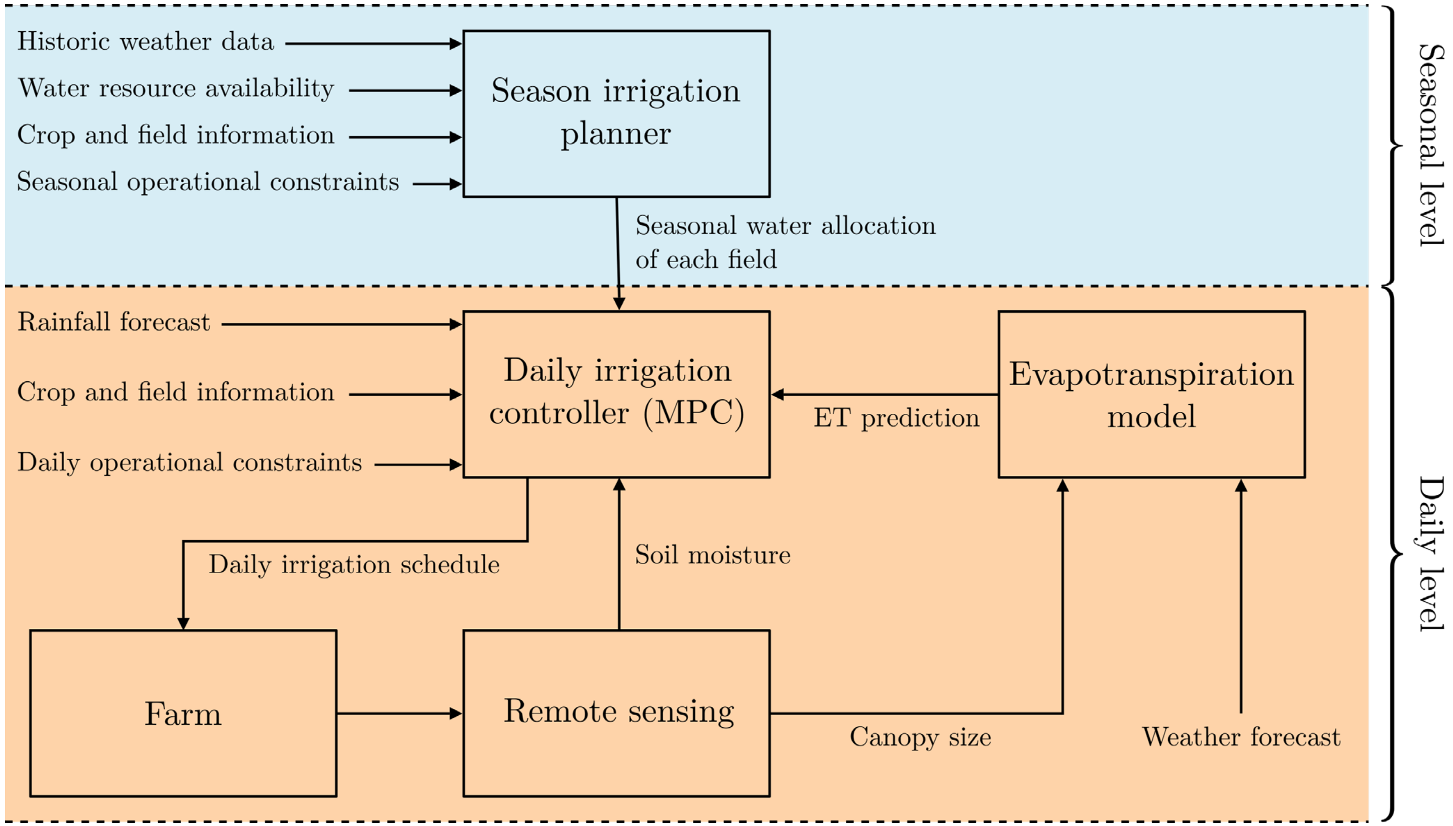


- Determining this daily schedule to maximize crop yield over a full season is a complex problem that farmers face daily.
- A possible solution is to irrigate to field capacity (maximum amount of water that the soil can hold against gravity) or even over-irrigate. However, this is not feasible when water is scarce and can result even lower yield from water logging.

Solving the problem

Solving the complete optimization problem for a full growth season is computationally infeasible (nonlinear, nonconvex with many integer decision variables).

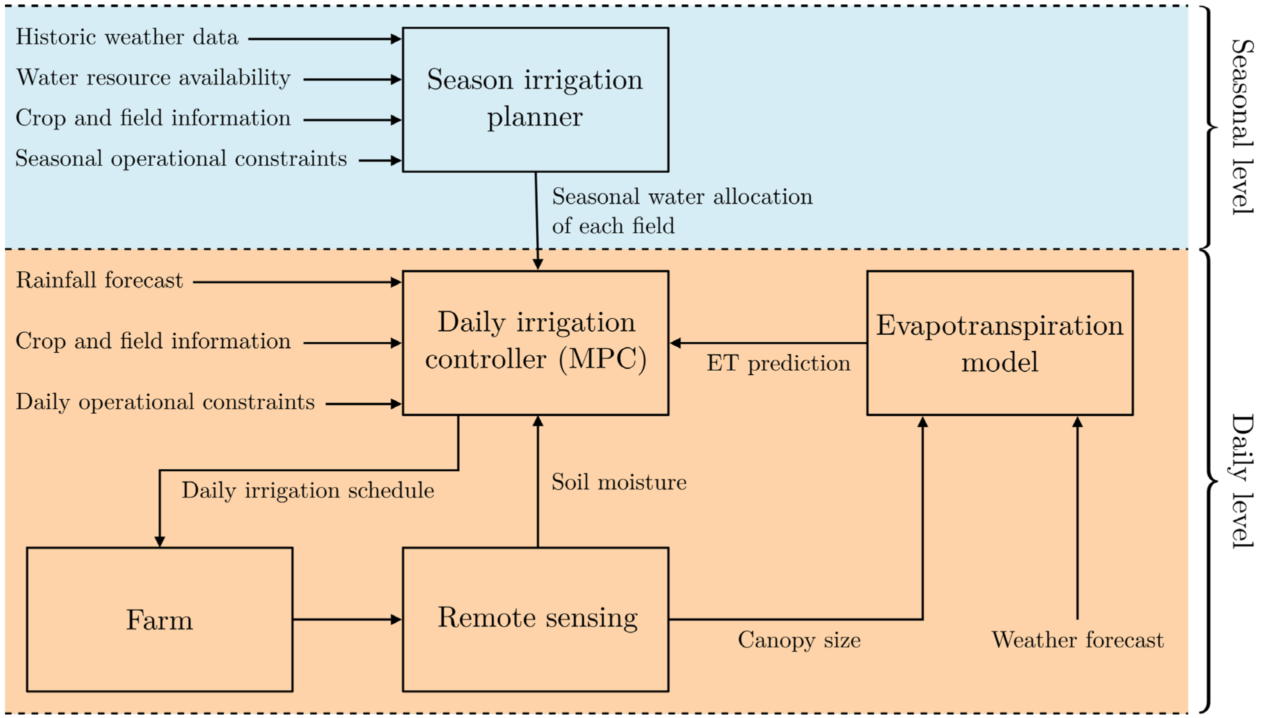
Therefore, we propose a two-level control strategy:



Solving the problem

The Seasonal irrigation planner solves the optimal water allocation problem of a full season a priori. Using the expected water availability, potential water use by the crop and constraints, the expected crop yield is maximized.

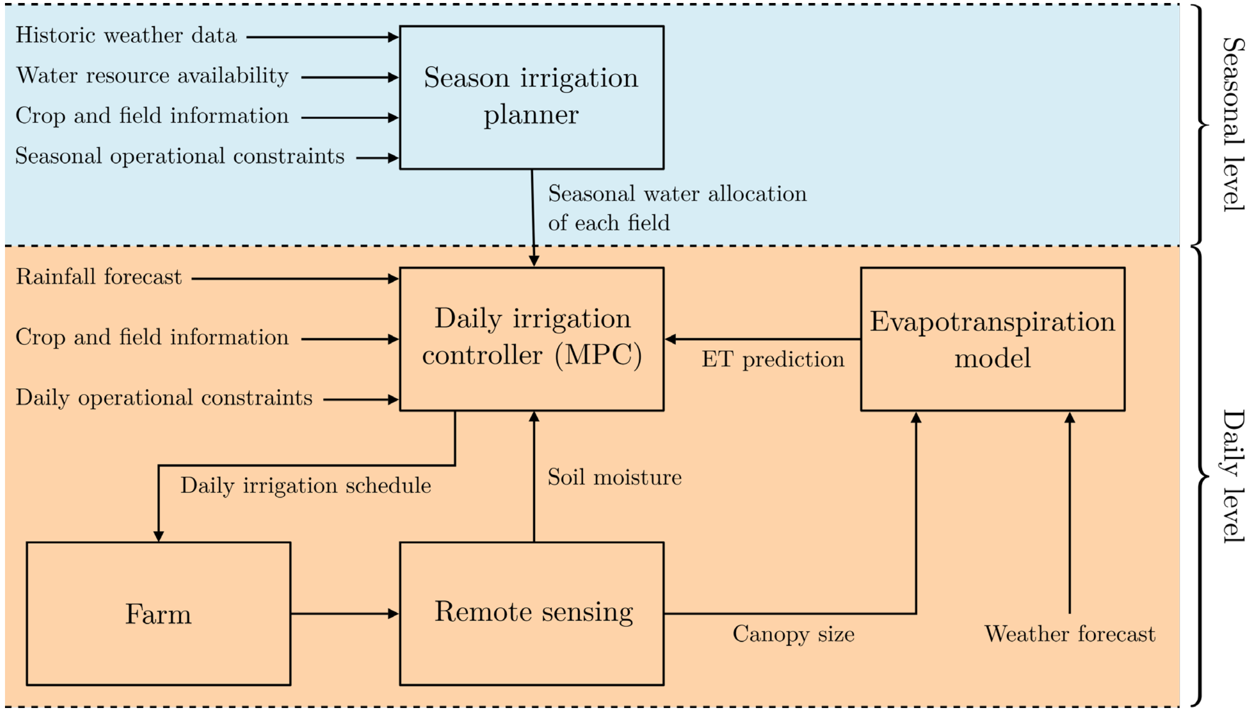
The Daily irrigation controller uses Model Predictive Control (MPC) to minimize the water deficit of the fields, while adhering to the maximum water amount that the Seasonal Irrigation Planner allocated.



Modelling

Our approach requires three models to work:

- Model to indicate the effect of irrigation on water deficit of a field (for the daily irrigation controller)
- Model to predict the evapotranspiration (for the daily irrigation controller, to predict the future water deficit of the fields and adjust irrigation accordingly)
- Model to relate water deficit to crop yield (essentially the objective function that is optimized by both the planner and controller)

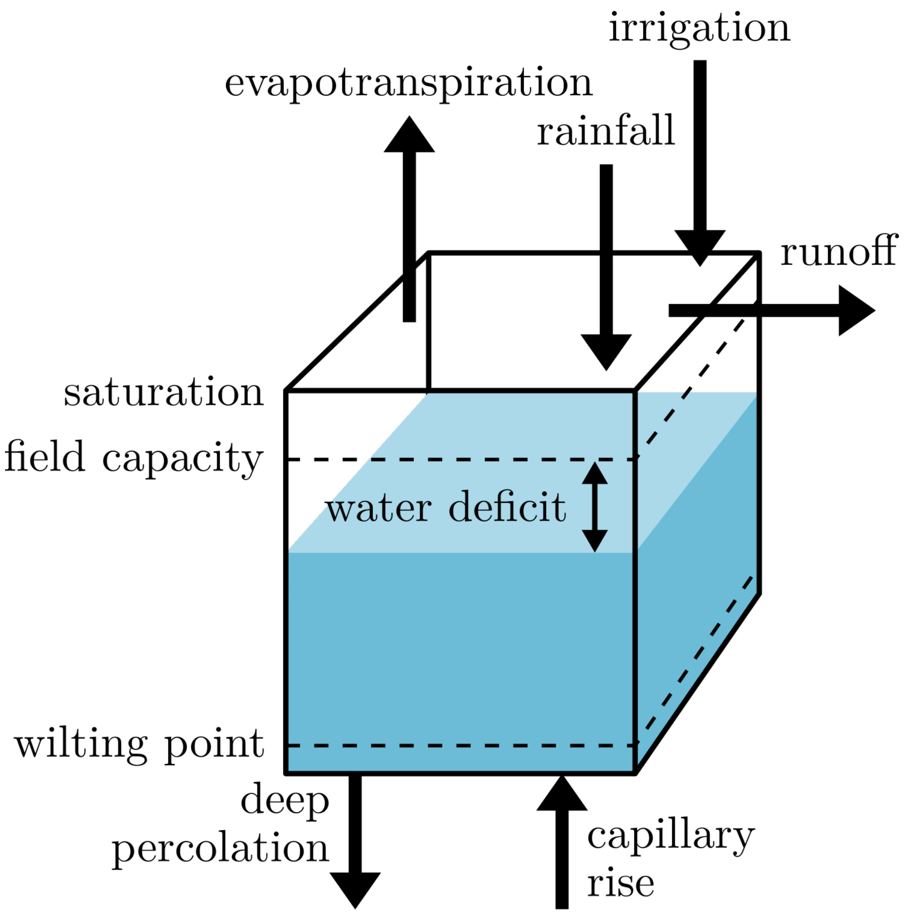


Modelling – Water balance of a field

A single field can be modelled using a water balance

Assumptions:

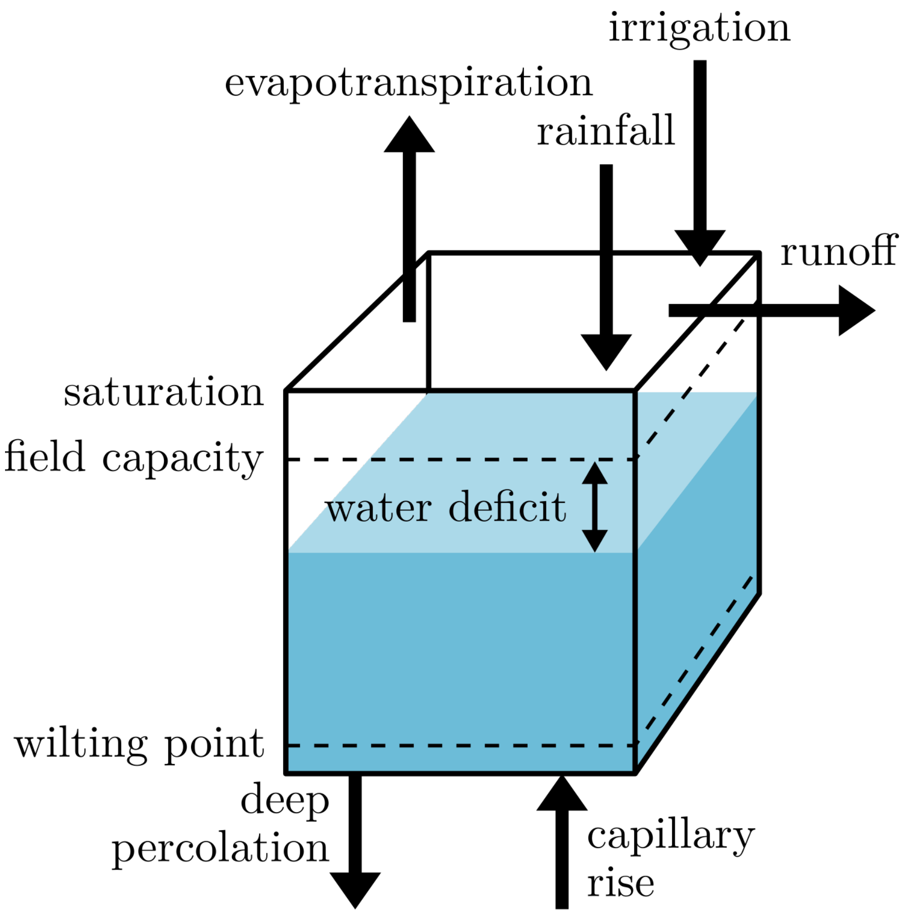
- Field drains excess water (past saturation) in one day
- Capillary rise is negligible
- Runoff dynamics are captured in the infield irrigation application efficiency



Modelling – Water balance of a field

To predict the future water deficit of each field we need:

- Evapotranspiration estimates
- Rainfall predictions (here we assume we have perfect predictions a priori)
- Irrigation schedules (our control variable)



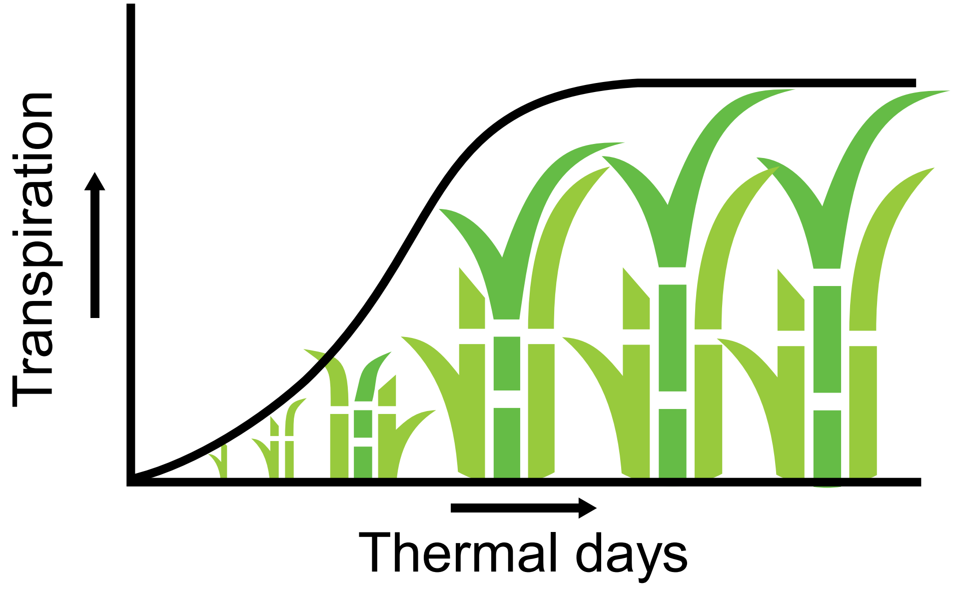
Modelling – Evapotranspiration

Transpiration is a function of the canopy size

Evaporation depends on the surface area of soil exposed to the sun

⇓

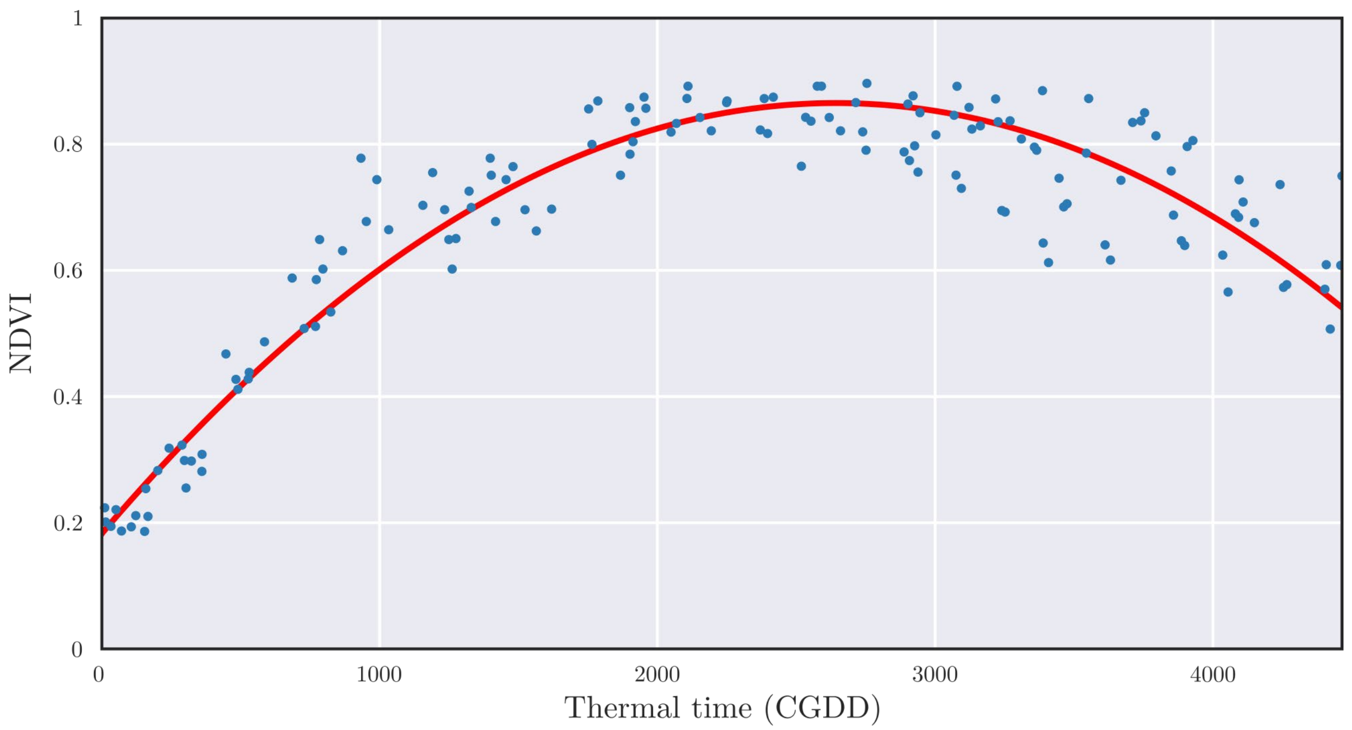
inverse relation with canopy size



As crop growth depends on temperature, we use thermal time instead of time

Modelling – Evapotranspiration

- Normalized Difference Vegetation Index (NDVI) is a remote-sensing measurement that indicates the amount of live vegetation.
- NDVI increases with canopy size
- In the image below NDVI is plotted for a real plantation in Xinavane, Mozambique
  - The blue dots are actual measurements
  - The red curve is a fitted quadratic line (using Least Absolute Residuals)



Modelling – Evapotranspiration

By using the NDVI as an indication of the evolution of transpiration and evaporation over a season, we can create a simple linear evapotranspiration (ET) model:

$$ET = \alpha_1 \cdot f_{transpiration} \cdot E_0 + \alpha_2 \cdot \left(1 - f_{transpiration}\right) \cdot E_0$$

where E_0 is the potential evapotranspiration that can be estimated using local weather data, $f_{transpiration}$ is the (normalized) NDVI curve and α_1 and α_2 are weights that are identified using ET measurements.

Modelling – Effect of water deficit on yield

Now that we have our water balance complete we can optimize irrigation to minimize water deficit of the fields. However: *What effect does a water deficit for a certain field have on the crop yield?*

This relationship is captured in the multiplicative crop yield function[2]:

$$\frac{Y_a}{Y_p} = \prod_{\ell}^{N_\ell} \left(1 - \lambda_\ell \left(1 - \frac{W_{a,\ell}}{W_{p,\ell}}\right)\right)$$

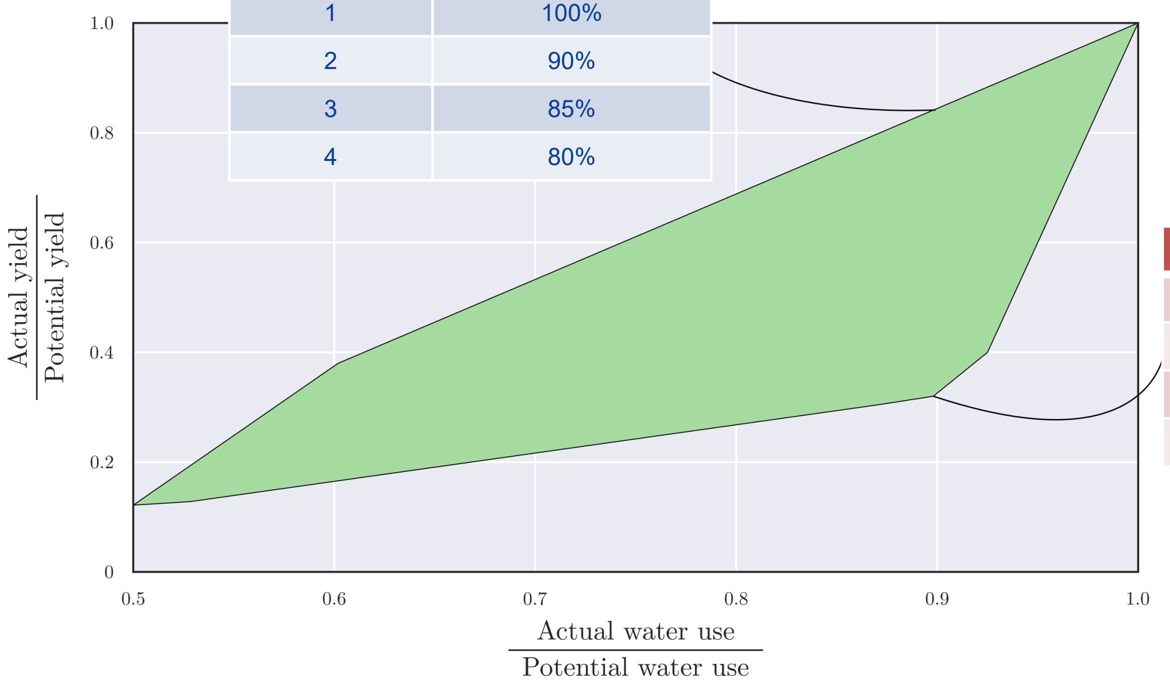
where $\frac{Y_a}{Y_p}$ is fraction of the maximum yield that is achieved, ℓ is the growth stage, λ_ℓ is the crop sensitivity to water deficit in stage ℓ and $\frac{W_{a,\ell}}{W_{p,\ell}}$ is the fraction of potential water use available to the crop in stage ℓ

[2] Raes, D., Geerts, S., Kipkorir, E., Wellens, J., & Sahli, A. (2006). Simulation of yield decline as a result of water stress with a robust soil water balance model. *Agricultural Water Management*, *81* (3), 335–357.

Modelling – Effect of water deficit on yield

This crop yield function can be visualized in a so-called crop kite[3]. Poor strategies result in yields at the bottom of the kite and good strategies at the top of the kite for any given water availability.

Crop stage	Relative water use
1	100%
2	90%
3	85%
4	80%

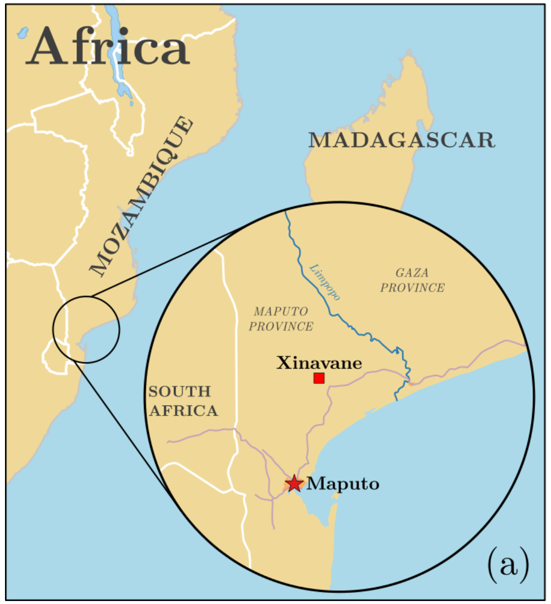


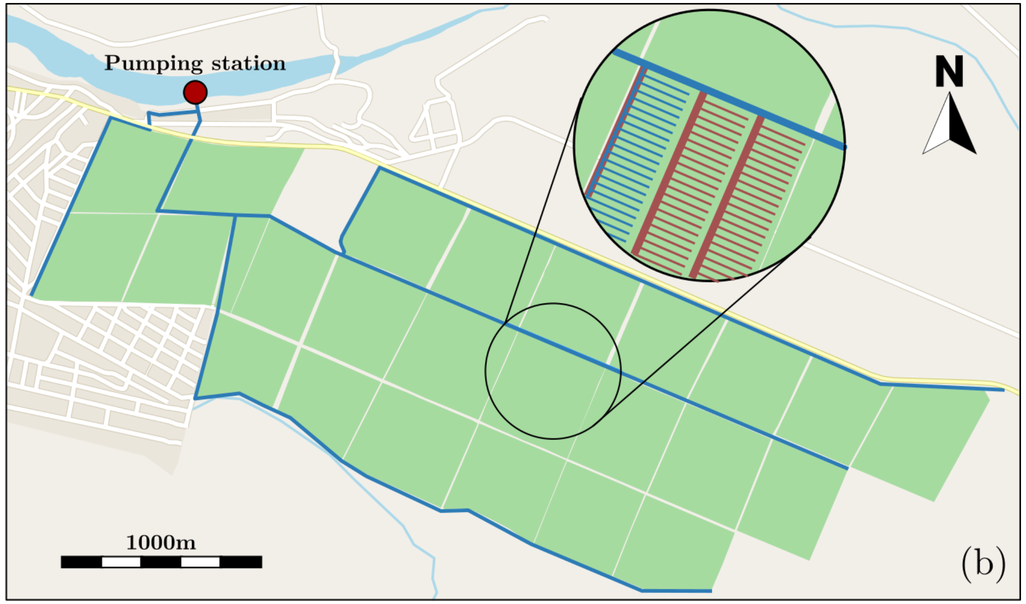
Crop stage	Relative water use
1	60%
2	90%
3	100%
4	100%

[3] Smilovic, M., Gleeson, T., & Adamowski, J. (2016). Crop kites: Determining crop water production functions using crop coefficients and sensitivity indices. *Advances in Water Resources*, *97* , 193–204.

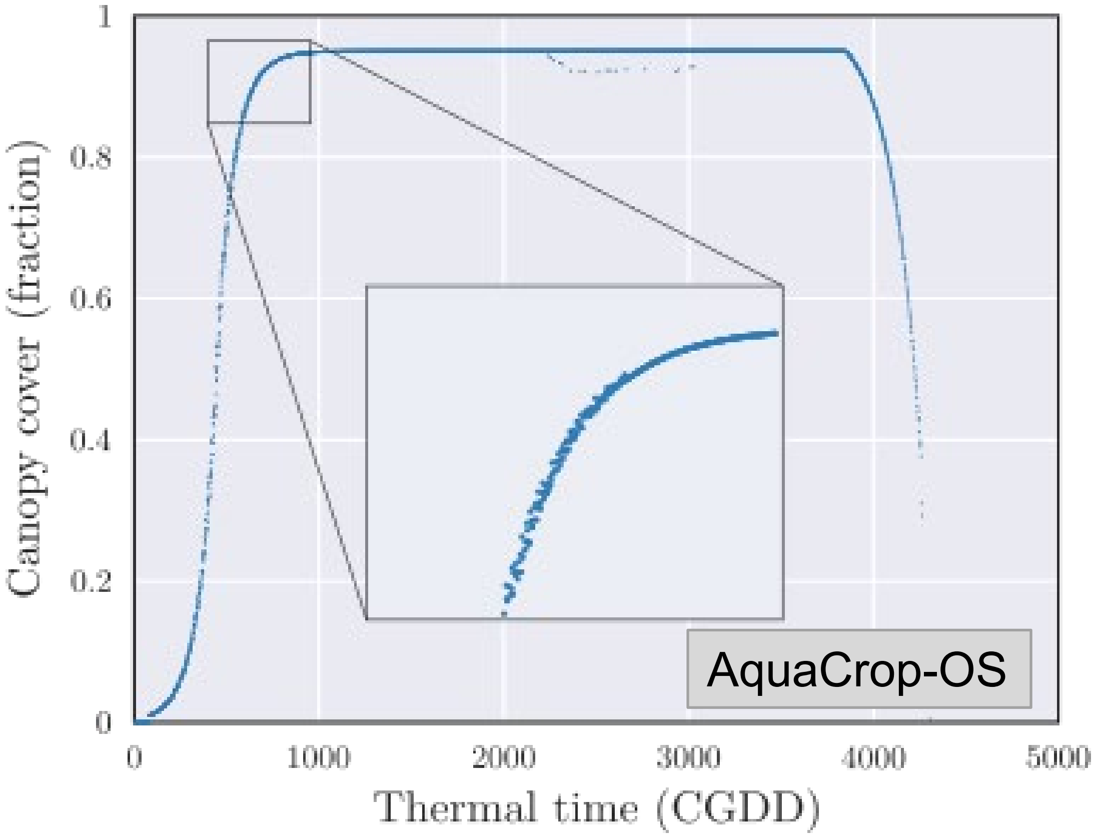
Case Study

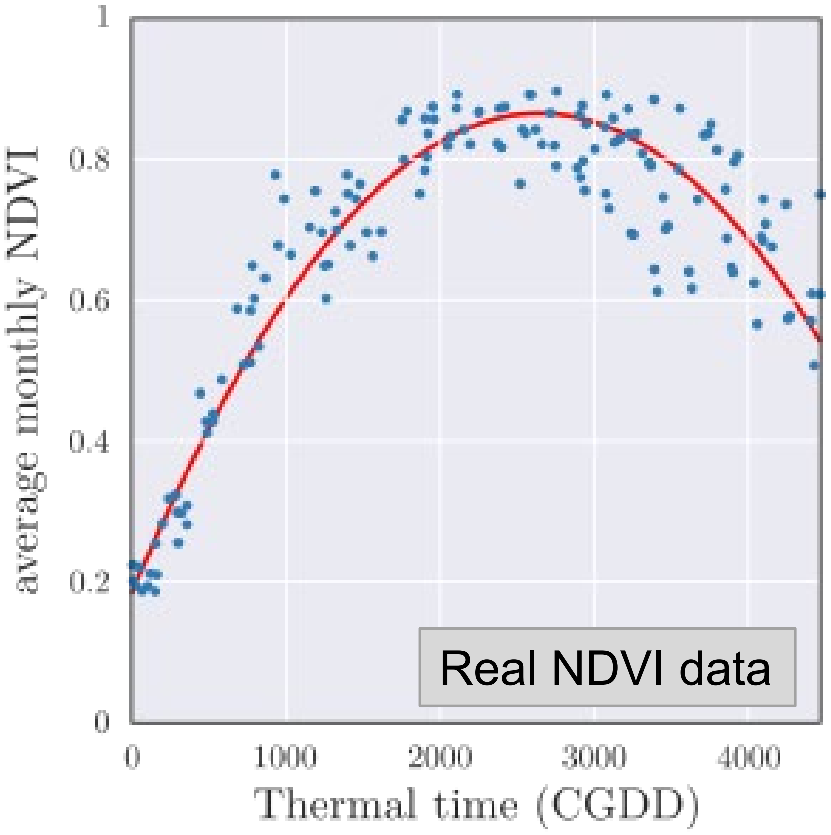
- AquaCrop-OS is the FAO standard crop water productivity modeling software
- In AquaCrop-OS we model a plantation in Mozambique
  - Using real local weather data
  - Instead of NDVI we use (perfect) canopy cover measurements
  - We modified Aquacrop-OS to run closed-loop simulations





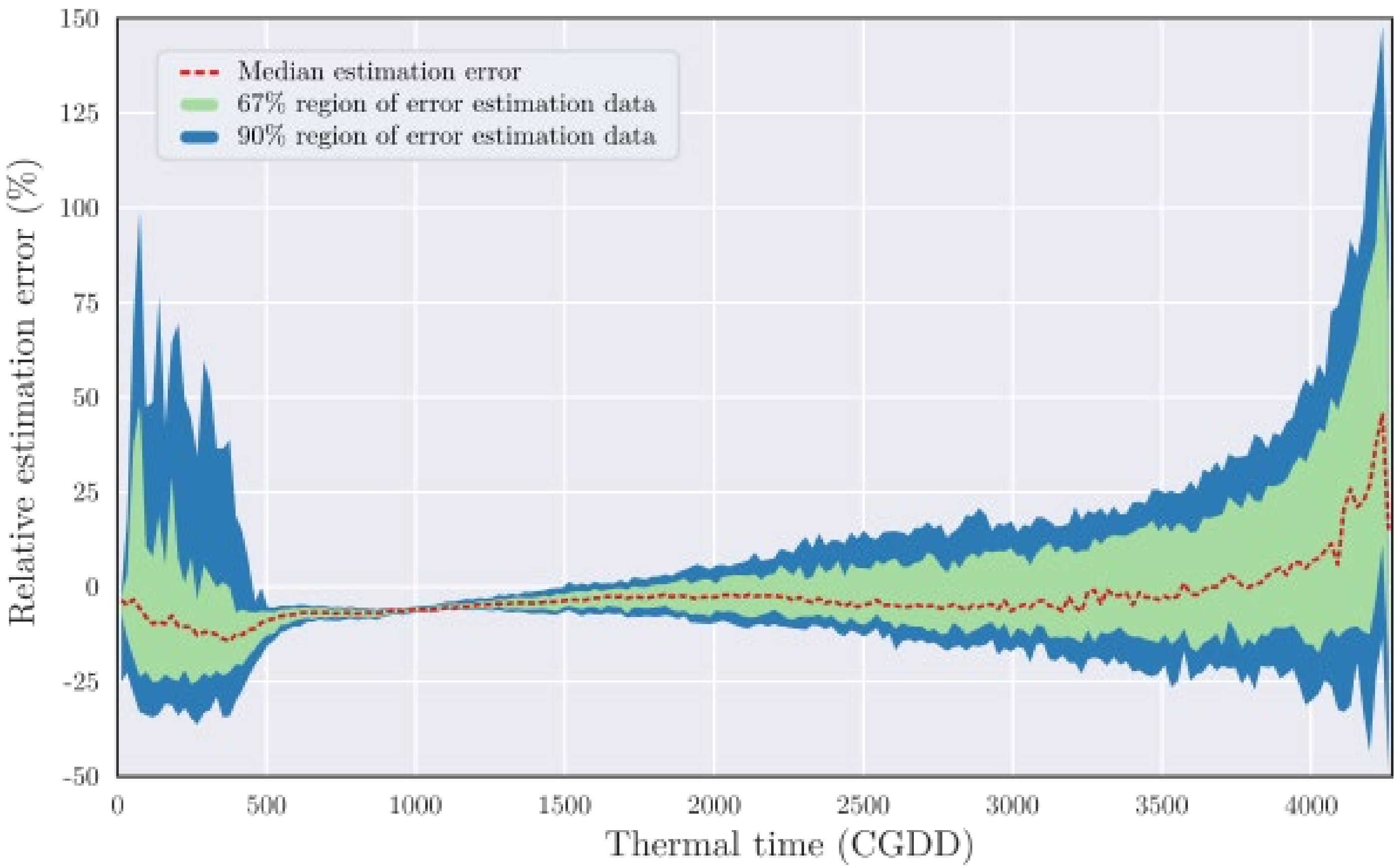
Results – Evapotranspiration modelling





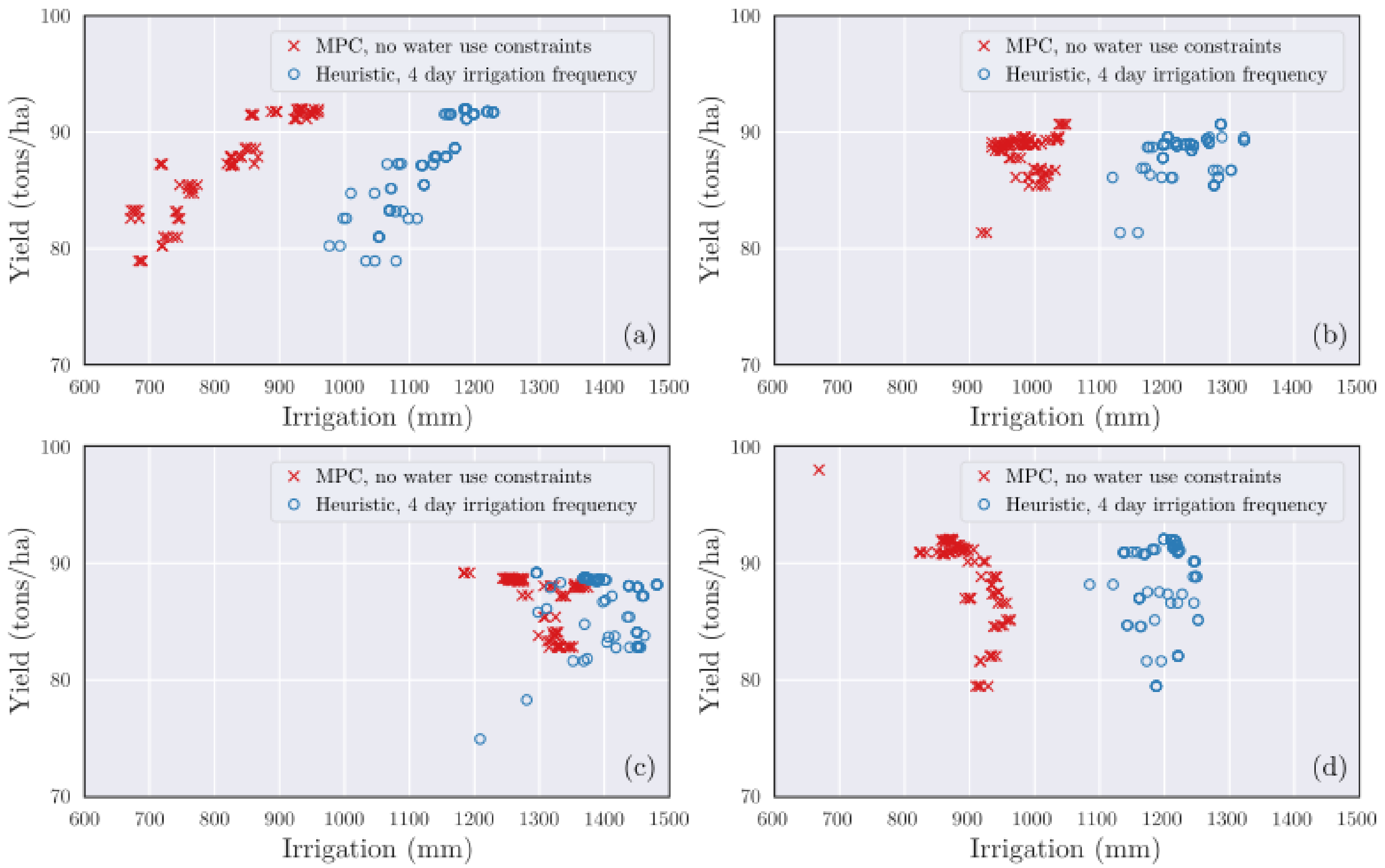
Results – Evapotranspiration modelling

- Model is trained on a random 80% of fields
- Model is validated (bottom plot) on a random 20% of fields
- Evapotranspiration model for Aquacrop-OS has generally good performance



Result: our controller vs. local schedule

- Local schedule (Mozambique)
  – Irrigate every field to field capacity every 4 days
  – Irrigate a field for 3 days straight after planting to establish germination
- Two-level controller:
  – Can decide which fields to irrigate, however only 1/4th of fields can be irrigated each day (corresponding to 4 day irrigation frequency of local schedule)
  – Can decide how much irrigation to apply
  – No limit on irrigation water
- Result
  – Our controller is able to achieve the same crop yield with less water

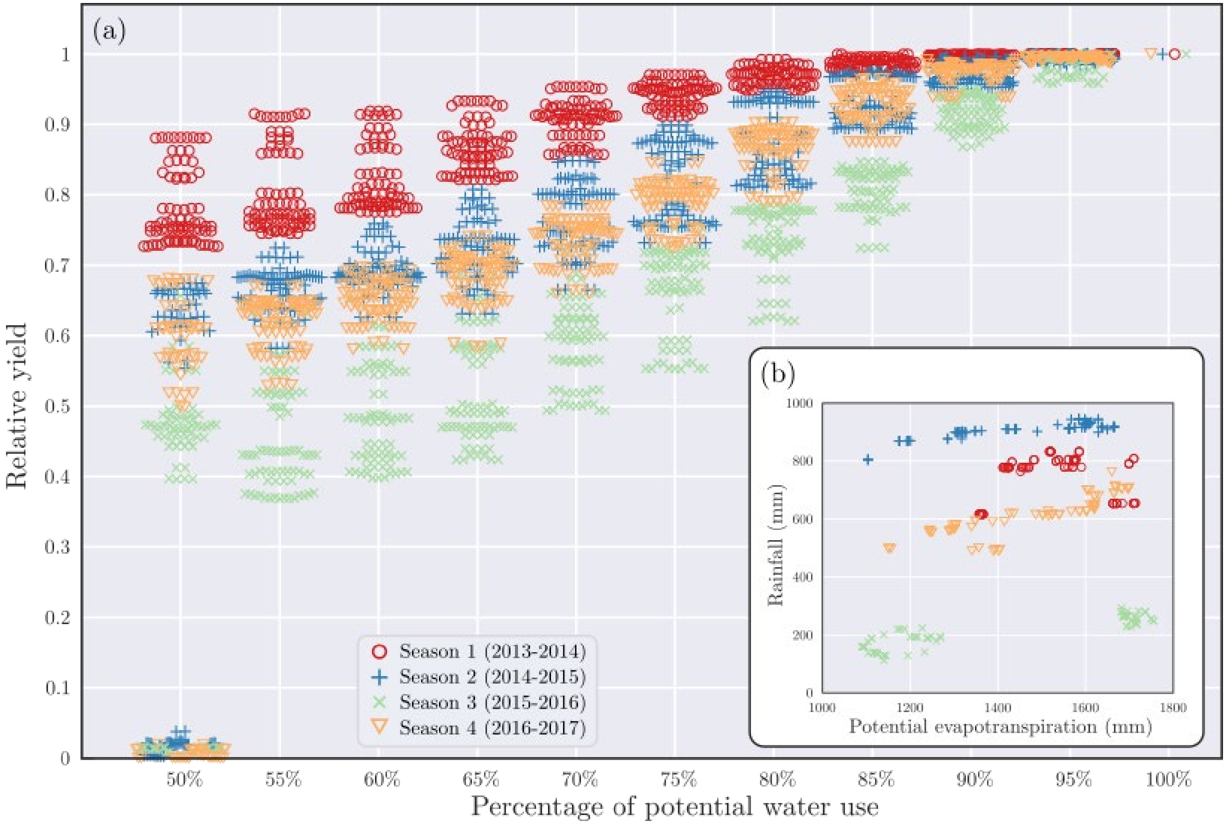


Result: effect of water deficit on yield

To investigate the effect of lower water availability on yield we run deterministic simulations with a water availability constraint of 50% to 100% of required water (for maximum yield) in steps of 5%. Note that:

- Every field can be irrigated each day
- Each field starts at season 1 with a different initial soil moisture (although close to field capacity) and planting date (which explains the different yields and evapotranspiration and the good performance of season 1, as the fields start off close to field capacity)
- In each iteration and season a perfect forecast of the precipitation and temperature is known a priori

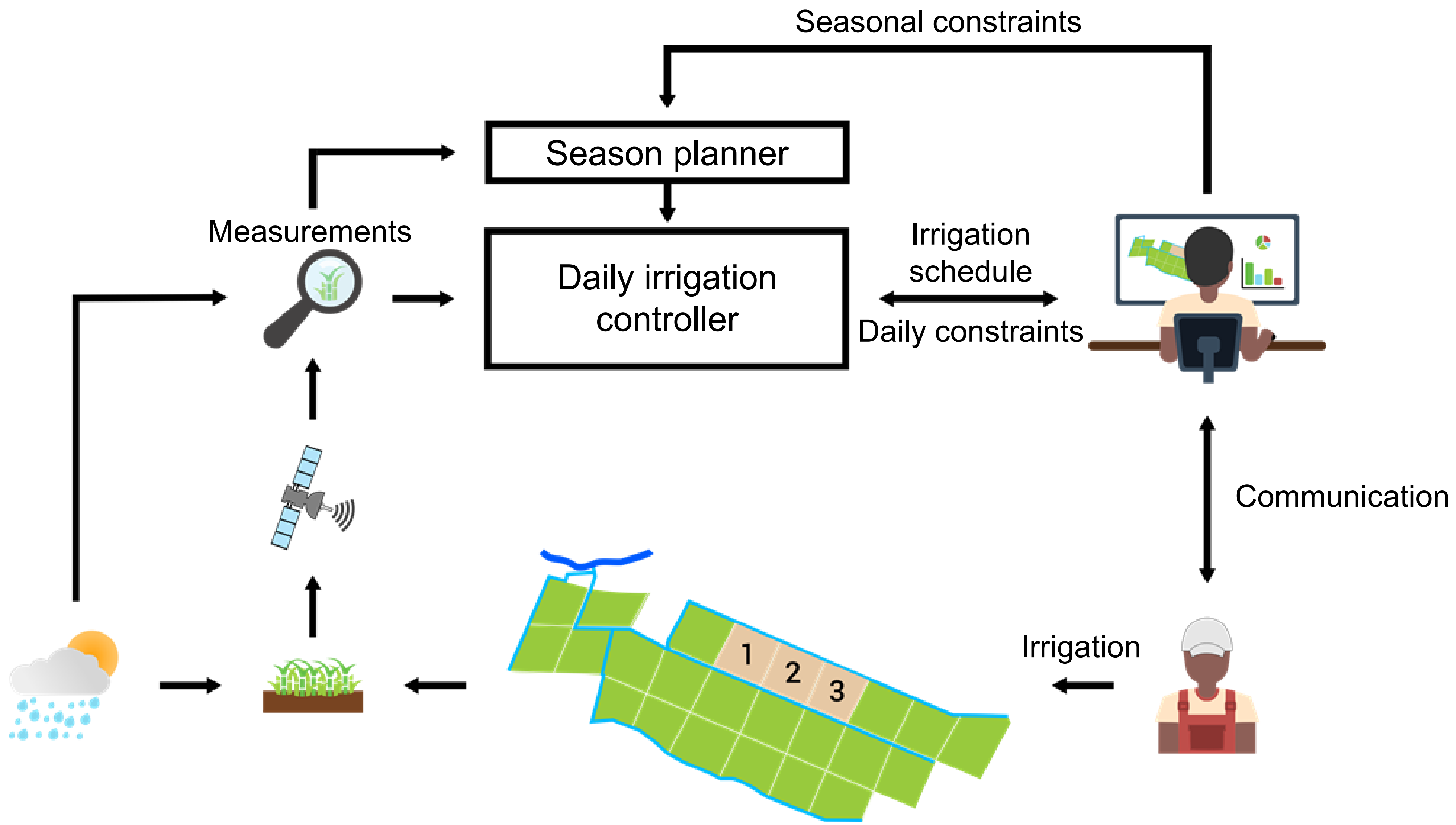
This results in an approximation of the upper bound of the crop kite. From the results we can conclude that deficit irrigation can still result in high yields as long as we allocate the water in a smart way.



Summary

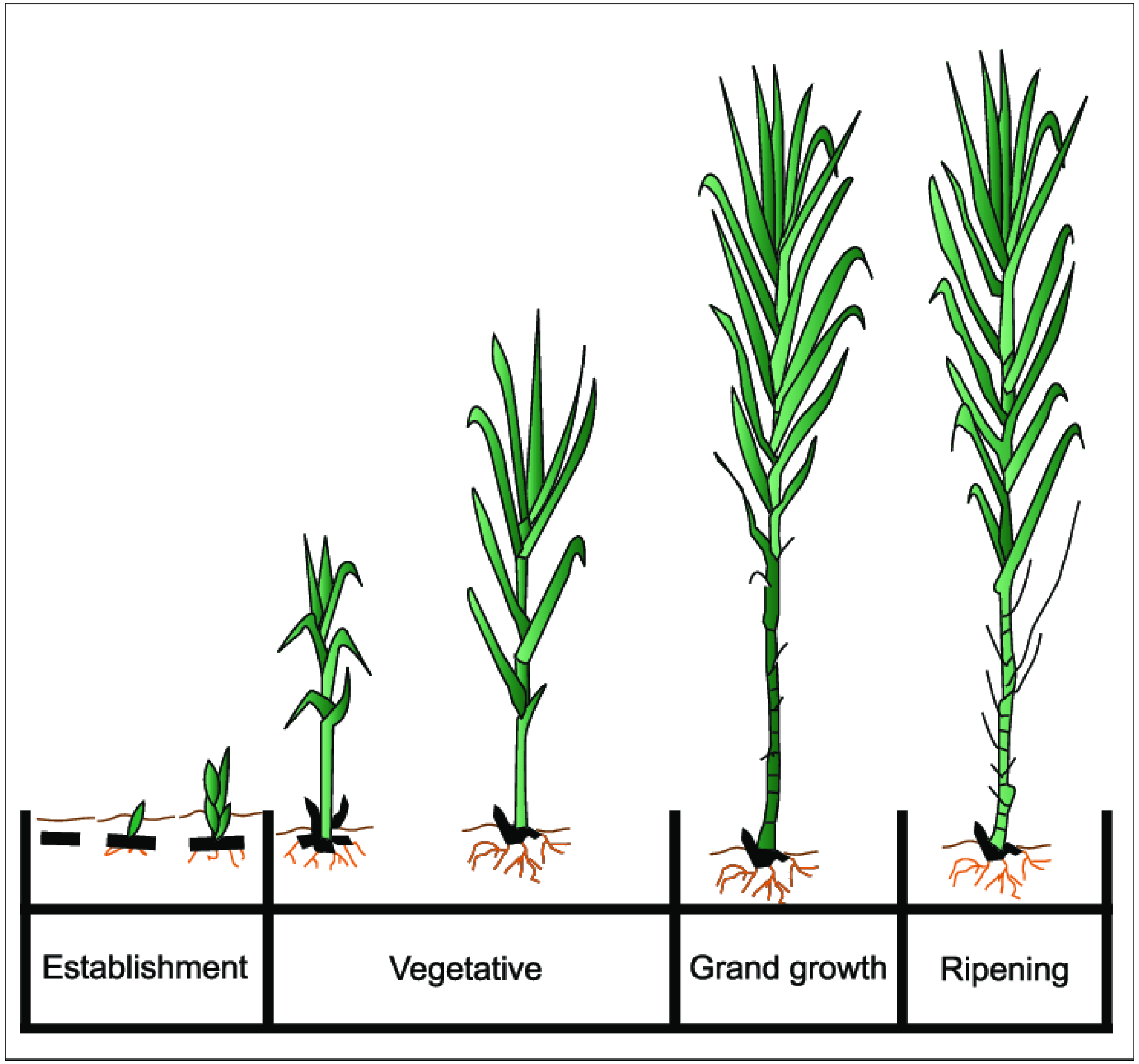
- A two-level approach is proposed to solve the optimal water allocation problem for large scale plantation, consisting of:
  - Season irrigation planner
  - Daily irrigation controller
- The proposed approach is evaluated on closed-loop simulations with a AquaCrop-OS model of a real plantation in Mozambique
  - The approach improves water use efficiency compared to local schedules
  - The approach provides optimal irrigation schedules in times of drought
- A next step towards implementation is creating reliable observers for soil moisture (using remote-sensing and in situ measurements)
- The effect of uncertainty of rainfall needs to be evaluated. However, under sparse rainfall events the effect will likely be minimal.

Schematic for real-life implementation



Growth stage example

For clarification purposes, an image[4] depicting the different growth stages of sugarcane.



[4] Irrigation of Sugarcane in Texas - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Growth-stages-of-sugarcane_fig1_237695968 [accessed 5 May, 2020]