Assessing waterlogging conditions across Ethiopia's rainfed agricultural landscapes

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Peter Molnar[1], **Mosisa Wakjira[2]**, Katrien Descheemaeker[2]

[1]Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland (molnar@ifu.baug.ethz.ch)
[2]Plant Production Systems, Wageningen University and Research, Wageningen, The Netherlands

Presenter: Mosisa Wakjira (mosisa.wakjira@wur.nl or mosisatujuba@gmail.com)

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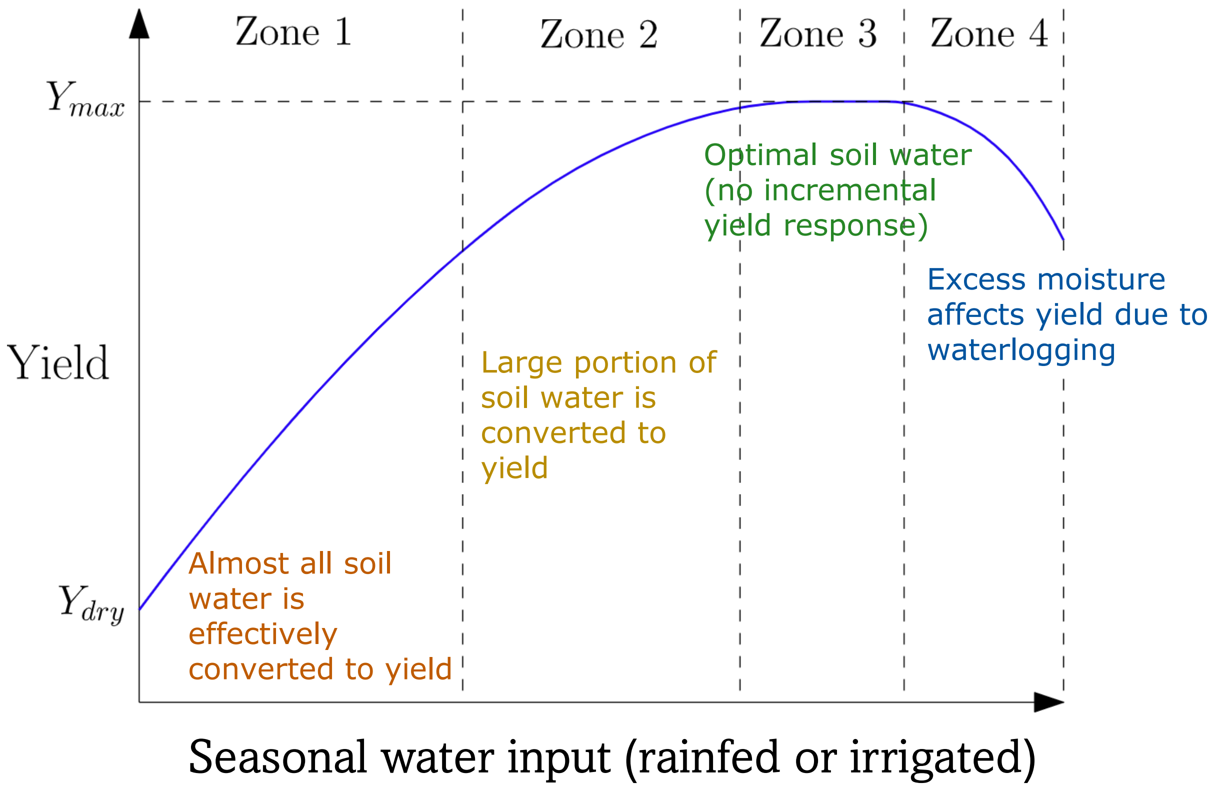
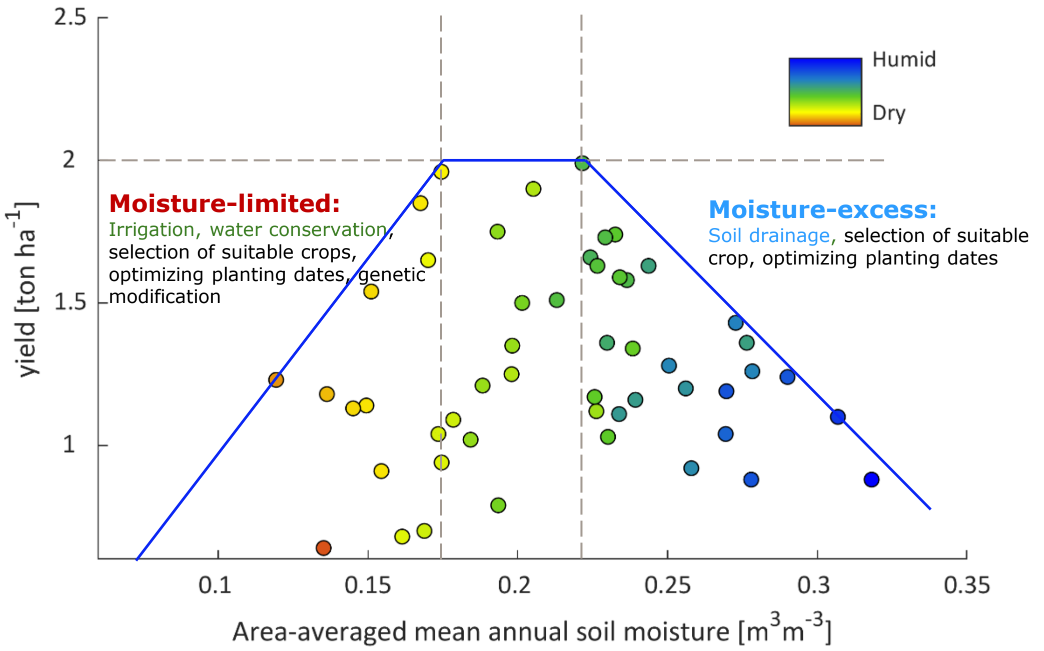
Crop-water use and yield relations

Theory



Foster and Brozović, (2018)

Reality (wheat yield)



Data: annual agricultural sample survey for the main growing season at 62 administrative zones of Ethiopia (CSA, 2003-2010)

Key drivers of waterlogging

Humid climate/over-irrigation/shallow watertable

~50% of the rainfed agriculture (RFA) region receives >1000mm rainfall

Poorly drained clayey soils

Vertisols cover about nearly 27% of cultivable lands in 30 most productive districts (Elias, 2016)

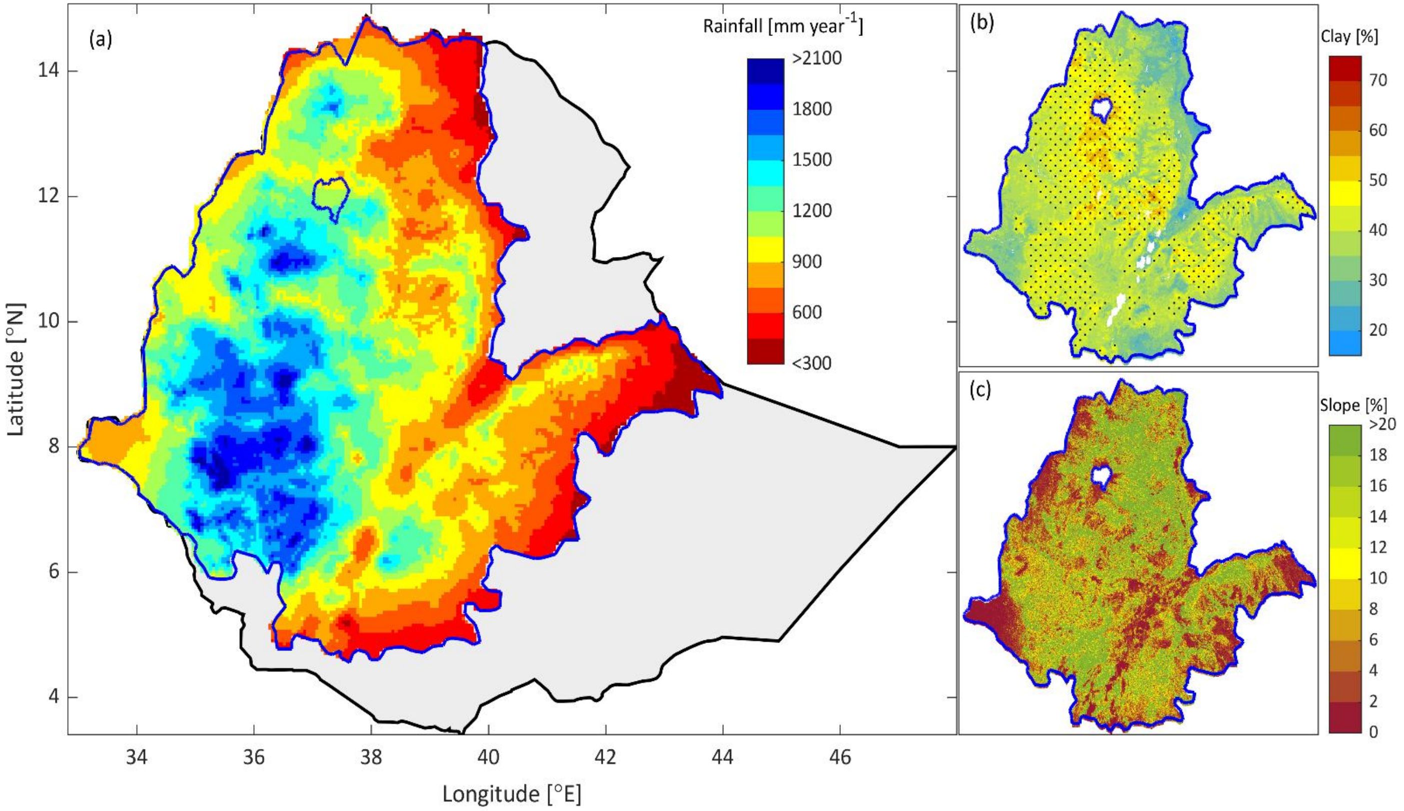
Flat to gentle slope

~14% of the region has slope <2%

Research Questions:

- Which parts of the RFA region are affected?
- What is the yield loss associated with waterlogging?
- How effective are agronomic and soil drainage measures?

Rainfed agricultural region of Ethiopia



Rainfall: CHIRPS (1981-2010) (Funk et al., 2015); soil: Soilgrids (Poggio et al., 2021); slope: derived from SRTM DEM

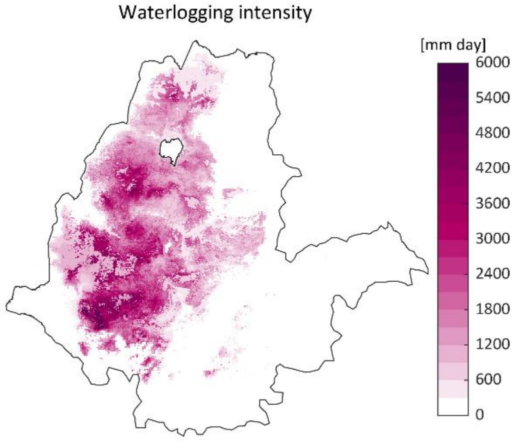
Assessment steps and results

Join us at the discussion:
PICO spot A, PICOA.6

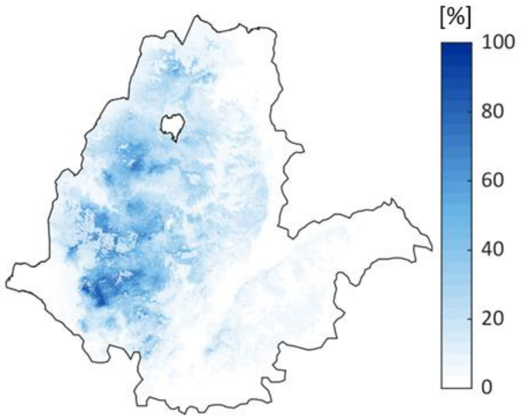
Analysis steps

1. Root-zone water balance modeling
2. Waterlogging impact analysis
3. Evaluation of management alternatives

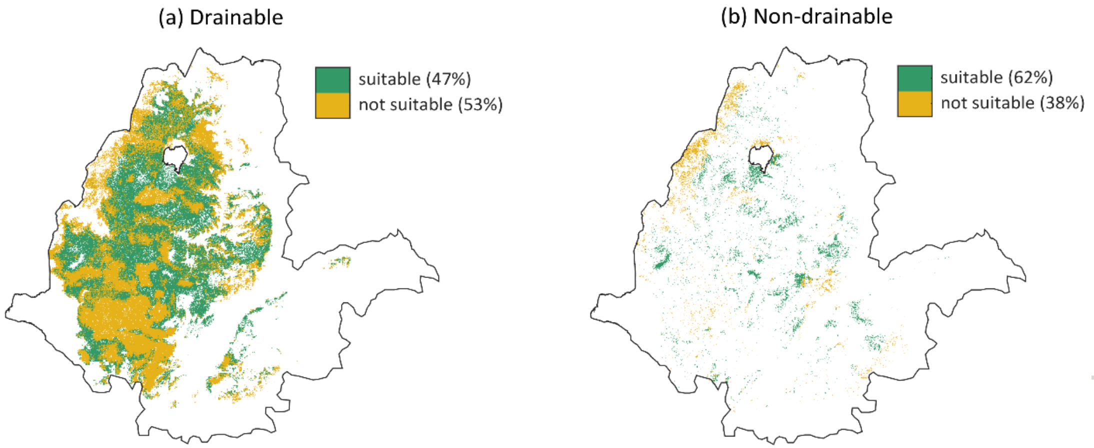
Waterlogging hotspots



Associated yield losses (wheat)



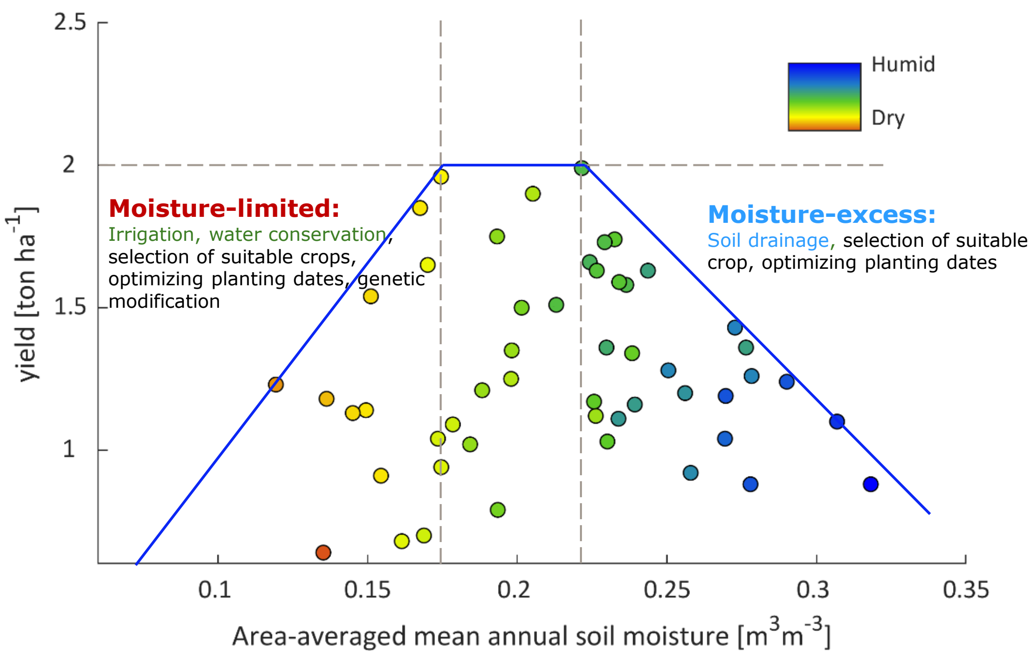
Suitability for rice – grass pea intensification



To the detailed slides

Crop-water use and yield relationship – management perspective

Reality (wheat yield)



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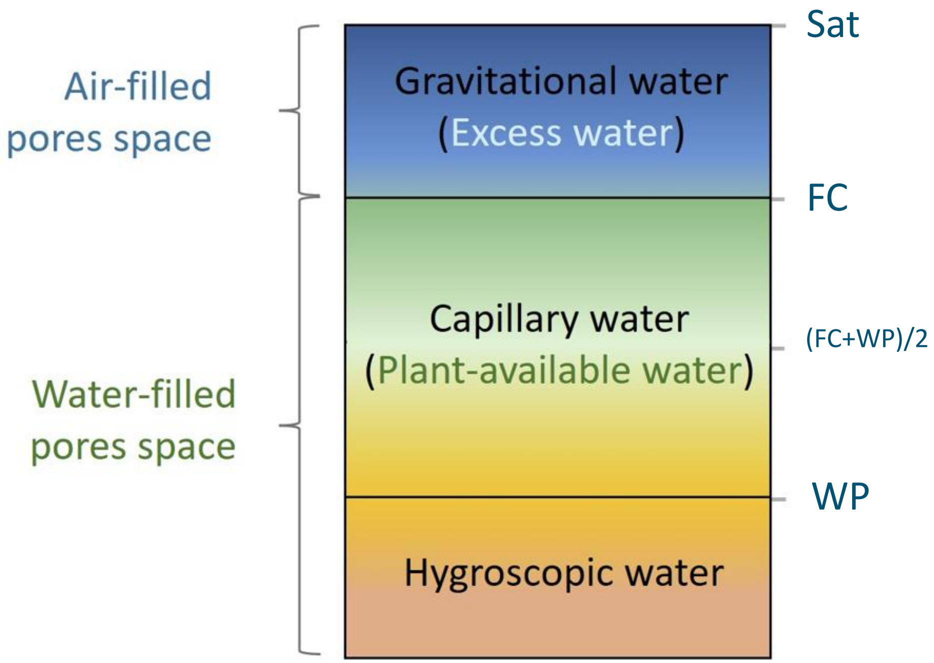
Soil moisture regimes



Water management objective is to maintain plant-available water at optimal level (or at least above half-way between FC and WP)

Objectives

To provide a detailed spatial analysis of waterlogging, its limitations to crop production, and management alternatives by addressing the following research questions:

- How do waterlogging conditions (intensity and duration) vary across the RFA region, and which areas are the most prone?
- What is the yield loss associated with waterlogging?
- What is the potential yield gain through improved soil drainage and agronomic measures?

The assessment was carried out at 1km x 1km grid resolution considering 1981-2010 as a reference period

Main analysis steps

1. Root-zone water balance modeling

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2. Waterlogging impact analysis

↓

3. Evaluation of management alternatives

1) Root-zone water balance

a) Bucket hydrological model

- Rainfall-runoff partitioning was based on curve number method with simple calibration of the parameter CN
- Soil moisture was simulated accounting for slope and content

$$\Delta SM(t) = P(t) - Q(t) - ETa(t) - Dp(t)$$

Change in daily soil moisture

$$S(t) = 254\left(\frac{100}{CN(t)} - 1\right)$$

Surface storage parameter as a function of CN

$$Q(t) = \begin{cases} \frac{(P(t)-0.071S(t))^2}{(P(t)+1.349S(t))}, & P(t) > 0.071S(t) \\ 0, & \text{otherwise} \end{cases}$$

Surface runoff

$$ETa(t) = Ks(t)ETo(t)$$

Actual evapotranspiration

$$Ks(t) = \begin{cases} \frac{\theta(t)}{f(\theta_{FC}-\theta_{WP})}, & \theta(t) < f(\theta_{FC} - \theta_{WP}) \\ 1, & \text{otherwise} \end{cases}$$

Water stress coefficient

$$Dp(t) = \begin{cases} 1440K_h, & \text{if clayey (i.e., clay>40\% and sand<45\%)} \\ 1000Zr(\theta(t) - \theta_{FC}), & \text{otherwise} \end{cases}$$

Deep percolation

1b) Adjustments for curve number (CN):

- Adjust for slope based on an empirical model (Williams et al., 2023)

- Calibration (scaling) using runoff data

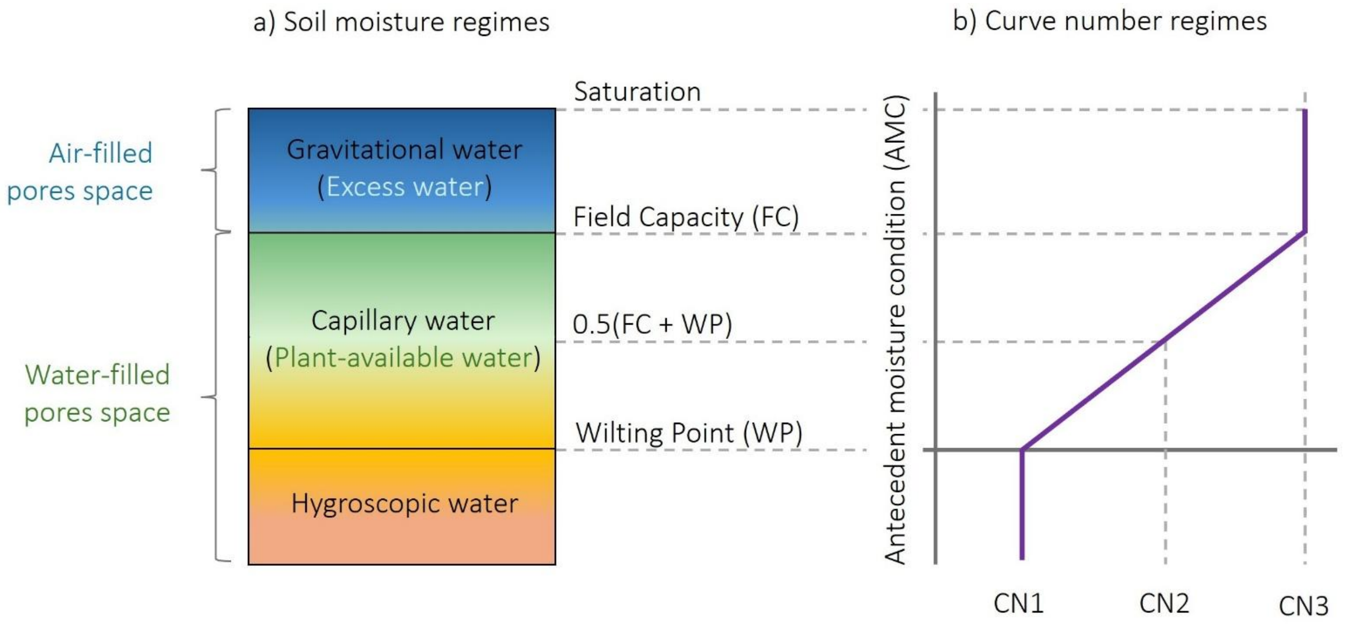
$$S_{adj} = S\left(1.1 - \frac{\text{slope}}{\text{slope} + e^{(3.7+0.02117\text{slope})}}\right)$$

$$CN_{adj} = \frac{100}{\left(\frac{S_{adj}}{254} + 1\right)}$$

- Adjustment for antecedent moisture conditions (Williams et al., 2023)

$$CN1 = CN_{adj} - \left(\frac{20(100 - CN_{adj})}{100 - CN_{adj} + e^{\left(2.533-0.0636(100-CN_{adj})\right)}}\right)$$

$$CN3 = CN_{adj} \cdot e^{0.00673(100-CN_{adj})}$$



1c) Accounting for slope effects surface runoff and soil moisture on gentle to flat landscapes:

- Slope < 2% is generally considered undrainable (Erkossa et al., 2014; FAO, 2006)
- For undrainable landscapes Q was adjusted using linear weights such that:

Qadj = 0 if Slope = 0 (weight = 0)
Qadj = Q if slope >= 2 (weight = 1)

1d) Accounting for clay content:

- Deep percolation in clayey soils was constrained by unsaturated hydraulic conductivity (Kh)

$$Dp(t) = \begin{cases} 1440K_h, & \text{if clayey (i.e., clay}>40\% \text{ and sand}<45\%) \\ 1000Zr(\theta(t) - \theta_{FC}), & \text{otherwise} \end{cases}$$

- Kh was determined following (Zayani et., 1992)

$$K_h = 0.231(\theta(t) - \theta_r)^{7.6512}$$

- Residual soil moisture was computed as a function of clay and organic carbon content (Poeplau et al., 2015)

$$\theta_r = 0.00145 + 0.00253soc + 0.00033clay$$

2) Waterlogging impact analysis

2a) Daily root-zone oxygen deficit (ROD [%])

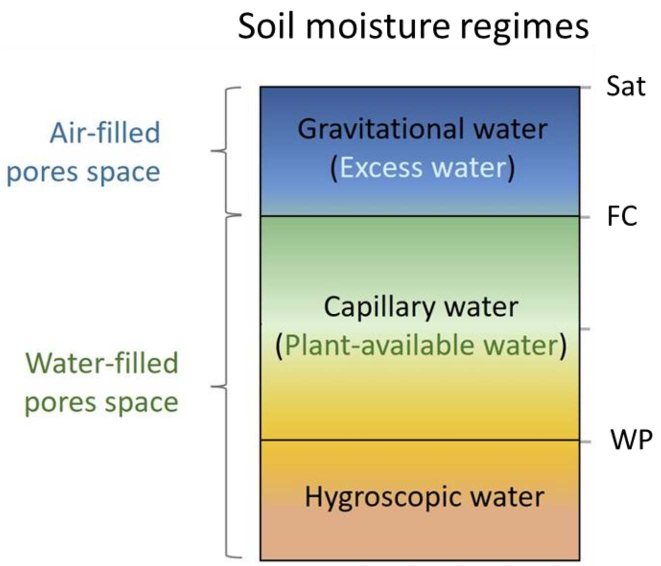
$$ROD(t) = \begin{cases} 100\left(\frac{\theta(t)-\theta_{FC}}{\theta_{Sat}-\theta_{FC}}\right), & \theta(\mathrm{t})>\theta_{FC} \\ 0, & \text{otherwise} \end{cases}$$

Impactful waterlogging events were identified as a condition where oxygen deficit is observed for at least three consecutive days (Githui et al., 2022; Shaw and Meyer, 2015)

2b) Mean annual impactful waterlogging intensity (WLI [mm day]) was calculated

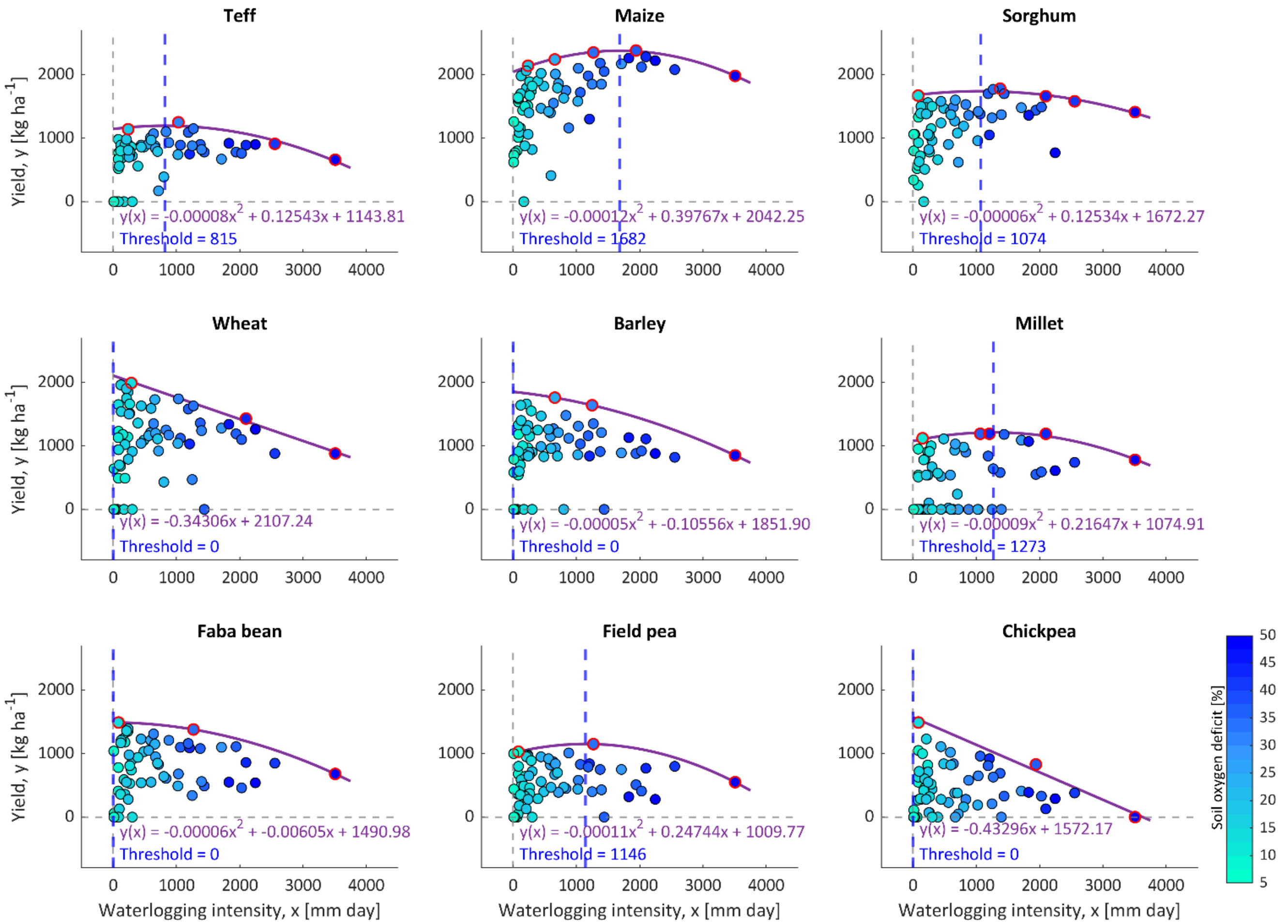
$$WLI = 10 \times ROD \times Zr\left(\theta_{Sat} - \theta_{FC}\right) \times DUR \times N$$

Zr = root-zone depth (top 60cm); DUR = mean duration of each waterlogging event [day]; N = number of waterlogging events per year



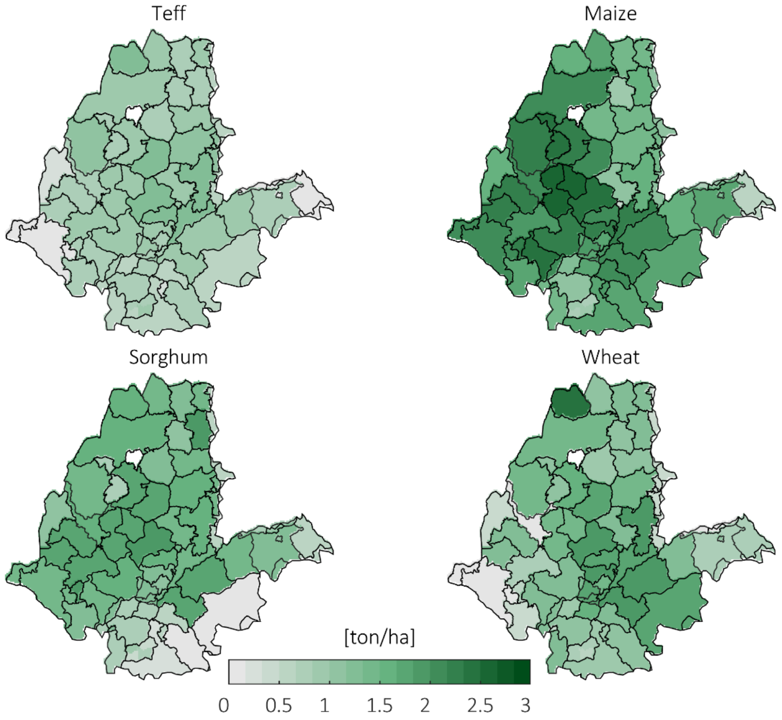
2c) Crop yield responses to waterlogging

Yield response analysis was based on envelope curve method (Wakjira et al., 2024)



Yield response function: Y = f(WLI)

Crop yields (Y) data for 9 major crops for the years 2000, 2003-2007, 2010 from the CSA agricultural sample survey (for 62 admin zones)



2d) Crop yield losses under waterlogging

- The yield response functions were applied to each grid cell at 1km x 1km
- Yield loss was computed as the percentage of the nationally attainable yield (Y_{max})

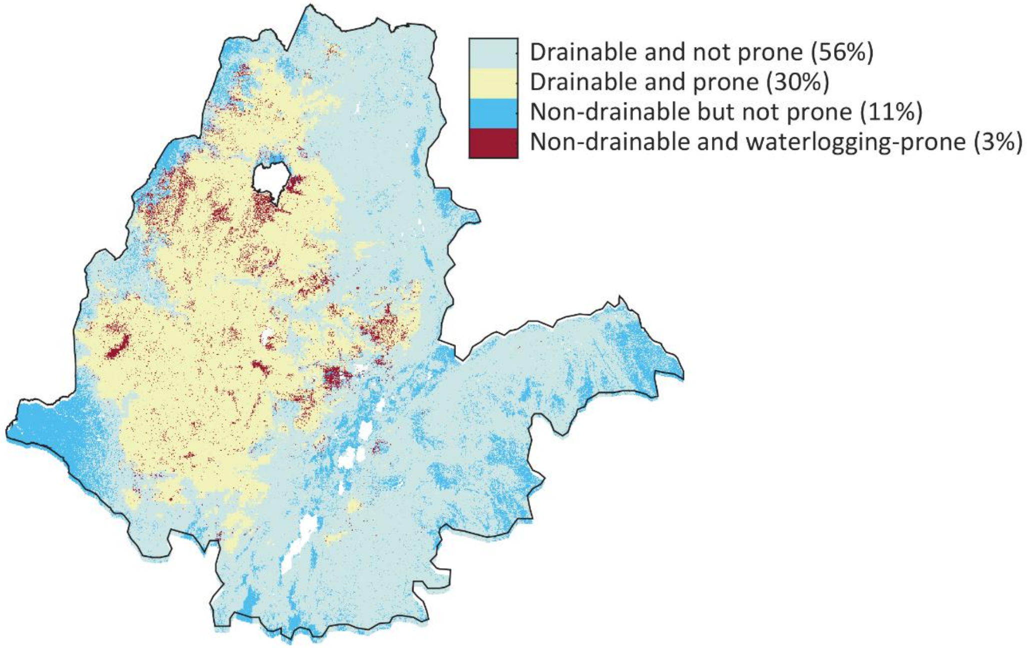
$$Y_{loss} = 100 \times \left(1 - \frac{Y}{Y_{max}}\right)$$

- Y_{max} corresponds to the threshold waterlogging intensity (WLI)

3) Evaluation of waterlogging management options

Naturally drainable (slope > 2 %) and non-drainable (slope <= 2%) landscapes were identified (Erkossa et al., 2014; FAO, 2006)

Natural drainability of agricultural landscapes as defined by slope



Two management options assessed by Erkossa et al., 2014 were re-evaluated at grid scale:

- Rice – legume system intensification
- Improved soil drainage

3a) Rice-grass pea intensification

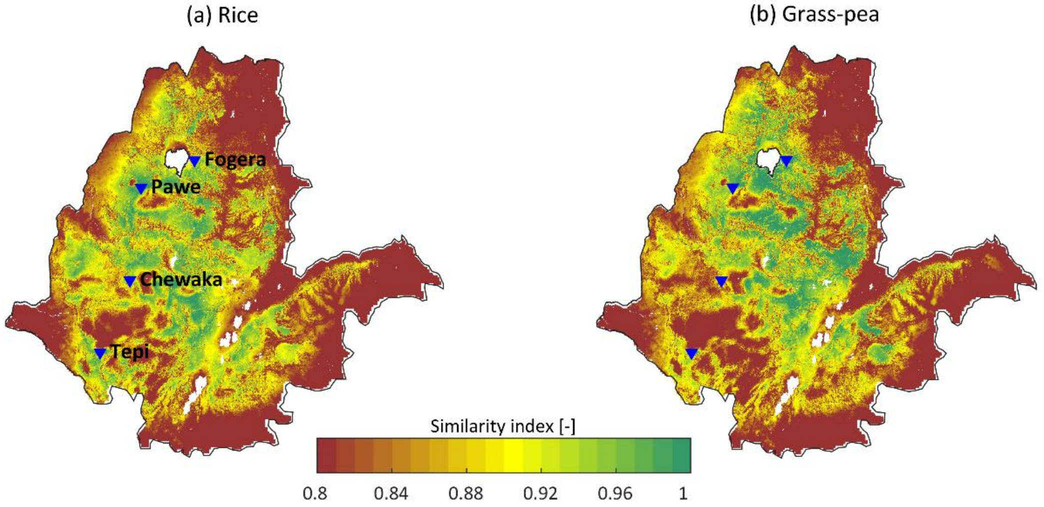
- Agroecological suitability for rice and legume fodder (grass-pea) were assessed using similarity analysis method (Ramirez-Villegas et al., 2011)

- The method is based on Euclidean distance between similarity features at the reference location (Xr) and the locations of interest (Xp) according to their weights (W)

$$Similarity = \left(\sum_{i-1}^{n} \sum_{j-1}^{m} W_{ij} (X_r - X_p)^2 \right)^{1/2}$$

- Four major rice producing locations (Fogera, Pawe, Chewaka and Tepi) were used as reference locations, considering climate aridity, soil texture and slope as similarity features

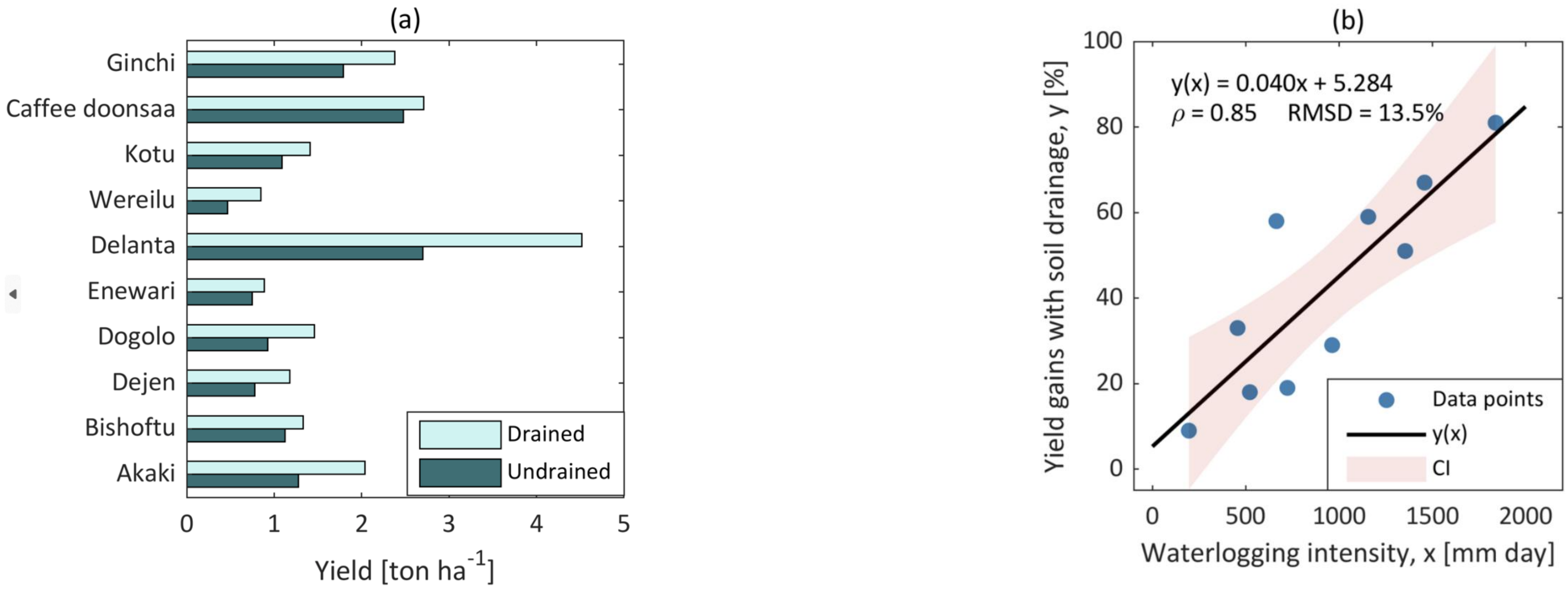
Agroecological similarity maps for rice and grass pea



3b) Wheat yield gains under improved drainage

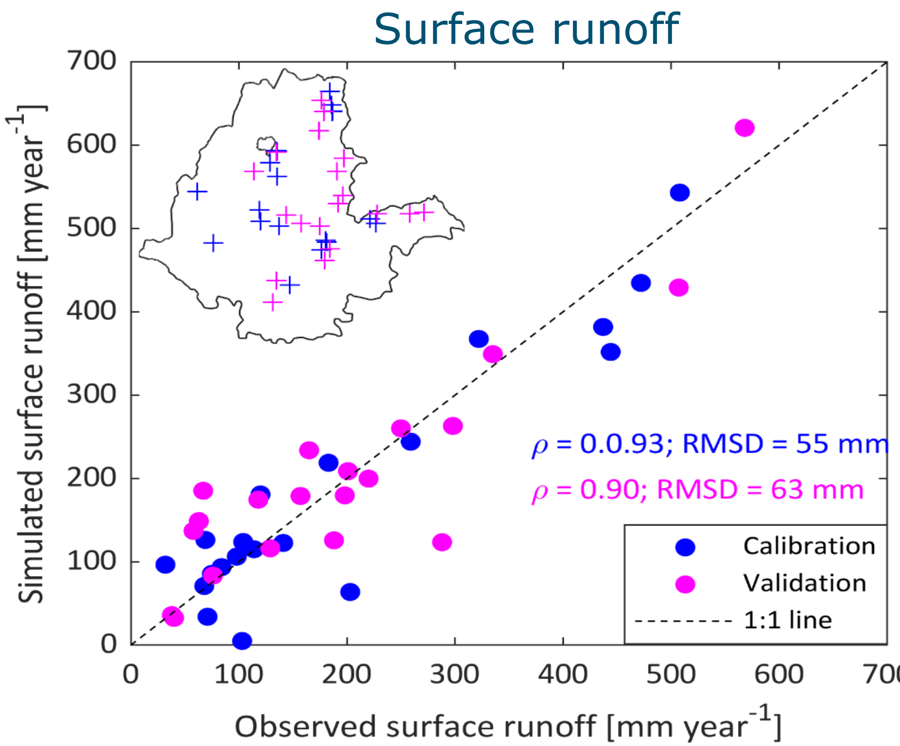
Empirical model of yield gains (%) under improved soils drainage, as a function of waterlogging intensity (mm day) was used

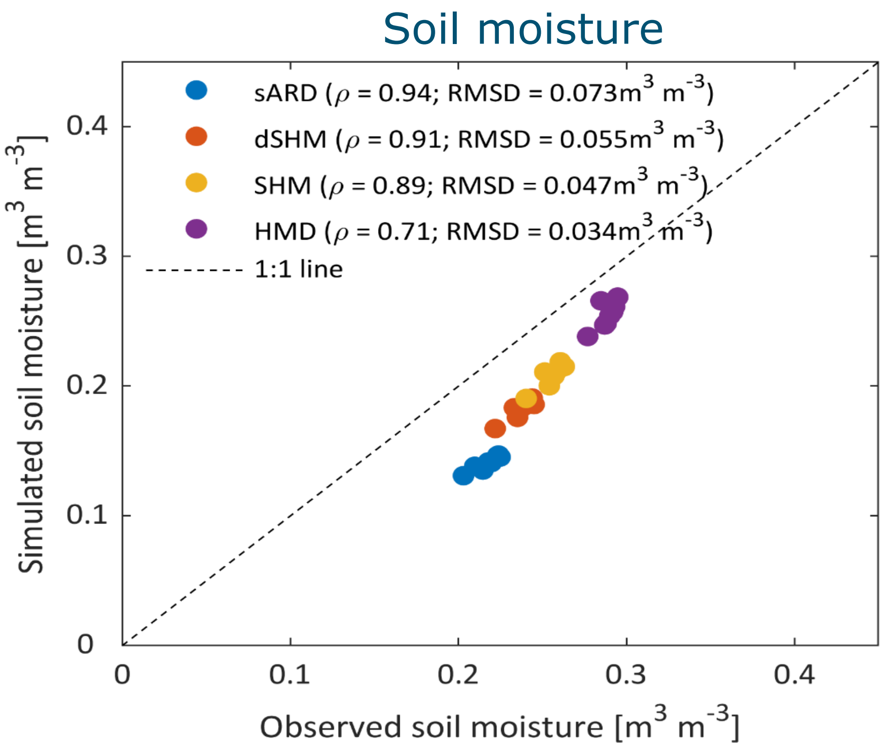
The model was derived from published field trials (at 10 locations) on paired comparisons of wheat yields under improved and traditional/no soil drainage



Results

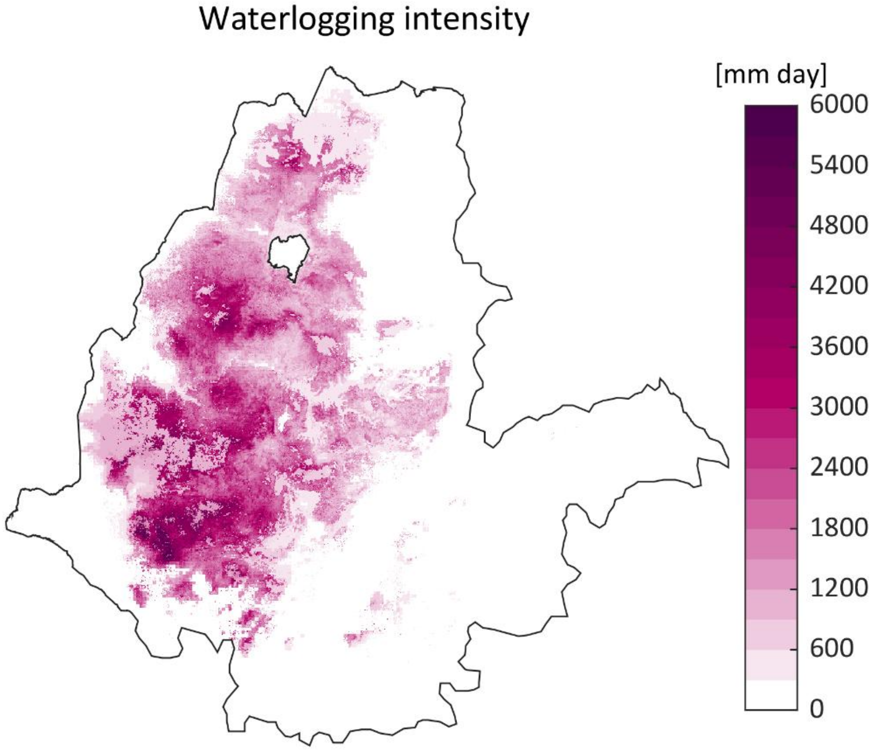
Validation of simulated surface runoff and soil moisture





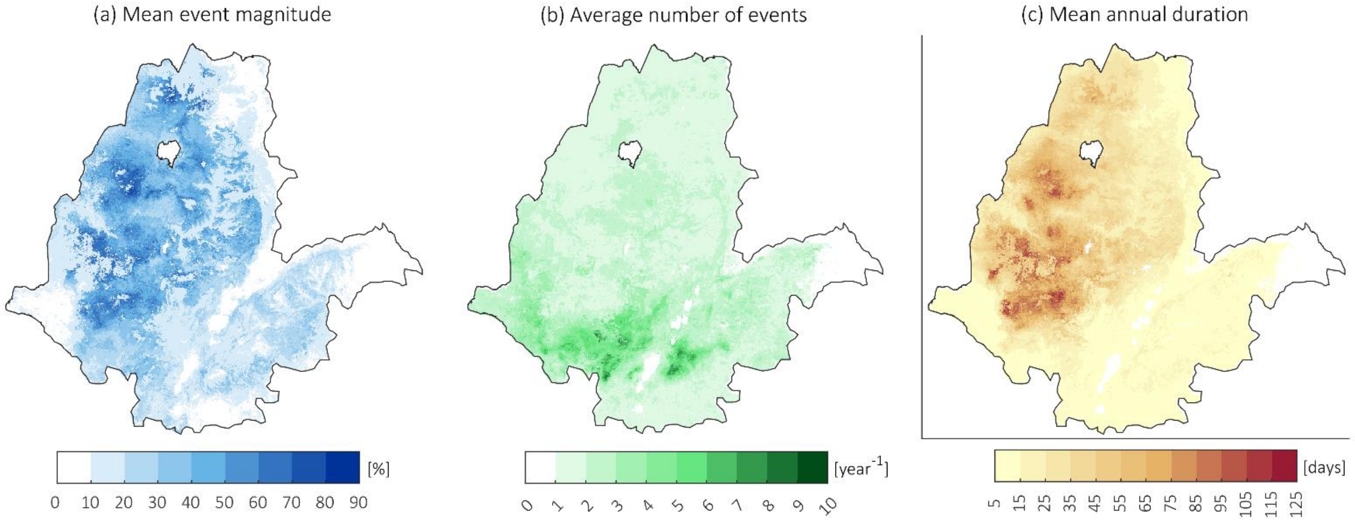
Observed soil moisture is the average of four independent global soil moisture products (ESA CCI, GLDAS 2.1, LPMR-TMI, and SGD-SM) over four climatic regions: semi-arid (sARD), dry sub-humid (dSHM), sub-humid (SHM), and humid (HMD)

Climatological of waterlogging characteristics and hotspot areas (1981-2010)



$$WLI = 10 \times ROD \times Zr\,(\theta_{Sat} - \theta_{FC}) \times DUR \times N$$

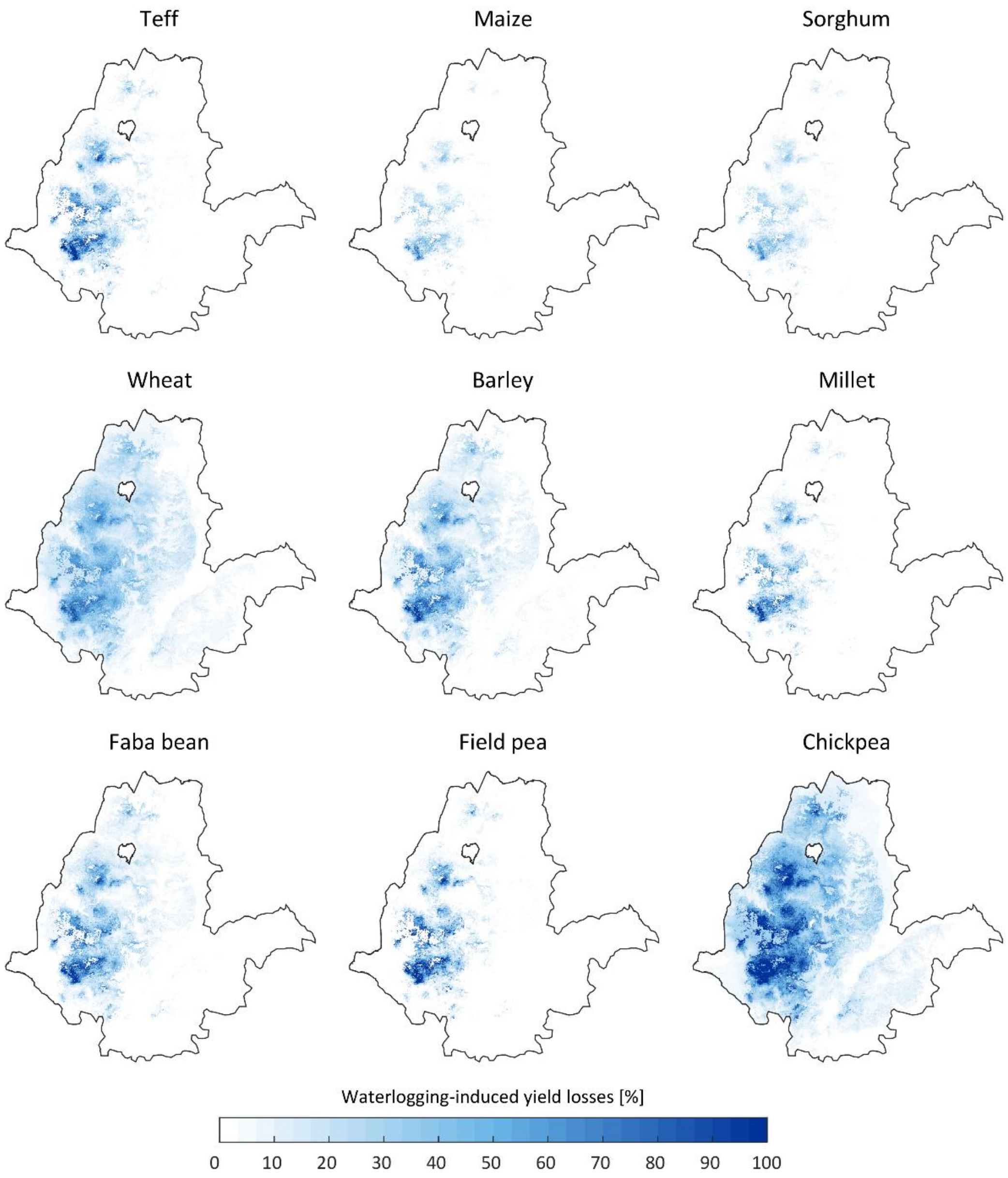
Waterlogging characteristics



- About 10% of the RFA region experience root-zone oxygen of 50% with an average duration of about 67 days.
- Hyper-humid areas experience high soil oxygen deficit persisting throughout the growing season

Estimated mean annual yield losses (1981-2010) as percentage of the nationally attainable maximum yield

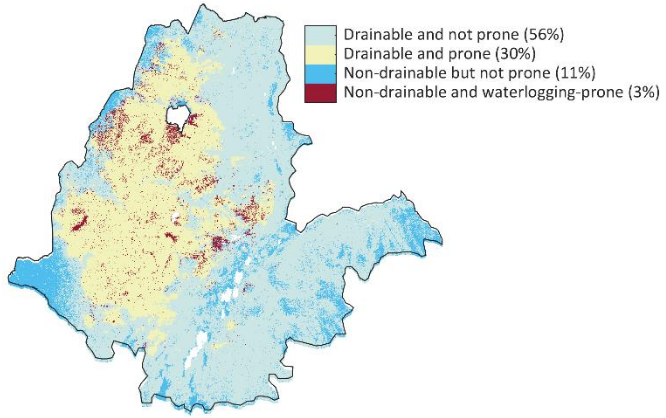
- Yield losses of up to 100% are observed, depending on the crop type and climate regime
- Chickpea, wheat, and barley are highly sensitive to waterlogging conditions
- Maize, sorghum, and millet are less affected, except in regions with a hyper-humid climate



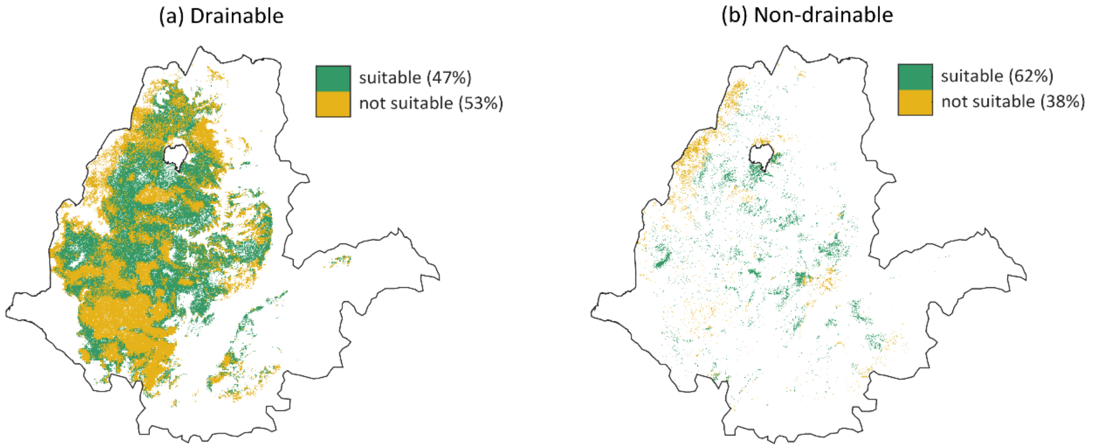
Rice-grass pea intensification as an alternative measure to increase the productivity of waterlogging-prone areas

- One third of the RFA region is prone to waterlogging limitations of different severity level
- About 47% of the prone areas with naturally drainable slope condition are suitable for rice-grass pea system
- Over 60% of the non-drainable areas are suitable for rice production in rotation with grass pea

Natural drainability of agricultural landscapes as defined by slope



Suitability for rice – grass pea intensification



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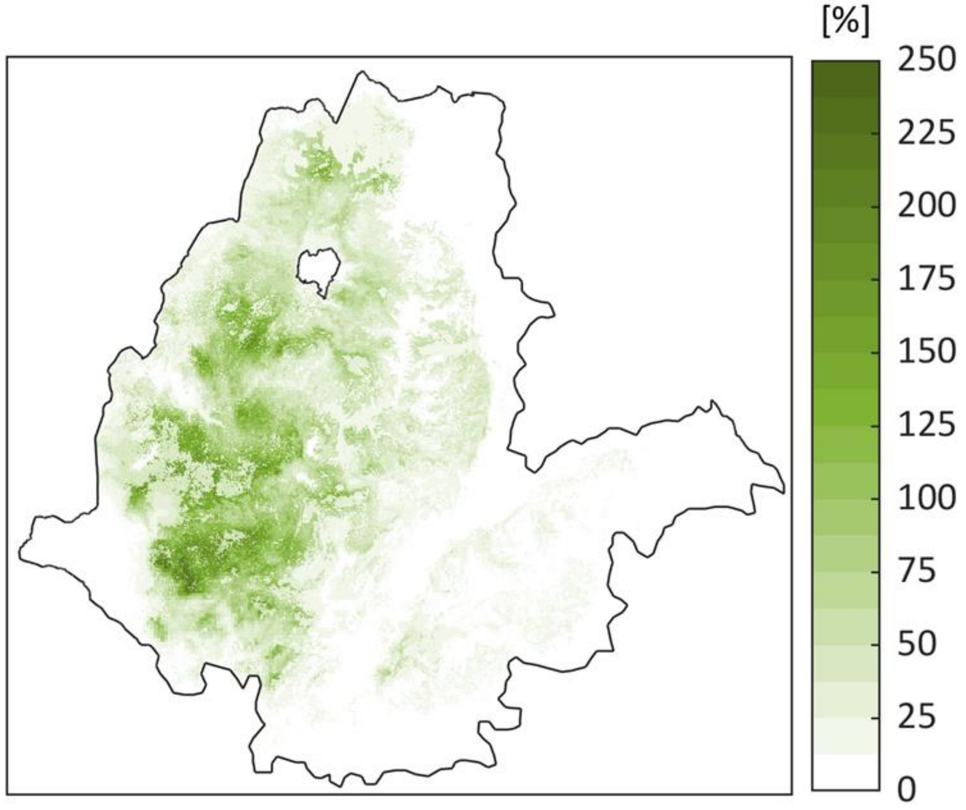
Improved drainage as a remedial measure:

- Improved drainage can increase wheat yield by up to 60% in dry sub-humid areas

- Under high waterlogging intensity in humid areas, improved drainage can the current yield by up to 250%



Conclusion

- The characteristics, limitations, and management strategies of waterlogging in Ethiopia’s rainfed agriculture (RFA) region were analyzed
- Waterlogging of different intensities affects about 33% of croplands in the RFA region Ethiopia
- Major cereals (wheat and barley), and legumes (chickpea and faba bean) are highly sensitive to waterlogging across the study region
- An estimated 50% of the identified waterlogging-prone areas appear suitable for rice intensification in rotation with grass pea
- Improved soil drainage has significant potential to enhance the current yields—by up to 60% in sub-humid zones and up to 250% in humid agroecological zones.

Acknowledgement

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