

Detection and quantification of irrigation at 500 m using Sentinel-1 surface soil moisture

Manuscript submitted to [RS](#)

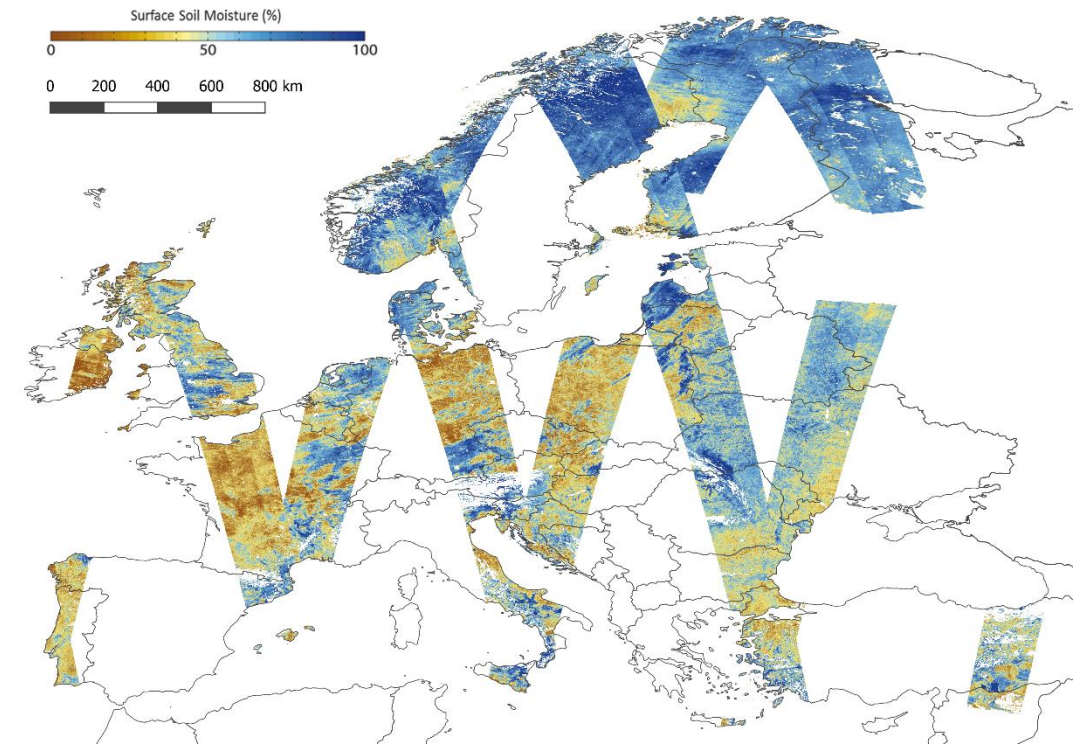
Short background

- Irrigation ..
 - .. plays a key role ensuring **food security**
 - .. accounts for **70% of water withdrawals** worldwide
 - .. can lead to various **environmental problems**
- There is a **lack of reliable information about irrigation** (**when** and **where** it occurs, **how much water** is used for each field, ..)
- **EO satellites** are emerging as a convenient means to map and quantify irrigation, however ..
 - .. **optical/thermal** observations are affected by **cloud cover**
 - .. **microwave** observations are generally characterized by **coarse spatial resolution**

→ **Potential of the Sentinel-1 mission to fill this gap**

Sentinel-1 surface soil moisture (S1-SSM)

- The **Sentinel-1** (S1) mission consists of **two** identical **satellites** carrying a **C-band SAR** sensor
- Backscatter observations are used to derive **surface soil moisture** (SSM) using the **TU Wien change detection** method *
- **Main characteristics** of the S1-SSM product used in this work
 - Spatial resolution: 500 m
 - Temporal resolution: 1.5-4 days (over Europe)
 - Unit: degree of saturation (0-100)
 - Lack of vegetation correction



Example of daily S1-SSM product over Europe

* *Bauer-Marschallinger et al. 2018 (TGRS)*

Ancillary datasets

- **Corine Land Cover 2018** used to mask non-agricultural areas
- **CGLS NDVI** used to monitor vegetation development
- **Soil porosity** (from SoilGrids) used to convert S1-SSM to volumetric units



Study sites

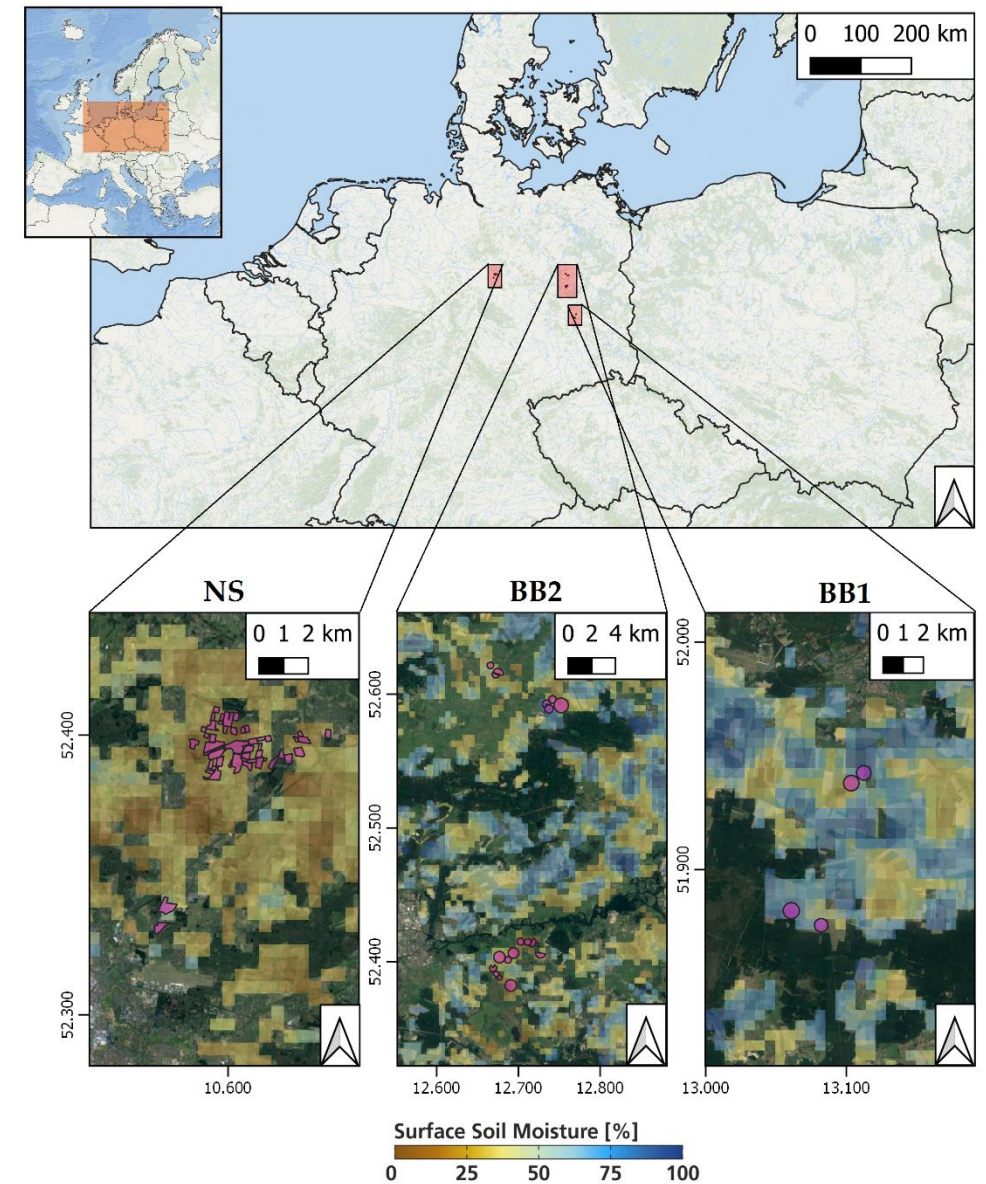
Three sites located in Northern Germany

- **Temperate Oceanic Climate** (mean annual temp 9°C and prec 550 mm)
- Predominance of **Sandy loam soil**

Detailed information about the study sites

	BB1	BB2	NS
N° fields	4	18	49
Mean field size (ha)	42	38	8
Mean n° irrigation events per field	12	6	24
Mean irrigation height per event (mm)	15*	27	13
Main crops	Potato, cereals, pea	Maize, cereals, sugar beet	Potato, sugar beet, cereals

* Exact measurements were not available



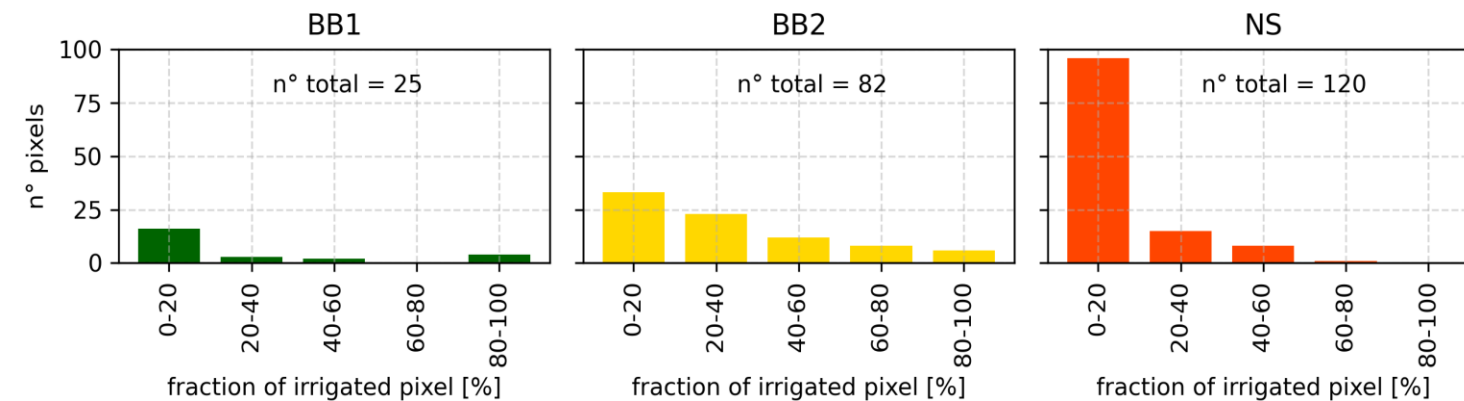
Location of the study sites, with S1-SSM map for June 7, 2018 with non-agricultural pixels masked

Study sites & S1-SSM

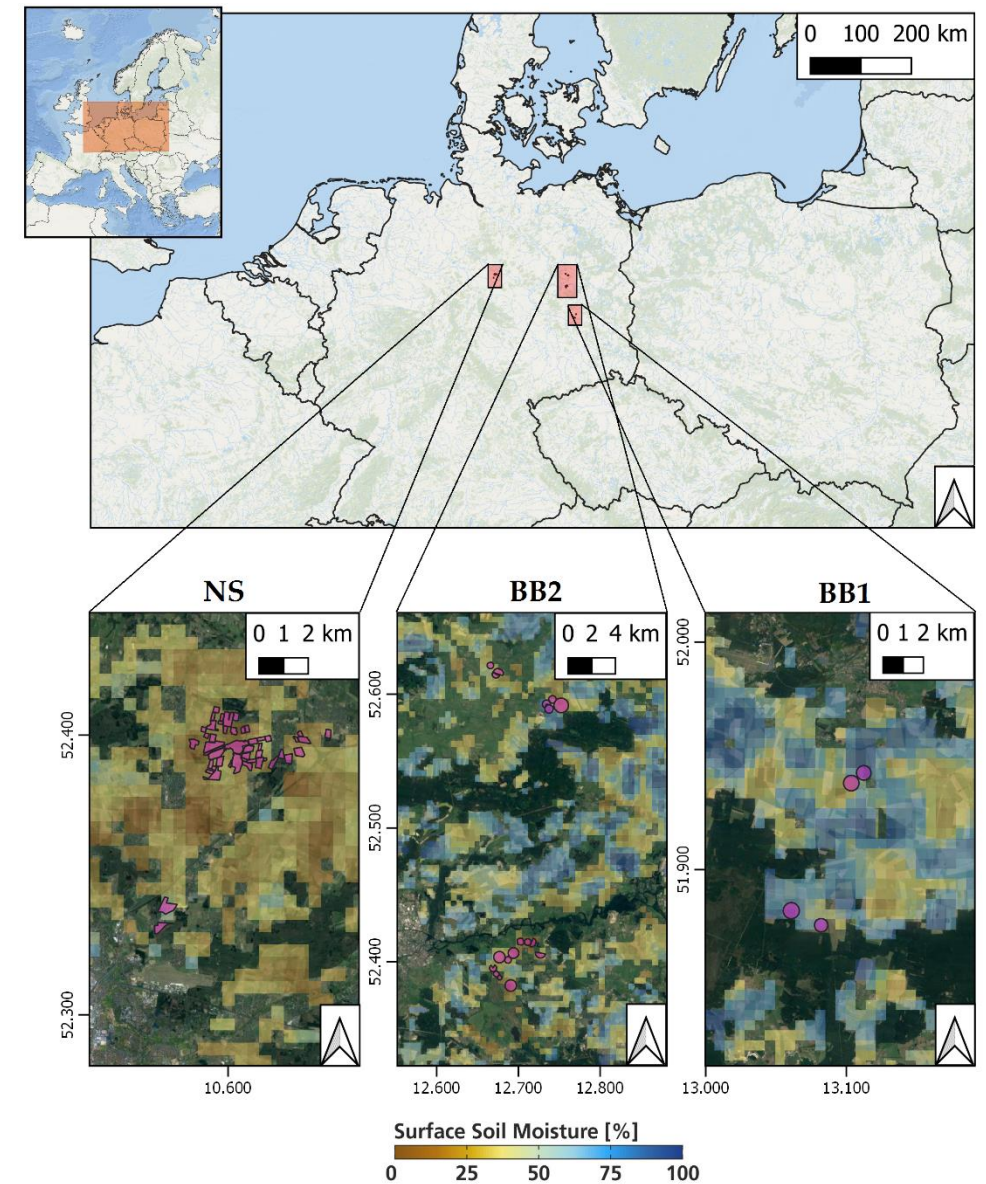
227 S1-SSM pixels cover irrigated fields in the three study sites

Pixels not aligned with field boundaries

→ Each pixel covers a diverse portion of the irrigated fields, i.e. **fractional irrigated area**

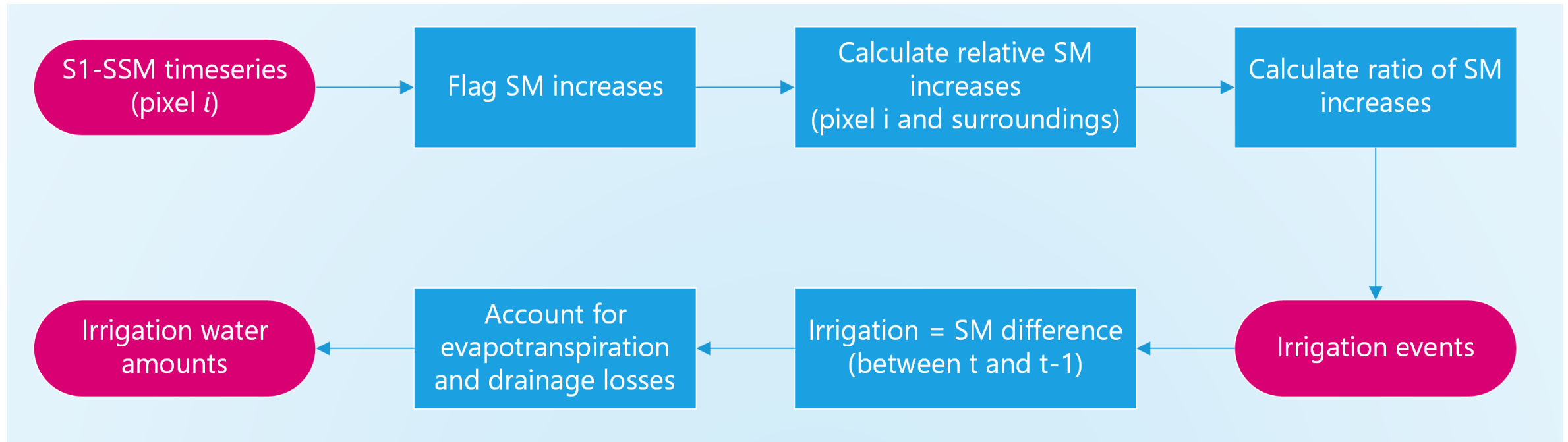


Number of S1-SSM pixels covering irrigated fields, grouped by the fractional irrigated area, i.e. the ratio between the irrigated area covered by S1-SSM and the pixel area



Location of the study sites, with S1-SSM map for June 7, 2018 with non-agricultural pixels masked

Methods



Simplified representation of the method proposed for the detection and quantification of irrigation

Methods

Detection of irrigation events

To discern irrigation from other factors causing a rise in soil moisture, e.g. precipitation and retrieval noise, we:

1. Calculated the relative soil moisture increase of a pixel (local) and that of its surroundings* (areal):

$$\Delta SM_t = \frac{SM_t - SM_{t-1}}{SM_{t-1}}$$

2. Calculated the ratio between them (SM_{ratio_t})
3. Tested various threshold values for irrigation flagging**

** Surrounding area defined as the $n \times n$ pixel grid around local pixel, further masked by land cover (only agriculture) and similar vegetation status (NDVI)*

*** Under the assumption that over a relatively large area, only a few fields are irrigated simultaneously*

Methods

Quantification of irrigation water amounts

For each detected event, we:

1. Estimated the local SM that would be found net of precipitation (if any):

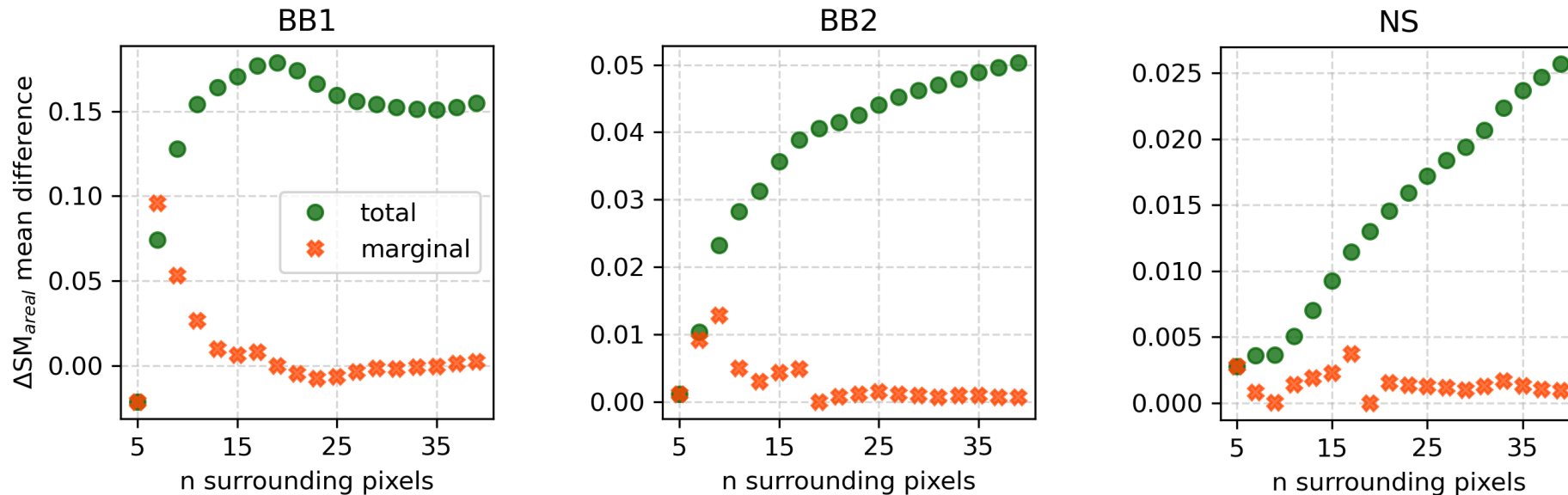
$$\Delta SM_{t,local}^* = \begin{cases} \Delta SM_{t,local} - \Delta SM_{t,areal} , & \Delta SM_{t,areal} > 0 \\ \Delta SM_{t,local} , & \Delta SM_{t,areal} \leq 0 \end{cases}$$

$$SM_{t,local}^* = (SM_{t-1,local} \cdot \Delta SM_{t,local}^*) + SM_{t-1,local}$$

2. Calculated Irrigation = $SM_{t,local}^* - SM_{t-1,local}$
3. Accounted for evapotranspiration (modified Thornthwaite eq.) and drainage (power-law eq.) losses

Results – optimal grid size

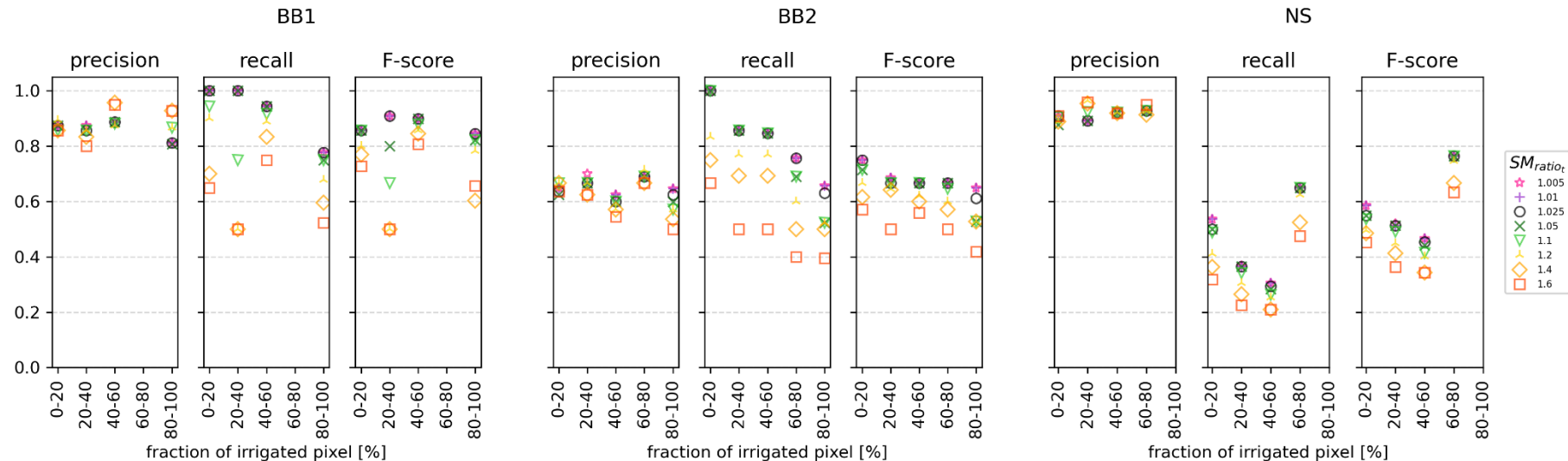
Benefit of employing larger grid sizes to calculate ΔSM_{areal} compared to the smallest possible grid, i.e. $n=3$ (green dots), and marginal improvements obtained for grid size n compared to the previous grid size (orange crosses)



- Amplitude of mean differences varies depending on irrigation system and management
- Marginal differences (orange) increase until grid size of 11-19 pixels

Results – detection accuracy

Detection accuracy expressed as precision, recall, and F-score. Results are grouped by the fraction of irrigated area within S1-SSM pixels



- Poor recall at the NS site due to irrigation management, i.e. frequent allocation of small amounts of water
- Accuracy did not always improve with increasing the fraction of irrigated area covered by S1-SSM pixels, likely due to lower reliability under dense vegetation

Results – detection accuracy

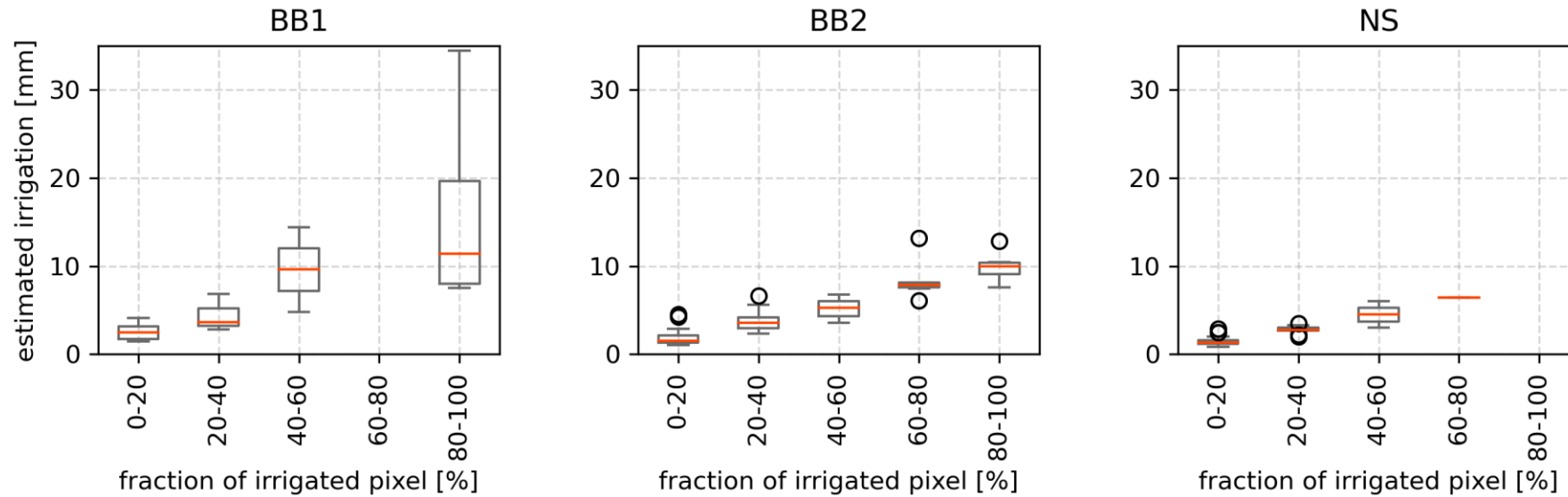
Summary of detection accuracy depending on the threshold (SM_{ratio_t}) value employed for discriminating soil moisture increases as irrigation

Site	Metric	SM_{ratio_t}					
		1.005	1.01	1.025	1.05	1.1	1.2
BB1	p	0,87	0,87	0,86	0,86	0,86	0,88
	r	0,98	0,98	0,97	0,96	0,89	0,82
	F	0,92	0,92	0,91	0,91	0,87	0,85
BB2	p	0,67	0,66	0,64	0,64	0,65	0,65
	r	0,88	0,88	0,88	0,87	0,87	0,76
	F	0,76	0,75	0,74	0,74	0,74	0,70
NS	p	0,91	0,91	0,91	0,89	0,91	0,91
	r	0,48	0,48	0,45	0,45	0,44	0,38
	F	0,63	0,63	0,60	0,60	0,59	0,53

- Overall detection of individual irrigation events consistently better for SM_{ratio_t} smaller than 1.05

Results – quantification of irrigation

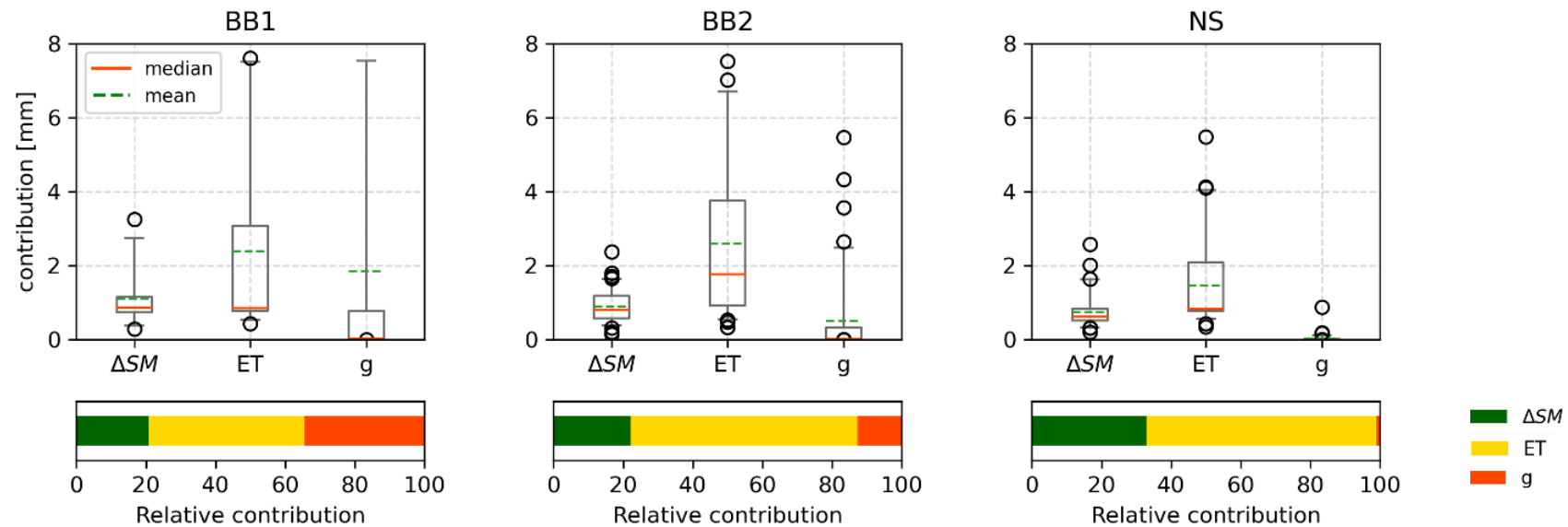
Median irrigation heights of individual events estimated for each pixel throughout the irrigation period, grouped by the fraction of pixel irrigated



- Differences in irrigation estimates among test sites consistent with data reported by farmers
- Estimated irrigation found to increase with increasing the fraction of irrigated pixel, i.e. higher irrigation amounts are expected over largely irrigated pixels

Results – quantification of irrigation

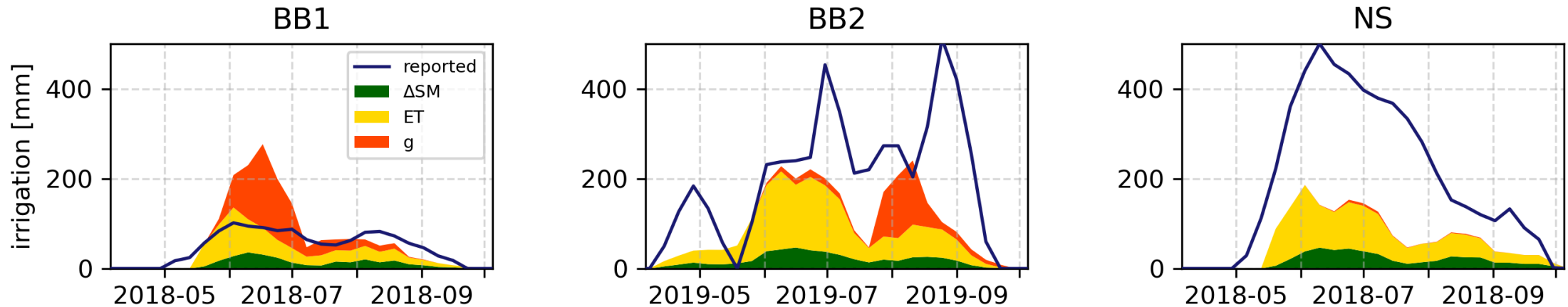
Contribution to the estimated irrigation from the following components: soil moisture increase between consecutive overpasses (ΔSM), evapotranspiration (ET), and drainage (g). Barplots show the mean relative contribution



- Predominant contribution of ET - in agreement with previous studies
- Extremes of g are the result of lack of vegetation correction in S1-SSM retrieval and (occasionally) long time between consecutive satellite acquisitions

Results – quantification of irrigation

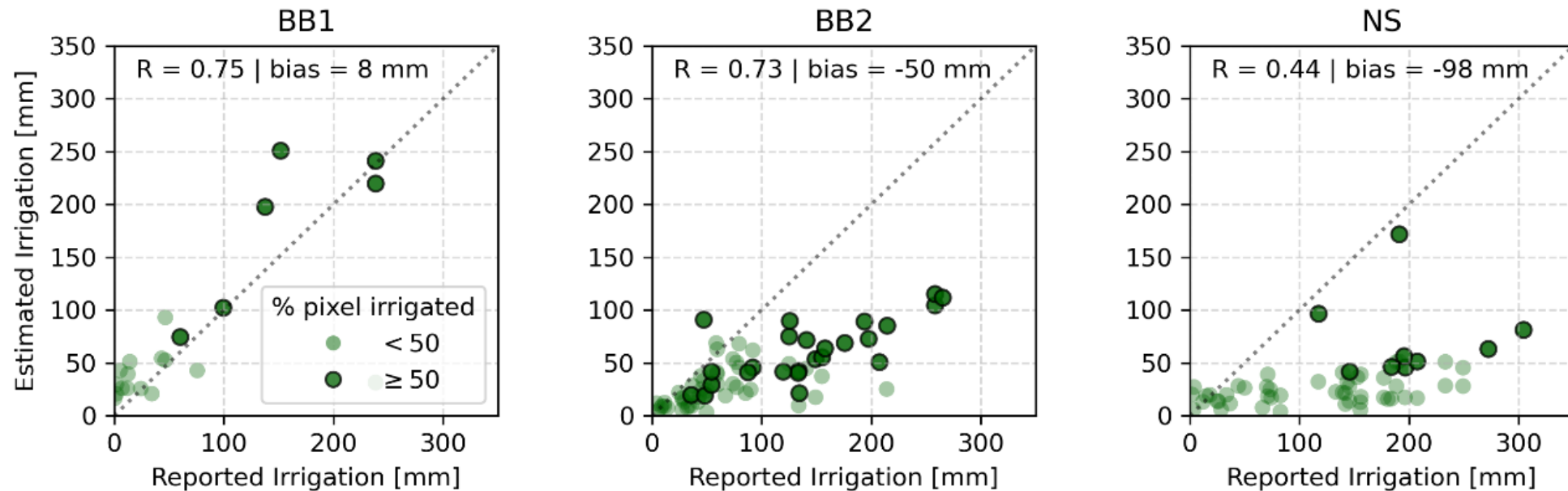
Time series of spatially cumulated irrigation water heights, aggregated on a weekly basis. Estimated irrigation, with the explicit contribution of each term to the total, is compared against reference data reported by farmers



- Sufficient temporal agreement between reported and estimated irrigation
- Overestimations (BB1) due to exaggerate drainage, while underestimations due to long gaps between S1 acquisitions (e.g. in mid-july at BB2) and undetected events (NS)

Results – quantification of irrigation

Pixel by pixel comparison of cumulative irrigation water heights between estimated and reference data. S1-SSM pixels with a fractional irrigation area higher than 50% are highlighted



- Good agreement between reported and estimated irrigation, notwithstanding considerable underestimation. Note that irrigation efficiency, specific for the irrigation system and the environmental conditions at the time of irrigation, is not considered

Conclusions

- **Novel approach** based on **S1-SSM**, does **not rely on additional datasets** (e.g. precipitation, model SM) either available over large scales but at coarse resolution or exist at (sub-) kilometeric resolution but only at the catchment or regional scale
- **Simple representations** of evapotranspiration and drainage ensure the **applicability to large regions** and locations without meteorological stations. **Improvements** can be expected when using **more sophisticated formulations**
- **Satisfactory accuracy** both in terms of **detection** (mean F-score = 0.77) and **quantification** (mean R = 0.64)