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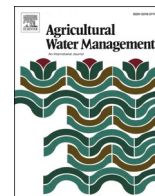
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# Retrieving the irrigation actually applied at district scale: Assimilating high-resolution Sentinel-1-derived soil moisture data into a FAO-56-based model

Pierre Laluet<sup>a,\*</sup>, Luis Enrique Olivera-Guerra<sup>a,2</sup>, Víctor Altés<sup>b,c</sup>, Giovanni Paolini<sup>b</sup>, Nadia Ouadi<sup>a,d</sup>, Vincent Rivalland<sup>a</sup>, Lionel Jarlan<sup>a</sup>, Josep Maria Villar<sup>c</sup>, Olivier Merlin<sup>a</sup>

<sup>a</sup> Centre d'Etudes Spatiales de la Biosphère (CESBIO), Université de Toulouse, CNES-CNRS-IRD-UPS-INRAE, Toulouse, France

<sup>b</sup> isardSAT, Marie Curie 8-14, Parc Tecnològic Barcelona Activa, Barcelona, Spain

<sup>c</sup> Soils and Water Research group, Universitat de Lleida, Lleida, Spain

<sup>d</sup> GMME/SURFACE, Météo-France/CNRM, Toulouse, France

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## ABSTRACT

Irrigation is the most water consuming activity in the world. Knowing the timing and amount of irrigation that is actually applied is therefore fundamental for water managers. However, this information is rarely available at all scales and is subject to large uncertainties due to the wide variety of existing agricultural practices and associated irrigation regimes (full irrigation, deficit irrigation, or over-irrigation). To fill this gap, we propose a two-step approach based on 15 m resolution Sentinel-1 (S1) surface soil moisture (SSM) data to retrieve the actual irrigation at the weekly scale over an entire irrigation district. In a first step, the S1-derived SSM is assimilated into a FAO-56-based crop water balance model (SAMIR) to retrieve for each crop type both the irrigation amount ( $I_{dose}$ ) and the soil moisture threshold ( $SM_{threshold}$ ) at which irrigation is triggered. To do this, a particle filter method is implemented, with particles reset each month to provide time-varying  $SM_{threshold}$  and  $I_{dose}$ . In a second step, the retrieved  $SM_{threshold}$  and  $I_{dose}$  values are used as input to SAMIR to estimate the weekly irrigation and its uncertainty. The assimilation approach (SSM-ASSIM) is tested over the 8000 hectare Algerri-Balaguer irrigation district located in northeastern Spain, where in situ irrigation data integrating the whole district are available at the weekly scale during 2019. For evaluation, the performance of SSM-ASSIM is compared with that of the default FAO-56 irrigation module (called FAO56-DEF), which sets the  $SM_{threshold}$  to the critical soil moisture value and systematically fills the soil reservoir for each irrigation event. In 2019, with an observed annual irrigation of 687 mm, SSM-ASSIM (FAO56-DEF) shows a root mean square deviation between retrieved and in situ irrigation of 6.7 (8.8) mm week<sup>-1</sup>, a bias of +0.3 (-1.4) mm week<sup>-1</sup>, and a Pearson correlation coefficient of 0.88 (0.78). The SSM-ASSIM approach shows great potential for retrieving the weekly water use over extended areas for any irrigation regime, including over-irrigation.

## 1. Introduction

Irrigation is the most water-intensive human activity, consuming more than 70% of the freshwater used worldwide (Foley et al., 2011; Qin et al., 2019). Pressure on water resources already exists in many regions and is expected to increase in the future (Wada et al., 2011, 2013; Campbell et al., 2017; FAO, 2021). This is largely due to the combined effect of increased food demand associated with economic and

population growth (Tilman and Clark, 2015), and the impact of climate change on hydrometeorological response (Ferguson et al., 2018; Malek et al., 2018; Williams et al., 2020). To best manage this situation, decision makers, including water resource managers need to know how much water is being used for irrigation, at regional (irrigation district, catchment), national and global scales (OECD, 2015). However, access to reliable information on irrigation water use is currently lacking. It either does not exist, or is subject to large uncertainties inherent in

\* Corresponding author.

E-mail address: [pierre.laluet@gmail.com](mailto:pierre.laluet@gmail.com) (P. Laluet).

<sup>1</sup> Present address: Department of Geodesy and Geoinformation, Vienna University of Technology, Vienna, Austria

<sup>2</sup> Present address: Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ-UPSACLAY, UMR 8212, IPSL, Gif-sur-Yvette, France

national or international databases, such as the AQUASTAT dataset (<http://www.fao.org/aquastat/en/>; accessed 16 June 2023) (Ajaz et al., 2020; Puy et al., 2022a), or in the predictions of hydrological models (Wada et al., 2016; Huang et al., 2018; Puy et al., 2022b). Indeed, models generally simulate irrigation based on empirically defined soil moisture thresholds, which are highly variable in space and time and therefore highly uncertain (Olivera-Guerra et al., 2023). In addition, irrigation modeling is affected by other sources of uncertainty, such as irrigated area or irrigation efficiency (Puy et al., 2021, 2022a, 2022b).

While the need for knowledge of irrigation water use is growing, and the irrigation models are still too uncertain to meet the challenge, more and more remote sensing observations relevant to irrigation retrieval are becoming freely available. Over the last two decades, the number of satellites carrying solar and thermal spectrum sensors (e.g., Moderate resolution Imaging Spectroradiometer (MODIS), Landsat, Sentinel-2 (S2), Sentinel-3) from which evapotranspiration (ET) products can be derived (such as SEN-ET; Guzinski et al., 2020), and passive (e.g., Soil Moisture and Ocean Salinity (SMOS), Soil Moisture Active Passive (SMAP)) and active microwave (e.g., Advanced SCATterometer (ASCAT), Sentinel-1 (S1)) sensors, from which soil moisture products can be derived (e.g., El Hajj et al., 2017; Ojha et al., 2019; Paolini et al., 2022), has steadily increased. This opens up increasingly interesting possibilities in terms of spatial and temporal resolution (Peng et al., 2021). The wealth of information available from remote sensing has led to the emergence of a community of researchers focused on irrigation estimation from satellite observations. Massari et al. (2021) recently provided an overview of the various existing approaches based on satellite observations.

Some of these works have attempted to retrieve irrigation by comparing the remotely sensed ET of two (one irrigated and one rainfed) neighboring crops (e.g., Romaguera et al., 2014; Vogels et al., 2020) or by assuming that it corresponds to the difference between simulated and remotely sensed ET (e.g., Anderson et al., 2015; López Valencia et al., 2020). In the same vein, Zhang and Long (2021) have retrieved monthly irrigation at the scale of US states by exploiting the difference between simulated and remotely sensed ET, by relying on a linear relationship between ET and root zone soil moisture. However, all these ET-based methods suffer from the same pitfall. The information contained in ET observations is limited to the water actually consumed by the crop fields, thus neglecting any excess water applied intentionally (e.g., to allow soil leaching) or unintentionally (due to suboptimal practices). Assuming that ET data can be used to determine the irrigation actually applied is equivalent to assuming that farmers never irrigate more than the crop can consume. However, over-irrigation may occur. This can be observed, for example, in the Algerri-Balaguer (AB) irrigation district in northeastern Spain, where the observed drainage (related to excess water in the soil) occurs mainly in summer, when irrigation is intensive and rainfall is low (Altès et al., 2022; Lалуé et al., 2023b).

Many other recently published approaches propose to estimate irrigation using the surface soil moisture (SSM) data derived from microwave observations. Remotely sensed SSM can detect the irrigation signal (Le Page et al., 2020; Jalilvand et al., 2021; Lawston et al., 2017) and theoretically both under-irrigation (below the amount of water needed to avoid crop stress) and over-irrigation (above the amount of water the soil can hold, resulting in drainage). An irrigation retrieval model based on SSM data was proposed by Brocca et al. (2018) using the SM2RAIN approach. It has since been used in various works (e.g., Jalilvand et al., 2019; Dari et al., 2020; Dari et al., 2022, 2022; Dari et al., 2023; Filippucci et al., 2020). SM2RAIN relies on a simple water balance equation whose terms depend on observed SSM and empirical parameters, which are previously calibrated over rainfed areas or during periods when there is no irrigation. Jalilvand et al. (2019) applied this method using SSM data from the Advanced Microwave Scanning Radiometer 2 (AMSR2; ~25 km resolution) over an irrigation district in Iran. Although the overall irrigation dynamics was well reproduced, irrigation was systematically overestimated. By applying a bias correction obtained

from the application of SM2RAIN over rainfed areas, the results were significantly improved with a root mean square deviation (RMSD) of 13 mm month<sup>-1</sup>. They highlighted the sensitivity of irrigation to the ET formalism and emphasized the need to use SSM observations at higher spatial resolution. Later, Dari et al. (2020) and (2022) applied the same approach to semi-arid irrigation districts in Spain at a finer spatial resolution using the SMOS and SMAP SSM data disaggregated at 1 km resolution (DISPATCH SSM datasets; Merlin et al., 2013). They showed that an improved formulation of ET (particularly using the FAO-56 approach of Allen et al., 1998) significantly improves irrigation retrievals. This highlights the importance of properly representing the processes involved in the crop water balance.

Recently, Dari et al. (2023) used SM2RAIN with S1 and Cyclone Global Navigation Satellite System (CYGNSS) derived SSM products (1 km and 6 km spatial resolution, respectively) on ten irrigation districts in Spain, Italy, and Australia. The retrieved irrigation reproduces in situ observations well, but with sometimes significant biases, especially for small irrigation districts. In fact, all the papers involving SM2RAIN have emphasized the importance of using a high-resolution SSM product to detect processes occurring at the field scale. In parallel with these works, Zappa et al. (2021) proposed an approach close to SM2RAIN, called SM\_Delta, based on the comparison of SSM variation between an irrigated pixel and the rainfed pixels surrounding it. Zappa et al. (2022) evaluated the performance of this approach on synthetic data and showed that it is highly sensitive to both spatial resolution and observation frequency. Performance declines sharply for periods of more than three days between two consecutive SSM observations, and when the irrigated fraction of a pixel falls below 70%. This illustrates the importance of high-resolution observations capable of providing pixels with a high irrigation fraction.

In addition to the issues of spatial resolution and revisit time of SSM datasets, another limitation of current SSM-based approaches such as SM2RAIN is that they neglect the issue of uncertainty, whether caused by the model (uncertainty in model parameters and formalism) or by satellite observations (uncertainty in input data). However, all models are sensitive to the choices made in the calibration step, to the model formalism and parameterization, and to the uncertainty of its input data (Foster et al., 2020; Beven et al., 2019; Puy et al., 2022b). Knowledge of the uncertainty in the model estimate is actually as important as the modeled value to provide reliable information to decision makers and managers (Saltelli et al., 2020).

Other approaches based on the assimilation of satellite SSM data into land surface models (LSMs) have recently been developed, enabling uncertainty to be taken into account in irrigation simulations. Assimilation methods are based on the prior distributions of both model and observational errors. Felfelani et al. (2018) assimilated SMAP (36 km spatial resolution) SSM data into the Community Land Model version-4.5 LSM (Lawrence et al., 2011; Oleson et al., 2013) over a large irrigated area in the USA, using the one-dimensional Kalman filter method. The goal was to constrain the so-called "target soil moisture" parameter, which determines the irrigation triggering and amount. They obtained a significant improvement in the simulated annual irrigation compared to the baseline simulation performed using the default parameter value. In the same vein, Abolafia-Rosenzweig et al. (2019) inverted irrigation amounts by assimilating (synthetic) SSM data into the variable infiltration capacity LSM using the particle batch smoother data assimilation approach. The results of the twin experiment indicated that the assimilation approach is better when the timing of irrigation is known, and when the revisit time of the SSM observation is less than three days. They also highlighted the importance of addressing the issue of persistent biases between simulated and observed SSM. Jalilvand et al. (2023) applied the same approach but using the 1 km resolution SMAP-S1 SSM data (Das et al., 2019) over an irrigation district in Iran. They confirmed the importance of an a priori knowledge of irrigation frequencies in their approach and obtained an underestimation of seasonal cumulative irrigation at the irrigated pixels by an average of 19%,

explained by the loss of irrigation signal due to the mismatch between the spatial resolution (1 km) of the SSM data and the scale of irrigation practices.

Modanesi et al. (2022) assimilated the S1 backscatter (aggregated to 1 km resolution) to improve the performance of the Noah-MP.v.3.6 LSM (Niu et al., 2011) coupled with an irrigation module (Ozdogan et al., 2010), using an ensemble Kalman filter. The assimilation resulted in an improvement of the simulated irrigation, but to a limited extent. In particular, they emphasized the importance of dealing with observations and simulations at higher spatial resolution (with low performance when pixel had low irrigation fraction), as well as the need for more frequent SSM observations and improvement of the Noah-MP.v.3.6 irrigation module formalism. At a finer spatial scale, Ouaadi et al. (2021) estimated the timing and amount of irrigation for five wheat plots in Morocco. They assimilated a high-resolution (15 m, revisit time of six days) SSM product derived from S1 into a model based on the FAO-56 method, using the particle filter (PF) approach (Vrugt et al., 2013). PF is one of the most efficient assimilation methods, able to take into account for model and observational uncertainties without the need for any assumptions about prior density functions or likelihoods and is adapted to nonlinear problems (unlike 4DVar or Kalman filter-based methods) (van Leeuwen et al., 2019; Alonso-González et al., 2022). For all five plots, Ouaadi et al. (2021) obtained a Pearson correlation coefficient  $r$  of 0.64 and an RMSD of 28.7 mm/15 days and were able to detect 50–70% of irrigation events. They also showed, using in situ data, that their approach performed better with a shorter revisit time (three days).

A recurring issue in assimilation approaches is the management of persistent differences between modeled and observed SSM. To reduce model or observation biases, one possible solution is to use a rescaling approach such as cumulative distribution function matching (Reichle and Koster, 2004) to fit the observed SSM to the simulated SSM. However, this approach has the disadvantage of potentially deleting signals when the observations contain some information that is not modeled, such as irrigation (Kumar et al., 2015; Nair and Indu, 2019). Another way to minimize such a bias is to calibrate model parameters on rainfed pixels (e.g., Dari et al., 2020, 2022; Jalilvand et al., 2023), although this implies the strong (and unverified) assumption that optimal parameters for rainfed pixels are also optimal for irrigated pixels. Another approach is to remove a systematic bias (calculated on rainfed pixels) from the simulated irrigations (Jalilvand et al., 2019), although part of the signal may be lost due to the difference in climatology or soil properties between both pixel types (Brombacher et al., 2022).

The above literature review of SSM-based irrigation retrieval methods indicates that state-of-the-art approaches are currently limited by (one or several of the following factors): 1) the coarse resolution of SSM remote sensing products used as input, 2) the impact of data gaps in SSM time series due to low revisit, 3) the non-explicit representation of irrigation-related (e.g., ET, deep percolation, etc.) processes which makes the calibration steps difficult and uncertain, and 4) the lack of consideration (by the irrigation retrieval methods that are not based on data assimilation) of uncertainties in both model parameterization and input data.

In this context, this study proposes a new assimilation scheme of a high (15 m) resolution S1-derived SSM product (Ouaadi et al., 2020) into the FAO-56-based crop water balance model Satellite Monitoring for Irrigation (SAMIR; Simonneau et al., 2009), using the PF method. The SAMIR model, implemented at the field scale, allows for a robust and explicit representation of crop ET from the crop coefficient values available for all common crops for different climates in the FAO-56 look-up tables. It can therefore be spatialized over large areas from readily available data (Laluet et al., 2023b). In addition, the assimilation approach developed by Olivera-Guerra et al. (2023) is used here to invert two parameters of the SAMIR irrigation module: the irrigation amount ( $I_{\text{dose}}$ ) and the soil moisture threshold ( $SM_{\text{threshold}}$ ) at which irrigation is triggered. Both parameters are retrieved over successive

monthly assimilation windows integrating several (up to five independent) S1-derived SSM observations. Such a strategy helps to reduce the impact of possible data gaps in SSM time series and allows for representing weekly district-scale water use in any (deficit, full or excess) irrigation regime (Olivera-Guerra et al., 2023).

The proposed approach is implemented over the 8000 hectare AB irrigation district located in northeastern Spain. It is evaluated at the field and AB scales using in situ irrigation measurements available at both scales. The paper is organized as follows: Section 2 presents the study area and the data used, Section 3 introduces the SAMIR model and its irrigation module (Section 3.1), as well as the assimilation scheme (Section 3.2), the strategy for performing plot-scale simulations (Section 3.3), and the evaluation step (Section 3.4). Section 4 presents and discusses the results obtained first at the field scale using in situ SSM data as input (Section 4.1), and then at the AB district scale using S1-derived SSM data as input (Section 4.2). Section 5 presents conclusions and perspectives of this work.

## 2. Study area and data

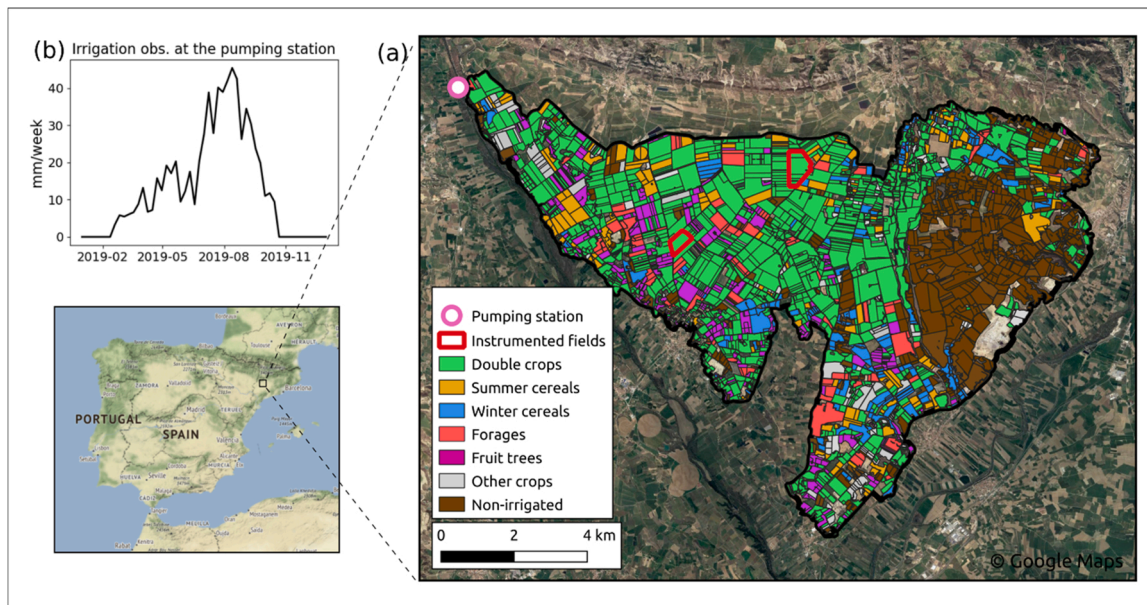
### 2.1. Study area

The study area is the 8000 hectare AB irrigation district located in northeastern Spain, 20 km north of the city of Lleida. The climate is continental Mediterranean with an average annual reference evapotranspiration ( $ET_0$ ) of 1027 mm and rainfall of 380 mm (2000–2021). For the year 2019, 6140 ha were irrigated, of which 94% were covered by five main crop types: double crops (62% of the irrigated area; mainly barley or wheat in winter-spring season and maize in summer-fall), summer cereals (9%; maize), winter cereals (8%; mainly barley or wheat), forages (8%; mainly alfalfa), and fruit trees (7%). The remaining 6% are composed of leguminous, oleaginous, horticultural and protein crops, as well as vineyards and olive trees. All the plots are irrigated by sprinklers (in summer the daily doses range from 5 to 15 mm), except for the fruit trees, which are irrigated by drip irrigation. The land use information used in this study comes from the Geographic Information System for Agricultural Parcels (SIGPAC), provided by the Department of Climate Action, Food, and Rural Agenda of the Region of Catalonia, and is available at <https://agricultura.gencat.cat/ca/ambits/desevolutamentrural/sigpac/descarregues> (accessed 16 June 2023). Fig. 1.a shows the AB district with the land cover for the year 2019 from the SIGPAC database.

### 2.2. In situ data

#### 2.2.1. District-scale in situ irrigation data

The district-scale irrigation data consists of the water flow pumped in the river Noguera Ribagorçana just next to the AB district (see Fig. 1.a for the location of the pumping station). This water, flowing through a canal and stored in a reservoir before reaching the plots, is the only resource used for irrigation in AB. It takes around 1 to 2 days from the pumping station to irrigation, so the dynamics of the pumped water are close to the irrigation dynamics. Flow measurements were made on a daily basis by the SAIH (Automatic Hydrological Information System of the Ebro Basin; available at <http://www.saihebro.com/saihebro/index.php>; accessed 16 June 2023) and were aggregated on a weekly basis to account for the time lag between pumping and actual irrigation (Olivera-Guerra et al., 2023). In addition, 5.8% of the pumped volume is removed to account for evaporative losses and leakage, based on a comparison made in 2021 between the annual pumped water and annual irrigation measured with flowmeters at the district level (Olivera-Guerra et al., 2023). The consistency of agricultural systems and practices from one year to the next means that the loss coefficient obtained in 2021 can be used for another year such as 2019. Moreover, this coefficient provides a less uncertain estimate of irrigation losses than those defined ad hoc (e.g., 10% for a modern irrigation district such as



**Fig. 1.** The AB irrigation district with the land cover for the year 2019, the location of the pumping station and of the two instrumented plots (Albesa and Castello) (a), and the weekly irrigation data measured at the pumping station in 2019 (b) (coordinates of the pumping station: 797157/4636983.4 ETRS89/UTM zone 31 N).

AB in [Dari et al., 2020, 2023](#)). Note that the 5.8% does not take into account evaporation losses of water intercepted from the leaves that may occur during irrigation, as this takes place mainly at night in AB, when evaporation demand is low. In situ weekly irrigation data for the year 2019 are shown in [Fig. 1.b](#).

### 2.2.2. Field-scale in situ data

The instrumented fields Castello and Albesa are two double-cropped plots of 35 and 21 ha respectively, located in the AB district (see [Fig. 1.a](#) for the location of the two instrumented fields). At Castello, SSM data every 15 min are available for a five-month period in summer-fall 2021. At Albesa, SSM data every 15 min are available for three periods: six months in summer-fall 2021, five months in winter-spring 2022, and five months in summer-fall 2022. For Castello, SSM data are obtained from the average of SSM measurements of two TERSO 10 sensors (METER group) installed at a depth of 5 cm and separated by about 100 m. For Albesa, they are derived from three sensors (two TERSO 10 and one EC-5; METER group) also about 100 m apart. For the periods mentioned, daily irrigation data from flowmeters are available at both Castello and Albesa fields. Note that no loss coefficient has been applied to the measured irrigation volumes, since the meters are located on the plots themselves (implying no significant leakage due to water transport), and irrigation takes place mainly at night, implying that evaporation losses due to interception by leaves can be considered negligible. These in situ data are used to test and evaluate the SSM-ASSIM approach on a simple case (crop type and irrigation practices spatially uniform), at the plot scale, and with in situ SSM data being more frequent and less error prone than satellite observations. The in situ SSM measurements were averaged on a daily basis and one day out of three was kept, resulting in an observation every three days. This provides a frequency higher than that of S1-derived SSM (the latter is six days), but low enough to mimic the frequency of satellite observations (2–3 days being the frequency of SMOS or SMAP).

### 2.2.3. In situ meteorological data

The meteorological data are obtained from five stations belonging to the Catalan meteorological station network (available at <https://ruralcat.gencat.cat/agrometeo.estacions>; accessed 16 June 2023). Two of them are located within the AB district, and three at a maximum distance of 5 km. The average standard deviation of both precipitation

and  $ET_0$  measurements from the five stations is low ( $29 \text{ mm year}^{-1}$  for precipitation and  $18 \text{ mm year}^{-1}$  for  $ET_0$ ). Therefore, their spatial averages (simple averages) were used as forcing in the SAMIR model.

## 2.3. Remote sensing data

### 2.3.1. S2-derived vegetation index

The Normalized Difference Vegetation Index (NDVI) is used in this study to drive the modeled crop development in SAMIR. It is derived from the S2 multispectral satellite constellation consisting of two satellites S2A and S2B, with a global revisit frequency of five days. S2A and S2B were launched by the European Space Agency (ESA) in 2015 and 2017, respectively. We used the level 2 surface reflectance data at 10 m spatial resolution from band 4 (red) and band 8 (near-infrared) to compute NDVI, and cloud masks (QA60 and band 10) were applied. When more than 25% of the pixels falling in a plot are affected by the cloud masks, all the pixels in that plot are removed to avoid cloud contamination. When less than 25% of the plot is affected by the masks, the average of the remaining NDVI values within the crop field is calculated. Finally, the field-scale NDVI data are interpolated to the daily scale using a piecewise cubic Hermite interpolation polynomial method ([Fritsch and Carlson, 1980](#)).

### 2.3.2. S1-derived SSM

The remotely sensed SSM data used in this study are derived from the S1C-band synthetic aperture radar satellite constellation, consisting of two satellites S1A and S1B, with a global revisit frequency of six days. S1A and S1B were launched by ESA in 2014 and 2016, respectively, and both provide dual acquisitions in VV (vertically transmitted, vertically received) and VH (vertically transmitted, horizontally received) polarizations. To invert the SSM from S1 microwave observations, the approach proposed by [Ouaadi et al. \(2020\)](#) is used. The retrieval method is based on the inversion of the water cloud model from the S1 VV polarization backscattering coefficient and the S1 interferometric coherence. The vegetation descriptor used in the water cloud model is the above ground biomass derived from the interferometric coherence. SSM is thus obtained at each S1 acquisition and for each pixel by minimizing the distance between the backscattering coefficient observed by S1 and that simulated by the Water Cloud model, using a brute-force approach. For more details on the S1-derived SSM product, the reader is referred to

the original paper by Ouaadi et al. (2020).

### 2.4. Ancillary soil data

The soil texture is relatively uniform over AB and corresponds to a silty clay soil (Jahn et al., 2006). It is derived from the SoilGrids product (available at <https://maps.isric.org>; accessed 15 May 2023) at 250 m resolution (Hengl et al., 2017; Poggio et al., 2021). Soil texture information is used in SAMIR to derive soil hydraulic properties, which control the amount of water the soil can hold and the evaporation dynamics of the surface soil layer.

## 3. Method

The overall methodology for retrieving the weekly irrigation at the district scale is presented in the flowchart of Fig. 2. First, the SAMIR model is described with its irrigation module (3.1). Then, the SSM-ASSIM approach to retrieve the daily irrigation parameters ( $SM_{\text{threshold}}$  and  $I_{\text{dose}}$ ) (3.2.1) and the strategy to simulate the weekly irrigation using the retrieved  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  as input parameters in SAMIR are

presented (3.2.2). Finally, the strategy for applying the SSM-ASSIM approach at the plot scale (Section 3.3) and for evaluating irrigation retrievals at both field and district scale (Section 3.4) are described.

### 3.1. SAMIR model

SAMIR is a FAO-56 double-crop coefficient-based model (Allen et al., 1998) originally designed to simulate the crop water balance components for estimating daily ET and optimal irrigation requirements, by considering the water status of plant and soil. It uses meteorological forcing variables to calculate  $ET_0$  (using the Penman-Monteith equation), precipitation, crop and soil parameters, and NDVI to drive plant development.

#### 3.1.1. SAMIR main equations

SAMIR simulates the daily water balance equation as:

$$Dr(t) = Dr(t - 1) + ET(t) - P(t) - I(t) + DP(t) \tag{1}$$

where  $Dr$  is the root zone depletion,  $ET$  the actual evapotranspiration,  $P$  the precipitation,  $I$  the irrigation and  $DP$  the deep percolation. Each term

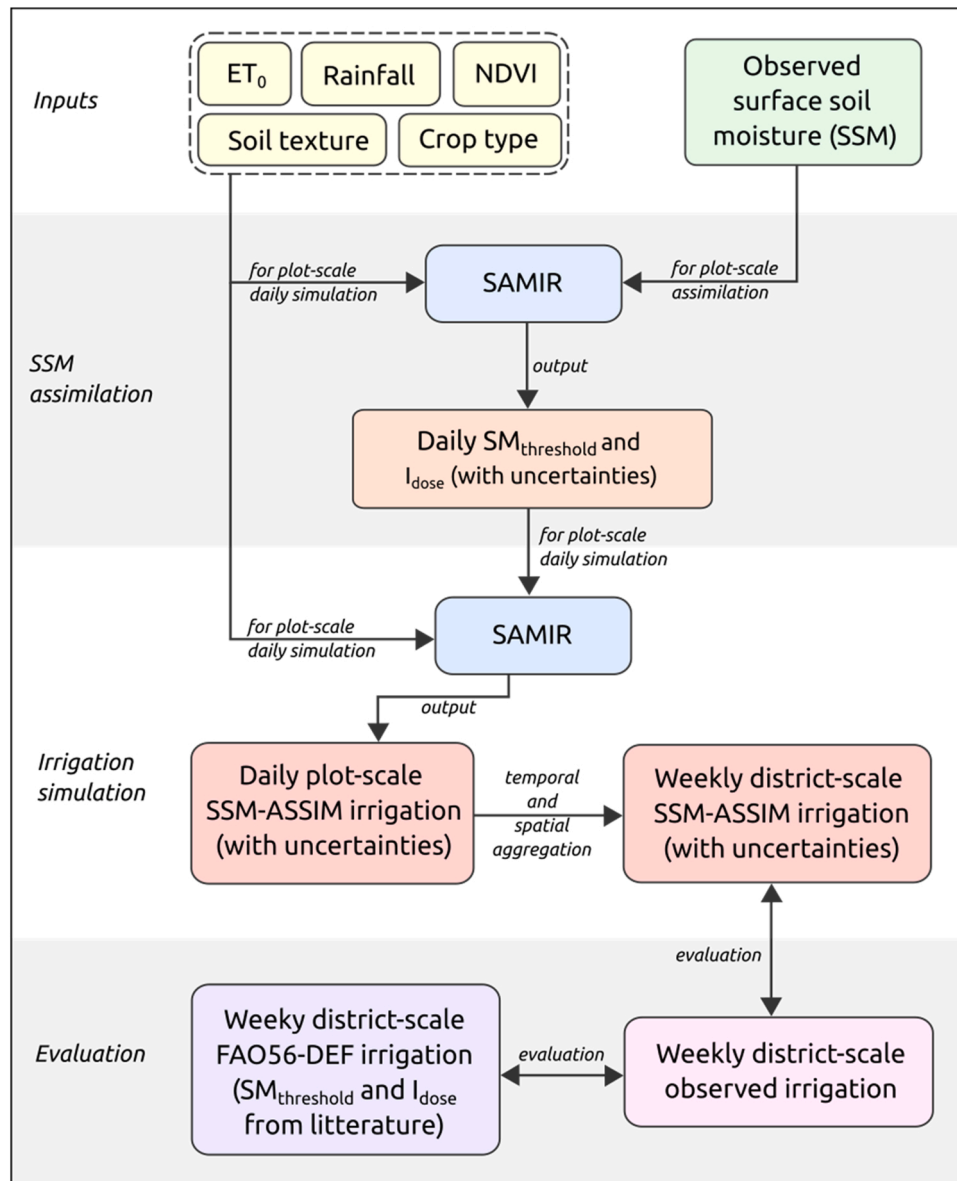


Fig. 2. Flowchart of the methodology to retrieve the weekly irrigation at district scale by assimilating SSM data into the SAMIR model.

is expressed in mm for day  $t$  (and  $t-1$  for  $Dr$ ) and  $ET$  is obtained by multiplying two crop coefficients to  $ET_0$  as follows:

$$ET(t) = [Kcb(t) \cdot Ks(t) + Ke(t)] \cdot ET_0(t) \quad (2)$$

where  $ET_0 \cdot Kcb \cdot Ks$  is the water transpired by plants ( $T$ , mm), and  $ET_0 \cdot Ke$  the soil evaporation ( $E$ , mm).  $Kcb$  (-) is the basal crop coefficient controlling potential crop transpiration, computed from a linear relationship with NDVI (bounded between 0 and the crop-specific parameter  $Kcb_{max}$ ),  $Ks$  (-) is the crop water stress coefficient reducing potential transpiration, and  $Ke$  (-) is the potential soil evaporation coefficient.

The calculation of  $Ks$  is based on the daily water balance calculation in the root zone layer, and can be written as:

$$Ks(t) = \frac{TAW(t) - Dr(t)}{TAW(t) \cdot (1 - p)} \quad (3)$$

where  $Dr$  is calculated from the daily water balance according to Eq. (1), and  $TAW$  (mm) is the total (maximum) available water in the root zone.  $p$  is a crop-specific parameter provided in the literature (Allen et al., 1998; Pereira et al., 2021), ranging between 0.4 and 0.6 for most crops and being corrected daily for weather conditions. Allen et al. (1998) suggest that  $p$  controls the water depth threshold below which irrigation should be triggered to avoid crop water stress (and irrigate optimally) by keeping  $Dr$  below  $TAW \cdot p$ . In other words,  $p$  triggers irrigation when soil moisture reaches a critical level (below which the crop experiences water stress) called  $SM_{critical}$ , provided in the literature.  $p$  can then be written as follows:

$$p = 1 - \left( \frac{SM_{critical} - SM_{WP}}{SM_{FC} - SM_{WP}} \right) \quad (4)$$

where  $SM_{FC}$  ( $m^3 m^{-3}$ ) is the soil moisture at field capacity and  $SM_{WP}$  ( $m^3 m^{-3}$ ) the soil moisture at wilting point, which are both derived from soil texture using the pedotransfer function proposed by Román Dobarco et al. (2019). In the AB district,  $SM_{FC}$  and  $SM_{WP}$  derived from SoilGrids are fairly homogeneous with values of  $0.330 (\pm 0.005) m^3 m^{-3}$  and  $0.207 (\pm 0.006) m^3 m^{-3}$ , respectively. For the Castello instrumented plot,  $SM_{FC}$  and  $SM_{WP}$  are  $0.339 m^3 m^{-3}$  and  $0.186 m^3 m^{-3}$ , respectively, and for Albesa  $0.336 m^3 m^{-3}$  and  $0.191 m^3 m^{-3}$ .

Olivera-Guerra et al. (2023) proposed an alternative to the  $p$  parameter for triggering irrigation, called  $p_{trigger}$ . Unlike  $p$ ,  $p_{trigger}$  does not trigger irrigation when  $SM_{critical}$  is reached, but when  $SM_{threshold}$  is.  $SM_{threshold}$  is time-varying and can be different from  $SM_{critical}$ , allowing to reproduce farmers' current practices.  $p_{trigger}$  is written as follows:

$$p_{trigger}(t) = 1 - \left( \frac{SM_{threshold}(t) - SM_{WP}}{SM_{FC} - SM_{WP}} \right) \quad (5)$$

$TAW$  of Eq. (3) is computed as follows:

$$TAW(t) = (SM_{FC} - SM_{WP}) \cdot Zr(t) \quad (6)$$

where  $Zr$  (mm) is the rooting depth, varying between a minimum value (set at 100 mm for annual crops) and a crop-dependent maximum value (reached at the maximum NDVI of the simulated field).

$Ke$ , the potential soil evaporation coefficient, is computed as follows:

$$Ke(t) = Kr \cdot (Kc_{max} - Kcb) \leq_{f_{ew}} Kc_{max} \quad (7)$$

Where  $Kc_{max}$  is the maximum value that  $Kc$  (equal to  $Kcb + Ke$ ) can reach,  $Kr$  is the evaporation reduction coefficient, and  $f_{ew}$  is the fraction of the soil that is both exposed and wet (where evaporation occurs).

$Kr$  is written as follow:

$$Kr(t) = \left[ 0.5 - 0.5 \cdot \cos \left( \frac{\pi \cdot SSM(t)}{SM_{saturation}} \right) \right]^p \quad (8)$$

where  $SM_{saturation}$  is the soil moisture at saturation derived from the soil

texture using a pedotransfer function, and  $P$  is a semi-empirical parameter also derived from the soil texture (Amazirh et al., 2021; Merlin et al., 2016). Since  $SSM$  is not explicitly represented in SAMIR, it is derived from the soil surface water depletion ( $De$ , mm; residue of the surface soil water balance) and the soil evaporation layer depth ( $Ze$ , fixed at 150 mm), as follows:

$$SSM(t) = SM_{FC} - \frac{De}{Ze} \quad (9)$$

### 3.1.2. Default irrigation simulation with SAMIR (FAO56-DEF approach)

SAMIR simulates irrigation using two irrigation parameters:  $SM_{threshold}$  and  $I_{dose}$ .  $SM_{threshold}$  is the soil moisture level at which irrigation is automatically triggered and is used to calculate  $p_{trigger}$  (see Eq. 5).  $I_{dose}$  is the irrigation dose applied when irrigation is triggered. By default, SAMIR uses  $SM_{threshold}$  and  $I_{dose}$  values that produce a theoretically optimal irrigation regime. We call this default irrigation mode FAO56-DEF. In the FAO56-DEF approach, irrigation is triggered when  $SM_{threshold}$  equals  $SM_{critical}$  (see Eq. 5) and  $I_{dose}$  is calculated as the amount of water required to completely fill the root reservoir, without exceeding  $SM_{FC}$ . With this approach, irrigation is triggered as soon as the simulated soil moisture reaches  $SM_{critical}$ , thus avoiding crop water stress. Excess irrigation (generating drainage loss) is also avoided as  $I_{dose}$  fills the root reservoir up to the  $SM_{FC}$  and not beyond.

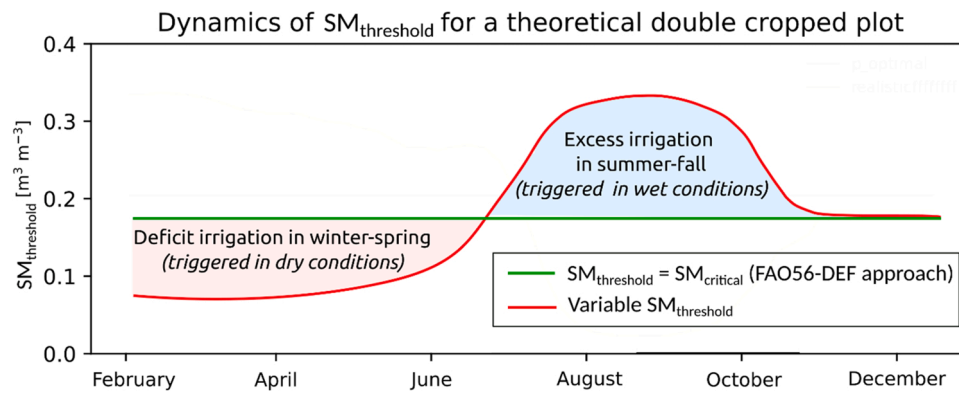
### 3.1.3. Irrigation simulation in any irrigation regime with SAMIR

To represent real agricultural practices and associated irrigation regimes, Olivera-Guerra et al. (2023) proposed a time-varying  $SM_{threshold}$  and  $I_{dose}$  able to simulate actual irrigation. With time-varying values different from those used by FAO56-DEF, it is possible to simulate time-varying irrigation water use in irrigation regime any (optimal, deficit or even over). When  $SM_{threshold}$  is lower than  $SM_{critical}$ , this corresponds to a deficit irrigation regime, whereas when it is higher, it corresponds to an over irrigation regime. Fig. 3 illustrates for a hypothetical double-cropped plot, the relative difference between  $SM_{threshold}$  values for an ideal ( $SM_{threshold}$  set at  $SM_{critical}$ ) and real (time-varying  $SM_{threshold}$ ) case. We use herein the term "real case" as opposed to "ideal case" here but note that the variable  $SM_{threshold}$  in Fig. 3 is hypothetical, shown for explanatory purposes, and does not correspond to a real experiment. The green line represents the ideal case where irrigation is triggered at the onset of crop water stress (FAO56-DEF approach). The red line represents the hypothetical real case, with a variable  $SM_{threshold}$  (e.g., inverted from SSM data). In Fig. 3,  $SM_{threshold}$  values below  $SM_{critical}$  in winter-spring would result in a deficit irrigation regime (cf. red shaded area), as the theoretical irrigator waits for the soil moisture level to be low before irrigating. Conversely,  $SM_{threshold}$  values above  $SM_{critical}$  in summer-fall lead to over-irrigation (cf. blue area), as the theoretical irrigator irrigates while the soil moisture is still high.

## 3.2. Retrieving irrigation from the assimilation of SSM observations (SSM-ASSIM)

### 3.2.1. Inverting the $SM_{threshold}$ and $I_{dose}$ parameters

To retrieve the variable  $SM_{threshold}$  and  $I_{dose}$ , SSM observations are assimilated into SAMIR using the PF method. The first step of the PF method consists of randomly draw  $N$  initial samples (particles) with different parameter values. In our case, 300 particles with different ( $SM_{threshold}$ ,  $I_{dose}$ ) pairs are generated following a uniform distribution between  $SM_{WP}$  and  $SM_{FC}$  for  $SM_{threshold}$ , and between 0 and 20 mm  $d^{-1}$  for  $I_{dose}$ . Next, simulations are performed for each particle and for each day, until an observation is available (every six days for S1-derived SSM, every three days for in situ SSM). On the day of the SSM observation, the  $N$  simulated variables (here the 300 SSM simulated by SAMIR) are confronted with the observation. During this evaluation step, each particle ( $SM_{threshold}$  and  $I_{dose}$  pairs, resulting in SSM simulation) is assigned a weight according to its likelihood with the observed SSM. The



**Fig. 3.** Schematic dynamics of  $SM_{\text{threshold}}$  for a hypothetical double-cropped plot for an ideal (FAO56-DEF; green line) and real (red line) case. The red shaded area represents deficit irrigation due to  $SM_{\text{threshold}}$  values lower than  $SM_{\text{critical}}$  (during winter-spring in this theoretical example) and the blue shaded area represents excess irrigation due to  $SM_{\text{threshold}}$  values higher than  $SM_{\text{critical}}$  (during summer-fall in this theoretical example).

best particles are duplicated a number of times relative to their likelihood, and the worst ones are discarded.

In order to calculate the weight of the particles, and also to prevent their degeneracy, the PF method takes into account the model and observational errors. For the observed SSM errors, a standard deviation of 20% of the observed SSM value is set for both S1-derived SSM and in situ SSM, this value being in line with the errors of the existing SSM satellite products (Das et al., 2019; Kerr et al., 2010). For the model error, a standard deviation of 10% of the parameter value is applied to the three most sensitive SAMIR parameters (two parameters related to the NDVI-Kcb relationship and  $Zr_{\text{max}}$ ; Laluet et al., 2023a), as well as to the surface and root compartment depletions (De and Dr). To avoid particle degeneracy as much as possible, their weights are reset whenever the effective sample size  $N_{\text{eff}}$  reaches a threshold of one third of the initial particle size number (for details see Moradkhani et al., 2005; van Leeuwen et al., 2019).

In addition, the 300 particles are reset to their initial values every 30 days, i.e. every five consecutive S1-derived SSM observations and ten in situ SSM observations. This results in monthly mean and standard deviation  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  values which are calculated using the particle weights obtained at the end of the month. The monthly timescale allows accounting for changes in irrigation regime throughout the year, while ensuring a certain number of observations required for the PF method to converge with satisfactory uncertainty. To obtain smoother  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  values, the entire assimilation scheme is then repeated five times, shifting the start date by six days each time. Subsequently,  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  are then obtained on a daily basis (mean and standard deviation) by averaging the five time series of monthly retrieved  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$ . Fig. 4 shows a flowchart describing the PF-based approach used in this study.

### 3.2.2. Simulating irrigation from the retrieved $SM_{\text{threshold}}$ and $I_{\text{dose}}$ parameters

Once daily  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  have been retrieved with the PF-based assimilation approach, they are used as input in SAMIR to simulate irrigation. For this, 1000 time series of  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  are randomly sampled following a normal distribution with their retrieved daily mean and standard deviation, and are then used as input parameters in SAMIR to simulate 1000 time series of daily irrigation. Daily irrigations are then aggregated at the weekly scale, and the mean and standard deviation of weekly irrigation are obtained from the 1000 simulated weekly irrigation time series. During this step, we excluded simulated irrigation values below 3 mm/week, deemed too low to be realistic.

### 3.3. Aggregation at the crop type scale

To simplify our approach as much as possible, and to minimize its computational cost, we selected the five main crop types (double crops, summer cereals, winter cereals, forages, and fruit trees) representing 94% of the irrigated area in 2019, and computed the average of their inputs (NDVI, SSM, and soil texture) weighted by their total surface area. This results in five average plots representing 94% of the irrigated part of AB. The remaining 6% is represented by the average of the five main crop types. Averaging the plots by crop type is justified by the fact that the soil texture is fairly homogeneous over the area (in addition to having a low sensitivity in SAMIR; Laluet et al., 2023a). Fig. 5 shows the mean and standard deviation of the S1-derived SSM and the S2-derived NDVI time series for the five average plots. The dynamics of NDVI and SSM time series observed for plots belonging to a given crop type are not strongly scattered (Fig. 5) reflecting homogeneity in terms of farming practices (sowing date, irrigation practices). At the end of the SSM-ASSIM process, the simulated irrigations for each of the five average plots are averaged and weighted by their total area within AB to obtain an irrigation amount representative of the entire AB district.

### 3.4. Evaluation of retrieved irrigation

The Root Mean Square Deviation (RMSD), the Pearson correlation coefficient ( $r$ ) and the bias between retrieved and in situ weekly irrigation are calculated. At the district scale, this is done for both SSM-ASSIM and FAO56-DEF approaches, and the uncertainty simulated with SSM-ASSIM is assessed. At the plot scale, only SSM-ASSIM is evaluated.

## 4. Results and discussion

In this section, we first present the irrigation results obtained by applying the SSM-ASSIM approach at the scale of the Albesa and Castello plots, using in situ SSM data every three days for assimilation (Section 4.1). Then, the irrigation results obtained with the SSM-ASSIM and FAO56-DEF approaches at the district scale using S1-derived SSM data are presented and discussed (4.2.1). Finally, the results of the SSM-ASSIM approach are put into perspective with other work (4.2.2) and limitations and perspectives are highlighted (4.2.3).

### 4.1. Field-scale experiment using in situ SSM

This section aims to assess the performance of SSM-ASSIM at the field scale where the crop type and irrigation practices can be considered spatially uniform. In situ SSM data from the double-cropped fields Albesa and Castello are used. Fig. 6 shows the results for the two plots



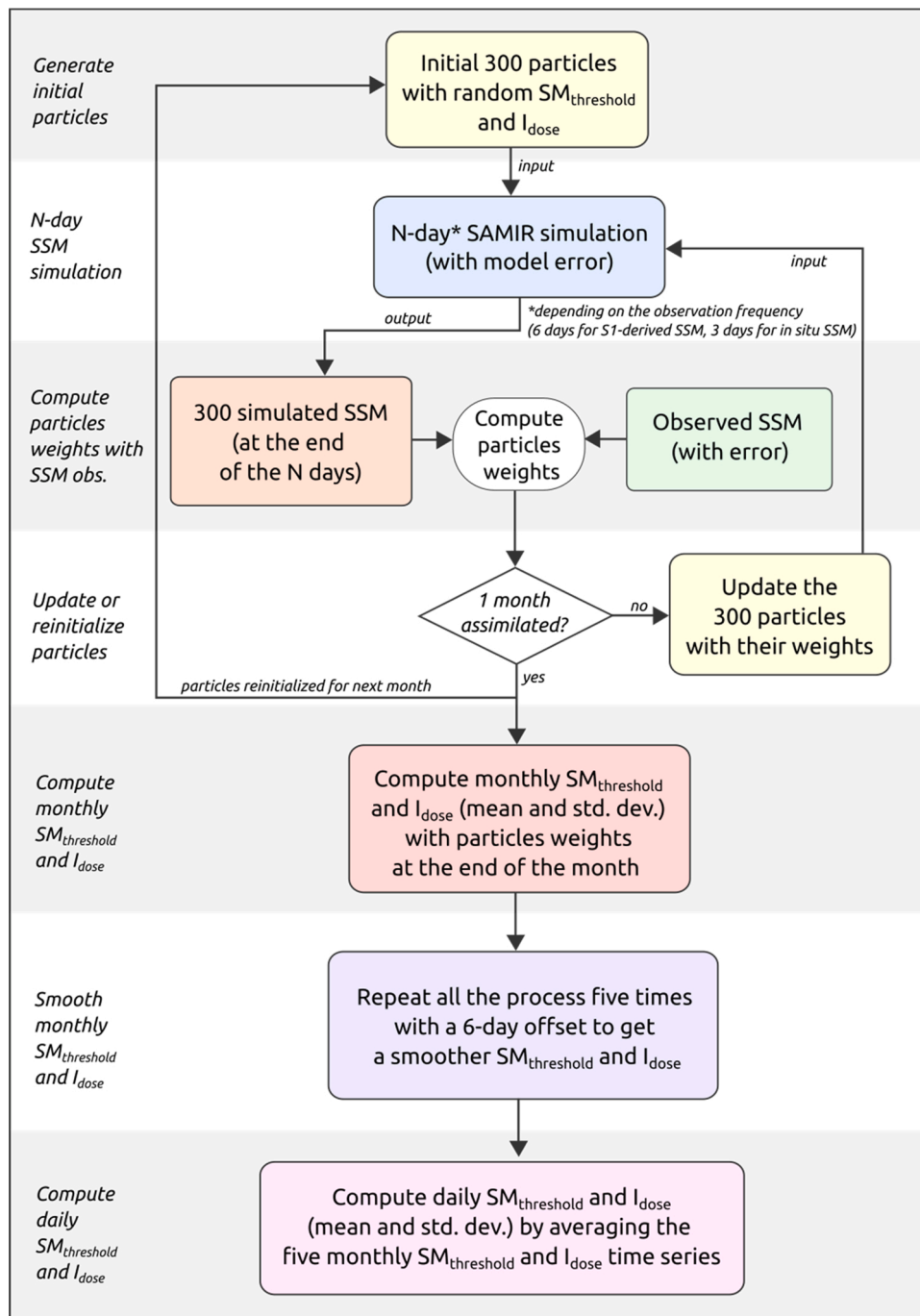


Fig. 4. Flowchart of the PF-based assimilation approach of SSM data into SAMIR every six days for S1-derived SSM (every three days for in situ SSM), within 1-month periods.

and the four periods studied: Castello summer-fall 2021 (a), Albesa summer-fall 2021 (b), Albesa winter-spring 2022 (c), and Albesa summer-fall 2022 (d). Each plot shows, in addition to rainfall, the in situ SSM (purple line), the  $SM_{threshold}$  (dark blue line) and the  $I_{dose}$  (light blue line) retrieved with SSM-ASSIM, and the simulated irrigation using the retrieved  $SM_{threshold}$  and  $I_{dose}$  as forcing in SAMIR (green line) along with the observed irrigation (black line). Standard deviation of the input SSM data set (used for assimilation; 20% of the observed value),  $SM_{threshold}$ ,  $I_{dose}$  and simulated irrigation are shown. Bias and RMSD values are given in the chart titles. Note that no bias correction between simulated and observed SSM was applied.

Fig. 6 should be read as follows: the assimilation of in situ SSM data in SAMIR results in a daily  $SM_{threshold}$  and a daily  $I_{dose}$  which, given as

forcing to SAMIR, provides the irrigation retrieved by the SSM-ASSIM approach. For example, in Fig. 6.b we can observe that the relatively low in situ SSM values at the beginning of the season (about  $0.20 \text{ m}^3 \text{ m}^{-3}$ ) suddenly increase to about  $0.28 \text{ m}^3 \text{ m}^{-3}$  when the irrigation season starts. This results in a retrieved  $SM_{threshold}$  that rapidly increases from  $0.23$  to  $0.27 \text{ m}^3 \text{ m}^{-3}$ , and an  $I_{dose}$  that rises from about  $10 \text{ mm d}^{-1}$  to over  $15 \text{ mm d}^{-1}$  when the irrigation season begins. By using these  $SM_{threshold}$  and  $I_{dose}$  pairs as forcing in SAMIR, the simulated irrigation reproduces pretty well the start of the irrigation season.

Fig. 6 shows that our approach correctly reproduces the irrigation start and end dates for each season. It also indicates that SSM-ASSIM slightly overestimates irrigation during the winter-spring season (mostly in June; Fig. 6.c), while underestimating it during the three

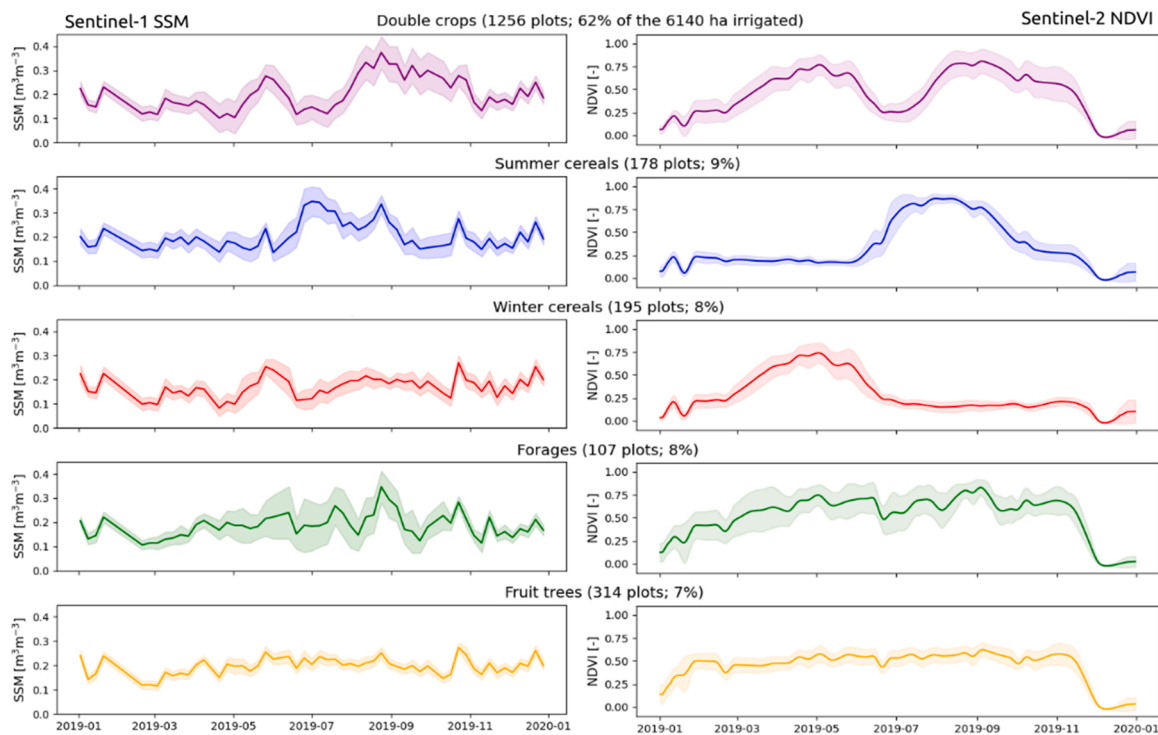


Fig. 5. Mean and standard deviation of S1-derived SSM (left) and S2-derived NDVI (right) for each of the five main crop types for 2019.

summer-fall seasons (Fig. 6.a, 6.b, and 6.d). This results in a bias of +4.6 mm week<sup>-1</sup> for Albesa winter-spring 2022, -2.3 mm week<sup>-1</sup> for Castello summer-fall 2021, -5.4 mm week<sup>-1</sup> for Albesa summer-fall 2021, and -9.4 mm week<sup>-1</sup> for Albesa summer-fall 2022. The RMSD for Albesa winter-spring 2022 is 9.3 mm week<sup>-1</sup>, while it is slightly larger for Castello summer-fall 2021 (12.2 mm week<sup>-1</sup>), Albesa summer-fall 2021 (14.6 mm week<sup>-1</sup>) and Albesa summer-fall 2022 (14.7 mm week<sup>-1</sup>). Note that the irrigation amounts are much higher during summer-fall (between 40 and 70 mm week<sup>-1</sup> for the most intensive irrigation period in August-September) than during the winter-spring season (between 0 and 40 mm week<sup>-1</sup>), hence explaining the higher RMSD values obtained in summer-fall.

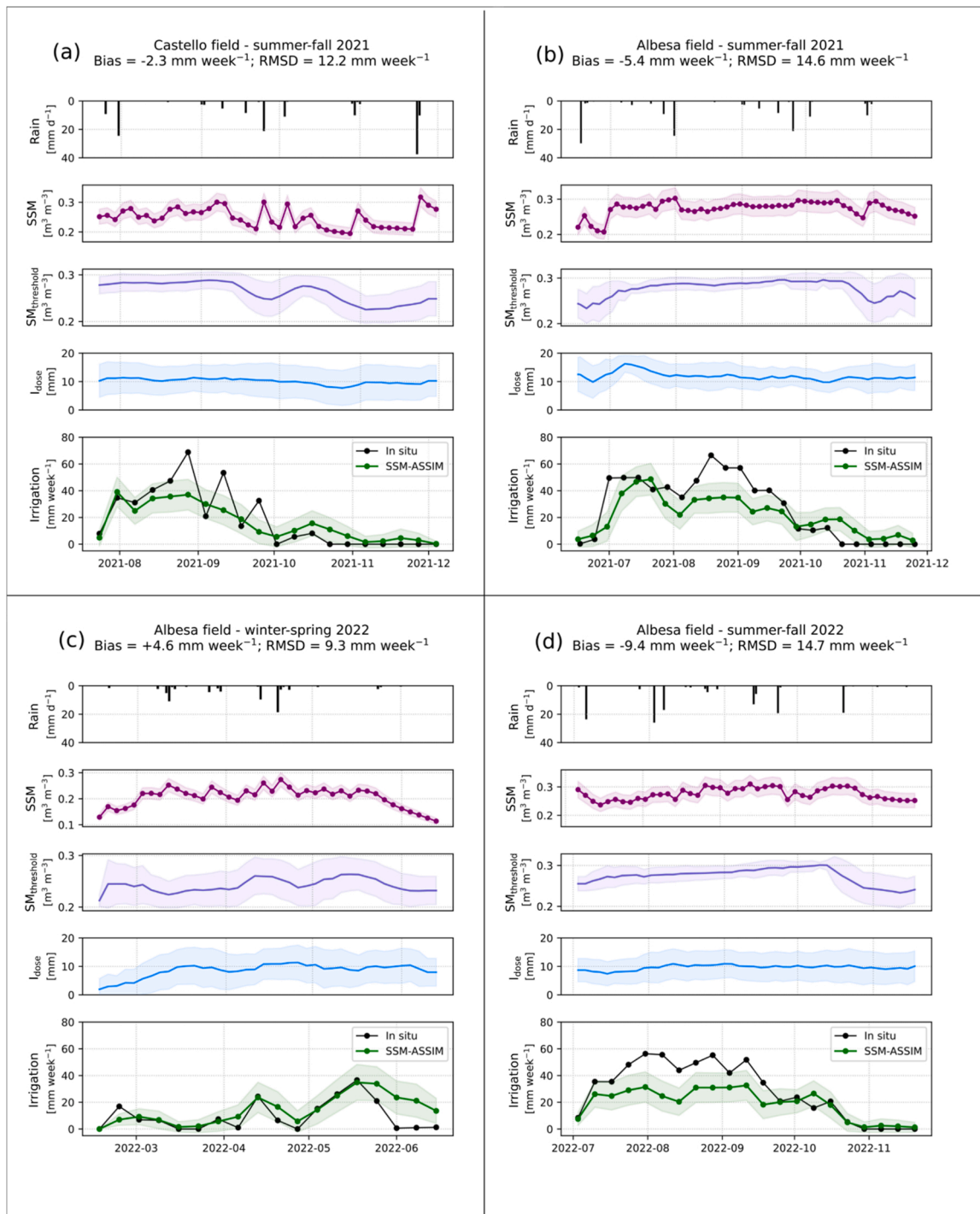
For the three summer-fall seasons, SSM-ASSIM generally underestimates irrigation (-12% for Castello summer-fall 2021, -20% for Albesa summer-fall 2021, and -32% for Albesa summer-fall 2022). For these three seasons, simulated weekly irrigation never exceeds 50 mm week<sup>-1</sup>. During the most intensive irrigation period, simulated weekly irrigation is generally between 25 and 40 mm week<sup>-1</sup>, while the observed irrigation is between 40 and 60 mm week<sup>-1</sup>. This means that the weekly simulated irrigation, although too low, is sufficient for the simulated SSM to match the observed SSM. Indeed,  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  are inverted from the observed SSM. Therefore, if more irrigation would have been needed to better match the simulated and observed SSM, the inverted  $SM_{\text{threshold}}$  would have been larger during the intensive irrigation seasons (to trigger more frequent irrigation events), as well as the inverted  $I_{\text{dose}}$  (to irrigate with a larger amount of water). We hypothesize that one of the reasons for this is the nonlinearity in the relationship between SSM and irrigation. Let's consider a farmer who irrigates a field heavily with sprinklers (e.g., 10 mm d<sup>-1</sup>). During the first hour of irrigation, the SSM can vary rapidly from low (dry soil) to high values (wet soil). As the irrigation event continues, the water applied will generate a weaker response in terms of SSM variation than at the start of irrigation, due in particular to infiltration into the underlying soil layer. This is illustrated in Fig. 6, where we can see that the underestimation in summer generally occurs when the in situ SSM is at high values, close to  $SM_{FC}$  (~0.34 m<sup>3</sup> m<sup>-3</sup>).

## 4.2. District-scale experiment using satellite SSM

### 4.2.1. Evaluation of the SSM-ASSIM and FAO56-DEF approaches

Fig. 7 shows the retrieved weekly irrigation at AB in 2019 with SSM-ASSIM (green line) and FAO56-DEF (orange line), together with in situ irrigation data (black line). SSM-ASSIM reproduces the beginning and end of irrigation season and the general irrigation dynamics quite well (RMSD of 6.7 mm week<sup>-1</sup>, bias of +0.3 mm week<sup>-1</sup>, and r of 0.88; Table 1). FAO56-DEF also manages to reproduce the beginning and end of the irrigation season but does not reproduce irrigation dynamics as well as SSM-ASSIM, particularly in summer when irrigation is most important (RMSD of 8.8 mm week<sup>-1</sup>, bias of -1.4 mm week<sup>-1</sup>, and r of 0.78). Cumulative in situ irrigation for 2019 is 687 mm year<sup>-1</sup>, while that simulated by SSM-ASSIM is 706 mm year<sup>-1</sup> and that of FAO56-DEF is 611 mm year<sup>-1</sup>. Note that, as with the field experiment, no bias correction between simulated SSM and observed S1-derived SSM was applied.

In line with the results for the field-scale experiment using in situ data (Section 4.1), SSM-ASSIM underestimates irrigation for the summer-fall period (bias of -2.6 mm week<sup>-1</sup>). However, the underestimation in summer is less pronounced at the district scale than at the field scale (Albesa summer-fall 2021 has a bias of -5.4 mm week<sup>-1</sup> and Albesa summer-fall 2021 of -9.4 mm week<sup>-1</sup>). In contrast to the latter, at the AB district scale, SSM-ASSIM is able to simulate summer irrigation values close to the observed maxima (41 mm week<sup>-1</sup> simulated in mid-August 2019, for an in situ irrigation of 46 mm week<sup>-1</sup>; cf. Fig. 7). This may be due to the lower values of observed irrigation during the intensive summer irrigation period at the AB scale (around 40 mm week<sup>-1</sup>), where there are different types of crops, compared to the Albesa and Castello fields (around 50 to 60 mm week<sup>-1</sup>), where there is only maize. Consequently, the limitation mentioned in Section 4.1 regarding the difficulty of simulating high weekly irrigation amounts, even with high observed SSM values, is less of a problem at the AB scale. This suggests that the SSM-ASSIM approach is particularly suited to the district scale: different crop types with different irrigation regimes are considered together at the district scale, and the weighted (by crop type) average of



**Fig. 6.** Daily rainfall (black bars), in situ SSM every three days (purple line), daily  $SM_{\text{threshold}}$  (dark blue line), daily  $I_{\text{dose}}$  (light blue line), and weekly irrigation retrieved with the SSM-ASSIM approach (green line) and weekly in situ irrigation (black line), for Castello summer-fall 2021 (a), Albesa summer-fall 2021 (b), Albesa winter-spring 2022 (c), and Albesa summer-fall 2022 (d) separately.

the observed irrigation in summer is lower than on highly irrigated (100% maize) plots such as Albesa and Castello.

The irrigation simulated by FAO56-DEF corresponds to theoretical crop water requirements. On the basis of this optimal irrigation, we can determine whether the weekly in situ irrigation or the one retrieved with SSM-ASSIM corresponds to an optimal irrigation regime (irrigation equal to the irrigation simulated by FAO56-DEF), to an under-irrigation regime (irrigation lower than the irrigation simulated by FAO56-DEF) or to an over-irrigation regime (irrigation larger than the irrigation simulated by FAO56-DEF). During the winter-spring season, in situ irrigation

is lower than that simulated with FAO56-DEF, indicating an under-irrigation regime over AB during this period. During the summer-fall season, in situ irrigation is considerably larger than that simulated with FAO56-DEF, indicating significant over-irrigation at this time. During this season, the irrigation retrieved with SSM-ASSIM is also larger than that simulated with FAO56-DEF, indicating that the SSM-ASSIM approach is capable of simulating over-irrigation.

SSM-ASSIM tends to overestimate irrigation during the winter-spring season (bias of  $+3.7 \text{ mm week}^{-1}$ ), consistent with the field scale results (Section 4.1). While irrigation amounts and dynamics are well

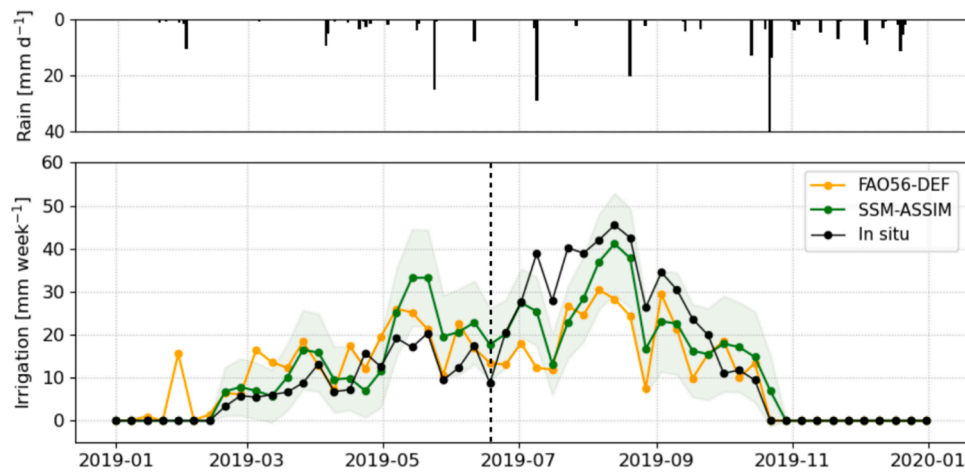


Fig. 7. Top: daily rainfall at AB. Below: weekly irrigation simulated at the AB scale with the SSM-ASSIM approach (green line), with the FAO56-DEF approach (orange line), and observed irrigation (black line) for 2019. The vertical dotted line divides the winter-spring and summer-fall irrigation seasons.

Table 1

RMSD, bias, and r between retrieved and in situ irrigation for SSM-ASSIM and FAO56-DEF at the AB scale for 2019, as well as for the winter-spring and the summer-fall seasons separately.

	SSM-ASSIM			FAO56-DEF		
	RMSD [mm week <sup>-1</sup> ]	Bias [mm week <sup>-1</sup> ]	r [-]	RMSD [mm week <sup>-1</sup> ]	Bias [mm week <sup>-1</sup> ]	r [-]
All 2019	6.6	-0.06	0.88	8.8	-1.4	0.78
Winter-spring [01/01/2019 to 18/06/ 2019]	6.1	+3.3	0.90	6.2	+4.0	0.81
Summer-fall [19/06/2019 to 31/12/ 2019]	7.0	-3.1	0.94	10.4	-6.3	0.90

reproduced for the months of January to April, an overestimation occurs in May-June. To understand why, Fig. 8 shows the time series of precipitation (a), S1-derived SSM (b), as well as the retrieved  $SM_{threshold}$  (c),  $I_{dose}$  (d), and irrigation (e) with SSM-ASSIM for the main crop type (double crop) in the area. From May to mid-June 2019, S1-derived SSM detects irrigation, with the SSM increasing from  $0.11 \text{ m}^3 \text{ m}^{-3}$  at the beginning of May to  $0.28 \text{ m}^3 \text{ m}^{-3}$  at the end of May. This large difference in SSM generates a significant increase in both retrieved  $SM_{threshold}$  and  $I_{dose}$ , leading to important weekly irrigation in May for the double-cropped plots, which in turn led to an overestimation of irrigation at the AB scale at that time. In fact, the moments of strong SSM growth correspond to those when simulated irrigation is largest. Furthermore, although the average weekly irrigation simulated with SSM-ASSIM for all AB performs satisfactorily, the associated uncertainty is significant ( $\pm 53\%$ ,  $706 \pm 375 \text{ mm year}^{-1}$ ; shaded green area in Fig. 7).

#### 4.2.2. Comparison of SSM-ASSIM results with other works

This section aims to put the results obtained with SSM-ASSIM into perspective by comparing them with other results obtained for the same irrigation district using a different approach. The latter is that proposed by Dari et al. (2023), which, to our knowledge, is the only work to date that has dealt with the estimation of irrigation from satellite-based SSM data on the AB district for the year 2019 (their study covers the years 2016 to 2019). This comparison is made possible by the fact that Dari et al. (2023) provided that the weekly irrigation they simulated at the 1 km pixel scale for several irrigation districts, including AB (<http://zenodo.org/record/7341284>; accessed 20 June 2023).

Dari et al. (2023) used an approach based on the SM2RAIN algorithm described in the introduction (Section 1), which differs significantly from SSM-ASSIM, in particular because of its simpler formalism which relies heavily on observed SSM data and empirical parameters that require calibration. The spatial resolution of the S1-derived SSM product they use is 1 km, as are the irrigation simulations. In contrast, our approach is based on a finer scale simulation of crop water consumption, taking into account model and observational errors. Furthermore, SSM-ASSIM uses an S1-derived SSM product with a resolution of 15 m.

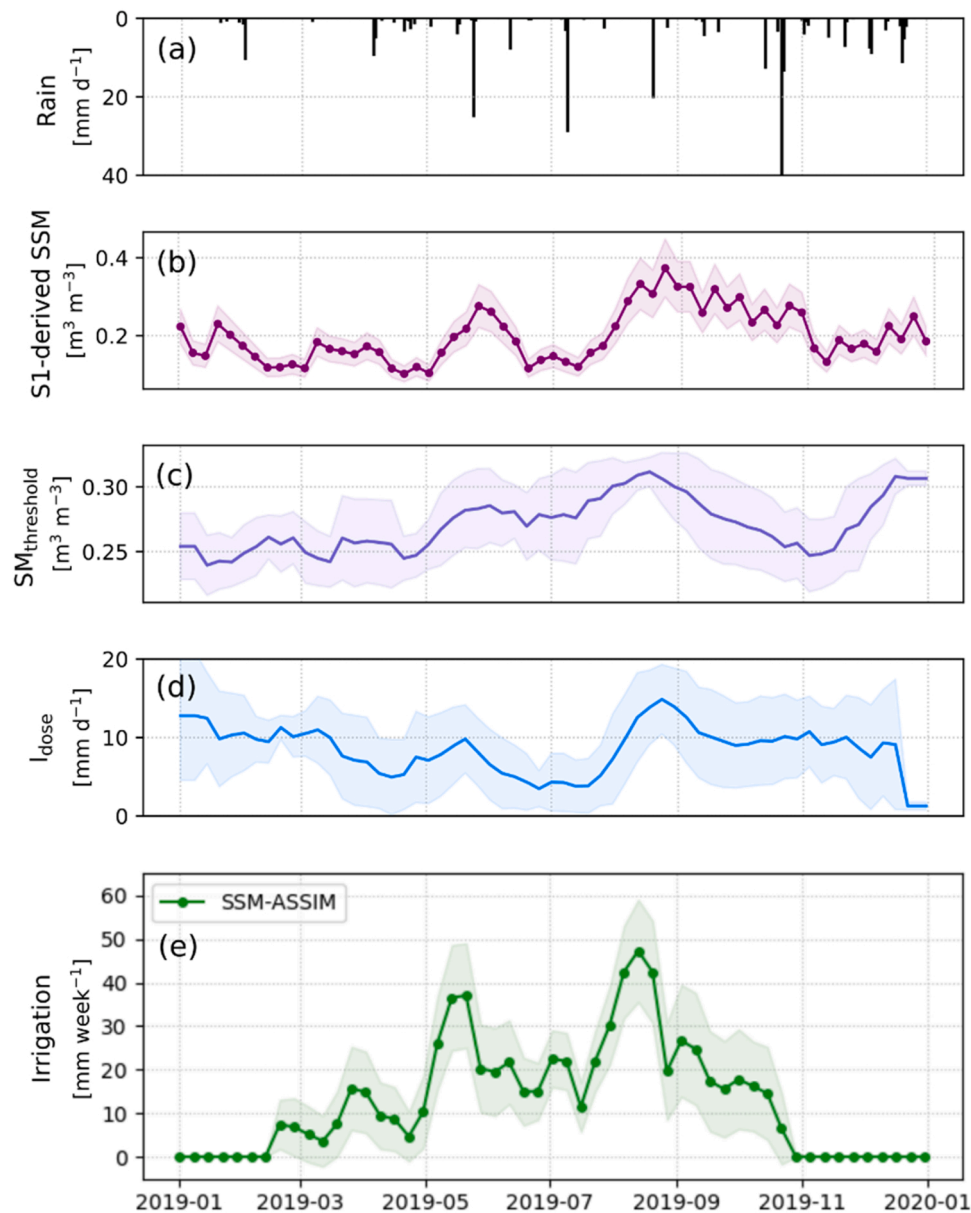
Another point distinguishes the two approaches. SSM-ASSIM simulates only the plots in AB that were actually irrigated during the study year, representing  $61.4 \text{ km}^2$  in 2019. On the other hand, Dari et al. (2023) simulated all AB plots equipped for irrigation, regardless of whether or not they were actually irrigated during the study year, i.e.,  $70.9 \text{ km}^2$ . In this section, in order to compare the results obtained with the two approaches, the irrigation (in mm) simulated with SSM-ASSIM (and in situ) were adjusted to represent the irrigation applied on the  $70.9 \text{ km}^2$ , consistent with the irrigation simulated by Dari et al. (2023). In addition, Dari et al. (2023) removed 10% of the in situ irrigation data to account for losses, while only 5.8% was removed in this study as explained in Section 2.2.1.

Fig. 9 shows for the year 2019 the weekly irrigation obtained with SM2RAIN (red line), the one obtained with SSM-ASSIM (green line), and the in situ irrigation (black line). Although both approaches are able to capture the irrigation signal, SM2RAIN underperforms SSM-ASSIM, with a more pronounced underestimation of irrigation and an RMSD of  $9.7 \text{ mm week}^{-1}$  ( $6.7 \text{ mm week}^{-1}$  for SSM-ASSIM), a bias of  $-3.3 \text{ mm week}^{-1}$  ( $+0.3 \text{ mm week}^{-1}$ ), and an r of 0.65 (and 0.88) for the year 2019 (Table 2). While SM2RAIN manages to reproduce relatively well the dynamics at the start of the 2019 summer-fall irrigation season in July, it significantly underestimates irrigation during the months of August and September, when irrigation is particularly intense (Fig. 9).

Such differences in terms of performance may be a consequence of certain features of the SSM-ASSIM approach. In particular, we believe that the implementation of the approach at the plot scale, which allows to capture the plot-level processes governing crop consumption, is key to simulating irrigation dynamics. This plot-scale approach is made possible by the quality and the fine spatial resolution of the S1-derived SSM product used in this study, which provides a distinct SSM signature for each plot and thus an irrigation signature for each plot.

#### 4.2.3. Quality of S1-derived SSM product and its impact on the SSM-ASSIM irrigation retrieval

Fig. 7 shows that most of the irrigation underestimation with the SSM-ASSIM approach using S1-derived SSM occurs in July (at the



**Fig. 8.** For double crop plots: daily rain (black bars) (a), S1-derived SSM (purple line) (b),  $SM_{\text{threshold}}$  (dark blue line) (c),  $I_{\text{dose}}$  (light blue line) (d), and irrigation (green line) retrieved with SSM-ASSIM (e).

beginning of the summer-fall irrigation season). We believe that these underestimates are related to the difficulty of the S1-derived SSM product in detecting the actual SSM at the beginning of the second irrigation season (when vegetation is poorly developed) for double-cropped fields.

This assumption is supported by two elements:

1) Fig. 8.b shows low S1-derived SSM values for double-cropped plots in late June and early July, at the beginning of the summer-fall irrigation season. However, in situ irrigation at the AB scale (black line in Fig. 7) shows that the summer irrigation season has already started by then. There is a difference of about one month between the start of the summer-fall irrigation season at the AB scale and the increase in S1-derived SSM for the double-cropped plots. However, we would expect the reanalyzed SSM to increase more rapidly after the start of the irrigation season, since the double-cropped plots represent 62% of the irrigated AB area.

2) At the plot level, the time lag between the first irrigation events of the second growing season and the first significant increase in S1-derived SSM is also observed. Fig. 10.a shows rainfall (black bar) and in situ irrigation (orange area) for the summer-fall 2021 season at the Albesa instrumented plot. Fig. 10.b shows the daily in situ SSM (red line) and the S1-derived SSM (blue line) for the same plot. Note that the in situ and S1-derived SSMs have been normalized between their minimum and maximum values to facilitate their comparison. It appears that when the irrigation season starts at the end of June, in situ SSM increases almost immediately, while the S1-derived SSM starts to increase a month later, around the end of July.

Figure A1 was added to the Appendix to explain why low S1-derived SSM values are observed over the double-cropped plots at the beginning of the summer season. Figure A1 shows time series of S1 backscattering coefficient, S1-derived interferometric coherence (used as vegetation descriptor), S1-derived SSM and S2-derived NDVI (related to vegetation development) over the Albesa field for 2019. During the intercrop

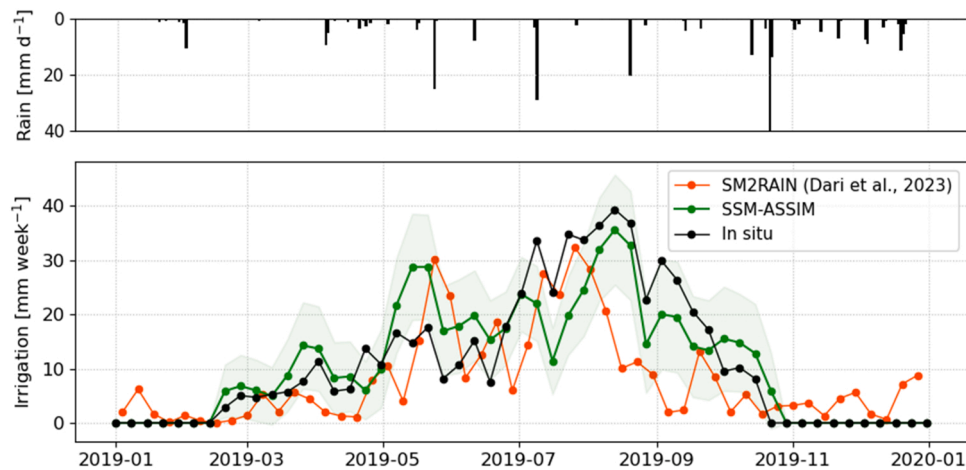


Fig. 9. Top: daily rainfall in AB. Bottom: weekly irrigation simulated at the AB scale with the SM2RAIN approach (Dari et al., 2023) (red line), with the SSM-ASSIM approach (green line), and observed irrigation (black line), for 2019.

Table 2

RMSD, bias, and r between retrieved and in situ irrigation for SM2RAIN and SSM-ASSIM at the AB scale for all 2019.

	RMSD [mm week <sup>-1</sup> ]	Bias [mm week <sup>-1</sup> ]	r [-]
SM2RAIN (Dari et al., 2023)	9.7	-3.3	0.65
SSM-ASSIM	6.6	-0.06	0.88

period in early summer, the maximum coherence is 0.6 while in winter it is above 0.7 (as in Ouadi et al., 2021; Santoro et al., 2011). This low level of interferometric coherence in early summer indicates that the scatterer structure is different between the winter and summer inter-seasons. This is probably due to the fact that in AB maize is directly sown without tillage in summer, leaving the soil partially covered by the remaining stalks, unlike in winter. However, the relationship between coherence and above-ground biomass used in the inversion process is calibrated assuming that the growing season begins with bare soil (and therefore with a coherence value assumed to be greater than 0.7). With a coherence of 0.6 observed in AB during early summer, a bias appears in the SSM retrieved at that time. This is explained by the fact that the radiative transfer model used for the inversion process reaches the observed level of backscatter with the contribution of the canopy only with dry soil underneath. Furthermore, this phenomenon seems to occur only in the case of double-cropped plots; other crop types with a single

crop per year (winter cereals and summer cereals) don't seem to be affected by this problem.

Identifying this difficulty in detecting SSM in early summer (when two crops are grown consecutively in the same year) in the SSM inversion algorithm proposed by Ouadi et al. (2020) represents an important avenue for improving the quality of S1-derived SSM on double crop fields, and consequently the performance of the SSM-ASSIM approach. With a higher S1-derived SSM value at the beginning of the summer irrigation season, more irrigation would be retrieved by SSM-ASSIM, thus reducing the summer underestimation issue, and improving the assimilation performance.

It should be noted that S1 may have difficulty detecting SSM on drip-irrigated plots (since drip irrigation only moistens limited parts of the fields), which may reduce the performance of SSM-ASSIM in such conditions. Although data collected on drip-irrigated plots were not available in AB, future study should further assess the performance of SSM-ASSIM for various irrigation types.

#### 4.2.4. Impact of a lower observation frequency on the performance of SSM-ASSIM

In December 2021, the Sentinel-1B satellite failed, reducing the temporal observation frequency of S1 from 6 to 12 days. To assess the impact of such a reduced frequency on SSM-ASSIM performance, irrigation was retrieved by assimilating SSM observations every 12 days (keeping one date out of two). Fig. 11 shows the retrieved irrigation with

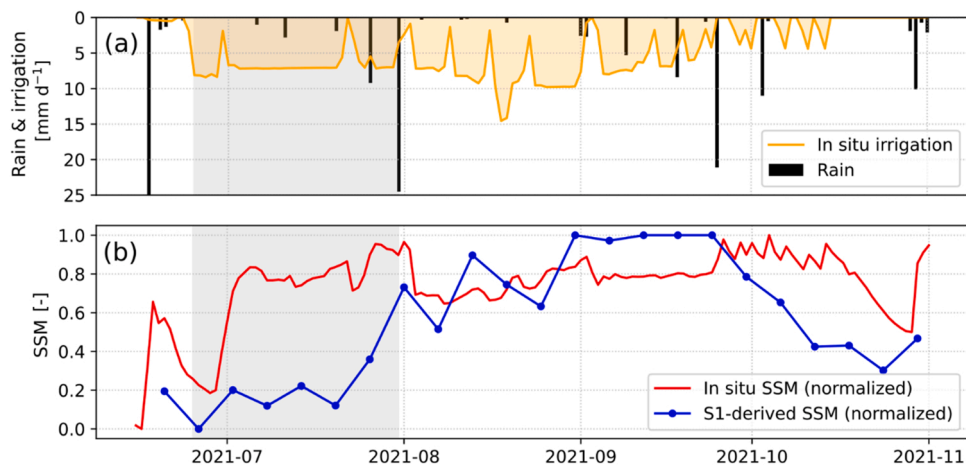


Fig. 10. For the Albesa (21 ha) double crop plot: daily in situ rain (black bars) and irrigation (orange line) (a), daily in situ SSM (red line) and S1-derived SSM every six days (blue line) normalized between their minimum and maximum values (b), for the period from June 2021 to November 2021.

SSM-ASSIM (blue line) and the in situ irrigation data (black line). The performance obtained by assimilating SSM data every 12 days (RMSD of  $6.4 \text{ mm week}^{-1}$ , bias of  $+0.84$ , and  $r$  of  $0.90$ ) is close to that obtained by assimilating SSM data every 6 days (RMSD of  $6.7 \text{ mm week}^{-1}$ , bias of  $+0.3$ , and  $r$  of  $0.88$ ).

However, halving the frequency of observations has two effects. First the uncertainty in retrieved irrigation is larger ( $731 \pm 421 \text{ mm year}^{-1}$ ) with an observation frequency of 12 days than with an observation frequency of 6 days ( $706 \pm 375 \text{ mm year}^{-1}$ ), regardless of the irrigation period. Second, the largest irrigations observed at AB in August are less well reproduced with an observation frequency of 12 days than with an observation frequency of 6 days. Indeed, the larger the time window between two observations, the less SSM (and therefore irrigation) simulations are constrained by the assimilation scheme. However, the observed SSM is high and varies very little throughout the summer. This discrepancy between an important variability of simulated SSM due to the low observation frequency (e.g., 12 days), and the quite constant and high observed SSM, leads to an underestimation of irrigation in summer.

## 5. Summary and conclusion

With increasing pressure on water resources, managers and decision makers need to know how much water is being used for irrigation. However, there is a lack of reliable information on these quantities at all spatial scales. To address this need, a growing number of studies have proposed approaches combining models and satellite observations, in particular SSM. Although encouraging results have been obtained, state-of-the-art SSM-based irrigation retrieval methods have been limited by the spatio-temporal resolution of available SSM data, and the difficulty of representing irrigation-related processes over large areas and to explicitly account for uncertainties in irrigation estimates.

To fill this gap, we propose a new approach (SSM-ASSIM) to assimilate high spatial resolution (15 m) SSM data into the FAO-56-based SAMIR model at the plot scale using a PF assimilation method that address the above-mentioned challenges. The output of SSM-ASSIM is the mean and standard deviation of two smoothed monthly parameters of the SAMIR irrigation module, namely  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$ , which control the irrigation trigger and dose, respectively. The retrieved irrigation and its uncertainty are obtained at weekly scale by running SAMIR with the retrieved distribution of  $SM_{\text{threshold}}$  and  $I_{\text{dose}}$  as forcing. For validation, the approach is applied to two instrumented fields for which in situ SSM and irrigation data are available, and to the 8000 ha AB irrigation district for which in situ irrigation data are available. At the district scale, irrigation is also simulated with the FAO-56 default configuration (FAO56-DEF) as a benchmark to assess the performance of

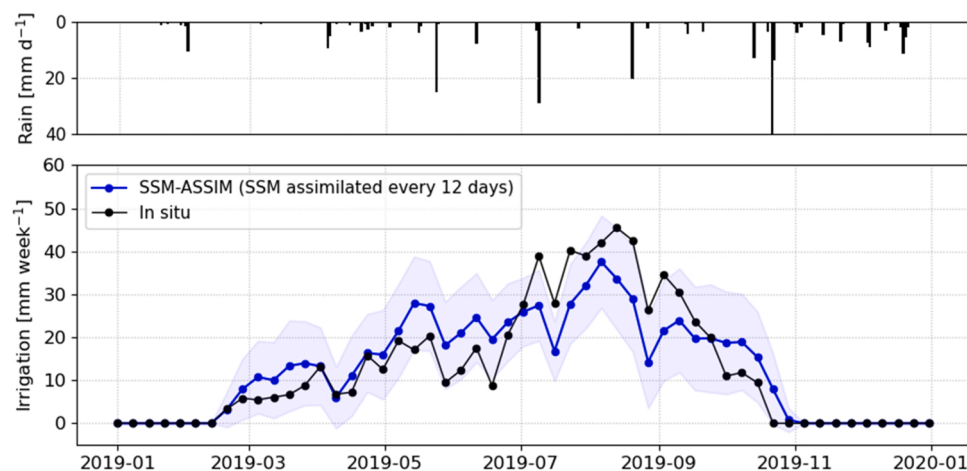
SSM-ASSIM.

Results at the plot scale using in situ SSM data show that SSM-ASSIM reproduces the irrigation dynamics very well throughout the agricultural season. However, an underestimation occurs during periods of intense irrigation for the three summer-fall seasons. This can be explained by the large amounts of irrigation applied to these plots in summer, which are not fully captured in the SSM signal as they exceed  $\sim 50 \text{ mm week}^{-1}$ . A slight overestimation is also observed for the winter-spring season. When applied at the district scale using S1-derived SSM data, SSM-ASSIM clearly outperforms FAO56-DEF and can reproduce the observed weekly irrigation quite well, with an  $r$  of  $0.88$  and an RMSD of  $6.7 \text{ mm week}^{-1}$  for the year 2019. However, as with the field-scale experiments, SSM-ASSIM tends to overestimate irrigation in winter-spring (bias of  $+3.7 \text{ mm week}^{-1}$ ) and underestimate it in summer-fall ( $-2.6 \text{ mm week}^{-1}$ ). The overestimation in winter-spring is related to the discrepancy between very low SSM values at the start of the season, followed by a sudden increase in SSM (observed for the double-cropped plots representing 62% of the AB area), resulting in high levels of simulated irrigation. The underestimation in summer is attributed to the degraded quality of the S1-derived SSM in early summer for the double-cropped plots.

The performance of SSM-ASSIM depends on the quality of the SSM product. Therefore, any improvement in the accuracy and precision of field-scale SSM estimates would improve the quality of irrigation retrievals. In addition, the relationship between SSM and irrigation is highly non-linear due to the shallow depth ( $\sim 0\text{--}5 \text{ cm}$ ) sensed by microwave sensors. Saturation of SSM sensitivity to large amounts of irrigation is an intrinsic limitation of SSM-based assimilation approaches. This problem could eventually be solved by the joint assimilation of thermal-derived ET data, which, in hydric stress conditions are directly linked to the soil moisture accumulated in the root zone. This prospect is all the more encouraging as new thermal missions will soon be launched with Land Surface Temperature Monitoring (LSTM; Koetz et al., 2018) and Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment (TRISHNA; Lagouarde et al., 2018), which will provide ET and crop stress index products with unprecedented high spatial and temporal resolution in the near-future. Finally, the SSM-ASSIM approach could be integrated into large scale LSM to take more realistically account for irrigation and its impact on the hydrological cycle.

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**Fig. 11.** Top: daily rainfall at AB. Below: weekly irrigation simulated at the AB scale with the SSM-ASSIM approach by assimilating Sentinel-1 SSM data every 12 days (blue line) and observed irrigation (black line) for 2019.

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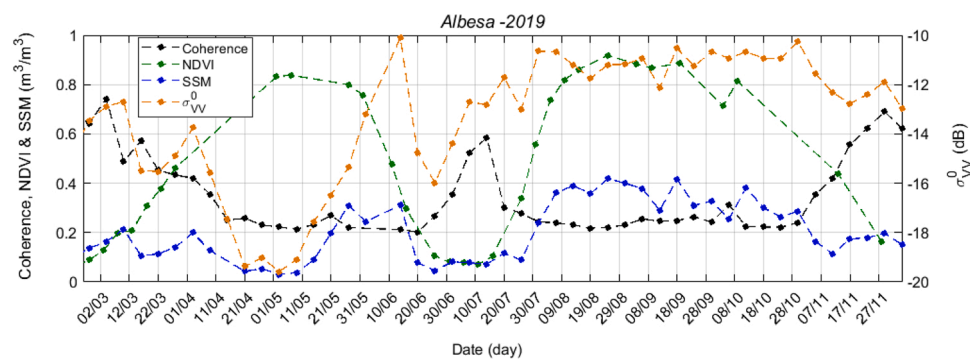
### CRedit authorship contribution statement

**Olivera-Guerra Luis Enrique:** Writing – review & editing, Software, Methodology, Conceptualization. **Laluet Pierre:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Paolini Giovanni:** Writing – review & editing, Data curation. **Altés Víctor:** Writing – review & editing, Data curation. **Rivalland Vincent:** Writing – review & editing, Software. **Ouadi Nadia:** Writing – review & editing, Visualization, Methodology. **Jarlan Lionel:** Writing – review & editing, Methodology. **Merlin Olivier:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Villar Josep Maria:** Writing – review & editing, Supervision, Data curation.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

### Appendix



**Fig. A1.** Time series of the S1 backscattering coefficient at VV polarization ( $\sigma_{VV}^0$ ) (orange line), S1-derived interferometric coherence (black line), S2-derived NDVI (green line), and S1-derived SSM (blue line) over the Albesa field for 2019.

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the work reported in this paper.

### Data Availability

Data will be made available on request.

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### Software Availability

SAMIR is an open-source software implemented in Python 3 and is available at the following address: <https://gitlab.cesbio.omp.eu/modelisation/modspa/>. The assimilation scheme introduced in this work will be implemented soon and made available on the same link. Contact information: vincent.rivalland@univ-tlse3.fr.



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