Performance analysis of regional AquaCrop (v6.1) biomass and surface soil moisture simulations using satellite and in situ observations

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Abstract. The current intensive use of agricultural land is affecting the land quality and contributes to climate change. Feeding the world's growing population under changing climatic conditions demands a global transition to more sustainable agricultural systems. This requires efficient models and data to monitor ~~good insight in~~ land cultivation practices at the field to global scale.

5 This study outlines a spatially distributed version of the field-scale crop model AquaCrop version 6.1, to simulate agricultural biomass production and soil moisture variability over Europe at a relatively fine resolution of 30 arcseconds (~1 km). A highly efficient parallel processing system is implemented to run the model regionally with global meteorological input data from the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2), soil textural information from the Harmonized World Soil Database, version 1.2 (HWSDv1.2), and generic crop information. The relative temporal variability in d~~D~~aily crop biomass production is evaluated with the Copernicus Global Land Service dry matter productivity (CGLS-DMP) data. Surface soil moisture is compared against NASA Soil Moisture Active Passive surface soil moisture (SMAP-SSM) retrievals, the Copernicus Global Land Service surface soil moisture (CGLS-SSM) product derived from Sentinel-1, and in situ data from the International Soil Moisture Network (ISMN). Over central Europe, the regional AquaCrop model is able to capture the temporal variability in both biomass production and soil moisture, with a spatial mean temporal correlation of 0.8 (CGLS-DMP), 0.74 (SMAP-SSM) and 0.52 (CGLS-SSM), respectively. The higher performance when evaluating with SMAP-SSM compared to Sentinel-1 CGLS-SSM is largely due to the lower quality of CGLS-SSM satellite retrievals under growing vegetation. The regional model further captures the short-term and interannual variability, with a mean anomaly correlation of 0.46 for daily biomass, and mean anomaly correlations of 0.65 (SMAP-SSM) and 0.50 (CGLS-SSM) for soil moisture. It is shown that soil textural characteristics and irrigated areas influence the model performance. Overall, the regional AquaCrop model adequately simulates crop production and soil moisture and ~~proves to be useful in assessing crop production and soil moisture at various scales and~~ provides a suitable setup for subsequent satellite-based data assimilation. ~~could serve as a bridge between point-based and global models.~~

1 Introduction

Over the past 60 years, global agricultural production has more than tripled (FAO, 2017). This became possible through productivity-enhanced technologies, industrialization and expansion of agricultural land. However, the current intensive use of cropland is resulting in reduced land quality and increased greenhouse gas emissions, which in turn impact agricultural systems (Foley et al., 2011; Kopittke et al., 2019). To meet the future crop demand of a vastly growing population, while minimizing the ecological footprint and increasing the crop resilience for changing climatic conditions, the need to adapt to more effective and sustainable land cultivation practices is urgent (Aznar-Sánchez et al., 2019; Pingali, 2012; Raes and Vanuytrecht, 2017).

To evaluate the effect of environmental conditions and different management practices on crop production, there exists a variety of models that simulate the biophysiological growth of crops at the field scale. An overview of 70 of such crop models is given by Di Paola et al. (2016). Some of these point-based crop models have more recently been upscaled and assessed at a regional to global level (Balkovic et al., 2013, Boogaard et al., 2013, ~~De Wit and van Diepen, 2007,~~ Folberth et al. 2019, Liu et al., 2007, Müller et al., 2017~~2018~~, Nichols et al., 2011, Resop et al., 2012, Roerink et al., 2012, Stöckle et al., 2014). Large-scale crop models are a valuable asset in providing information to policy makers and for applications in climate scenario analyses (Asseng et al., 2013, Iizumi et al., 2018). A downside of large-scale ~~upscaled~~ crop models, especially at a ~~the~~ global scale~~level~~, is that they often suffer from the generalization of input data~~, resulting in a higher bias~~ and loss of information that is typically available at smaller scales, resulting in larger errors at the local scale. The AgMIP Global Gridded Model Intercomparisons (GGCMI) is a framework initiated to overcome this issue. It is built on a large group of crop modelling researchers that combine and intercompare a set of upscaled point models or global gridded crop models to assess and reduce the bias and uncertainties at a global level (Elliot et al., 2015~~Müller et al., 2017~~). ~~However, the transitions between plant, field, and regional scales in agricultural modelling remains a challenge, and more insight is needed in agricultural crop responses at various spatial and temporal scales with different levels of agricultural practices. To this end, a high resolution regional crop model can serve as a bridge between the point and global level, combining information from various scales. Some studies have attempted to reduce such errors by assimilating satellite observations in a crop modelling system (Mladenova et al., 2019)~~A possibility to correct for scaling errors, is the updating of the model simulations with remote sensing observations via data assimilation. There are several studies that have already used data assimilation in regional crop modelling systems (De wit & van Diepen, 2007; Mladenova et al., 2019; Zhuo et al., 2019), either for parameter or state updating. Parameter updating or calibration allows to match the absolute values of the simulations with (most often historical) observations. State updating allows to correct the relative temporal evolution and to obtain better initial conditions for subsequent model predictions. To get the most optimal results with data assimilation, it is important to start with a reliable model that is able capture the seasonal as well as interannual temporal variabilities.

This study presents a methodology to apply the original field-scale AquaCrop model version 6.1 efficiently over a large region and for ~~at~~ any spatial resolution. The flexible model setup will allow for many different applications, but in this study the focus

is on the preparation of a satellite-based data assimilation system. AquaCrop was developed by the FAO to estimate responses of herbaceous crops to water (Raes et al., 2009; Steduto, et al., 2009). It differs from most other crop models by its low requirement of detailed input data, as it aims for a balance between simplicity, accuracy and robustness (Steduto, et al., 2009). The model has been applied in numerous studies for various crop types and environmental conditions and shows good results in simulating crop biomass and yield, especially when calibrated for local field conditions (Abedinpour et al., 2012; Geerts et al., 2009; Maniruzzaman et al., 2015; Razzaghi et al., 2017; Sandhu and Irmak, 2019). Earlier spatially distributed versions of AquaCrop were developed by e.g. Lorite et al. (2013), Sallah et al. (2019) and Huang et al. (2019), using a Geographic Information System or batch processing with remote sensing data input. Some challenges of existing distributed AquaCrop systems are related to the limited scalability and high computational cost when they are applied to any large domain at any resolution, ~~the difficulty to adapt to new AquaCrop model versions,~~ the limitations in the upscaling of crop parameters from the plant or field to the grid scale (Han et al., 2020), or the availability of other suitable spatially distributed parameters or input information. Applications of the AquaCrop model at a continental scale exist, but are very limited (Dale et al., 2017) and so far are only used in combination with coarse spatial resolutions. To our best knowledge, no study has yet reported on high-resolution and large-scale (beyond country level) applications of AquaCrop.

To evaluate, or later update, select variables within such a regional modeling system, in situ data only ~~only~~ provide sparse ~~data from in situ networks are available~~ information. However, a range of optical and microwave-based satellite data are available at various temporal and spatial resolutions. A confrontation between model simulations and satellite data to evaluate or update the model simulations is not always trivial. Most importantly, the magnitude of model simulations and satellite retrievals of soil moisture or biomass are often not directly comparable. Biases between models and observations are inevitable, because they represent different quantities (Koster et al., 2009, Reichle et al., 2004) or are simply based on different assumed parameterizations. Via parameter estimation, soil and vegetation parameters can be spatially tuned to reduce such biases, but this is often not feasible for satellite retrievals or difficult with more detailed models at the regional to global scale. For this same reason, state-of-the-art data assimilation systems for state updating are designed to correct for random error, and not for systematic bias. Therefore, satellite products of relative soil water indices or~~f~~ anomaly ~~products~~ total water storages are often distributed (Wagner et al., 1998, Albergel et al., 2008, De Lannoy et al., 2016, Li et al., 2019), and the performance of large-scale model simulations is often evaluated using bias-free temporal skill metrics (De Lannoy et al., 2015, Gruber et al., 2020). The ~~main~~ objective of this research is to assess whether a high-resolution regional gridded AquaCrop model can capture seasonal, inter-annual and short-term temporal variability, as well as the spatial variability, of biomass and surface soil moisture, when using global spatially distributed input data about soil texture and meteorology and assuming a generic crop. The model performance will be evaluated over Europe at a spatial resolution of 30 arcseconds ($1/120°$; ~1 km at the equator), using satellite products derived from both optical and microwave sensors and in situ measurements.

The structure of the paper will be as follows: sections 2 and 3 will cover the methodology, with a description of the regional AquaCrop model setup, the evaluation datasets and performance metrics. In section 4 the results will be presented and discussed, followed by a conclusion in section 5.

2 The regional gridded AquaCrop model

2.1 AquaCrop equations

AquaCrop is a daily crop-water productivity model that translates, on a daily basis, the simulated amount of crop transpiration into a proportional amount of biomass for a single field, which is assumed to be homogeneous (Raes et al., 2009, Steduto et al., 2009). The relation between transpiration and biomass production is defined by a Water Productivity (WP) factor:

$$B = WP^* \sum \frac{Tr}{ET_o} \tag{1}$$

B (ton ha^{-1}) is the cumulative biomass produced, WP^* is the WP (g m^{-2}) factor normalized for atmospheric CO_2 (369.41 ppm for the year 2000) and for climate, and Tr (mm day^{-1}) is the transpiration, also normalized for climate after division by the reference evapotranspiration, ET_0 (mm day^{-1}). Because of this normalization, the WP^* factor only significantly differs between C3 and C4 crops, where C4 crops have a higher WP* due to a more efficient carbon assimilation process. The calculation of Tr is dependent on ET_0, the adjusted green canopy cover (CC^*; -), the crop transpiration coefficient ($K_{c,tr}$; -), the cold stress coefficient (Ks_{Tr}; -) and the soil water stress coefficient (Ks; -).

$$Tr = Ks.Ks_{tr}.(K_{c,tr}.CC^*).ET_0 \tag{2}$$

In AquaCrop, the water reservoir in the root zone is balanced by ingoing fluxes of precipitation (minus runoff) and potentially irrigation and capillary rise, and outgoing fluxes of evaporation and deep percolation. To calculate the soil water balance, AquaCrop divides the soil profile into multiple compartments (default 12) with depth increments Δz (default 0.1 m). For deeper soils, Δz increases exponentially with increasing soil depth, so that the processes of the near surface layers can still be resolved with sufficient detail. The number of compartments is independent of the number of soil horizons and the hydraulic properties for each compartment will be used depending on the soil layer in which they reside. The simulation of the water content in each compartment is done with a set of finite difference equations (subroutines), that are defined in terms of the dependent variable θ, as represented in equation 3 (Raes, et al., 2012). First, the drainage of the soil profile is calculated. Then, the water infiltration is computed (after subtraction of surface runoff) and upward movement of water by capillary rise is estimated. Finally, the amount of water lost by evaporation and crop transpiration is subtracted.

$$\theta_{i,j} = \theta_{i,j-1} + \Delta\theta_{DF_{i,\Delta t}} + \Delta\theta_{I_{i,\Delta t}} + \Delta\theta_{CR_{i,\Delta t}} + \Delta\theta_{E_{i,\Delta t}} + \Delta\theta_{T_{i,\Delta t}} \tag{3}$$

115 where $\theta_{i,j}$ is the soil water content of compartment i at time step j, $\theta_{i,j-1}$ is the water content of compartment i at the previous time step and $\Delta\theta_{X_{i,\Delta t}}$ indicate the change in moisture due to various processes X, with X=DF: downward flow, I: infiltration, CR: capillary rise, E: soil evaporation, T: crop transpiration.

Downward flow over these compartments is described by an exponential drainage function (eq. 4) based on the volumetric water content in the compartment i (θ_i) within the soil layer and drainage characteristics of the soil layer (Raes et al., 2006, 120 Raes et al., 2009):

$$\Delta\theta_{DF_{i,\Delta t}} = \tau_i(\theta_{sat} - \theta_{FC})\frac{e^{\theta_i - \theta_{FC} - 1}}{e^{\theta_{sat} - \theta_{FC} - 1}} \tag{34}$$

$\Delta\theta_{DF\,i,\,t,\,j}/\Delta t$ is the decrease in water content over time ($m^3\,m^{-3}\,d^{-1}$), θ_{FC} and θ_{sat}, are the volumetric moisture content at field capacity and at saturation (i.e. the porosity) of the soil layer, and τ_i is the drainage coefficient derived from the saturated hydraulic conductivity (K_{sat}). Infiltration (I) is the sum of water that enters the soil, which is rainfall minus surface runoff, and 125 possibly irrigation. Internal drainage between compartments is defined by the drainage ability, which depends on θ_{sat} and θ_{FC} (eq. 4). The cumulative drainage amount from any compartment will percolate through as long as its drainage ability is greater than or equal to the drainage ability of the overlying compartment. If the drainage ability is lower than the overlying compartment, the cumulative drainage amount will be stored in that compartment, increasing the water content and thereby its drainage ability. If then the drainage ability is reaching the equal amount of that of the overlying compartment, excess drainage 130 will percolate through to the lower compartment. For the bottom soil compartment, the drainage is lost as deep percolation. The runoff is estimated based on the curve number (CN) method, developed by the US Soil Conservation Service (USDA, 1964). The CN values are dependent on K_{sat} of the topsoil layer. Upward flow by capillary rise is estimated based on the depth of the groundwater table and hydraulic characteristics of the soil layers. Since no groundwater table is implemented in the regional version of the model in this paper, capillary rise is not included in the simulations. Soil evaporation is based on the 135 soil wetness and crop cover (Ritchie, 1972) and water extraction by roots is described with the sink term from Feddes (1982). Because the root density for most crops is highest near the soil surface and decreases with increasing soil depth, the water extraction pattern by roots is simulated as follows: 40/30/20/10% for the upper quarter to the lowest quarter of the root zone (Raes et al., 2009). The estimated water retained in the root zone that will be available to the plants (Wr) at each daily timestep is described by the fraction of total available water (TAW) after subtraction of depleted water (Dr). TAW is the difference of 140 volumetric moisture content between field capacity (θ_{FC}) and wilting point (θ_{WP}) over the root zone and is therefore dependent on soil texture and depth.

Plant stresses, such as water excess or water limitation, cold/heat air temperature stress, soil fertility and salinity stresses, can affect biomass production during different steps of the calculation procedure, depending on the process that is affected (i.e. canopy expansion, crop transpiration, pollination). The inclusion of stress factors is done by assigning unique thresholds to 145 each of these biological processes (Raes et al., 2018). Further details on the AquaCrop equations can be found in the calculation procedure manual by Raes et al. (2018)

2.2 Regional model ~~structure~~setup

The model domain of this study covers the agricultural land in the central part of Europe (35°N-55°N, 10°E-20°E), and 45 pixels across all of mainland Europe where in situ soil moisture data are available for evaluation (three in situ points are also included in the central European domain). The model was run for the years 2011 through 2018, starting on the first of January 2011. The initial soil moisture content for the first year was set at θ_{FC}, since the runs were initiated mid-winter, and for the subsequent years the initial soil moisture content was based on the moisture content of the last day from the previous year. Because the evaluation for soil moisture was done with microwave-based satellite products that pertain to the surface layer, the AquaCrop volumetric moisture content of the top soil compartment (WC01), at a depth of 0.05 m (center of top 10 cm) was chosen for evaluation in this study. For the biomass, the daily productivity (t ha^{-1}) was derived from the cumulative biomass. In the regional version of AquaCrop, a single homogeneous field is represented by a 30 arcsecond (~1-km) pixel, and input and output were defined independently for each pixel. The system can easily be set up for any given resolution over any domain. In this study, the model was run exclusively for dominantly rainfed agricultural areas, based on the land use map of the CORINE Land Cover inventory (Büttner, 2014) for the year 2012. This dataset is available at 100-m resolution and was aggregated to 30 arcseconds. To best represent the pixels as agricultural fields, only pixels were included of which at least 50 CORINE pixels (~50% of one AquaCrop pixel) contained non-irrigated agriculture.~~For the regional AquaCrop model, the simulation unit of a single field was replaced by a 30 arcsecond (~1 km) resolution pixel, and input and output were defined independently for each pixel. The system can easily be set up for any given resolution over any domain.~~

The AquaCrop input data are categorized into several components e.g. climate, soil, vegetation and management. For each component, parameters are described in a text-file with a specific file extension that is recognized by the model. A Project Management (PRM) file oversees all the information for a single field (or pixel) and contains paths and names of these input files. This PRM-file is read and executed by AquaCrop, after which an output file is created.

The original Delphi source code of AquaCrop v6.1 was minimally adjusted and compiled on the Linux-based High-Performance Computer (HPC) of the Vlaams Superc~~C~~omputer Centrum (VSC), and the resulting executable was plugged into a Python wrapper to allow massively parallel simulations to optimize the model efficiency over larger spatial domains. The current system allows for easy implementations of later versions of AquaCrop. The regional input files ~~for the climate and soil~~ have to be prepared before model execution. The Python wrapper then creates the PRM-file for a pixel as a first step of the model run, after which the AquaCrop model is executed and time series output is stored into a new folder for each pixel. The reason for creating the PRM-files right before the model execution is so that changes to a project can be made quickly. With this setup, AquaCrop simulations over 1000 pixels for 8 years can be completed in a wall time of 2.2 minutes ~~wall time~~ when

using 36 processors. The runs over the domain and period used in this study were completed in approximately 20 hours on 36 processors.

2.3 Model input

The meteorological forcings were extracted from the global Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2; Gelaro et al., 2017). The MERRA-2 meteorological variables have a 3-hourly temporal resolution and a spatial resolution of 0.5° lat x 0.625° lon, and are readily available at a latency of about a month. A nearest neighbour function was used to identify the 30 arcsecond pixels situated within one MERRA-2 grid to assign meteorological input. Minimum and maximum temperature and precipitation were converted into daily data needed for the AquaCrop model. The reference evapotranspiration ET_0 was derived from the FAO Penman-Monteith equation, using radiation, wind speed, average temperature and dew temperature from MERRA-2 (Allen et al., 1998). For the FAO Penman-Monteith equation, a psychrometric constant of 0.067 was assumed for the entire domain and variations in topographic elevation were not taken into account. At high elevations (>1 km asl) this could result in deviations of ET_0 of max 0.2 mm day^{-1}. However, since most agricultural areas are located at much lower elevations, the effect of the psychrometric constant was assumed to be very small. The long record of mean annual CO_2 concentration observed at Mauna Loa (Hawaii, USA) was used as CO_2 input (default file in the database of AquaCrop).

The soil texture and organic matter was taken from the Harmonized World Soil Database version 1.2 (HWSDv1.2). The HWSDv1.2 has a spatial resolution of 30 arcseconds. The hydraulic soil properties for 253 different soil classes were linked to the information on mineral soil texture and organic matter from the HWSDv1.2 via pedo-transfer functions as in De Lannoy et al. (2014). More specifically, AquaCrop uses the soil water content at various matrix potentials, i.e. wilting point (θ_{WP}), field capacity (θ_{FC}), and saturation (θ_{sat}), and the saturated hydraulic conductivity (K_{sat}). These parameters are available for a top layer (0-30 cm) and a deeper layer (30-100 cm). The total soil depth available for root development is taken from the 1 km resolution root zone depth map of the European Soil Data Centre (ESDAC) (Hiederer, 2013). In case the root zone depth was less than or equal to 30 cm, only the top layer parameters were considered. The soil properties of the deeper layer were included when the root zone depth was deeper than 30 cm. Stoniness and soil salinity were not considered. No restrictions on the rootzone development by impermeable layers were included in the simulations. According to the 1-degree global dataset of soil depth to bedrock used by the Second Global Soil Wetness Project (Dirmeyer and Oki, 2002; Mahanama et al., 2015) and the 250 m resolution map developed by Shangguan et al. (2017), the bedrock is generally deeper than 1 m over the study area, which allows for reaching the maximum effective rooting depth. The modelled soil moisture was initialized at θ_{FC} on January 1st (winter in Europe) 2011 for all simulations.

A soil fertility stress parameter in the field management file provides an indication of the overall soil quality. The default of this parameter is 0%, referencing to unlimited soil fertility with the perfect concentrations of plant nutrients. Since this situation is very rare in real fields, even for well-maintained land, the value was manually tuned to 30% after initial model evaluation of daily biomass production with the CGLS-DMP (see section 3.1) product for several pixels. the value was set to 30% after

~~initial model evaluation~~ With this reduction in soil fertility, a good to moderate crop production over the entire domain can be simulated in absence of water stress.

A single crop file was created to simulate crop production over Europe. Since the focus of this research is to simulate relative temporal variation in ~~on~~ biomass (~~and~~ not ~~on~~ yield) for future use in a data assimilation system, a single generic reference crop was parameterized to simulate the seasonal crop development. Spatial and temporal gaps of information at the ~1-km resolution prevent the inclusion of a more detailed crop parameterization, and the results will confirm the adequacy of the generic crop file. ~~This file was minimally tuned~~ ~~A~~after visual model evaluation and quantitative comparisons against satellite-based dry matter productivity (DMP, see below; Smets et al., 2019), the date of senescence was tuned manually, to optimally capture the length of the growing season. ~~The~~A generic reference crop was developed to simulate annual biomass development of C3 crops~~,~~. C3 crops ~~which~~ are predominantly found in temperate climates, as opposed to C4 crops that are more common in hot and dry climatological zones (Monfreda et al., 2008, Still et al., 2003). The crop was simulated as a transplant, assuming a small presence of vegetation from the start of the season~~even during winter~~, and with an annual cycle of 365 days, starting on the first of January. Because of this fixed annual cycle, the canopy development had to be simulated in calendar days instead of the more commonly used growing degree days. This results in an error in the simulation of canopy expansion during cold periods, but due to the consideration of growing degrees in the simulation of crop transpiration with the cold stress factor (Ks_{Tr}; eq. 2), the reduced biomass production in these periods is still captured. As can been seen from equations 1 and 2, the factors that affect the crop development, simulated by canopy cover, are soil water stress and cold temperature stress. Th~~is~~e generic crop file is mostly suitable to simulate canopy development during the spring and summer season. The main crop parameters are presented in table 1 and a flowchart of the model setup with input datasets is shown in Fig. 1.

~~The model was exclusively run for dominantly rainfed areas, based on the land use map of the CORINE Land Cover inventory (Büttner, 2014) for the year 2012. This dataset is available at 100 m resolution and was aggregated to 30 arcseconds. If 50 or more classes within the aggregated pixel were identified as non-irrigated agriculture, the pixel was included for the regional AquaCrop model simulations.~~

Table 1 Main crop parameters of generic crop to simulate biomass over Europe

Generic crop main parameters	Input
Crop type	leafy vegetable crop
Crop is sown/crop is transplanted	crop is transplanted
Determination of crop cycle	calendar days
Coefficient for maximum crop transpiration ($K_{c,Tr,x}$; -)	1.10
Base temperature (°C) below which crop development does not progress	8.0
Upper temperature (°C) above which crop development no longer increases with an increase in temperature	30.0

Minimum effective rooting depth (m)	0.3
Maximum effective rooting depth (m)	1.0
Normalized Water Productivity factor ($WP*$; g m^{-2})	17.0
Calendar days from transplanting to recovered transplant	0
Calendar days from transplanting to maximum rooting depth	80
Calendar days from transplanting to start senescence	232
Calendar days from transplanting to maturity	365
Calendar days from transplanting to flowering	0
Minimum growing degrees required for full crop transpiration (°C - day)	10.0
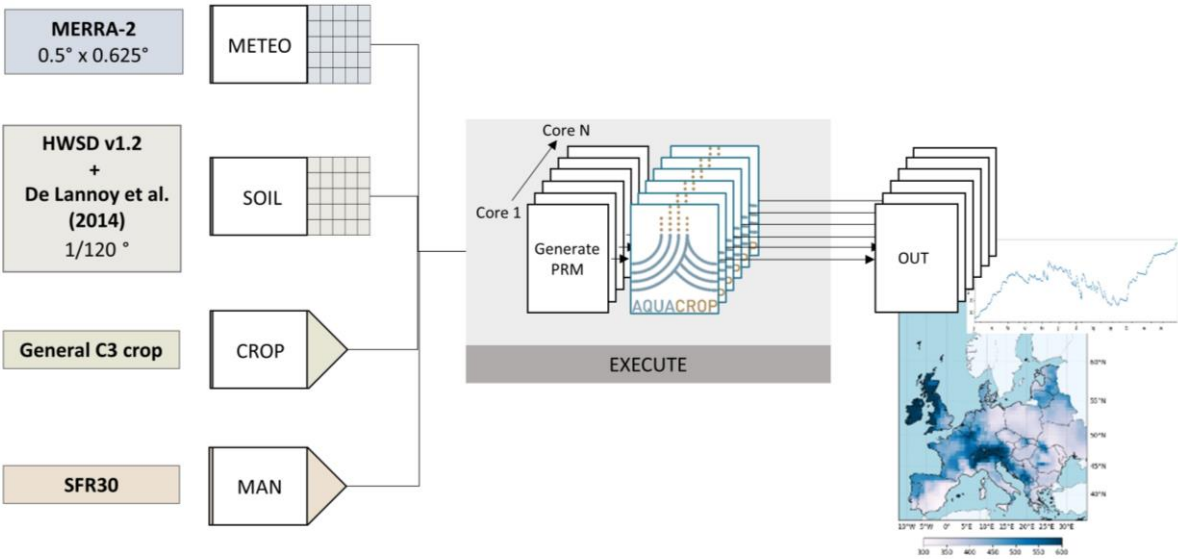
Figure 1 Flowchart of the regional model setup with gridded meteorological and soil input data and generic crop and management input data indicated on the left side. The parallel computing system with a maximum of N cores can execute N pixels at the same time. The composited output files can then be visualized as maps or timeseries

3 Evaluation datasets and metrics

3.1 CGLS – DMP

To evaluate simulations of daily biomass production, the ~1-km dry matter productivity product from the Copernicus Global Land Service (CGLS-DMP; kg ha^{-1} day^{-1}) was used (Smets et al., 2019). The CGLS-DMP is based on a simplified Monteith (1972) approach that makes use of the fraction of absorbed photosynthetically active radiation (fAPAR), which is derived from the optical satellite missions Satellite Pour l'Observation de la Terre (SPOT; 1999-2014) and Project for On-Board Autonomy - Vegetation (PROBA-V; 2014-presentJune 2020), ECMWF re-analysis estimates of atmospheric variables such as radiation

and temperature, and land cover information from the ESA CCA Land Cover Map. The retrieval algorithm is thus driven by atmospheric water availabilities, without explicitly accounting for water storage in the soil. The CGLS-DMP data product is are provided in 10-daily time steps, where each value is representative of the past 10 days for the years 1999 up to present date. To compare the data with the AquaCrop biomass, the nearest-neighbour function was used to spatially match the gridded

245   simulations to the grid of CGLS-DMP and the median of the modelled daily biomass production was computed for the corresponding 10-daily intervals of the CGLS-DMP products. Since the crop parameterization in AquaCrop is suited to simulate for the main growing season, the months November up to February were not included for the biomass evaluation.

3.2 CGLS – SSM

AquaCrop surface moisture content, i.e. the output of soil moisture in the top compartment of the soil profile, was evaluated

250   with the a second CGLS product, i.e. the relative surface soil moisture product (CGLS-SSM). CGLS-SSM provides data for the top few centimetres of the soil, available at the same ~1-km resolution as CGLS-DMP. This product is derived from the C-band radar onboard Sentinel-1, processed by the TU Wien (Bauer-Marschallinger et al., 2018), and available from October 2014 onwards. Processing steps included geo-correction, radiometric calibration and normalization of the incidence angle. No correction was included for dynamics in vegetation or surface roughness. The data are provided as relative soil moisture

255   estimates (%), that have to be multiplied by the porosity (θ_{sat}) to convert to absolute volumetric soil moisture contents ($m^3 m^{-3}$). The Sentinel-1 satellite has varying overpass densities, resulting in a slightly different number of data-points in various areas, but the temporal resolution is generally between 3 to 8 days. To exclude potential datapoints for days in which the soil was nearly frozen, the soil temperature variable from MERRA-2 was used to identify and remove all data at which the soil temperature was below 4°C, following the recommended data masking by e.g. Gruber et al. (2020). The CGLS-SSM product

260   contains masks for areas where it cannot be applied, i.e. a water mask, for pixels containing only water, a sensitivity mask, for pixels with a low sensitivity (urban, rivers, dense forests) and a slope mask, screening out pixels with a topographic slope higher than 17°. Since the simulation domain was restricted to agricultural areas, there is an implicit extra quality screening of trivial inferior data.

3.3 SMAP – SSM

265   Surface soil moisture simulations were further evaluated with retrievals from the NASA Soil Moisture Active Passive (SMAP) mission, from April 2015 onwards. More specifically, the enhanced level-2 radiometer half-orbit, version 4, was used at 9-km resolution (O'Neill et al., 2020, Chaubell et al., 2020). The SMAP radiometer measures L-band brightness temperatures in vertical and horizontal polarization at an incidence angle of 40°. It scans the earth's surface in a sun-synchronous orbit, which is 6:00 A.M. for descending and 6.00 P.M. for ascending mode, and with a temporal resolution of 2-3 days. The SMAP product

270   provides three estimates of surface (~5 cm) soil moisture ($m^3 m^{-3}$), derived from different retrieval algorithms (O'Neill et al.,

2020). The 'Single Channel Algorithm using vertical polarization' is the current baseline for SMAP soil moisture and was also used for AquaCrop evaluations.

SMAP data are projected onto the 9-km EASE grid version 2.0 (EASE2, Brodzik et al., 2012) and the AquaCrop soil moisture output was aggregated to this grid, by simply averaging all ~1-km pixels belonging to the same EASE2 grid cell. Only cells

275 that were at least 50% filled with AquaCrop output were included for evaluation. The number of AquaCrop pixels per 9-km grid cell varies, depending on the location on the EASE2 grid. For SMAP-SSM, the recommended conservative quality control was applied, and a ~~MERRA-2 based~~ temperature threshold of 4°C, derived from the GMAO GEOS land surface model, was applied to exclude nearly frozen soils (O'Neill et al., 2018).

3.4 In situ – SSM

280 In situ soil moisture measurements up to 5 cm depth were taken from the International Soil Moisture Network (ISMN, Dorigo et al. 2011) to evaluate AquaCrop simulations and satellite soil moisture products across all of mainland Europe. The corresponding soil temperature data were used to exclude the dates with temperatures below 4°C. Whenever multiple in situ observation points were available within one AquaCrop pixel, the mean of those points was taken. ~~This resulted in a total amount of 42 pixels over Europe where ISMN data could be used to evaluate CGLS-SSM and 32 points for SMAP-SSM, in~~

285 ~~non-irrigated agricultural areas.~~ AquaCrop simulations were crossmasked with both in situ data and ~~CGLS-SSM~~the respective satellite product (CGLS-SSM, SMAP-SSM) to perform an in situ (and satellite-based) evaluation at ~~42 points~~each point. ~~(Crossmasking AquaCrop using in situ and the satellite product SMAP-SSM data with 32 points resulted in similar metrics for AquaCrop)~~ In situ data from the Hydrological Open Air Laboratory (HOAL) in Petzenkirchen, Austria (~ 49°57'N, 14°52'E) were made available by partners of the SHui consortium and contributed data to three extra clustered pixels for CGLS-SSM,

290 resulting in a total of 45 evaluation points ~~with~~for CGLS-SSM and 32 for SMAP-SSM in non-irrigated agricultural areas.

3.5 Metrics

~~The regional model was run over a part of Europe (35°N-55°N, 10°E-20°E; and all ISMN sites), for the years 2011 through 2018. Daily simulated biomass and surface soil moisture (WC01 in AquaCrop) were evaluated.~~ To assess the temporal performance of the AquaCrop model, the bias, root mean square difference (RMSD), unbiased RMSD (ubRMSD), temporal

295 Pearson correlation (R), anomaly correlation (anomR), ~~bias and unbiased root mean square difference (ubRMSD)~~ were calculated with ~~against~~ satellite and in situ products, as follows:~~.~~

$$Bias = \frac{1}{N}\sum_{n=1}^{N}(x_n - y_n) \qquad (5)$$

$$RMSD = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(x_n - y_n)^2} \qquad (6)$$

$$ubRMSD = \sqrt{RMSD^2 - bias^2} \qquad (7)$$

$$R = \frac{\frac{1}{N}\Sigma_{n=1}^{N}(x_n - \bar{x})(y_n - \bar{y})}{\sqrt{\left(\Sigma_{n=1}^{N}(x_n - \bar{x})\right)^2 \left(\Sigma_{n=1}^{N}(y_n - \bar{y})\right)^2}} \qquad (8)$$

where x are the simulated output data from AquaCrop and y are the observations from the satellite products and N are the number of observations. $\bar{x}$ and $\bar{y}$ are the time mean values. For the anomR, x and y are anomaly time series.

Comparing products with different spatial resolutions will always result in representativeness bias, which is especially acute when using in situ observations to evaluate pixel-scale estimates. Therefore, the focus of the evaluation was~~will be~~ on temporal variability, using the R, anomR and ubRMSD metrics.

The time period used for validation depended on the evaluation product. When using satellite-based soil moisture, only grid cells were included when at least 150 CGLS-SSM or 200 SMAP-SSM retrievals (after quality control) were available during the overlapping period of satellite data (starting in 2014 for CGLS-SSM and in 2015 for SMAP-SSM) and simulations. When further comparing the satellite products to in situ data, a relaxed minimal threshold of 100 data pairs was set for the period of available data for each satellite product. For CGLS-DMP, the 10-daily data are complete between 2011-2018 and only March through November are included in the evaluation metrics.

The anomR was computed to assess both the short--term and inter-annual variability of biomass and soil moisture compared to the satellite products only, for lack of sufficiently long records of in situ data. A multi-year climatology (8 for CGLS-DMP, 4 for CGLS-SSM and 3.5 for SMAP-SSM) was computed and subtracted from the datasets to obtain anomalies as described by Gruber et al. (2020). The climatology is built on 31-day moving window averages, requiring either a minimum of 3 10-daily CGLS-DMP estimates or a minimum of 10 instantaneous CGLS-SSM and SMAP-SSM observations within a 31-day window. The climatology of AquaCrop was computed using the same moving window and time period as the evaluation product. For surface soil moisture, only daily model output that matched the days of observations of the evaluation product was used, whereas for biomass evaluations, the data consisted of the ~~matching 10 daily medians~~median of the matching 10-day period.

In this study, only rainfed agriculture is considered. However, it is very likely that irrigation will occasionally take place on rainfed fields, where the timing and volume is based on local decisions made by farmers. Irrigation practices were not included in the model simulations. To analyse how this human-driven process could influence the model performance, ~~To further analyse possible influencing factors on the model performance,~~ the FAO map 'Area Equipped for Irrigation' (AEI: Siebert et al., 2015), was used to identify areas that are occasionally irrigated and which were not necessarily captured by the irrigation class the C~~orine~~ORINE land cover inventory. The latter~~, which~~ only considers regularly irrigated areas to distinguish rainfed from irrigated land. The available 1-km and 10-km AEI map version were used to stratify correlation values with CGLS-DMP and with SMAP-SSM, respectively.

4 Results and discussion

4.1 Biomass

A visual comparison of simulated and satellite-based biomass at different days in the year of 2017 is presented in Fig. ~~1~~2 and gives an indication of the spatial performance of the regional AquaCrop model against the CGLS-DMP product. The figure shows that the model is able to capture large regional and temporal differences in biomass production, but the absolute values can differ between CGLS-DMP and the model. The coarser resolution MERRA-2 climate input is visible in the blocky pattern of the AquaCrop biomass maps. For the days in June and July, simulations over most of Italy ceased to produce biomass, whereas the CGLS-DMP product shows spatial variability in productivity. Water stress in the simulations is putting crop production to a halt, which is not in agreement to the CGLS-DMP. This can be either caused by an overestimation of water stress by the model, unmodelled irrigation, or because the CGLS-DMP product does not account well for drought stresses. Drought stress is indirectly included in the CGLS-DMP via the observed fAPAR, but could still lead to overestimations of DMP in drier periods (Smets et al., 2019).

Figure ~~2~~3~~a~~ summarizes the performance metrics of AquaCrop biomass simulations against CGLS-DMP. Differences in absolute values of biomass estimates are inevitable, because of representativeness errors in both the model and satellite retrievals. For example, the model uses a generic crop, for which the parameters could be locally optimized. Nevertheless, the long-term biases are limited and cancel out over the entire domain. When focusing on the temporal variability, the temporal correlations indicate a high performance, with an overall mean of R=0.8. Higher correlations are mostly found in the northern part of Europe. Lower correlations are specifically found in the North and Southwest of Italy. Similarly, the ubRMSD is highest in the southern half of the study domain.

The spatial variability in ubRMSD can be attributed to different factors that limit crop growth, which will be mostly cold temperatures in the North, and low soil water contents in the South. Across the domain the ubRMSD is 0.03 ~~t~~T ha^{-1} day^{-1} and typically less than 20% of the amplitude in biomass production. The anomaly correlation is lower than the correlation, but still significant, with a mean of anomR=0.46. The raw correlation includes the trivial agreement in the seasonal variability and is thus inevitably higher, whereas the anomaly correlation only evaluates short-term and interannual variability, as illustrated in
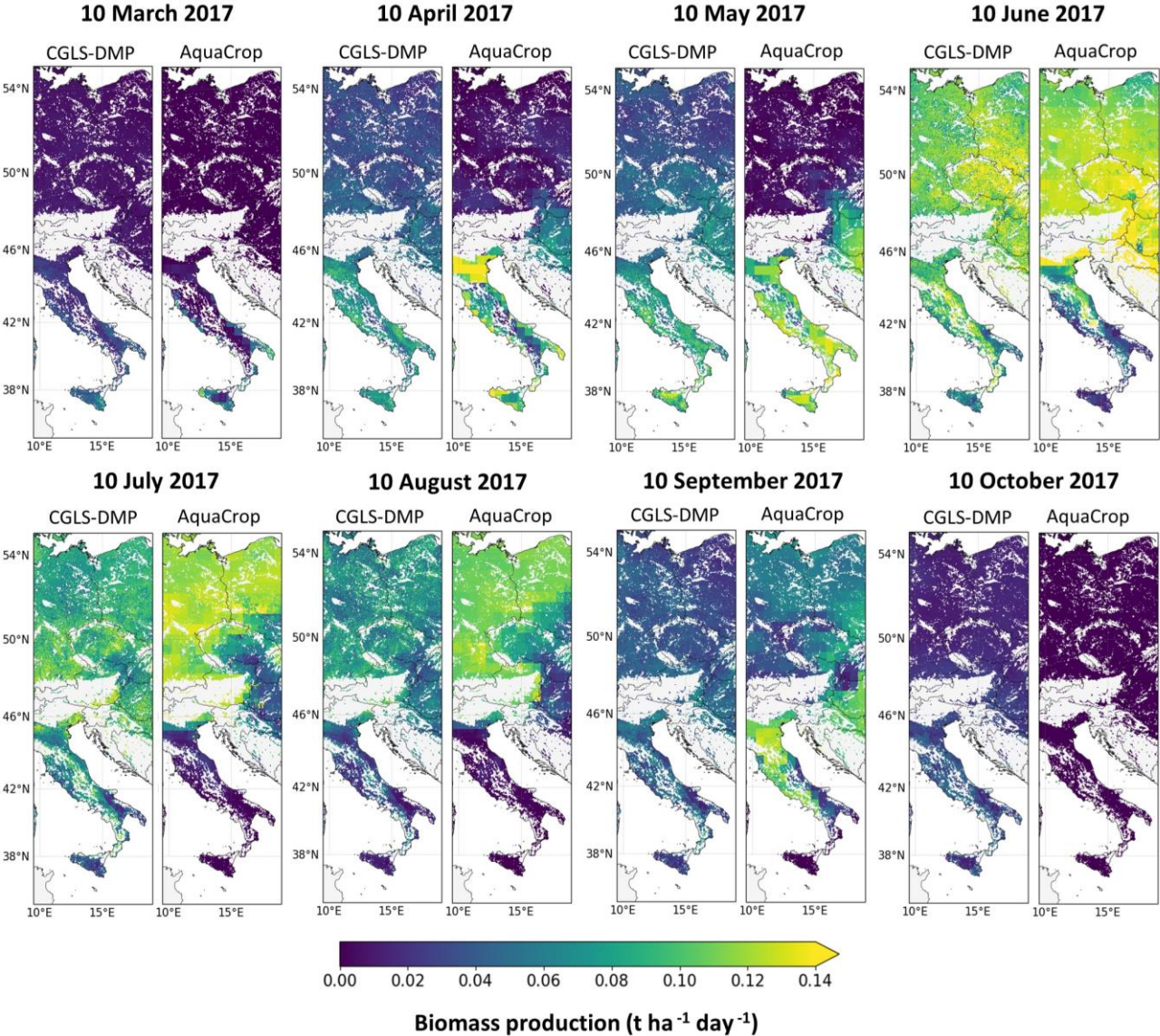
Figure 2 Biomass production of CGLS-DMP and AquaCrop during different days of the year 2017.

Fig. ~~2b~~4 for the HOAL catchment in Austria.

Both the model and satellite data show anomalous high biomass production in June 2017, whereas anomalous low values are
355   found in both datasets in June 2013. The short-term anomaly biomass productivity increments are also corresponding well to
the evaluation data, but for AquaCrop they are often more pronounced. For regions in the South of Europe (Italy), simulated
productivity anomalies are much more pronounced, clearly showing the modelled response on stronger rainfall events after a
relatively dry period. When comparing this to the CGLS-DMP product, it shows anomalies that are either less extreme or do
not match the anomalies of the model simulations, resulting in lower anomaly correlations (Fig. 4). This emphasizes the
360   importance of high--resolution precipitation information for climatic regions in which precipitation is the main limiting factor
for crop production. Across the northern region, the lower anomaly correlation values can be partly associated with soil texture
(TAW) -as can be seen from Fig. 3. In areas where there is a sufficient amount of rainfall, but soils are typically sandy and
have a low TAW and high K_{sat}~~sat~~, soil water easily drains through the profile, which prevents optimal crop production. ~~In
areas with typically sandy soils, defined by a low TAW and high K_{sat}, and a high rate of rainfall, such as northern Germany~~
365   ~~and Poland,~~ the drain, ~~soils can be quickly drained, resulting in water stress, thereby limiting crop growth, even during the
main growth season.~~ The effect of such stresses may not be observed in the CGLS-DMP, and will result in deviating interannual
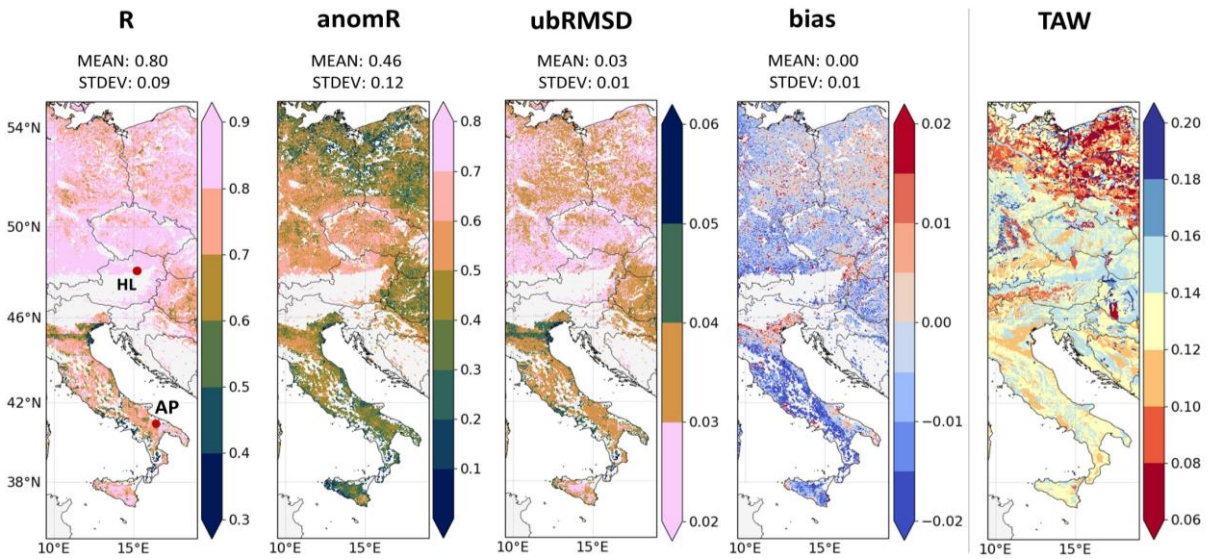
Figure 3 Temporal performance metrics of AquaCrop biomass evaluated against CGLS-DMP, with metrics R (-), anomR (-), bias (t
ha day^{-1}), ubRMSD (t ha day-1). Spatial mean and standard deviation of the metrics are indicated with MEAN and STDEV. Also
shown is the TAW (m^{3}m^{-3}) computed as the field capacity minus wilting point, without taking rooting depth into account. Light grey
areas represent no data.

variabilities.
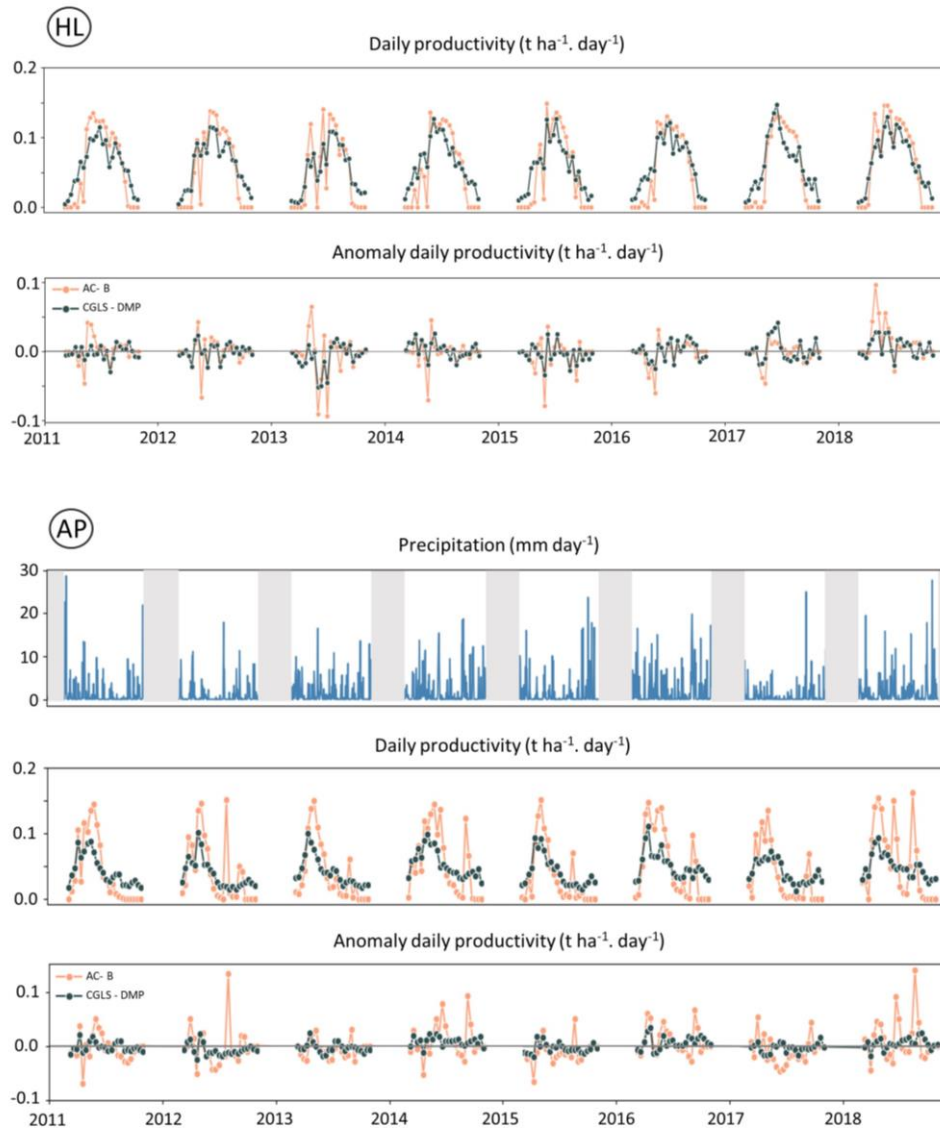
Figure 4 Time series of biomass productivity, anomaly daily productivity (and precipitation) for (HL) the HOAL catchment in Austria, and (AP) a pixel in the Apulia region of South Italy, both marked in Fig. ~~2~~3. Precipitation is only shown for AP, because ~~where~~ it has a marked effect there on short-term anomaly productivity. Periods between October and March are masked out in grey for precipitation

4.2 Surface moisture content

370 Surface soil moisture content was evaluated using three products at different scales; point measurements from ISMN and some additional sites in the HOAL catchment, 1-km CGLS-SSM and 9-km SMAP-SSM. Figure 35 shows the AquaCrop performance metrics against the satellite data. The spatial mean R and anomR value with SMAP retrievals are 0.74 and 0.65, respectively. The anomR is especially high in the central part of Europe and decreases towards the North. Overall, AquaCrop is much better correlated with SMAP-SSM than with CGLS-SSM. The mean R and anomR value of AquaCrop with CGLS-

375 SSM are 0.52 and 0.50, respectively. When aggregating CGLS-SSM to the EASE2 9-km grid using the same spatial mask of SMAP-SSM, temporal correlations with AquaCrop increase slightly, with a mean R of 0.57 (spatial standard deviation STDEV: 0.08) and a mean anomR of 0.56 (STDEV: 0.06) (not shown), but do still not reach correlations close to that ofand remain well below the correlation values between SMAP-SSM and AquaCrop SSM. Several areas with higher elevations have
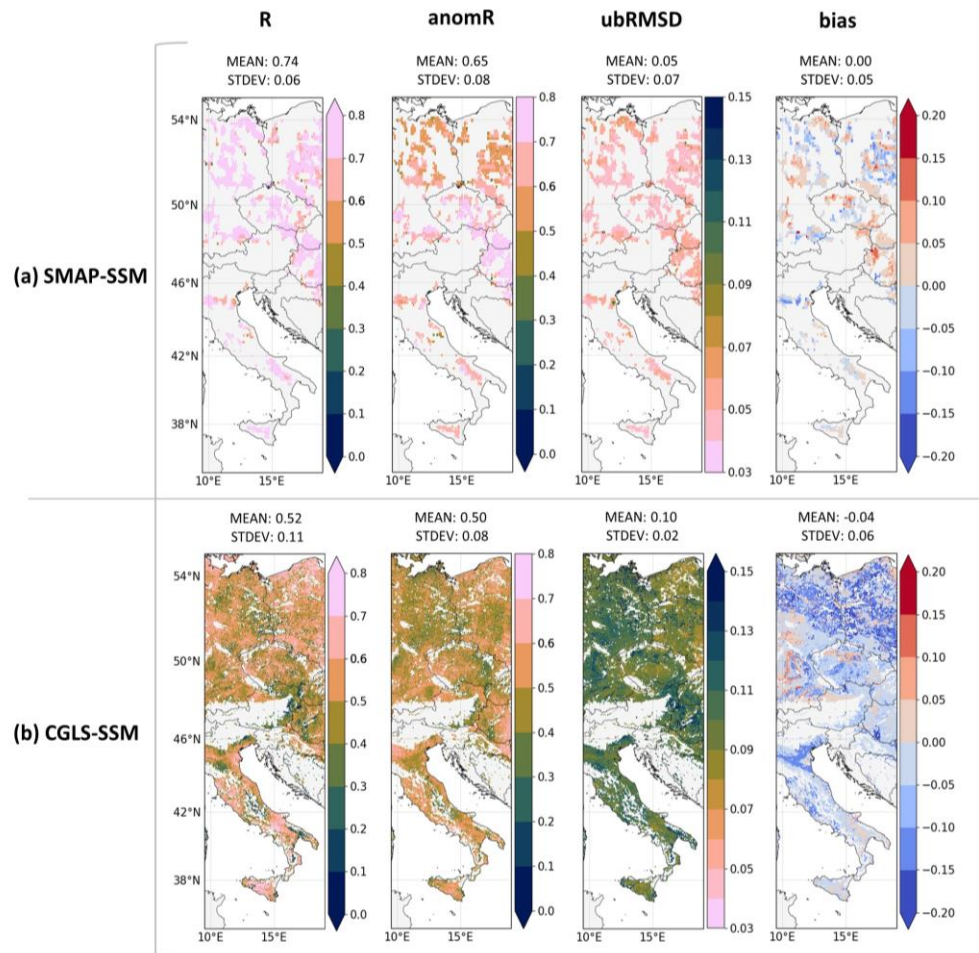
Figure 5 Temporal performance metrics of AquaCrop surface soil moisture evaluated against (a) SMAP-SSM and (b) CGLS-SSM, i.e. R (-), anomR (-), bias (m^3 m^{-3}) and ubRMSD (m^3 m^{-3}), with indication of the spatial mean and standard deviation of the metrics (MEAN, STDEV). Light grey areas represent no data.

lower correlation values (central Italy, eastern Alps). The spatial correlations of AquaCrop SSM on the 9-km EASE2 grid with CGLS-SSM and SMAP-SSM reveal a large variability in time, with a temporal mean spatial R of 0.38 and temporal standard deviation of 0.21 for CGLS-SSM and a mean R of 0.32 and temporal standard deviation of 0.22 with SMAP-SSM.

When looking at the absolute values of the bias and ubRMSD, the evaluation of AquaCrop against CGLS-SSM is also far worse than that against SMAP-SSM, but the spatial pattern of the errors is similar for SMAP-SSM and CGLS-SSM. The spatial mean ubRMSD against SMAP-SSM is 0.05 $m^3 m^{-3}$, close to the global target product uncertainty of 0.04 $m^3 m^{-3}$ (Entekhabi et al., 2014), and the spatial mean ubRMSD against CGLS-SSM is 0.10 $m^3 m^{-3}$. For both datasets, the larger errors correspond again to areas with sandy soils. Also here, the effect of soil texture on model performance was found. The ubRMSD values of 0.14 $m^3 m^{-3}$ and higher for CGLS-SSM, correspond to outliers exactly to a specific soil class in the HWSDv1.2 classification, that contains of extremely sandy soils (93%) sand. This soil class is characterised by very high K_{sat} and very low values for θ_{WP} and θ_{FC}, resulting in extremely low simulated available moisture content in the top layers. Because the low θ_{WP} is very close to the soil evaporation demand, the model is not able to simulate soil moisture correctly for the top layers for such short, daily timesteps. It is important to note that AquaCrop is a crop simulation model and this soil class is unrealistic for agricultural land. In future applications when multiple datasets from different sources are combined, it is recommended to limit the simulations to possibilities soils that are actually suitable for the specific simulation purposeto cultivate crops, or else to adapt the soil paramters. Nonetheless, the poor performance against the 1-km Sentinel-1-based CGLS-SSM is in general not due to model shortcomings, but dominated by poor satellite retrievals, as will be discussed below.

A comparison between in situ data, CGLS-SSM, SMAP-SSM and AquaCrop surface soil moisture at ISMN sites and 3 sites in the HOAL catchment is shown in Fig. 64. Across the in situ sites, the mean R value between AquaCrop and in situ soil moisture is 0.61 (Fig. 64a) and higher than the mean R value of 0.52 with CGLS-SSM (Fig. 64b). The mean ubRMSD between AquaCrop and in situ measurements is 0.06 $m^3 m^{-3}$, significantly lower than the mean between AquaCrop and CGLS-SSM (0.10 $m^3 m^{-3}$). The mean R between Sentinel-1 CGLS-SSM and in situ data is even lower, with a value of 0.42 and a mean ubRMSD of 0.11 $m^3 m^{-3}$ (Fig. 6c). The comparison with the satellite products over32 in situ sites shows that SMAP-SSM mean temporal correlations are significantly better with both AquaCrop simulations (Fig. 65b; R=0.81, ubRMSD=0.05 $m^3 m^{-3}$) and in situ measurements (Fig 6c; R=0.69, ubRMSD= 0.05 $m^3 m^{-3}$) than CGLS-SSM, even though SMAP-SSM has a lower spatial resolution. This is further illustrated in the time series at three locations presented in Fig. 57, where SMAP-SSM follows the pattern of in situ data well and slightly better than AquaCrop, whereas the pattern of the CGLS-SSM values is more erratic. The high correlations between SMAP-SSM and in situ measurements show that SMAP-SSM is better at capturing variations at smaller scales than the current system of AquaCrop, due the coarse resolution of meteorological input data. Additionally, SMAP-SSM retrievals probably benefit from a more accurate background representation of the vegetation, whereas AquaCrop uses a generic crop description. For CGLS-SSM, lower observed soil moisture was often found for the months April, May and June, as can be seen in Fig. 75b and c. The poor correlation of CGLS-SSM during these months is most likely due to the fact that the Sentinel-1 backscatter signals are dynamically affected by changing vegetation during the growing season, but the soil moisture retrievals are only corrected for with a static vegetation value for every day of the year. Furthermore, changes in

surface soil roughness are not accounted for in the retrievals and could play an important role in the lower quality of the CGLS-SSM retrievals (Bauer-Marschallinger et al., 2018).

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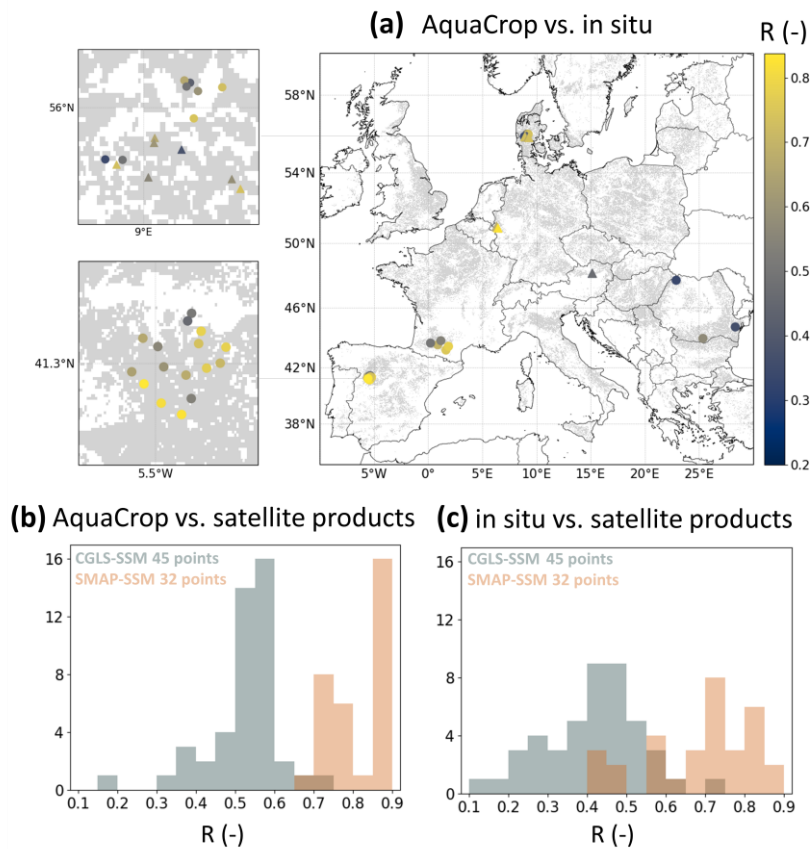
Figure 6 (a). Pearson correlation R values between in situ measurements from the ISMN and AquaCrop surface soil moisture, at 45 locations over Europe, with grey pixels containing at least 50% rainfed agriculture according to the CORINE land cover map 2012. Correlations shown are from crossmasked data with CGLS-SSM. The circles indicate the locations used for both evaluation with CGLS-SSM and SMAP-SSM, whereas triangles show locations that were only used for CGLS-SSM. (b) Histogram of R values between AquaCrop surface soil moisture and the two satellite products CGLS-SSM (45 points) in grey and SMAP-SSM (32 points) in orange, at the locations of the in situ sites. (c) Histogram of the R values between the in situ measurements and the two satellite products CGLS-SSM (45 points) in grey and SMAP-SSM (32 points) in orange.
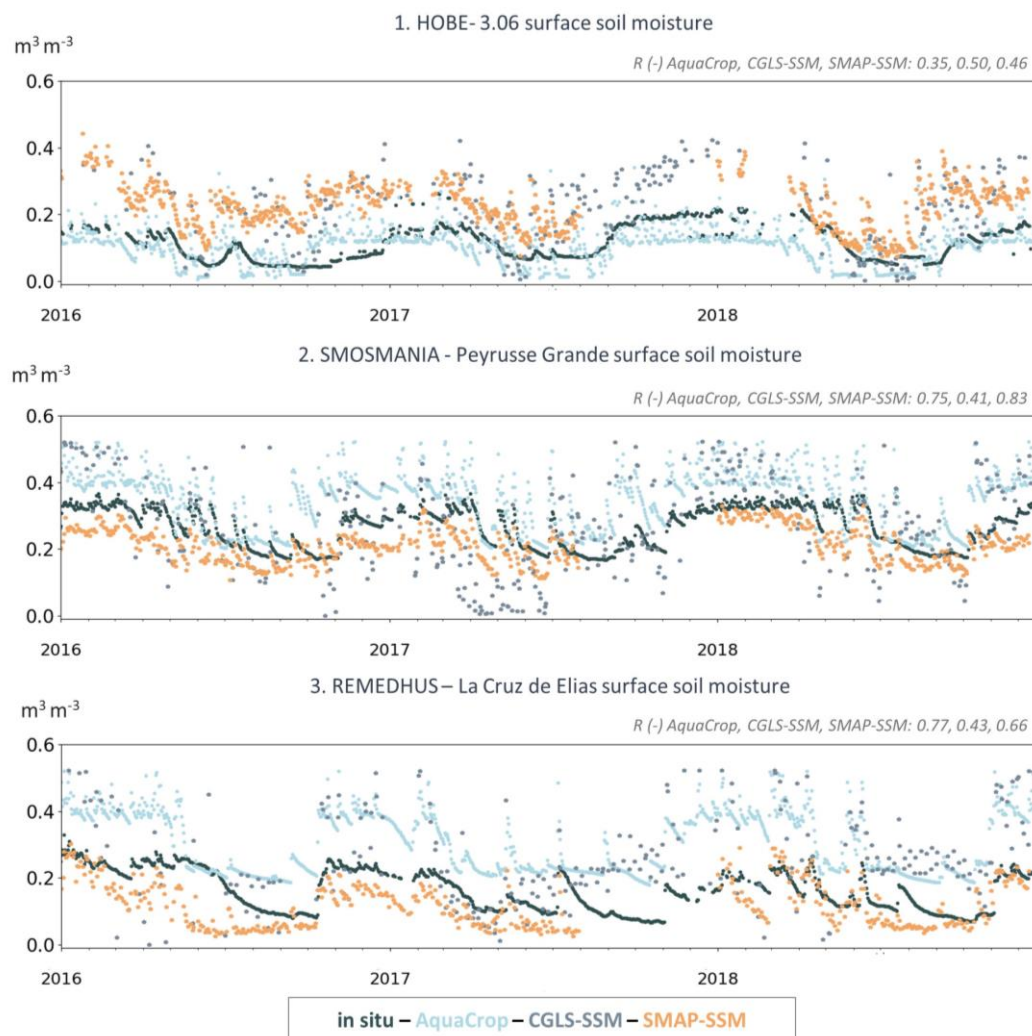
Figure 7 Time series of daily surface soil moisture at three locations marked in Fig. 64a: 1 (~ 55°54 N,8°52 E), 2 (~ 41°17 N, 5°18 W) and 3 (~ 43°39 N, 0°13 E): AquaCrop (light blue) in situ measurements (dark grey), CGLS-SSM (light grey) and SMAP-SSM (orange). Pearson correlations R of in situ data with the different products are given for each location.

4.3 Effect of irrigation

Figure 87 shows the spatial distribution of the R values of AquaCrop biomass and soil moisture with CGLS-DMP and SMAP-SSM, respectively, grouped into two percentage classes of AEI. In terms of biomass, higher R -values between AquaCrop and CGLS-DMP (mean R= 0.81) are found for pixels where AEI < 10% than for areas where AEI >= 10% (mean R= 0.72). For soil moisture, the correlation with SMAP-SSM shows barely any difference between the AEI groups (AEI < 10%: mean R = 0.74; AEI >= 10%: mean R= 0.73). It should be noted that SMAP-SSM has a much smaller coverage than the CGLS-DMP, because SMAP-SSM is screened conservatively based on its quality flags. The results of this comparison suggest that, even if

the ~~model and evaluation datasets should not be neglected.~~ even if the simulations were limited to dominantly rainfed agricultural areas according to the CORINE land use map and therefore did not include irrigation, it is possible that in reality irrigation is occasionally applied in rainfed fields and seen by the satellite data, resulting in lower correlation metrics.~~did not include irrigation, it is possible that in reality irrigation is occasionally applied in rainfed fields and seen by the satellite data, resulting in lower correlation metrics.~~
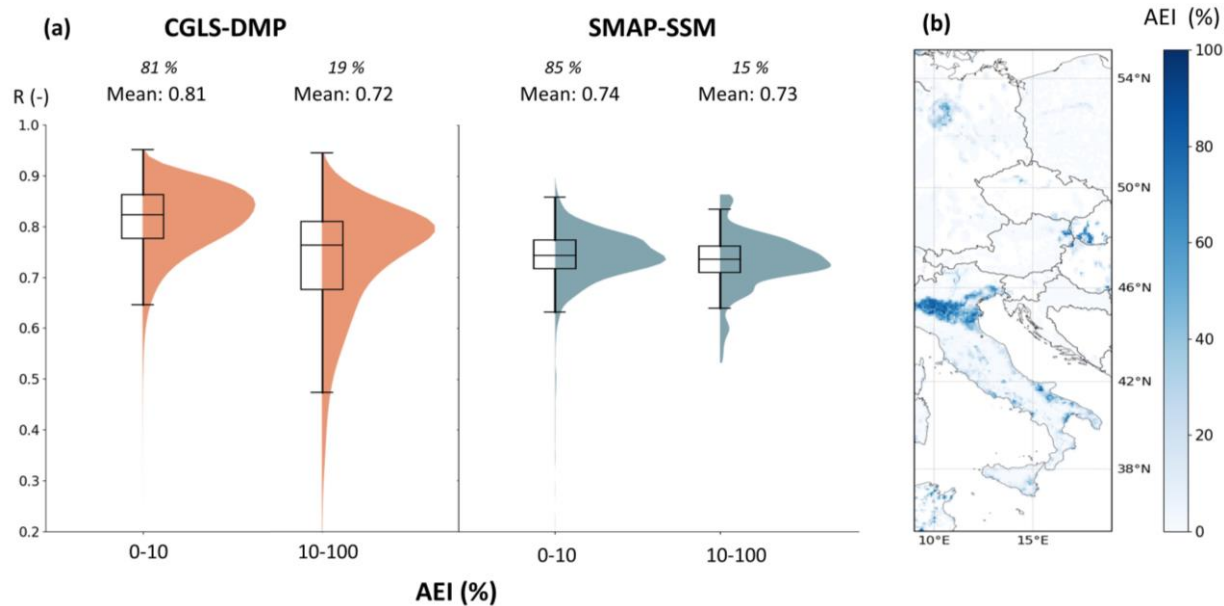
Figure 8 (a) Boxplots with violin curve of temporal -R values grouped by FAO's percentage of Area Equipped for Irrigation (AEI), group1: 0-10% and group2: 10-100%, on the left side for CGLS-DMP and on the right side for SMAP-SSM. The percentage of the total amount of pixels for each group, and the spatial mean R value is noted at the top of the figure. (b) AEI map over study domain.

4.4 Discussion of the regional AquaCrop model

The current gridded AquaCrop model has several conveniences, such as the efficient parallel processing structure, the ability to run at any resolution and domain, and the modular setup in which a compiled executable can be easily replaced by newer AquaCrop versions. The model setup is chosen to facilitate subsequent embedding within a future satellite-based data assimilation system.

The regional modelling system was designed to capture the seasonal and inter-annual variability, with some important simplifications. A general C3 crop was assumed and management data was considered as homogeneous over the entire study area, whereas meteorology and soil information were spatially variant. Therefore, the evaluation of this regional crop model setup against satellite products was mainly done in terms of unbiased temporal metrics. AquaCrop accurately simulates the

440 temporal variability in biomass and surface soil moisture, especially in the northern regions and if the soil's TAW is not limiting. Limitations in the accuracy of the input precipitation (MERRA-2) causes slightly worse simulations in the water limited southern regions, where biomass shows a fast response to limited (but sometimes inaccurately timed) rainfall events. The use of high-resolution meteorological forcing is likely to be most important next step to further improve fine-scale AquaCrop simulations. The evaluation was limited to surface soil moisture and biomass, but could be further expanded to

445 other variables such as root-zone soil moisture and transpiration in the future. Reference data for the latter variables are always informed by strong (often modelled) background information (Martens et al., 2017, Reichle et al., 2019) and not directly observed over large regions.

The suitability of this modelling system to estimate the spatial variability in soil moisture and yield production for specific crop types would require further analysis and more detailed input information. For example, by combining input datasets from

450 different sources, some unsuitable cropland areas were identified (e.g. too low TAW in combination with high K_{sat}) that were not filtered out from this analysis. Furthermore, unmodeled irrigation could influence the regional model performance. Most importantly, the relative spatial variability in biomass is likely not dominated by meteorology and soil texture, but by the various types of crops. The parameters associated with each of these crops could be spatially optimized (calibration, data assimilation for parameter estimation) in future work, using historical time series of spatially covering reference data, e.g.

455 optical Sentinel-2 data.

The regional model evaluation could only be performed with satellite retrievals, but such an evaluation is limited to the days of overpass, and to times and locations where retrievals are of sufficient quality. For example, SMAP-SSM retrievals are filtered out under too dense vegetation or frozen conditions. Furthermore, the satellite signal may represent a slightly different quantity than what is modelled. Additionally, microwave signals only pertain to the upper 5 cm of the soil, but the model's

460 surface layer is 10 cm. The provided quality flags on CGLS-SSM are less strict, providing a better spatial coverage of fine-scale data. However, the C-band soil moisture measurements pertain to an even shallower soil depth and are likely more affected by vegetation. In any case, both the satellite retrievals and model simulations have their own systematic and random errors. The influence of the former is suppressed in this study by focusing on relative temporal variability. To further dynamically improve model simulations, or to add value to the available satellite data (e.g. dynamically interpolate) via

465 AquaCrop modelling, random errors in both sources can be limited via data assimilation for state updating.

5 Conclusions

In this paper, a spatially distributed version of the field-scale AquaCrop model v6.1 is presented and evaluated against various satellite data products and in situ data. The new regional AquaCrop infrastructure allows to simulate biomass and soil moisture over large domains in an efficient way, due to the massive parallelization of the gridded simulations. In this case study, the

470 regional AquaCrop model is forced with meteorological input based on MERRA-2 re-analysis data, the soil information is extracted from the HWSDv1.2, and a generic crop is parameterized. Even when using coarse meteorological input data, the

AquaCrop model ~~is able to~~can capture seasonal, interannual and short-term temporal dynamics of biomass over Europe at a fine ~1-km resolution. For the years 2011 through 2018, the temporal R between the AquaCrop biomass production and CGLS-DMP is 0.8, and the anomR is 0.46, across central Europe. The R values are higher in the northern half of the study domain, where crop growth is generally temperature limited, whereas in the southern half of the domain, water stress becomes more important and the R values are lower. Likely factors that can influence this difference in correlation are an underrepresentation of drought stress by the CGLS-DMP product, the effect of occasionally applied irrigation which is not included in the model, or possibly overestimations of simulated drought stress by the model. Additionally, the impact of soil parameters is apparent in the anomR values, where lower TAW values in the northern part result in differing anomalies for modelled biomass and CGLS-DMP.

The AquaCrop simulations for surface moisture content show that seasonal, interannual and short-term temporal dynamics correspond well to the 9-km SMAP-SSM data, with a mean R value of 0.75 and an anomR value of 0.65 across the study domain. Lower R values are found for Sentinel-1 CGLS-SSM, with a mean temporal R of 0.52 (aggregated to 9-km EASE2 grid: 0.57) and a similar anomR of 0.50 (aggregated to 9-km EASE2 grid: 0.56). The comparison between AquaCrop, CGLS-SSM, SMAP-SSM and in situ data for 45 (32 for SMAP-SSM) locations in Europe shows that both AquaCrop and SMAP-SSM better agree with in situ data (mean R= 0.61, 0.69, respectively) than Sentinel-1 CGLS-SSM (mean R= 0.52). The lower performance of Sentinel-1 CGLS-SSM can be attributed to the static correction for vegetation, which causes soil moisture retrieval errors during the growing season, and the fact that there is no correction for surface roughness (Bauer-Marschallinger et al., 2018). For both the evaluations with SMAP and Sentinel-1 retrievals, the effect of soil characteristics influences the evaluation performance of the AquaCrop model. When certain soil characteristics are unsuitable for crop cultivation, such as a high K_{sat} and a very low θ_{WP} and low TAW, soil moisture becomes inaccurately represented by the AquaCrop model, increasing the model error. At the same time, ~~the errors in~~ satellite-based soil moisture retrievals also contain errors related to a priori defined ~~might also differ for various~~ soil hydraulic parameters~~textures~~.

Improvements to the regional AquaCrop model can be made in terms of higher resolution meteorological input data to better capture small-scale spatial differences, by revising the soil hydraulic parameters to better represent soil types used for agricultural land, and by introducing spatio-temporally varying crop parameters when such information becomes available. Overall, the current model is able to well represent temporal and spatial differences at the field and regional scale in both biomass production and surface soil moisture, requiring only easily accessible input data. The computationally efficient modelling system is ideal to foster future improvements in the spatial patterns in both soil moisture and biomass production via local parameter optimization based on historical records of satellite data, and improvements in the short-term and interannual temporal variations via sequential satellite data assimilation.

Code and data availability. The code and data needed to run the regional version of AquaCrop v6.1 on a Linux-based system is available on Zenodo, with DOI: 10.5281/zenodo.4770738. ~~are currently only available to the editors and reviewers. After~~

acceptance, a repository will be made publicly available on Zenodo with a citable DOI. Apart from the code, this repository
will include the generic crop file, the management file and ancillary soil data from De Lannoy et al. (2014). All other input
data and evaluation datasets are freely available, except for the in situ measurements of the HOAL experiment site. Please visit
the following links for data access.

MERRA-2 variables (accessed on March 2019): https://disc.gsfc.nasa.gov/datasets?project=MERRA-2; the soil mineral
classification and organic matter originates from HWSDv1.2: http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/; the CORINEorine land cover map (accessed on September 2019):
https://land.copernicus.eu/pan-european/corine-land-cover; the rootzone depth map from ESDAC (accessed on October 2019):
https://esdac.jrc.ec.europa.eu/content/european-soil-database-derived-data; evaluation datasets from COPERNICUS Global
Land Service (CGLS-DMP, CGLS-SSM; accessed on February 2020, June 2020):
https://land.copernicus.eu/global/themes/vegetation; SMAP Enhanced L2 Radiometer Half-Orbit 9 km EASE-Grid Soil
Moisture, Version 4 (accessed on September 2020): https://nsidc.org/data/SPL2SMP_E/versions/4; ISMN soil moisture at 5
cm depth (accessed on August 2020): https://ismn.geo.tuwien.ac.at/en/; FAO irrigation maps (accessed on June 2020):
http://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas.

Author contributions. SDR created the code to execute the regional version of the model, prepared the input data and conducted
the model evaluation. GDL prioritised the main steps taken in the paper, provided supervision and scientific guidance
throughout all research advances and manages HPC usage. DR provided scientific guidance regarding the use and
interpretation of the AquaCrop model, developed the generic crop file, and provided the Delphi source code of AquaCropv6.1.
SDR wrote the paper and all authors contributed.

Competing interests. The authors declare that they have no conflict in interest.

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