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Abstract

Crop models allow simulating irrigated plant dynamics at the plot level. However, in many places irrigation is managed collectively to share water at the network level. To study the impact of the irrigation network constraints on plant dynamics, we proposed a co-simulation approach based on the coupling of the Optirrig crop model at the plot level with the WatASit agent-based model at the network level. As a proof of concept applied on a typical gravity network of the South-East of France, the approach allowed to consider the effects of the network spatial (i.e. water flow gradient) and temporal (i.e. network coordination) constraints on leaf area index and water stress index dynamics of 16 cereal plots. Four progressive levels of collective irrigation constraints are simulated: no collective constraints, space collective constraints, time collective constraints, and space and time collective constraints. Retrospective simulation of the 2017 irrigation campaign is consistent with field surveys, and simulation results suggest that plant water stress could be underestimated when simulated at the plot level rather than at the network level. Spatially, the most severe water stress was observed for the plants located furthest downstream of the network. Temporally, the absence of network coordination can lead to earlier plant water stress and lower plant growth during the collective irrigation campaign, while time-slot-based coordination tends to delay the impact. For future research, reinforcing the coupling from the crop model to the agent-based model could allow to study the feedback loop of plant dynamics on irrigation practice adaptations. It is also a first step towards an optimization approach for irrigation networks.

Keywords: co-simulation; irrigation network; crop model; agent-based model; water stress; WSI; LAI.

1. Introduction

Crop models simulate plant dynamics according to the climate-soil-plant interactions. Therefore, they are useful to evaluate the effects of irrigation on plant growth and water stress at the plot level. In recent years, several simulation platforms (e.g. RECORD, HarvestChoice; MAELIA) have been developed firstly to facilitate the automation of crop models, but also to better take into

account context-dependent constraints at other levels than the plot level (HarvestChoice, 2010; Gaudou et al., 2013).

On the other hand, agent-based models (ABMs) have been widely used within the last few years to study systems involving complex interactions between human actions and their biophysical and/or social environment. They offer possibilities for incorporating disparate entities and for studying their local interactions (Bousquet and le Page, 2004; Matthews et al., 2007). They are well suited to take into consideration key micro-level constraints rather than aggregated system representations (Filatova et al., 2013), especially the agriculture-environment interactions (e.g. Valbuena et al., 2010).

Scholars have explored various ways for associating agent-based models (ABMs) with crop models for two decades, leading to modeling and simulation environments embedding biophysical, economic, or socioeconomic components (Berntsen et al., 2003; Belcher et al., 2004). AquaCrop (Raes et al., 2009; Steduto et al., 2009) was combined with an economic model (García-Vila and Fereres, 2012). STICS (Brisson et al., 2003) was implemented in the RECORD platform to represent farming practices into agro-ecosystems. APSIM (McCown et al., 1995; Keating et al., 2003) or DSSAT (Jones et al., 2003) have been embedded in the HarvestChoice (2010) platform to nourish regional-scale decision-making. WOFOS (Wolf and van Diepen, 1995; Reidsma et al., 2009; Supit et al., 2012) was reformulated into the modular Python Crop Simulation Development programming structure (de Wit, 2015). Gaudou et al. (2013) have integrated AqYield (Nolot and Debaeke, 2003; Murgue et al., 2014; Constantin et al., 2015) into the MAELIA multi-agent platform.

Several studies have shown the usefulness of coupling cellular components representing a landscape with an agent-based simulator at the household or farmer level with behaviors that alter the landscape (Parker et al., 2003; Verburg et al., 2004; Berger et al., 2006). Such approaches enable assessing the environmental, economic, and social impacts of the combined changes in agricultural activities (demography, dynamics of land cover and climate). Thanks to these platforms, changes in cropping systems, access to water, irrigation inputs cost and availability, have been assessed in terms of their impact on plant dynamics, notably through proxies of plant development and production such as the *Leaf Area Index* (*LAI*; Monteith, 1977) and the *Water Stress Index* (*WSI*; Jones, 1992).

However, few scholars have proposed to study the potential impacts due to irrigation network constraints on plant dynamics. In particular, in gravity-fed networks, Merot et al. (2008) have shown the importance of water distribution constraints and irrigation inter-related practices to ensure irrigation operations in the Crau plain (France). At the level of the irrigated scheme, the spatial constraints to operate irrigation include, for example, the variation of flow rate and water availability along the upstream-downstream gradient in the abduction network, according to its withdrawals, seepage, and hydraulic limitations. During the irrigation campaign, the possibilities for temporal adjustment of irrigators' calendar are thus limited by these spatial constraints and depend on the

behavior of other irrigators influencing the network flow rate. In particular, irrigation coordination is a key factor for sharing water resource that must be distributed through a common network in the right place and time to all along the irrigation campaign. In this context, our simulation approach aims at capturing the potential impacts of spatial (i.e. network flow gradient) and temporal (i.e. network coordination) constraints due to a gravity irrigation network on plant LAI and WSI dynamics.

Integrated simulation approaches that merge models into a unified software package (e.g. Matthews, 2006; Schreinemachers et al., 2007; Gaudou et al., 2013) are useful to capture the complex human-environment interactions and shed light on the understanding of the system dynamics with potential entry-points for policy design (Dragan et al., 2003). However, model simplifications commonly occur when merging modules, especially of environmental processes (e.g. Schreinemachers et al., 2007, 2010), altering the model's ability to fully capture interactions. A more flexible method called co-simulation, also used by scholars in farming and environmental modeling (e.g. Warner et al., 2008; Bithell and Brasington, 2009; Bulatewicz et al., 2010), consist in coupling simulation software together rather than integrating individual components in a single modeling and simulation software. The main advantage is that there is no need for recoding components and consequently the users and developer's community of each model component may be asked to help with the coupled model (control code, provide and test new modules, ...). However, it involves conceptual and programming developments to ensure compatibility of many characteristics including basic assumptions, spatial and time scales. First, it requires to make sure that models components and associated software have communication features and manage disruption correctly. Last but not least, it requires a clear conceptual approach to organize scheduling between the models and between the simulation software.

The objective of this paper is to present a co-simulation approach based on the coupling of the Optirrig crop model at the plot level with the WatASit agent-based model at the irrigation network level. As a proof of concept, we applied the approach for capturing the potential impact of a typical gravity-fed network in the South-East of France on 16 cereal plots. We simulated a dry year irrigation campaign under four levels of collective irrigation constraints (i.e. no collective constraint, space collective constraint, time collective constraint, and space and time collective constraints), and we compared LAI and WSI dynamics of cereal plots.

The next sections present the overall co-simulation approach (Section 2), the study area and the specific models developed for the proof of concept (Section 3), and the simulation results for the four levels of collective irrigation constraints (Section 4), before discussing the added-value, limitations and perspectives in Section 5.

2. Singular features of the co-simulation approach

2.1 Overview

The purpose of the co-simulation is to capture the potential impacts on crop LAI and WSI dynamics induced by the gravity irrigation network when operating irrigation during a collective irrigation campaign. The approach consists in linking a crop model at the plot level, and an ABM at the network level, based on the daily coupling of their two simulation software described in Table 1. It uses the Optirrig crop model for simulating *LAI* and *WSI* as a proxy for crop development and water stress, and the WatASit ABM at the network level for generating irrigation operations under four progressive levels of collective irrigation constraints (see Section 3.6). Optirrig simulates climate-soil-plant interactions daily in which irrigation dates (I+) on each plot are forced by WatASit through a daily coupling (Fig. 1). WatASit is itself nourished by the state of maturity of the crops (*TT*) provided by the Optirrig model. If there is a conflict for the sharing of water in the collective gravity network, it is managed by the ABM and may induce a delay in irrigation for some of the irrigators who would aim to irrigate at the same time.

Table 1. *Main characteristics of Optirrig and WatASit models and simulation software.*

Characteristic	**Optirrig**	**WatASit**
Scientific domain	Irrigation optimization, plant production, soil science	Operational management of collective irrigation, coordination
Type of model	Process-based crop model	Agent-based model of irrigation operations under space and time collective constraints
Main assumptions	- The time-evolution of crop water stress quantified by *WSI* values is the main control over *LAI* values, with dedicated effects associated with the severity and time of occurrence of water stresses, and this time-evolution is the consequence of both rain and irrigation events	- Priority is given to the plot that has not been irrigated for the longest time - A maximum irrigation operations at a time per irrigator - Number of irrigators per farm is taken into account
Components	- Soil water balance - Plant growth - Total dry matter and agricultural yield - Crop water stress	- Irrigation possibilities simulator - Decision-making (irrigation strategy under collective constraints)
Internal processes	- Soil water reservoirs dynamics - Biomass growth - Crop management options	- Multi-scale irrigation constraints - Network flow - Network coordination options
Inputs and parameters	- Climate inputs - Land cover inputs - Soils parameters	- Climate inputs - Land cover inputs - Network parameters
Temporal resolution	Daily time step	Hourly and daily time steps
Spatial resolution	1D with no explicit representation of domain size. The nominal scale is plot-scale with possible adaptations by assuming "homogeneous" domains of any size and performing "1D multi-local" runs for down-scaling or up-scaling	Grid-cell based ; size and number of pixel user defined
Simulation platform	R (R Core Team, 2018)	CORMAS (Bommel et al., 2015)

Programming language	R	SmallTalk

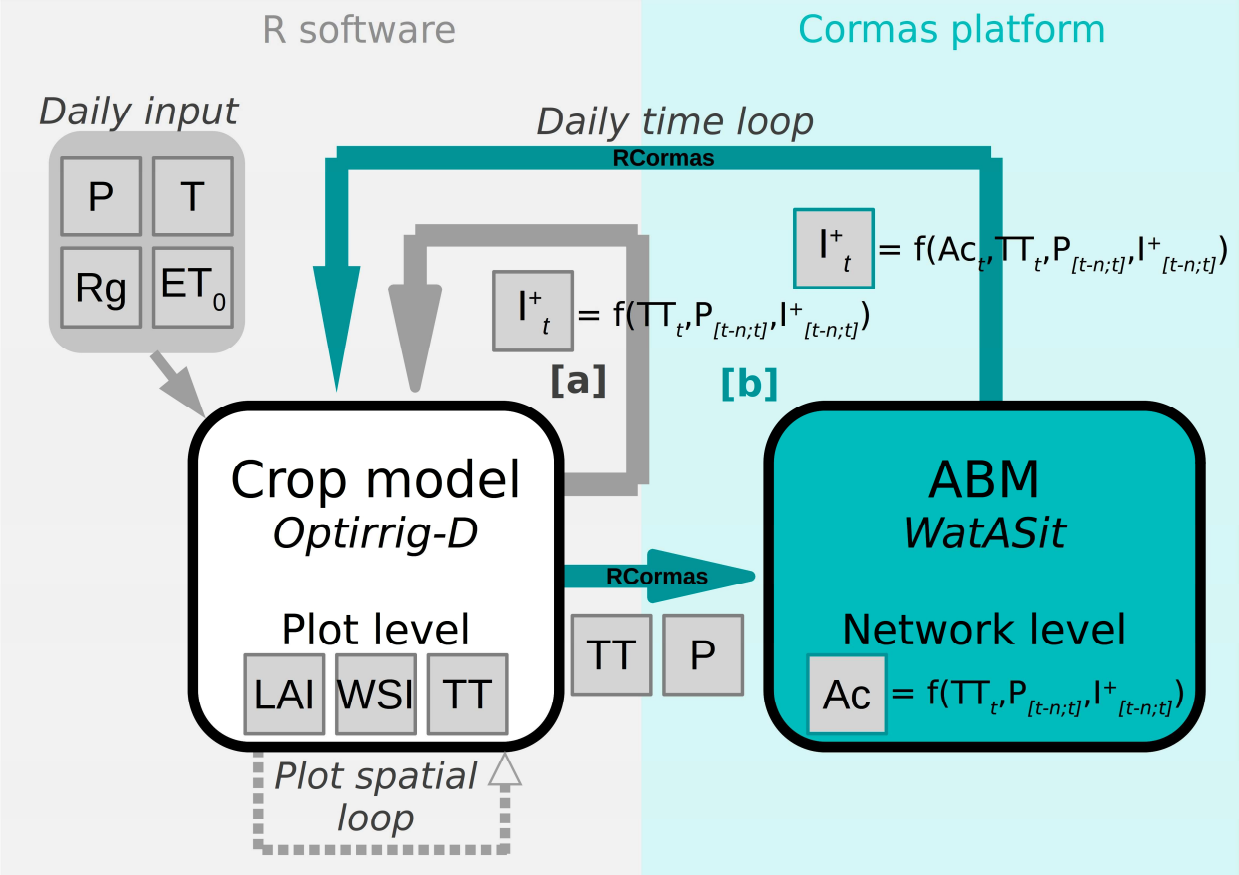

Fig. 1 (to be printed in color): Scheme of the co-simulation approach. [a] indicates the simulation processes which shortcuts the coupling with the ABM (grey arrows), whose grey boxes are the main variables. The precipitation, temperature, global radiation, and reference evapotranspiration are denoted P, T, Rg, and ET0, respectively. LAI is the Leaf Area Index, WSI the Water Stress Index and TT the sum of temperature. I+ stands for irrigation, which is denoted with a "+" to indicate it depends on the irrigation decision rules. t is the current time step, whereas [t-n;t] is the time period of the last n days. [b] indicates the simulation chain which integrates the coupling with the ABM at the network level (blue arrows). In this case, I+ also depends on the actions (Ac) carried out by the agents. RCormas refers to the API used for activation of the coupling and communication between the R software and the CORMAS platform.

2.2 Technical features

Co-simulation involves the communication of several model components that include their solvers (meaning that the components can compute of the effects of external events and time advance). These components are viewed as slaves' processes and are orchestrated by an external program referred to as a master algorithm.

The co-simulation approach has required then the development of specifics *Application Programming Interface* (APIs) designed as sets of R functions, so that the model components that

we used can be driven as slave processes by the master algorithm. The first API called *RCormas*[1], is based on the HTTP protocol and allows communication between the R software in which the master algorithm is implemented and the CORMAS platform running the ABM. We will call the second API the Roptirrig that enable the master algorithm to communicate with the Optirrig-D simulator already coded in R. Both APIs allow piloting the simulations by initializing the model, getting and setting values from entities, and running simulation steps.

The master algorithm uses those APIs to first initialize both models and then to run two phases of simulation that are organized as follows:

[a] In the time period from the beginning of the simulation to the beginning of the irrigation campaign, no irrigation is present and the crop-related *LAI*, *WSI*, and *TT* variables are calculated by the crop model from the climatic forcing only (Fig. 1 [a]),

[b] During the irrigation campaign, the coupling between the crop model at the plot level and the ABM at the network level is activated. The crop model (Otpirrig-D) keeps the history of all necessary state variables from one day to another and calculates the state variables according to the daily update of *I+* transmitted by the ABM on each plot (Fig. 1 [b]). Each day, first the crop model simulates *LAI*, *WSI,* and *TT* for each crop. We assume that the crop growth process is slow enough that we do not need to calculate it by the hour. The precipitation *P* and the sum of temperature *TT* are then transmitted to the ABM. Second, the ABM generates the irrigation operations made by the agents constrained by the collective network that could modify *I+* for the current day. Third, *I+* is collected and transferred to the crop model for each plot, and new *LAI* and *WSI* are computed. This sequence is repeated every day until the end of the simulation period.

In both [a] and [b], if *TT* exceeds the cereal temperature of maturity *TM*, the irrigation campaign is stopped for the cereal plot (*I+* is null). In the end, the original features of the approach are the consideration of a collective level of spatial and temporal constraints to operate irrigation, simulated within the gravity network thanks to the ABM, and their daily consequences for the dynamics of plants LAI and WSI at the plot level.

3. Study area and specific models developed for the proof of concept

3.1 Study area and data collection

To illustrate the co-simulation approach, we selected the Aspres-Sur-Buëch case study (Fig. 2), in which 83 plots can be irrigated by 10 irrigators sharing the gravity-fed network. The case study is located in the Buëch catchment, a sub-basin of the Durance with a surface area of 1490 km^2 in France. Collective irrigation constitutes by far the use that takes the most from the water resource during the low water period from May to October. Several irrigator unions are equipped either for gravity-fed irrigation, or for pressurized irrigation, or both (Fig. 2, right-side). The Aspres-sur-Buëch

1 RCormas is available at https://gitlab.irstea.fr/cormas-dev/r-cormas.

gravity network is fairly representative in terms of location (in the upstream part of the basin), irrigable area (with 75 ha whereas the average is 50 ha in 2017), and crop rotation (23.7% cereals in 2017).

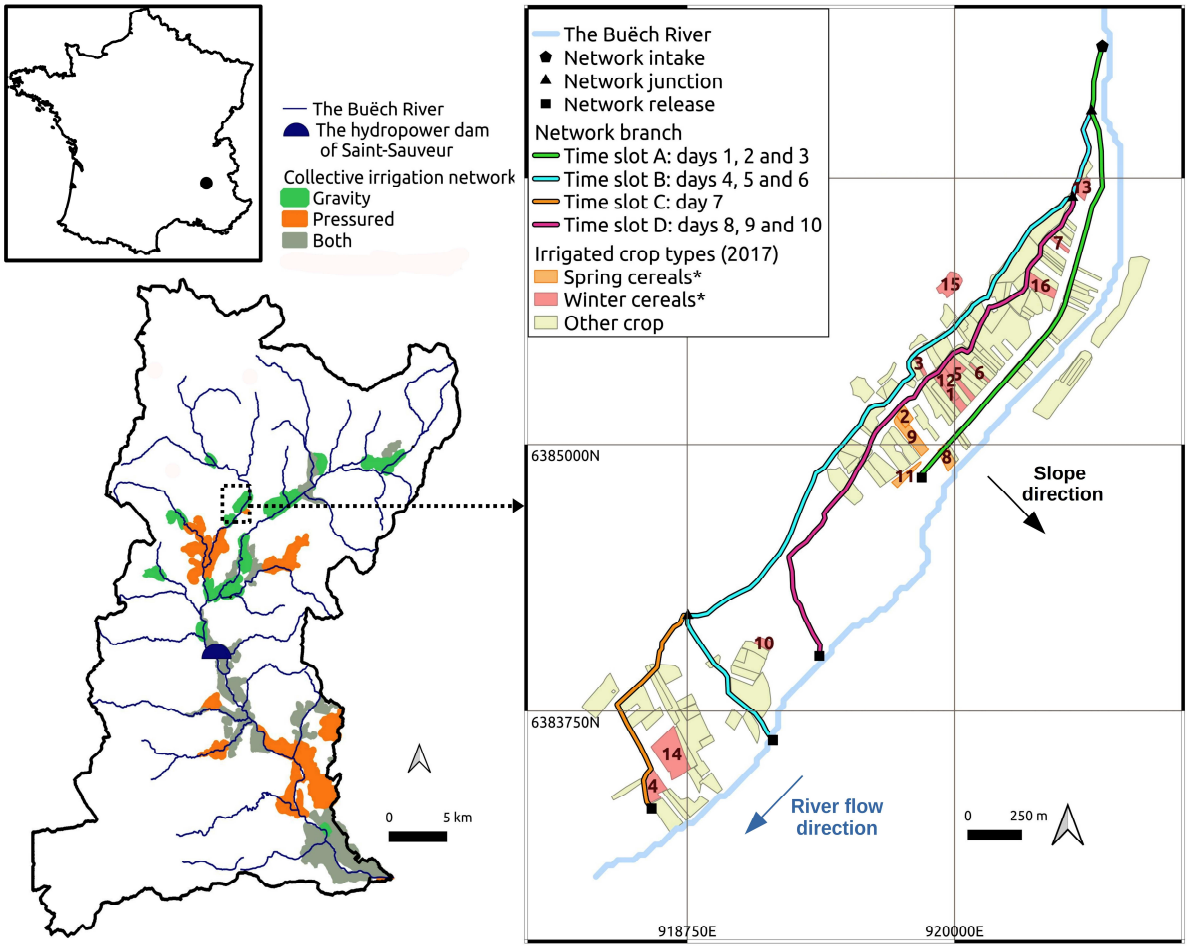

Fig. 2 (to be printed in color): Presentation of the Aspres-Sur-Buëch study area (right-side box) located in the Buëch River basin (left-side) in the South-East of France. Within the study area, the colors represent the types of crops irrigated by the gravity-fed network (source: BD Hydra V2 and RPG 2017). Bold numbers on the plots correspond to their identifiers. denotes crops simulated by the Optirrig-D model.*

For practical reasons of crop model parameterization, we focus on 16 plots of cereal (Fig. 2, right-side) made of 12 plots of winter cereal and 4 plots of springs cereal, that belong to 6 of the 10 irrigators sharing the gravity network. A description of the crop type, plot area and irrigator identifiers of the 16 cereal plots is available in Supplementary materials. Irrigation on the other plots served by the network is thus not driven by *TT* to be stopped at the end of the simulation period.

To verify that the co-simulation results are trustworthy, we conducted field surveys on the study area as direct observation of irrigators' practices and semi-structured interviews about the irrigation campaign that took place between May and September 2017. The interviews were conducted with four irrigators, the technician in charge of the water network regulation, and the President of the irrigator union as the information collected covered the entire irrigated command

area. The coordination of the gravity network through a daily slot calendar has been gradually abandoned during the last 15 years as it was temporally very restrictive according to the interviewees. We have captured the latest version in place, the one known to all the interviewees. The branches of the canal were watered according to four time-slots (A, B, C, and D, Fig. 2). During a time-slot, water flows only in the branches designated by the calendar (e.g. the green branch during slot A, the blue branch during slot B, etc.). The different daily slots follow one after the other in ten days. Currently, irrigators don't coordinate the water network anymore to trigger irrigation: the water flows simultaneously and continuously in all the branches of the canal until the end of the irrigation campaign. Other information collected is further detailed in Supplementary materials.

3.2 Optirrig-D: crop dynamics at the plot level

The Optirrig model is a two-layer structure in which the inner layer performs hydro-agronomic calculations, having rewritten and modified the concepts originally present in the PILOTE model (Mailhol et al., 1997, 2011; Khaledian et al., 2009; Feng et al., 2014) and now termed PILOTE-R as

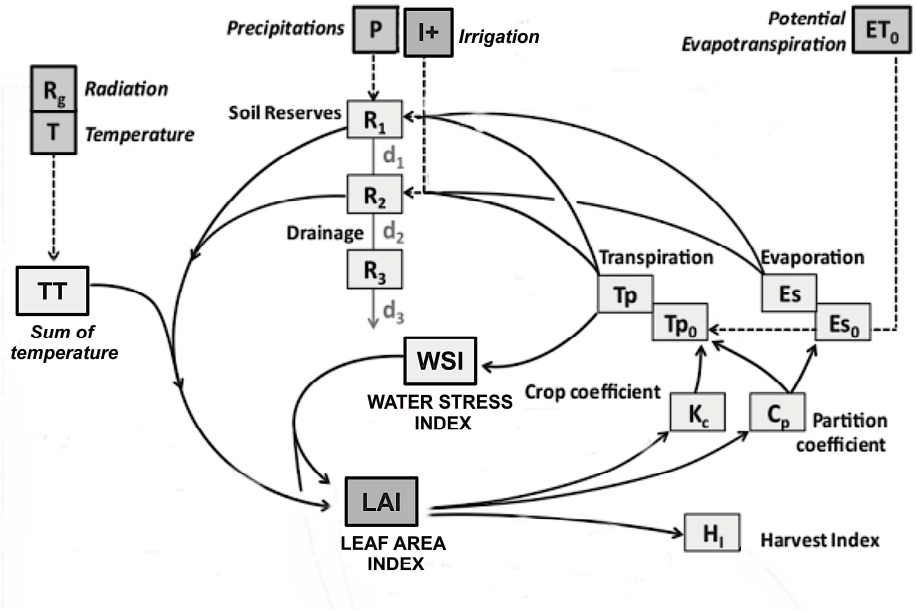

Fig. 3 (can be printed in black and white): Overview of the Optirrig model for the simulation of WSI and LAI variables (adapted from Cheviron et al., 2016). Climatic forcing are squares with thick contour lines, intermediate variables are pale grey sketches and key state variables are grey sketches with thick contours. Irrigation is noted I+ to indicate that this model forcing depends on the irrigation decision-rules.

coded in the R language. The outer layer of Optirrig allows the use of multiple runs for various numerical purposes, e.g. exploratory scenarios of irrigation and fertilization and/or climatic scenarios, uncertainty and sensitivity analysis, model fitting or irrigation. Figure 3 gives an overview of the structure and main variables of the model, among which are *LAI* and *WSI*.

The *Water Stress Index WSI* (the ratio between actual transpiration and maximal transpiration), is calculated by the soil module as a moving average of 10 days. The *Leaf Area Index LAI* simulation is performed using the following equation:

$$LAI(j) = LAImax\left[\left(\frac{TT(j)-Ts}{tf}\right)^{\beta} exp\left(\frac{\beta}{\alpha}\left(1-\left(\frac{TT(j)-Ts}{tf}\right)^{\alpha}\right)-\left(1-WSI^{\lambda}\right)\right)\right] \text{(Eq. 1)}$$

$$\text{where } TT(j) = \sum_{k=1}^{k=j}(T(k)-Tb) \text{(Eq. 2)}$$

and subscript *j* corresponds to a given *LAI* date, *T(k)* the average daily temperature of day *k*, *Tb* the base temperature of the crop, *LAImax* the maximum value of the *LAI* and *Ts* the temperature of emergence, *α* and *β* two shape parameters for *LAI* curves, *WSI* the water stress factor and *λ* a parameter governing plant sensitivity to water stress. Complementary description of the soil and crop modules of Optirrig are available in Supplementary materials.

Practically, we involved a recent version of the Optirrig model (Cheviron et al., 2016) developed at INRAE G-Eau. This Optirrig-D version specifically developed for the co-simulation approach ("D" denotes the specific daily horizon of simulation) allows the external forcing of irrigation instructions for certain time steps, before the calculation of model state variables which are always passed to the ABM at the end of the daily time step, whether irrigation takes place or not.

The Optirrig-D version developed in this study is thus a daily function derived from the Optirrig model, which is usually run without interruption from the beginning to the end of the simulation period. In this classical use, irrigation (I_+, in L m^{-2} d^{-1} in legal units, often given as mm) is either scheduled according to decision rules, resulting in an irrigation calendar, or decided from field data and/or model predictions, typically when the amount of water available in the root-zone reservoirs (R_1, R_2) goes under a certain threshold (see Supplementary materials). However, as the coupling with the ABM requires forcing I_+ according to agent actions, it is necessary to be able to modify it during the course of the simulation, at each daily time step.

3.3 WatASit-Aspres: collective irrigation at the gravity network level

We use the ODD protocol (Grimm et al., 2006; 2010) to describe the model.

3.4.1 Overview

The WatASit ABM is designed to simulate the irrigation operations of irrigators sharing a common water network during a collective irrigation campaign. It explicitly represents the irrigation

options left by the network constraints of the irrigators. The constraints taken into account in WatASit-Aspres are presented in Table 2. An irrigation possibility is generated on the plots where these constraints make irrigation possible at a given hourly time step.

Table 2: *The gravity network constraints in the WatASit-Aspres model.*

Network constraint	Case study specification
Number of irrigators per farm	*One irrigator per farm*
Number of simultaneous irrigations per irrigator	*One irrigation at a time per irrigator*
Daily time window (maximum daily working time of each irrigator)	*12h*
Plot flood duration	*Fixed*
Target irrigation dose	*Fixed*
Required branch canal flow serving the plot floodgate	≥ *plot flood rate (Qflood)*
Functioning of the network while raining	*Irrigation is not triggered if there is precipitation*

Entities

The model is based on the distinction between the elements that are involved in irrigation operations (called operational entities) and the areas over which operational entities can operate (called spatial entities) which are the farm plot, the farm, and the irrigation scheme area. In the model, the operational entities are the irrigator agents and the objects which are actionable by an irrigator agent, such as the network branch, intake, junction and release points, the floodgate at each farm plot, and the crops. The third kind of entity is an artifact that makes explicit some abstract things of the real world such as options to irrigate, called affordances, resulting from the interactions between an irrigator agent and a hydraulic object (typically a floodgate). Description of all entities is available in Supplementary materials.

Process overview and scheduling

The model is based on a double-time step. Each day, there is first initialization of the current precipitation conditions, and also of the number of days since the crops have not been irrigated. Then, every hour, the flow is updated in the network according to network junction state (i.e. ”opened ” or ”closed ”) and ended actions. Irrigation options are then generated on each farm. Depending on the irrigator’s decision-making rules (Fig. 4), an option can be chosen to make a flood action or ask for more water in the canal. An activity diagram presenting process scheduling is available in Supplementary materials, as well as detailed descriptions of the affordance generation sub-model, action execution sub-model, and simplified hydraulic sub-model of the gravity network.

3.4.2 Design concepts

WatASit represents the phase of implementation of actions according to the theory of Situated Action (Dreyfus, 1972, Suchman, 1987). In the model, the behavior of the irrigator agents is determined by their options to irrigate, which are re-evaluated at each hourly time step. Each agent chooses none or one option among its set of options and performs it. When one agent has performed an option, sets of options of all agents need updating. Irrigator agents interact indirectly with each other by reducing the amount of water available in the network which affects the options of the other agents sharing the same or a downstream branch. Design concepts of the model are further detailed in Supplementary materials.

3.4.3 Details

The model, called WatASit-Aspres, has been already deployed to represent the Aspres-Sur-Buëch case study (Richard et al., 2020) for which the specific parameterization has been detailed. Spatial entities were initialized using a pre-processing that consists of rasterizing the farm plot shapefiles (Table 3) onto a 54x44 cell grid with a resolution of 75 m. The water network was also initialized using shapefiles (Table 3). At the initialization, farm plots served by the network were listed for each canal branch. Daily precipitation input comes from the French near-surface SAFRAN reanalysis (Vidal et al., 2010).

Table 3: *Data type and sources for the initialization of the WatASit-Aspres model.*

Data type	**Data source**
Daily precipitation	SAFRAN reanalysis (Vidal et al., 2010)
Farm plot shapefiles, areas and crop types	"*Registre Parcellaire Graphique*" (RPG) 2017[2]
Water network shapefile	BD HYDRA (v2) 2015[3]

3.5 Coupled model inputs and parameterization

As for WatASit, Optirrig-D inputs are the climatic forcing (precipitation, temperature, global radiation, and reference evapotranspiration) and were obtained from the French SAFRAN reanalysis (Vidal et al., 2010) from January 1, 2017, to December 31, 2017.

Parameters of both models are specified in Appendix A (Table A.1). Concerning Optirrig, typical parameters of winter soft wheat have been considered for all winter cereals. Parameters for spring cereals are based on typical spring oat parameters. For a given crop, literature (e.g. Cox and Joliff, 1986; Howell et al., 1996) can provide some parameters such as the *LAImax*, *tf*, and the *TM* parameter. All these parameters are linked to the base temperature *Tb* parameter, which is also

2 A version 2.0 distributed since 2015 is directly accessible online at http://professionnels.ign.fr/rpg
3 Accessible online at http://hydra.dynmap.com/index_.php?grFrame=1

given in relevant literature (see Mailhol et al., 1997). Sowing DOY are average dates reported by irrigators during the 2016-2017 crop campaign for the study area. Available water reserve (*AWR*) and maximum profile and rooting depth (*Pmax*) for the study area are from the PACA Regional Soil Reference System described in Braud et al. (2013). Moreover, *AWR* in the soil of the plots in the study area was calculated from the PACA Regional Soil Reference System using a method presented in Manus et al. (2009).

Concerning WatASit-Aspres, the key parameter is the target plot flood duration (*D*) as irrigation continues until reaching 4 hours for a plot area of 1 hectare. As the flow rate of the floodgate (*Qflood*, see Table A.1) is fixed, it is equivalent to inject a fixed irrigation dose of 43.2 mm per per day (*Idose,* see Table A.1). Other parameters are specific irrigation operations and gravity-fed network characteristics mentioned by the irrigators for the study area. In particular, the reference flow rate at the network intake (*Qref*, see Table B.1) was determined by the irrigators to avoid overflow and comply with the river abstraction rules during the 2017 low-flow period (also note that no irrigation restrictions came into effect during the 2017 cereal campaign).

Decision-making for irrigation consists in irrigating crops after several days without sufficient precipitation inputs to contain as much as possible a maximum of successive non-irrigated days (Fig. 4). As water is not always sufficiently available to irrigate a plot, irrigator agents have three kinds of options: irrigate a plot with a *Flood* option, ask for increasing the water flow in the network with an *AskMoreWater* option, and do something else during this time step. Finally, a plot for which the irrigator has not had an option to irrigate for a certain period of time is abandoned for irrigation (see Fig. 4).

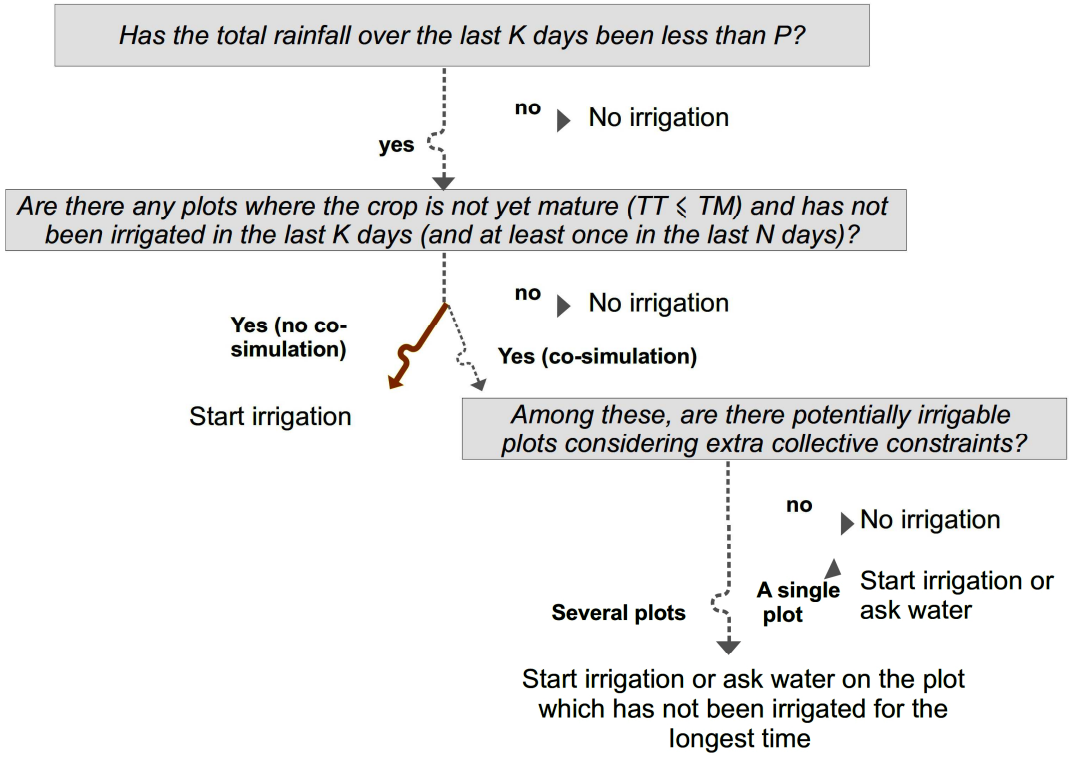

Fig. 4 (can be printed in black and white): Irrigation decision-rules considered for the case study. Typical values are K=12 days, P=120 mm, N = 45 days and TM = 1200°C for spring cereals and 1700°C for winter cereals.

297

298 3.6 Simulations

299 We simulated the 2017 retrospective irrigation campaign under four levels of collective
300 network constraints (Table 4). The co-simulation approach is used for simulating the space collective
301 constraint due to the sharing of water among irrigators through the gravity (Fig. 1 [b]). The time
302 collective constraint is represented by the time-slot-based coordination (described in Section 3.1 and
303 Fig. 2 right-side) for the study area, either in the ABM or directly implemented in the crop model.

304 ***Table 4.*** *Levels of collective irrigation constraint to operate irrigation during the 2017 irrigation*
305 *campaign of the four simulation runs. The time collective constraint is the daily time-slot-based*
306 *coordination presented in Section 3.1 and Figure 2. The space collective constraint is the sharing of*
307 *water through the gravity network simulated by the WatASit-Aspres model with constraints detailed*
308 *in Table.*

Simulation name	Abbreviation	Collective constraint type		Co-simulation
		Gravity network	Time-slot based coordination	

No collective constraint	*NoCollCons*	*No*	*No*	*No*
Space collective constraint	*SpaCollCons*	*Yes*	*No*	*Yes*
Time collective constraint	*TimCollCons*	*No*	*Yes*	*No*
Space and time collective constraints	*SpaTimCollCons*	*Yes*	*Yes*	*Yes*

We called “No collective constraint” (NoCollCons) the simulation in which irrigators optimally irrigate at the plot level without nor the spatial collective constraint due to the gravity network neither the time collective constraint due to the time-slot-based coordination. Irrigation is simulated at the plot level by the Optirrig-D model only (Fig. 1 [a]). This simulation thus shortcuts the WatASit-Aspres model during the whole simulation period, including the irrigation campaign. NoCollCons does not consider any possibility of conflict between irrigators for the sharing of water. Irrigation decisions are then equivalent to a regular plot-based calendar.

We called “Space collective constraint” (SpaCollCons) the simulation in which irrigation is simulated at the network level by the coupled models (Fig. 1 [b]) without the time collective constraint due to time-slot-based coordination. The sharing of water for the irrigation operations is spatially driven by the gravity network constraints (Table 2) that cannot allow distributing water everywhere at the same time. As irrigators do not coordinate the network, water flows simultaneously in all the branches of the gravity network during the irrigation campaign.

“Space and time collective constraints” (SpaTimeCollCons) is the simulation in which irrigation is simulated at the network level by the coupled models (Fig. 1 [b]), driven both by the gravity network constraints (Table 2) and by the time-slot-based coordination. It depicts flow coordination using a daily slot (i.e. A, B, C or D) for each network branch constraining temporally irrigation operations, as described in Section 3.1 and presented in Fig. 2 (right-side).

Finally, “Time collective constraint” (TimCollCons) is the simulation in which irrigators irrigate at the plot level following the time-slot based coordination but without the gravity network constraints. Irrigation is simulated at the plot level by the Optirrig-D model only (Fig. 1 [a]) with irrigation dates constrained by similar daily slots as in the SpaTimCollCons simulation, but directly generated in the Optirrig-D model.

The total simulation period runs from 15 October or Day of Year 1 (DOY 1), when the winter cereals are sown, to the end of the cereal season on July 31 (DOY 289). The co-simulation starts at the beginning of the irrigation campaign on May 1st (DOY 198) when irrigators of Aspres-Sur-Buëch water their network each year. 2017 is taken as a reference for the climatic forcing. Simulation output (i.e. dates of irrigation, *LAI*, *TT,* and *WSI* on each farm plot) are collected from the two models by recording attributes of WatASit-Aspres entities (i.e. irrigated state of farm plot entities) and Optirrig-

D variables (i.e. cereal *LAI*, *TT,* and *WSI*) in the R software during the irrigation campaign. In sections 4.3 and 4.4, we also indicate an output from an extreme simulation run called “NoIrri” without any irrigation input during the irrigation campaign, as a benchmark. *WSI* equals 1 is corresponding to low plant water stress. Blue, yellow, orange and red colors denote low (WSI > 0.75), medium (0.5< WSI ≤0.75, high (0.25 < WSI ≤ 0.5) and very high (WSI ≤ 0.25) water stress, respectively.

4. Simulation results

4.1 Irrigation dates for the four levels of gravity collective network constraints

This section presents the irrigation dates of the 16 cereal plots simulated for the four levels of collective irrigation network constraints (Table 4).

The two top lines NoCollCons and SpaCollCons of Figure 5 correspond to irrigation dates when the network is not coordinated. In the NoCollCons simulation, the plots are irrigated simultaneously on a regular 12-days basis until maturity temperature is reached (materialized by the green lines). This is not the case in the SpaCollCons simulation in which we observed significant delays between the series of irrigation, and no irrigation for the most downstream plots 10, 14 and 4. For instance, 28 days separate the series of irrigation between DOY 207 and DOY 235. Taking into account the spatial network constraint thus leads to both the abandonment of the most downstream plots (i.e. plots 4, 10, and 14) and significant delays in series of irrigation. As a consequence of irrigation delays, maturity of the crops is reached later for some of the crops (e.g. 3 and 4 days for plots 15 and 16, respectively) in the SpaCollCons simulation than in the NoCollCons.

The two bottom lines TimCollCons and SpaTimCollCons of Figure 5 correspond to irrigation dates when the network is coordinated. Irrigation operations simulated in the TimCollCons are distributed differently over time from one plot to another and form a pattern driven by the four A, B, C, and D slots that irregularly repeats until the maturity temperature is reached. In the SpaTimCollCons simulation, the pattern is not exactly repeated as irrigation operations are constrained both by daily slots and the gravity network constraints, notably the precipitation of the day (Table 2). However, reaching plant maturity is not necessarily penalized, and happens even earlier on some plots (2, 5, 6, 10, and 16).

Comparing the SpaCollCons and the SpaTimCollCons simulations, the plots are almost always irrigated at the same time when irrigation is not coordinated (SpaCollCons). But the absence of network coordination leads to significant delays from a series of irrigation to another, and a lack of irrigation in most downstream plots, which is prevented by the coordination of the network (SpaTimCollCons).

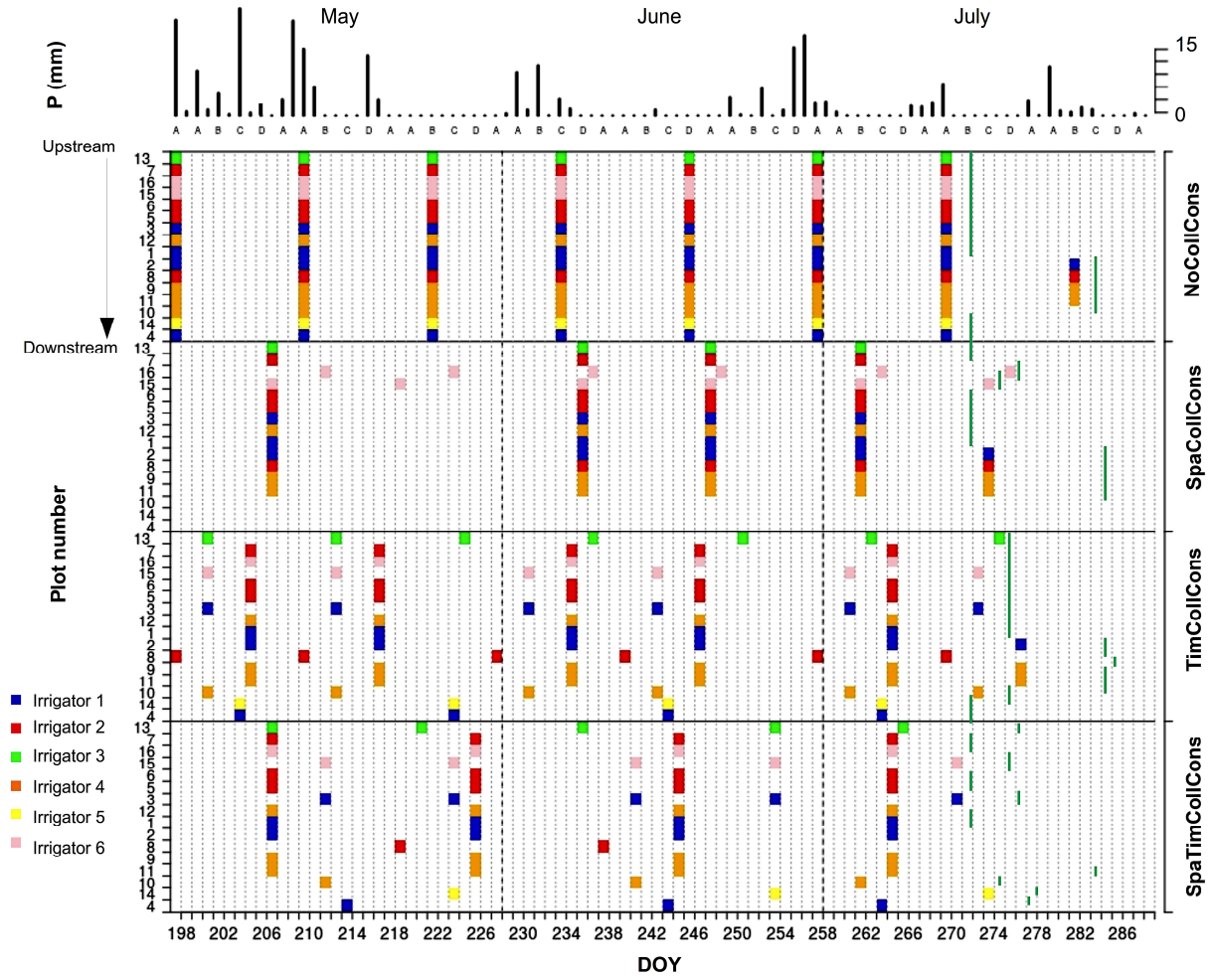

Fig. 5 (to be printed in color): Irrigation dates within the 16 cereal plots from May 1st (DOY = 198) to July 31 (DOY = 289). NoCollCons and TimCollCons are simulations at the plot level. SpaCollCons and SpaTimCollCons depict co-simulations at the network level. Colors are irrigator identifiers, black ticks are precipitation (P, in mm). "A", "B", "C", and "D" labels indicate the coordination daily slots. Green ticks show when the maturity is reached by the plant.

4.2 Elements of model validation

Results of the SpaCollCons retrospective simulation are consistent with the elements identified during the field survey for the 2017 real irrigation campaign that took place as in the SpaCollCons simulation in the absence of time-slot-based coordination of the network branches. Namely, the plots located downstream of the gravity-fed network (cereal plots 10, 14, and 4) were not irrigated at all during the 2017 irrigation campaign. The interviewees mentioned 4 irrigation dates by plot for the middle plots (i.e. plots 2, 8, 9, and 11), and 5 for the upstream plots (i.e. the other plots) during the cereal campaign, which is in line with the SpaCollCons simulation results. In addition, harvest dates for the 2017 cereal campaign on the study area range from July 15th (DOY 273) to July 30th (DOY 288), which is very close to the simulation window for cereal maturity dates ranging from July 14th (DOY 272) to July 26th (DOY 284).

4.3 Potential impacts of the collective irrigation constraints on average LAI and WSI dynamics

This section focuses on the average LAI and WSI time-series integrated over the irrigation campaign (Fig. 6).

In the SpaCollCons simulation, the absence of network coordination (Fig. 6, *WSI*, green line) leads to earlier medium water stress on average (i.e. 10 days earlier) than when the network is also coordinated in the SpaTimCollCons simulation (orange line). The absence of coordination induces an impact on cereal growth: maximum of average *LAI* (Fig. 6, *LAI*, green line) is reached 12 days earlier and about 1 point lower than when the network is coordinated (green line). Irrigation operations are less frequent and less distributed over time in the absence of coordination (Fig. 6, irrigation number). The network specific constraints therefore significantly impact average crop water stress when the network is not coordinated, while network coordination tends to delay the impact over the irrigation campaign.

394

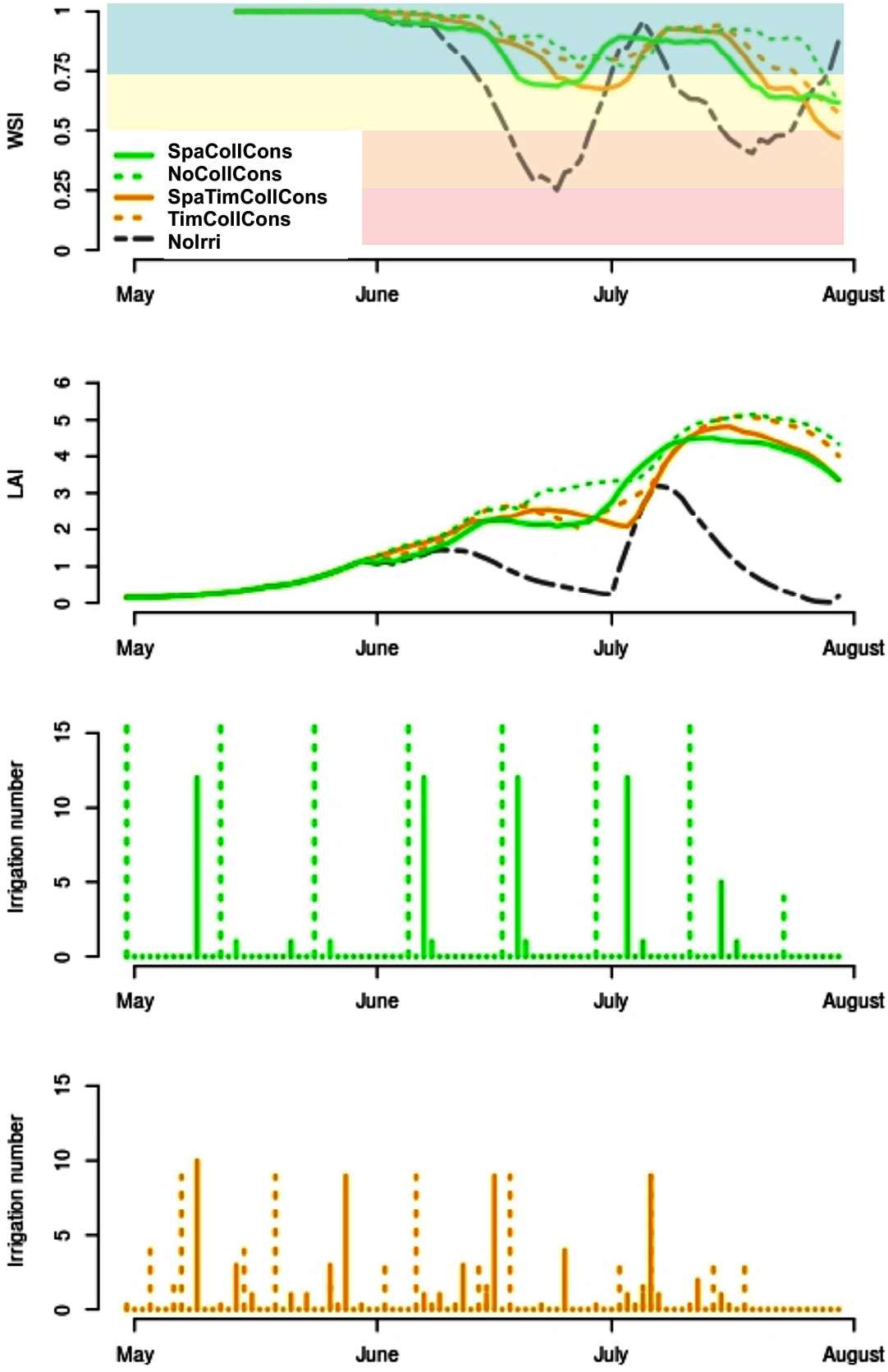

Fig. 6 (to be printed in color): LAI, WSI and irrigation number evolution for all cereals during the irrigation campaign from May 1st to July 31. Green and orange lines are the SpaCollCons and SpaTimCollCons simulations, respectively. Dotted green and orange lines are the NoCollCons and TimCollCons simulations, respectively. Background blue, yellow, orange and red colors indicates low, medium, high and very high plant water stress severity, respectively.

395 4.4 Spatial distribution of water stress severity at the irrigation network level

396 In this section, we measure the water stress severity of a cereal plot as the greatest stress
397 level undergone by this cereal over a simulation. In Optirrig-D the time-evolution of *WSI* values is
398 the consequence of both precipitation and irrigation events from the 10 past days, and *WSI* is the
399 main control over *LAI* values. Since severe water stress has an exponential impact on biomass
400 growth, it makes sense to locate it during the irrigation campaign

401 Figure 7 shows the cereal number for each water stress severity level and Figure 8 locates
402 maximum stress severity within the 16 cereal plots. In the NoCollCons simulation, cereal maximum
403 stress is low (blue plots) for all spring cereals and is high (orange plots) for all winter cereals. This
404 difference is due to the Optirrig-D parameters that differentiate these two cereal types, especially the
405 sowing period (see Appendix A). In the TimCollCons simulation, the coordination of the irrigation
406 network induced fewer differences in cereal stress severity than in the NoCollCons simulation: three
407 plots move from high to medium stress (Fig. 7, yellow plots). Daily slot coordination has thus a slight
408 beneficial impact when irrigation is simulated without the specific gravity network constraints. In the
409 absence of irrigation (NoIrri), winter cereals have dropped one class of maximum stress, from high
410 to very high (Fig. 8, the red plots), and spring cereals have dropped two classes, with high stress
411 (Fig. 8, the orange plots).

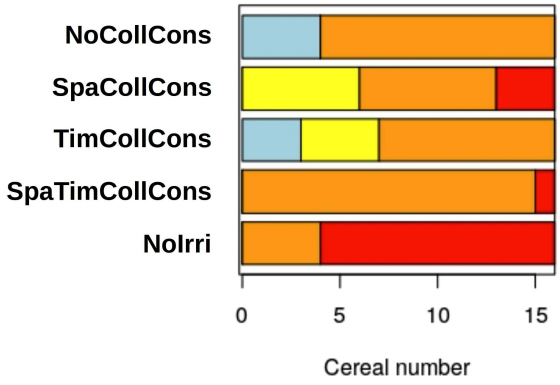

Fig. 7 (to be printed in color): Cereal number for each water stress severity level. Blue, yellow, orange and red colors denote low ($WSI > 0.75$), medium ($0.5 < WSI \leq 0.75$, high ($0.25 < WSI \leq 0.5$) and very high ($WSI \leq 0.25$) stress, respectively.

412 In the SpaCollCons simulation, a spatial dichotomy appears between the upstream part of
413 the network, where stress severity is medium to high, and the downstream part, where all three
414 cereal plots have very high maximum stress (Fig. 7 and Fig. 8). This dichotomy is not observed in
415 the TimCollCons simulation and is less obvious in the SpaTimCollCons simulation when irrigation is
416 simulated at the network level with daily slot coordination. In addition, maximum water stress globally
417 occurs earlier when the network is not coordinated (Fig. 8, SpaCollCons).

418

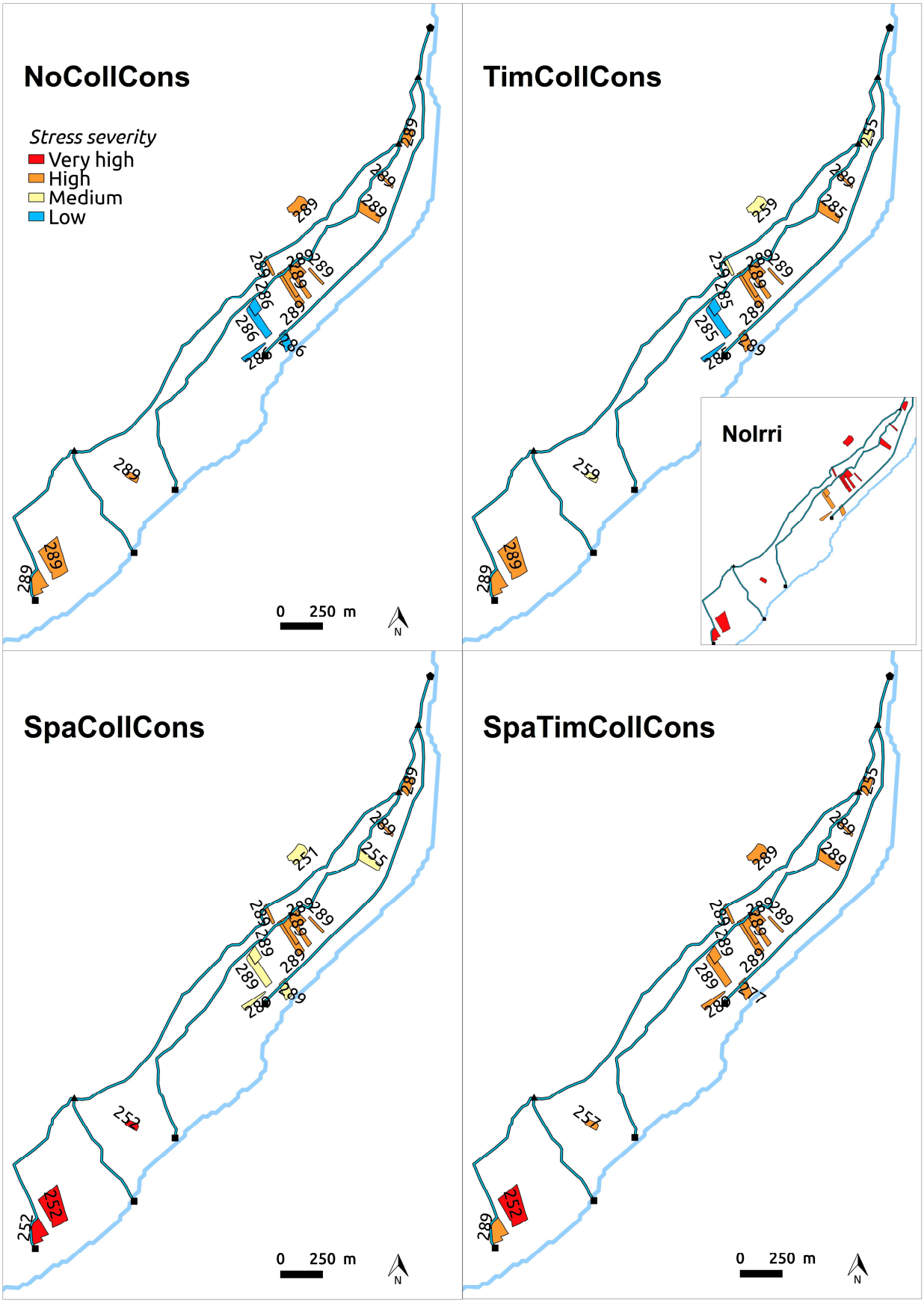

Fig. 8 (to be printed in color): Location of the maximum stress severity within the 16 cereal plots, according to the NoIrri, NoCollCons, TimCollCons, SpaCollCons and SpaTimCollCons simulations. Numbers are Days of Years of occurrence of the maximum water stress.

5. Discussion

In this section, we first discuss the proof of concept and the added value of the co-simulation approach for the study area. We also provide a sensitivity analysis to the key parameters. Then we consider the limitations of using coupled models and co-simulation, before presenting the key perspectives for future research.

5.1 Proof of concept and added-value of the co-simulation approach

Applied on a typical gravity network in South-Est of France, the co-simulation approach allowed to capture the potential impacts of the space and time constraints due to a gravity network on plant LAI and WSI dynamics in the study area. Compared to the first approach developed in Richard et al. (2020a) with the ABM alone, the co-simulation makes it possible to tackle the impact on some crop variables (i.e. *LAI, WSI*) widely used in agricultural system studies. The key point was the derivation of the crop model into a daily function, which made possible to run it as a slave model of the ABM during the course of the simulation, and thus to give daily irrigation orders at the plot level according to the collective sharing of water in the ABM.

The proof of concept also lies in comparing progressive levels of irrigation collective constraints on irrigation dates (Section 4.1), LAI and WSI dynamics (Section 4.3), and provides access to a tactical assessment of the spatial variability of plant water stress occurring at the network level during a collective irrigation campaign (Section 4.4). Simulation results highlight that network coordination tends to limit the impact of the gravity network constraint by delaying average plant water stress and increasing maximum average plant growth in comparison with simulation at the plot level. This is because the time-slot-based coordination reduces the effect of network flow along its upstream-downstream gradient, limiting missed irrigation for the most downstream plots, and thus reducing severe stresses on them.

Most approaches in the literature are merging crop models into a unique integrated simulation platform (e.g. Belcher et al., 2004; Raes et al., 2009; García-Vila and Fereres, 2012). As experienced by Marohn et al. (2013), coupling individual models in a co-simulation approach prevented simplifying many dynamics that are exogenous to the coupled model. For example, the precocity of plant water stress when the network is not coordinated (i.e. SpaCollCons simulation), as a result of irrigation delays caused by the network gravity constraint, could not have been represented by either model individually. The approach, therefore, enables the development of individual models simultaneously and independently, with people yet familiar with them.

5.2 Sensitivity analysis to key parameters

We performed a one-at-a-time exploration to assess the influence of key parameters (i.e. the maximum flow at the gravity network intake *Qmax*, the *flood duration* for irrigating 1 ha of plot, and the *time slot period* for the gravity network coordination) on the percentage of days with low, medium, high and very high plant water stress during the irrigation campaign. We changed parameter values

one at a time by letting the other parameters to their nominal values: *network intake flow* is 0.09 m^3 s^{-1} (the river flow is considered as non-limiting), the *flood duration* is 4 hours per hectare, and the *daily slot period* is 10 days. We repeated each exploration run for the two SpaCollCons and SpaTimCollCons simulations that rely on the coupled models and co-simulation. Results are plotted in the graphic available in Supplementary materials.

The percentage of days with plant water stress during the irrigation campaign is not sensitive to the *Qmax* and *flood duration* parameter when the gravity network is coordinated (SpaTimCollCons). In the absence of network coordination (SpaCollCons), higher *Qmax* parameter value reduces plant water stress. The percentage of days with low plant water stress increases from 83 to 87 when Qmax exceeds 0.3 m^3 s^{-1}. The optimum of 87 days is reached when *Qmax* equals 0.35 0.3 m^3 s^{-1}. In addition, the percentage of days with medium, high and very high plant water stress is null when the *flood duration* paremeter is 4 hours per hectare, that correponds to the value mentionned by the irrigators for the study area. Concerning the effect of the modalities of network coordination through daily slots (i.e. the *time slot period* parameter), a period of 8 consecutive days (the two first days for *Slot A*, the next two days for *Slot B,* day 5 for *Slot C,* and the last 3 days for *Slot C)*seems to be slightly more advantageous than the other modalities for increasing the percentage of days with low plant water stress during the irrigation campaign.

5.3 Limitations of the co-simulation approach

As described by Letcher et al. (2013), the coupling of individual models is only possible under certain conditions. First, individual model components do not necessarily work on the same space and time scale, but disaggregation or aggregation must often be applied to link models. In our approach, the water network results from aggregation in the ABM of the elementary spatial entities (the plots). In addition, the ABM has also a double-time scale (hourly and daily). These double space and time scales make it possible to link daily irrigation at the plot level in the crop model, with the constrained operations at the network-scale.

Specific protocols and associated computer software and API exist to develop and merge models components in integrated development environment. A famous example is the Functional of such standard Mock-up Interface specification (FMI) and the FIDE environment (Cremona et al., 2016). Bulatewicz et al. (2010) who used similar standards for model linking called OpenMI raised several benefits of using such standard specifications methods. In our case, as a proof of concept of a specific coupling, we did not develop such generic components but our work is a first step for doing this since the model components that we developed provide almost the same API that the one that Bulatewicz et al. (2010) developed for the model components they developed (namely: get values, set values and advance simulation in time).

The level of detail should also be appropriate for a specific purpose otherwise the coupled model could be overly complex, with difficulty to identify feedback drivers and over-parameterization. In our approach, the chosen parameters have been kept as simple as possible. It distinguishes only

two classes of crops, summer and winter cereals, whereas it could be specific to each cereal variety (barley, wheat, etc.).

In addition, the inter-related operations between hay-mowing, garden watering, and irrigation has not been considered but could have a significant impact on gravity-fed irrigation (Merot et al., 2008). This could be achieved by adding an explicit representation of garden watering and mowing operations in the WatASit-Aspres model or using a crop model representing such operations.

5.4 Perspectives for future research

5.4.1 Complementary elements for model validation and genericity

For future research, validating further the coupled model to site-specific data can be addressed by comparing simulated *LAI* with *LAI* retrieved from optical or remote sensing techniques (e.g. Zheng and Moskal, 2009).

Deploying the co-simulation approach to another case study means that detailed information is required to set up the model parameters, potentially limiting the spatial scale. The conceptual structure of the ABM, designed to be as generic as possible, allows changing the major structural constraints. However, the use of different irrigation decision rules may require specific crop indicators to be coupled. For instance, in systems where irrigation is finely controlled, evapotranspiration or *AWR* are often used to pilot irrigation. Such variables could be easily retrieved from the crop model.

Coupling further specialized models to the system, as the SIC hydraulic model (Baume et al., 2005), could also be useful for the modeling in the study area where the representation of flow in the network is a key issue.

5.4.2 Using the co-simulation approach to study the feedback loop of plant dynamics on irrigation practices

The proposed coupling is bi-directional, but the coupling from the crop model to the agent-based model is probably less impacting than the coupling from the agent-based model to the crop model. Indeed, we dictated crop dynamics by forcing irrigation from the agents but only precipitation *P* and sum of temperature *TT* come from the crop model to drive the agent's behaviors (see Fig. 1 [b]). Reinforcing the coupling from the crop model to the agent-based model could allow studying the feedback loop of plant dynamics on irrigation practice adaptation. It could be achieved by integrating, for example, the *WSI* variable in the irrigation decision-rules, as a proxy for crop water stress.

However, rather than looking at *WSI* which is an elaborated variable, and which corresponds to a conceptual representation, we could also reason in the percentage of the available water reserse *AWR* which is a phenomenological variable and concretely observable (sensors in the ground). This would avoid the *WSI* threshold phenomenon: when *WSI* decreases from 1 to *X*, no effect, then the effect is exponential when *WSI* decreases from *X* to 0 (especially if we reason on *WSI* averaged

over time, and even more so over long periods). This is why we used *WSI* classes in sections 4.3 and 4.4 rather than comparing values directly.

5.4.3 Requirements to be addressed for achieving an operational approach

The co-simulation approach entails the optimization of gravity irrigation networks in terms of retrospective analysis. A follow-up of this work could be to assess variants of the daily slots coordination to determine optimal coordination modalities for maximizing plant growth or minimizing crop water stress during an irrigation campaign.

The impact of such irrigation network optimization could be evaluated in terms of criteria such as water productivity, crop yield, or water-saving per season. As agricultural yield can be simulated by the crop model with extra parameters (e.g. plot density) it would be possible to establish the link between the maximum plant water stress that has occurred during an irrigation campaign and the final yield obtained. This could be of interest to make a cost-benefit analysis of different irrigation solutions. Overall, to be performed in an operational mode for optimizing an irrigation network in real-time conditions, the approach should integrate climatic forcing forecasts, and be further validated to site-specific data.

6. Conclusions

In this study, we proposed a co-simulation approach to tackle the potential impacts on crop growth and water stress of four progressive levels of spatial and temporal constraints due to a gravity irrigation. The approach relies on the coupling of a crop model at the plot level with an ABM at the network level. As a proof of concept, we applied it on a typical gravity network in South-East of France. Four progressive levels of collective irrigation constraints were simulated (i.e. no collective constraints, space collective constraints, time collective constraints, and space and time collective constraints). Retrospective simulation of the 2017 irrigation campaign is consistent with field surveys, and simulation results suggest that plant water stress could be underestimated when simulated at the plot level rather than at the network level. The co-simulation approach provides access to a tactical assessment of the spatial variability of plant water stress occurring during a collective irrigation campaign. Spatially, the most severe water stress was observed for the plants located furthest downstream of the network. Temporally, the absence of network coordination can lead to earlier plant water stress and lower plant growth during the collective irrigation campaign, while time-slot-based coordination tends to delay the impact. For future research, reinforcing the coupling from the crop model to the agent-based model could allow to study the feedback loop of plant dynamics on irrigation practice adaptations. It is also a first step towards an optimization approach for irrigation networks.

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764 **Appendices**

765 Appendix A

766 Table A.1: Parameters used in the co-simulation approach.

Category	Name	Description	Unit	Value	
Optirrig model				*Winter cereal*	*Spring Cereal*
Plant	a_w	Controls the decrease of H_I for low *LAI* values	-	0.1	0.2
	$H_{I\,pot}$	Potential H_I (Harvest Index)	-	0.5	
	$K_{c\,max}$	Maximum value of K_c (crop coefficient)	-	1.2	
	LAI_{max}	Maximum LAI value	-	6	7
	G_{hu}	Percentage of grain humidity	-	15	
	RUE	Radiation Use Efficiency	-	1	
	α *1*	First shape parameter for LAI curves	-	2	20
	α *2*	Second shape parameter for LAI curves	-	2	3.5
	β	Third shape parameter for LAI curves	-	6	2.5
	λ	Harmfulness of the water stress	-	1.25	
Soil	K_{ru}	Easily usable reserve/field capacity	-	0.6	0.65
	P_{max}	Maximum profile and rooting depth	m	0.36	
	θ_{fc}	Field capacity	-	0.29	
	θ_{wp}	Wilting point	-	0.12	
Temperature	T_i	Temperature sum for root installation	°C	450	200
	T_M	Temperature sum to reach the maximum LAI	°C	1700	1200
	T_s	Temperature sum for crop emergence	°C	100	80
	T_{s1}	Temperature sum for the 1st critical stage	°C	900	
	T_{s2}	Temperature sum for the 2nd critical stage	°C	2100	1600
Management	-	Soil reserve when starting the simulation	mm	340	
	-	Sowing DOY	-	1	198
WatASit model					
	K	Maximum number of days since the last irrigation of the plot, or with precipitation inferior to P	-	12	

Irrigation decision-rules	*N*	Maximum number of days without irrigation, if this number is reached, irrigation shall be abandoned on that parcel for the remainder of the irrigation campaign	-	45
	P	Amount of precipitation receive during the last N days. Irrigation of the plot is considered only if this quantity is not reached.	mm	120
Irrigation operation	*D*	Target duration to flood a plot	h/ha	4
Gravity-fed network	*Qref*	The reference flow rate at the network intake	$m^3 s^{-1}$	0.09
	DivCoeff	The diversion coefficient at the network junctions	-	0.5
	S	The seepage rate considered along each network branch	$m^3 s^{-1} .km^{-1}$	0.0067
	Qflood	The minimum flow rate required to flood a farm plot served by the gravity-fed network	$m^3 s^{-1}$	0.03
	Qrung	The flow rate corresponding to a floodgate rung at the network intake. When agents ask for more water, flow at the network increases by this value, until overflow rate is reached.	$m^3 s^{-1}$	0.01
	Qmax	The overflow rate of the network : flow rate at the intake cannot exceed the value	$m^3 s^{-1}$	0.15
Irrigation dose	*Idose*	Fixed irrigation dose	mm	43.2
Co-simulations				
Start_simulation_date (DOY)	*startDate*	The date when simulation starts.	-	15/10/2016 (1)
Start_irrigation_date (DOY)	*irriDate*	The date when the irrigation campaign starts.	-	1/5/2017 (198)
End_simulation_and_irrigation_date (DOY)	*endDate*	The date when the irrigation campaign ends, and also the simulations.	-	31/7/2017 (289)

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