Irrigation efficiency and optimization: the Optirrig model

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Developed by INRAE, Optirrig is a software tool for generating, analysing and optimising irrigation scenarios. It is based on a simplified description of plant growth according to the evolution of water and nitrogen resources in the soil. It compares the merits of different irrigation strategies according to different constraints (water quota, periods of limited availability, prefectoral decrees, water and energy costs), for operational objectives at the plot, farm or territory level.

The Optirrig model

The Optirrig model (Cheviron et al., 2016) is a two-layer structure that takes most of its inner loop from the former Pilote model (Mailhol et al., 2018) following the original principle of parsimony for the number and nature of mattering variables, and the links between them. However, this "hydro-agronomic" loop has been recently rewritten in R language and modular form, so as to allow collaborative development, model analysis and the inclusion of new processes, among others the irrigation efficiency module. The outer layer of Optirrig consists in a series of scenarios modes that have in common the use of multiple runs, either to achieve exploratory scenarios (tests of irrigation and fertilization practices, climatic scenarios), numerical analysis (uncertainty and sensitivity analysis), model fitting) or irrigation optimization (ex-post optimization up to now, quasi-real-time optimization in ongoing projects).

Figure ❶ details the hydro-agronomic loop (Figure ❶a), how the irrigation signal spreads across the model variables (Figure ❶b) then where calculations dedicated to irrigation efficiency take place (Figure ❶c) and finally how different irrigation scenarios are handled in "scenarios mode" to evaluate their impact on irrigation efficiencies (Figure ❶d). The model runs at a daily timestep but its seasonal variables (e.g. harvest index Hi, crop yield Y) as well as the final values of the underlying daily variables (e.g. total dry matter TDM) may be anticipated, provided the user is far enough in the course of the season. And so are the values of the seasonal indicators (e.g. total water amounts used, financial profit) which provides a possible control over optimization attempts, linking the operational (short-term) and tactical (season) horizons.

Overall, the key parameters of the hydro-agronomic loop are field capacity and soil depth (i.e. a correct determination of the available water reserve) and the central variable is the leaf area index LAI. Good predictions of the LAI dynamics, leaning on "phenological" thermal time parameters associated with crop development stages, generally ensure reliable dynamic predictions for model variables calculated next. It should be noted that water stress affecting LAI is calculated as a relative deficit of evapotranspiration while water stress affecting biomass production (TDM) is calculated as a deficit of transpiration, with the possibility to adjust specific and different values of stress "harmfulness" (the λ coefficient next to water stress in Figure ❶a). This is an interesting degree of freedom in model parameterization, to separately control the magnitude of the LAI and TDM terms once the correct dynamics have been found.

Irrigation efficiency

From the canal to plant leaves

Irrigation water goes from the water source (canal, river, groundwater table or reservoir) to plant roots and leaves through a sequence of processes and scales:

• pressurized flow for pumping and water abduction to the plot, with regular (leakage issues, or normal functioning of rainguns) or singular (accidental breakdowns of pipes, local damages to drip irrigation tapes) losses,

• multiphase flow in air when using sprinklers, with (i) atomisation and loss of a small mass fraction of the jet, whose transport is governed by wind and not by gravity anymore, and (ii) deformation of the wetted perimeter (the region impacted by liquid droplets) due to wind drift that takes a fraction of water out of the plot limits,

• possible ponding during excessive-rate irrigation, especially during the wetting phase of dry soils, at the risk of runoff, excessive evaporation or deep drainage,

• slow free surface flow during gravity irrigation, with the previous sources of losses plus uneven water distribution,

• matric and/or preferential flow in soils during infiltration, then possibly excessive storage in soils when compared to cumulative root water uptake,

• root water uptake and conduction in plant organs through successive thresholds of pressure difference, finally resulting in phase change (evaporation).

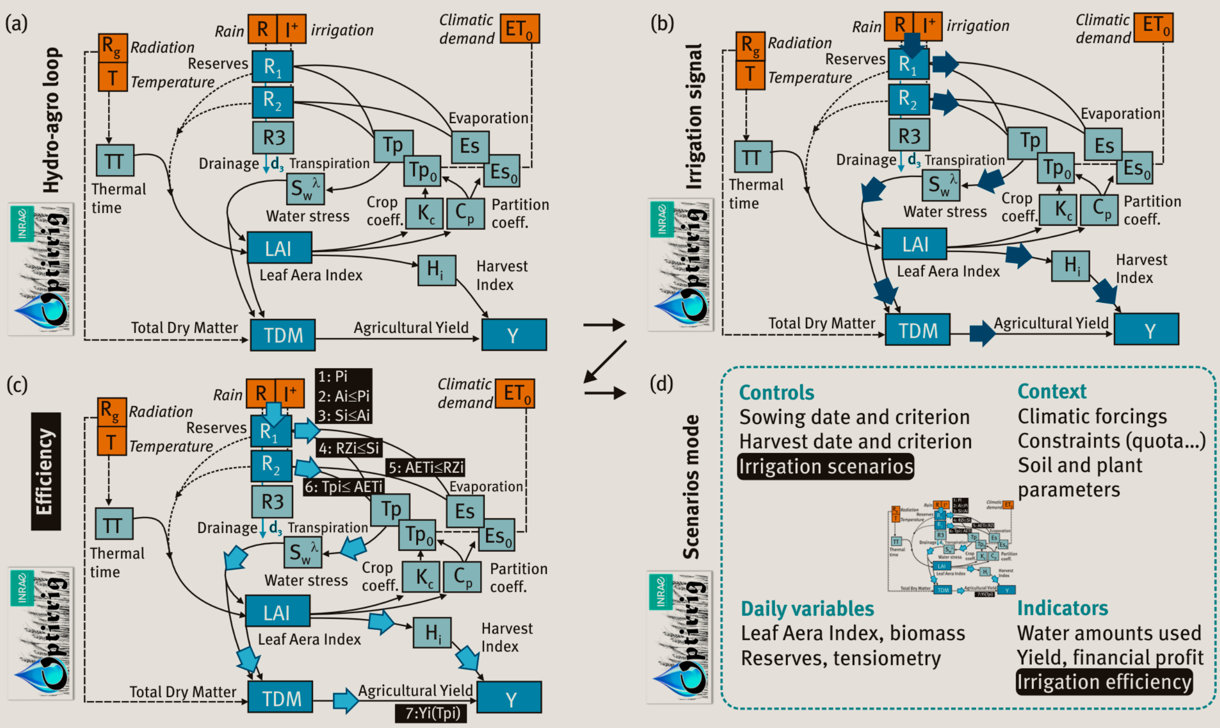
Although not fully covering the topic, the expression "from the canal to plant leaves" summarizes the chain of spatial scales, irrigation technologies and physical processes successively "experienced" by irrigation water. The OPTIMISTE research team (Optimization of the Piloting and Technologies of Irrigation, Minimization of Inputs, Transfers in the Environment) of UMR G-EAU, INRAE, at Montpellier, gathers detailed knowledge on the physical processes at play and their metrology, for data collection then to derive the simplified formulations and order-1 processes to be encoded in Optirrig.

Cascade Scheme

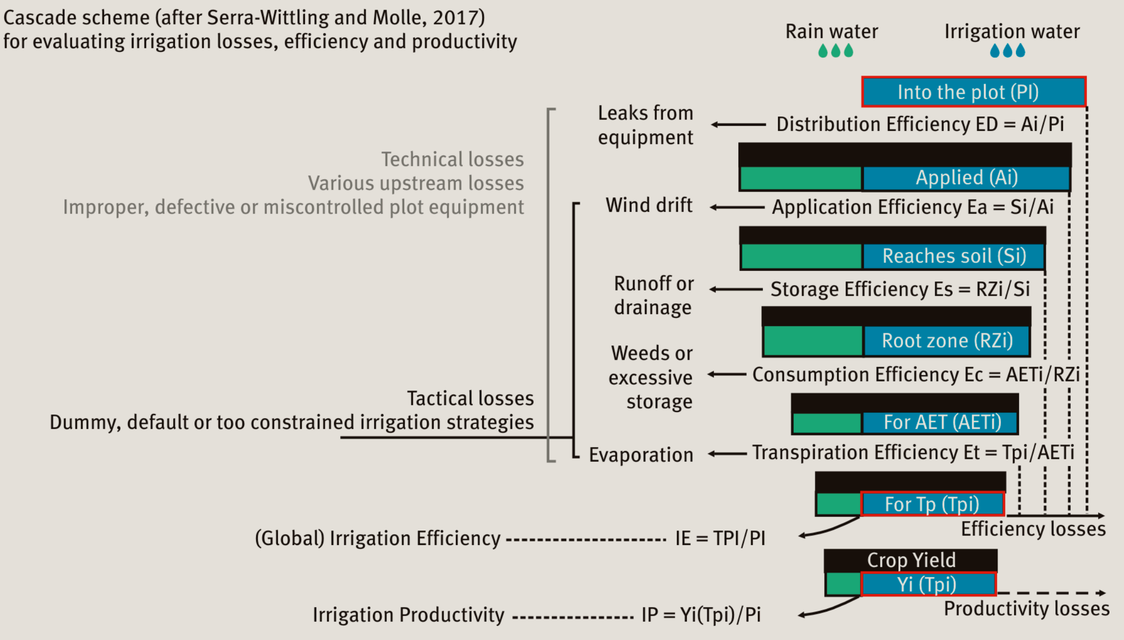
Figure ❷ illustrates this cascade of processes and associated losses, showing most of the elements currently included in the model, either already explicitly calculated as model variables or still indirectly addressed via coefficients (here, wind drift and competition by weeds). As could be seen from Figure ❶c, splitting the irrigation term in several terms (Pi: irrigation water brought to the plot, Ai: irrigation applied through irrigation equipment and Si: irrigation that reaches soil) allows a fine analysis of "upstream processes" (which the efficiency module extends further upstream, up to water pumping). .

Perhaps the most striking feature of Figure ❷ is the "artificial" partition between rain and irrigation water fractions (adapted from Serra-Wittling and Molle, 2017) with the very graphic cascade effects across successive processes

❶ Climatic forcings (orange), main and observable variables (medium blue) and auxiliary variables (pale blue) in the hydro-agronomic loop (a). Transmission of the "irrigation signal" across model variables (b). Focus on irrigation efficiency with dedicated, added variables: Pi irrigation water brought into the plot, Ai irrigation applied through irrigation equipment, Si irrigation that reaches soil, RZi irrigation stored in the root zone, AETi evapotranspirated irrigation, Tpi transpirated irrigation, Yi(Tpi) fraction of crop yield directly attributable to irrigation, see details in the Cascade Scheme of Fig.2 (c). Scenarios mode of Optirrig in which multiple runs of the hydro-agronomic loop are performed, for selected contexts and/or controls, testing here irrigation scenarios with expected impacts on the daily model variables and on seasonal indicators, here with emphasis on irrigation efficiency in addition to the typical target variables for optimization (d).



❷ Cascade scheme for listing and evaluating successive (technical and/or tactical) losses during plot irrigation events. The mentioned "process efficiencies" multiply into a "global efficiency" taken as the fraction of irrigation water brought into the plot (Pi) that is finally transpirated by the crop (Tpi). Also indicated is the expected link between irrigation efficiency and productivity.



and losses, finally reducing the useful part of irrigation to a sometimes very tiny part of the initially available irrigation water. Pretty much the same occurs for rain water, at the noticeable difference that irrigation is deliberate, while rain is not. Optimization applied to the irrigation fraction should thus (also) be decided from rain water amounts present in soils, which implied (i) identifying rain-related and irrigation-related soil reserves in the hydro-agronomic model loop, for example in Figure ❶c, and (ii) seeking guidance in Figure ❷ to find the relevant target variables.

Of course, the difficulty for optimization lies in the unpredictable nature of the climate on a short-time horizon of a few days and even more on seasonal horizons. Irrigation optimization in quasi-real time is therefore much more complicated than ex-post optimization, once the chronicle and final values of all variables are known and improved irrigation strategies may be safely sought. However, even if intended for an overall, efficiency-oriented view of past irrigation strategies, the Cascade Scheme also pertains to describe the real-time dynamics of the system, taking all mentioned quantities as daily variables thus allowing quasi-real time, efficiency-oriented optimization attempts.

Whatever the angle of attack on the optimization issue, losses emanate from technical (equipment) and/or tactical (strategy) defects. Technical losses and possible remediation measures have been described in Serra-Wittling and Molle (2017) and Serra-Wittling et al. (2019). How to work on the tactical losses is the scope of the present study and on-going developments of Optirrig.

Besides considering the successive losses (and probably representing how they sum up stage by stage into global losses) another reading of the Cascade Scheme is possible, in terms of "stage efficiencies" or "process efficiencies". These process efficiencies E (distribution Ed, application Ea, storage Es, consumption Ec and transpiration Et) all range between 0 and 1, and multiply into a global irrigation efficiency IE, thus also with a score between 0 and 1. This reading of the scheme proves useful to identify which (if any) is the weak link in the chain. To provide numerical examples, when all process efficiencies are E=0.9 (which is really good) the overall score is "only" IE = 0.95 = 0.69, and when all process efficiencies are E=0.75 (which is quite bad for Ed and Ea but fairly good otherwise) the overall score drops down to IE=0.24. Possible actions taken from this reading of the Cascade Scheme are (i) to estimate the contextual values of Ed, Ea, Es, Ec and Et, for a first guess of the weak points regarding irrigation efficiency on a given site, (ii) to design appropriate field measurements to confirm diagnosis, (iii) to establish new realistic targets given site management constraints and objectives, and (iv) to handle the associated optimization issue, either by hand, in trial-and-error type of attempts, or within more formal procedures.

The way to handle the optimization process certainly depends on the variables accounted for and on the interplay between these variables. For example, the presence of common terms (Pi, Tpi) in the expression of irrigation efficiency IE and productivity IP suggests a clear correlation between IE and IP. In addition, the financial profit is allegedly correlated with both, as "more crop per drop" cannot harm. Finally, the optimization problem becomes a bit more framed as known relations exist between its key variables (irrigation sum ΣI, crop yield Y, financial profit F) and the previously mentioned angle of attack is to reduce the losses (or, equivalently, to improve the process efficiencies).

Implementation in Optirrig

Hypotheses and verifications

So far, Figure ❶c and Figure ❷ insisted on the distinction between rain and irrigation water fractions in several model variables (soil reserves and drainage, evaporation, transpiration).The starting and key hypothesis behind this is that of total mixing between rain and irrigation water in soil reserves, and thus in plant organs. Hence, what is carried on through the model variables are the relative "fictitious", or say "effective", volume fractions of rain and irrigation water.

From reference works on diffusion processes in soil physics, turned towards the adaptation of Fick's diffusion laws (Crank, 1956; Carslaw and Jaeger, 1959; Kirkham and Powers, 1972) and relations between water diffusivity and soil water content (e.g. Millington and Quirk, 1961) it is very likely that complete mixture occurs between rain and irrigation, at the daily time step of the model, for the typical size of its reservoirs and for usual water contents. In particular, too low water contents are hopefully not reached when working on irrigation and they would simply delay the occurrence of complete mixing, not prevent it. In addition, the existence of convective gravity fluxes, either explicit as drainage between reservoirs in Optirrig or "silenced" as water movements inside each reservoir, is highly favourable for mixing (e.g. Flühler et al., 1996; Chalhoub et al., 2013).

Complete mixing means no stratification exists between rain and irrigation water in soil, neither based on density or rheology differences (highly unlikely for irrigation with conventional water) nor on the "order of arrival" in soil. The latter discards piston-effect types of fluxes thus somehow assumes that mixing occurs quicker than or before drainage takes place.

"Complete mixing" and "no stratification" hypotheses in soil reservoirs (R1, R2, R3, in Figure ❶) allow defining volume fractions (f1, f2, f3) attached to each soil reservoir, e.g. f1 = R1I/R1 where R1I is the irrigation water reserve and R1 the total water reserve, with similar definitions for f2 and f3. In coherence, we assume then that all physical processes (drainage, evaporation, root water uptake for transpiration) mobilize the same volume fractions. For example, if TP2I is the transpiration of irrigation water from the R2 reserve and TP2 the total transpiration from the same reserve, then TP2I/TP2 = f2.

Encoding the hypotheses in Optirrig

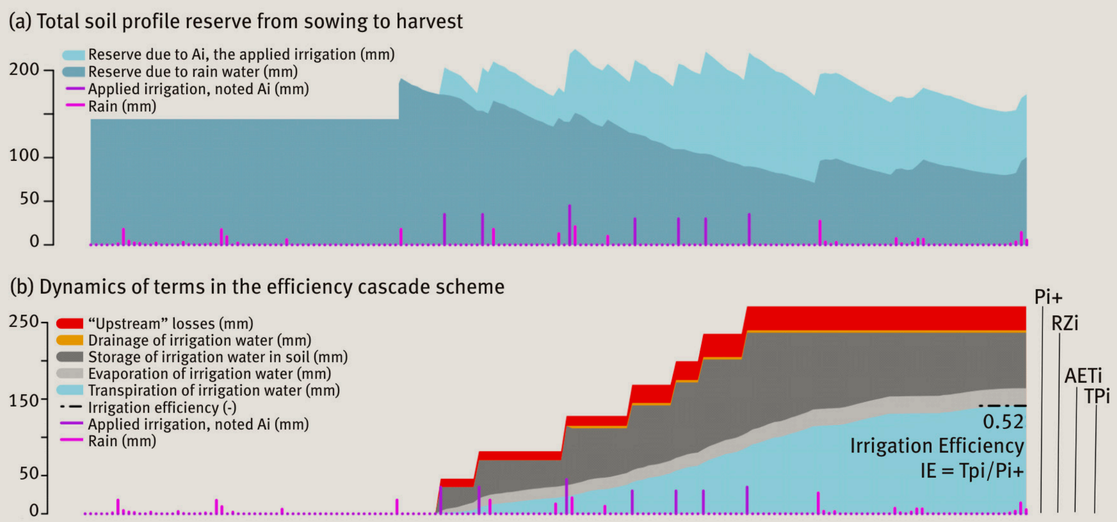
The encoding effort is first to plug the new series of efficiency-related variables as a module for the recently rewritten hydro-agronomic loop, and second to force the above "equal fractions" rule on all efficiency-related variables at once. This de facto preserves mass conservation but necessitates programming tricks to be presented elsewhere, with details on model structure.

Once it is possible to have the I-irrigation and R-rain fractions of the variables, all quantities in the Cascade Scheme of Figure ❷ become accessible at a daily time step, including process efficiencies. One may, for example, indicate that the 50-mm rain fallen on April 4th has filled the R1 and R2 reserves to a proportion of 90% rain water and 10% irrigation water, then triggered a 10-mm drainage composed of 90% rain water (9 mm) and 10% irrigation water (1 mm).

Model outcomes

In a textbook case slightly modified from a real case-study, Figure ❸a illustrates the dynamics of soil irrigation (pale blue) and rain (medium blue) water, as influenced by the indicated irrigation (violet) and rain (rose) events. At first glance, the irrigation strategy aims to maintain a

❸ Dynamics of the total soil profile reserve from sowing to harvest, discriminating the fraction due to irrigation (pale blue) and that fraction due to rain (medium blue) for indicated irrigation (violet) and rain (rose) events (a). Associated dynamics of the non-zero terms in the efficiency cascade scheme of Fig.2, also indicating the score of irrigation efficiency as well as the magnitude of upstream, drainage, storage and evaporation losses (b). This plot issues from a semi-fictitious example constructed on real soil and plant data (maize grown on the INRAE experimental platform of Lavalette, at Montpellier, France) but with modified rain and irrigation data.



sufficiently high total soil profile reserve, which is very classical. What also clearly appears is the increasing fraction of irrigation water, brought in to compensate (or maybe overcompensate?) the lack of rain during the hottest months.

Figure ❸b provides complementary indications and a tentative comprehensive view on the dynamics of the efficiency-related variables showing their cumulative values. "Upstream" losses in the form of material incidents have been supposed to occur during the 1st, 4th and 7th irrigations, where "upstream" stands for what lies before the Si term in the Cascade Scheme (and possibly extending the description to water pumping, transport and delivery to the plot). Hence, upstream losses (red in Figure ❸b) are all losses affecting the initially available irrigation water (Pi) or more upstream quantities (noted Pi+ in Figure ❸b).

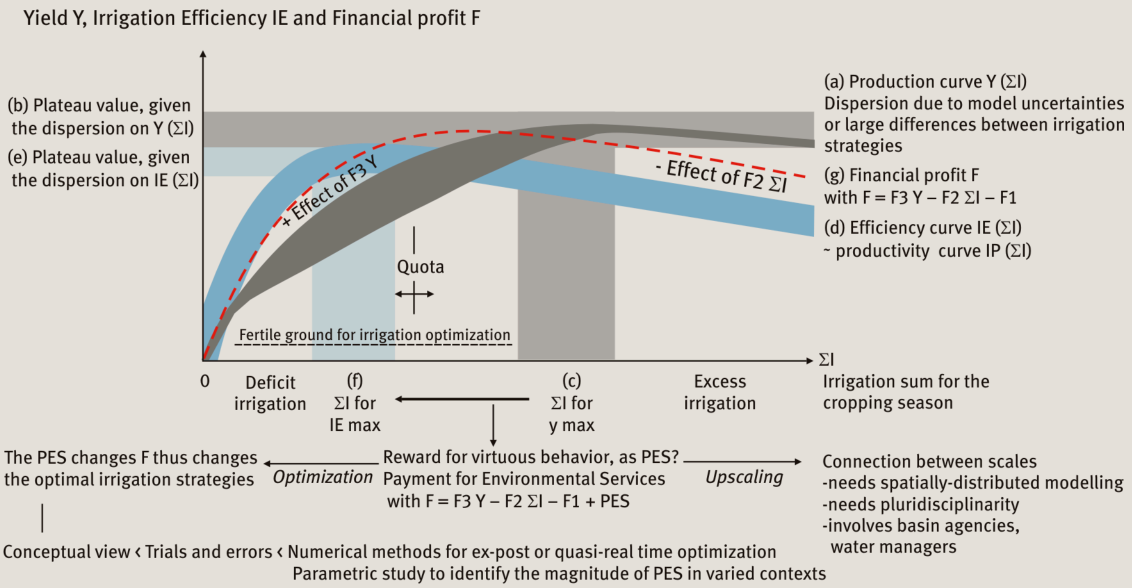
In this example, drainage of irrigation water (orange in Figure ❸b) takes place after the rain event immediately following the 3rd irrigation. By contrast, a large amount of irrigation water (medium grey in Figure ❸b) is progressively stored in soil, culminating after the 7th and last irrigation then slowly decreasing to a probably excessive final value. There was no need for the last one or two irrigation events during the final part of the cropping season. Nevertheless, the evaporation of irrigation water (light grey in Figure ❸b) remains limited and its ratio to the transpiration of irrigation water (pale blue in Figure ❸b) decreases with time, which is satisfying. Finally, a fair value of irrigation efficiency is reached, as IE=0.52, and the magnitude of the variables in pale blue in the Cascade Scheme is shown on the rightmost part of Figure ❸b to evaluate the losses.

Irrigation efficiency in real-life optimization issues

A typical real-life optimization issue is to find the irrigation scenario(s) that maximize the financial profit (say, F) by producing enough yield (Y>Y*) with less than the irrigation quota (ΣI<ΣI*), given additional constraints on the formulation of irrigation scenarios (e.g. water turn or technical limitations, resources availability over certain periods, prefectural decrees). There is a clear interplay between these variables, as Y(ΣI) is the production curve that relates crop yield to the seasonal amount of irrigation used to obtain it, and the financial profit writes F = F3 Y(ΣI) - F2 ΣI - F1 where F3 is the selling price of the crop, F2 the cost of water and energy per irrigation water volume, and F1 gathers all fixed costs. The expected limitations of resources availability (irrigation quotas for the whole season, prefectural decrees to rule irrigation) urge the search for sustainable and possibly virtuous alternatives, among which could be the inclusion of irrigation efficiency among the irrigation optimization targets, with associated, dedicated rewards. Figure ❹ attempts to illustrate this and should be read step by step following the (a) to (g) notes.

Figure ❹a shows the envelope of production curves with (i) unavoidable modelling uncertainties in the relation between ΣI and Y (modelling flaws, missed or ignored processes, fitting on uncertain site data) and (ii) large differences between more or less relevant irrigation strategies (decision rules) thus scenarios (chronicles of irrigations). Both (i) and (ii) trigger dispersion in the production curve, especially in deficit irrigation conditions prone to optimisation (belly of the curve). By contrast, all strategies tend to converge when almost no water is accessible

❹ Tentative illustration of the interplay between crop yield Y (a, b, c), global irrigation efficiency IE (d, e, f) and financial profit F (g), for various cumulative irrigation amounts ΣI. Irrigation optimization scenarios may intervene in the link between Y, IE and F, and prove especially relevant for deficit irrigation conditions, all the more in presence of irrigation quotas or limited resources availability over given periods. A slight complexity is added but an additional degree of freedom appears when considering Payment for Environmental Services as a possible reward for virtuous and/or parsimonious irrigation scenarios.



or way to much water is applied, and yield is expected to decrease due to anoxic soil conditions. Dispersion on the production curve means a fuzzy maximum and plateau value, shown by Figure ❹b, hence uncertainties on the maximum attainable value of Y. The Signal value for the maximum Y is also far from being unique, as in Figure ❹c.

As already mentioned, a strong correlation exists between irrigation productivity (IP) and efficiency (IE) and similar shapes may be hypothesized for the IP (not shown) and IE curves. What holds for the analysis of the IE curve of Figure ❹d therefore holds for that of the IP curve. A known feature of the latter "crop per drop" curve is that the "most crop per drop" value is obtained for irrigation amounts way lower than these necessary to reach maximum Y values, which is reflected by the (fuzzy) plateau value around the maximum IE values in Figure ❹e and corresponding (fuzzy again) ΣI value in Figure ❹f.

Keeping things again as simple as possible, the financial profit F in Figure ❹g strongly rises with increasing values of Y (as a result of relatively low water and energy costs) then reaches maximum before decreasing when Y saturates, as ΣI increases and water is obviously wasted. What could change when introducing irrigation efficiency among the mattering optimization variables is (for example) the possibility to reward virtuous strategies that spare water, with the objective of good irrigation efficiency scores. The Payment for Environmental Services (PES) offers a possible lever of action and may be introduced as an additional term in the calculation of F. This has two major implications: the optimal irrigation scenarios will certainly not be the same, and upscaling to the basin scale becomes necessary, with associated pluridisciplinarity (multiagent simulations, economy, water policy) and spatially-distributed modelling to map practices (remote sensing), resources (hydrology, hydrogeology) and eventually basin-scale feedbacks between water uses for irrigation and resource availability. ■

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