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From rainfed agriculture to stress-avoidance irrigation: II. Sustainability, crop yield, and profitability

Giulia Vico *, Amilcare Porporato

Department of Civil and Environmental Engineering, Duke University, Durham, NC, USA
Nicholas School of the Environment and Earth Sciences, Duke University, Durham, NC, USA

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ABSTRACT

The optimality of irrigation strategies may be sought with respect to a number of criteria, including water requirements, crop yield, and profitability. To explore the suitability of different demand-based irrigation strategies, we link the probabilistic description of irrigation requirements under stochastic hydro-climatic conditions, provided in a companion paper [Vico G, Porporato A. From rainfed agriculture to stress-avoidance irrigation: I. A generalized irrigation scheme with stochastic soil moisture. Adv Water Resour 2011;34(2):263–71], to crop-yield and economic analyses. Water requirements, application efficiency, and investment costs of different irrigation methods, such as surface, sprinkler and drip irrigation systems, are described via a unified conceptual and theoretical approach, which includes rainfed agriculture and stress-avoidance irrigation as extreme cases. This allows us to analyze irrigation strategies with respect to sustainability, productivity, and economic return, using the same framework, and quantify them as a function of climate, crop, and soil parameters. We apply our results to corn (*Zea mays*), a food staple and biofuel source, which is currently mainly irrigated through surface systems. As our analysis shows, micro-irrigation maximizes water productivity, but more traditional solutions may be more profitable at least in some contexts.

1. Introduction

The contrasting needs of securing food for an increasing global population and environmental preservation become apparent when attempting to achieve a sustainable use of soil and water resources, especially in relation to agriculture [1–7]. A sustainable water resource management that preserves ecosystems and their services while guaranteeing the necessary yields and economic profits requires optimization with regard to the conflicting needs of ecosystems, farmers, and society. Farmers are interested in maximizing profits or productivity, depending on their economic and social conditions, while water managers need to balance these water requirements with requests for competing uses (municipal, industrial, and recreational/environmental). Accordingly, choices of irrigation strategies and water management must simultaneously consider crop yield, profitability, and sustainability [8].

The choice of 'optimal' irrigation management is complicated by a number of uncertainties regarding both the economic situation and the actual crop productivity. The main economic uncertainty is represented by fluctuations in crop sale price, which complicate long-term planning of crops and investments. Conversely, many factors contribute to the uncertainty inherent in crop yield, including pest infestations and other diseases, temperature extremes, and timing of rainfall relative to growth stages, as well as crop physiological response to water availability, specific soil properties determining the amount of water lost to runoff and deep percolation, and irrigation efficiency [9]. Among these factors, rainfall variability represents the primary source of uncertainty, both at the growing season and at the multi-year level, significantly impacting productivity and profitability. Accounting for this uncertainty is of paramount importance in the context of climate change. In particular, the expected increase in frequency of dry spells and potential evapotranspiration [10] will likely alter the current geography of irrigation needs, increasing agricultural drought risk and threatening food security [11,12]. The inherent unpredictability of rainfall makes a probabilistic approach necessary to quantify irrigation requirements, crop yield, and economic risk. A probabilistic analysis with clearly defined soil, crop and climatic parameters is critical for long-term water resource management and infrastructure planning. A companion paper [13], hereafter referred to as Vico and Porporato I (VPI), provides a statistical description of soil moisture under stochastic steady-state conditions and irrigation requirements in terms of frequencies of application and water volumes, as a function of rainfall regime probabilistic features, as well as soil and crop characteristics.

* Corresponding author at: Department of Civil and Environmental Engineering, Duke University, 121 Hudson Hall, Research Drive, P.O. Box 90287, Durham, NC 27708, USA. Tel.: +1 919 660 5467; fax: +1 919 660 5219.

E-mail addresses: giulia.vico@duke.edu (G. Vico), amilcare@duke.edu (A. Porporato).

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Nomenclature

a	steepness parameter the of the seasonal evapotranspiration-yield function (Eq. (4))
C_0	irrigation-independent fixed costs (Eq. (7))
c_1, c_2, c_3	parameters of the function $\varphi(\tilde{s},\hat{s})$ (Eq. (2))
c_c	crop sale price (Eq. (7))
C_I	irrigation-dependent fixed costs (Eq. (6))
$c_{I,m}$	fixed cost of modern micro-irrigation per unit area (Eq. (6))
C_w	irrigation-related variable costs (Eq. (7))
c_w	cost per unit applied irrigation water (Eq. (7))
$ET_{\max}$	evapotranspiration rate under well-watered conditions
ET_{seas}	total evapotranspiration over the growing season
$ET_{seas,50\%}$	total seasonal evapotranspiration corresponding to $Y_{\max}/2$ (Eq. (4))
G	net economic return per unit area (Eq. (7))
J	gross income from crop sale
n	soil porosity
$p(s)$	steady state probability density function (pdf) of soil moisture for the generalized irrigation scheme (including rainfed agriculture and micro-irrigation as extreme cases)
$s(t)$	relative soil relative moisture
s^*	point of incipient stomatal closure, when plant transpiration is reduced
$\tilde{s}$	soil moisture 'intervention point' triggering an irrigation application
$\hat{s}$	'target level' to which soil moisture is restored by an irrigation application
s_1	soil moisture level at which deep percolation and runoff losses take place
$R_{tot} = \alpha\lambda T_{seas}$	total rainfall over the growing season
T_{seas}	length of the growing season
$V(\tilde{s},\hat{s})$	total irrigation volume per unit area over a growing season including application efficiency (Eq. (3))
$V_{ideal}(\tilde{s},\hat{s})$	total irrigation volume per unit area over a growing season under ideal conditions (Eq. (15) in VPI)
WP	water productivity (Eq. (5))
Y	crop yield (Eq. (4))
$Y_{\max}$	maximum crop yield (i.e., yield corresponding to $ET_{seas} \to \infty$) (Eq. (4))
Z_r	active soil depth
α	mean depth of rainfall events
$\eta = ET_{\max}/(nZ_r)$	maximum normalized evapotranspiration loss rate
$\eta_A(\tilde{s},\hat{s})$	application efficiency (Eq. (1))
$\eta_{A,f}$	application efficiency for furrow irrigation
$\eta_{A,m}$	application efficiency for micro-irrigation
λ	mean frequency of rainfall events
$\rho(s)$	normalized evapotranspiration loss rate
$\varphi(\tilde{s},\hat{s})$	dependence of application efficiency (and fixed costs) on irrigation parameters (Eq. (2))

Building upon the results presented in VPI, the main goal of this work is to assess the feasibility of different irrigation schemes in terms of sustainability, productivity, and profitability. Most of the existing literature on resources optimization for agricultural purposes focuses on economic profit maximization, often coupled with water requirement assessments and/or under limited water availabilities [see, among many others, 14–20]. A few studies couple the economic viewpoint with yield maximization [21–23] and issues of sustainability and food security [24–26]. However, a complete evaluation of irrigation scheduling and investments with a simultaneous assessment of yields, profitability, and water resource requirements, as well as their statistical characterization, is still missing. With this goal in mind, focusing on demand-based irrigation, often-employed irrigation methods (surface irrigation, sprinkler systems, and micro-irrigation) are here analyzed under the unifying framework presented in VPI. Accordingly, demand-based irrigation strategies are described by two parameters, i.e., the soil moisture level that triggers an irrigation application (the intervention point $\tilde{s}$), and the soil moisture level restored by each irrigation application (the target level $\hat{s}$). Building upon the analytical solutions with stochastic soil moisture given in VPI, we link the soil water balance to crop yield and net economic return using observed relationships between seasonal transpiration and crop yield (Section 4) and simple economic considerations (Section 5). Finally, in Section 6, the results from this analysis are used to compare different irrigation schemes, regarding required irrigation volumes, crop yields, and economic return, with reference to the case of corn (*Zea mays*).

2. Optimal irrigation strategies for sustainability, productivity, and profitability

An irrigation strategy may be considered 'optimal' under different points of view. We consider here three main criteria: sustainability, productivity and food security, and profitability.

2.1. Sustainability

Sustainability is achieved when local and regional agricultural practices are such that land, water, and other resources are not degraded, thus providing similar opportunities in the future in terms of both available resources and their quality (e.g., [27]). Clearly, irrigation sustainability can be assessed at different spatial and temporal scales, ranging from field scale to basin scale (accounting for return flows), and from intra-seasonal (e.g., the use of water from small reservoirs) to multi-decadal (e.g., impacts on soil fertility or groundwater levels) time scales [28]. In the most typical contexts, when water is diverted from natural streams and a minimal flow is required, or when groundwater is used and the aquifer natural recharge rate is low, the most sustainable irrigation strategy at the field scale may simply be minimizing the amount of applied water. Thus, focusing on sustainability with respect to water conservation, we will consider two complementary metrics: (i) the amount of irrigation water required per unit cultivated area (irrigation volume; Section 3.2), which clearly has a direct impact on cumulative water withdrawals from streams, reservoirs, or aquifers; and (ii) total amount of supplied water, through rainfall and irrigation, per unit crop yield (water productivity; see Section 4.2). Including rainfall in the second metric allows the assessment of how efficiently the cultivated crop exploits water supplied according to a certain irrigation scheme and rainfall regime.

It should be noted that the question of irrigation sustainability may be more complex than simply conserving water, as in the case of risks of soil erosion or soil salinization. In the latter case, for example, soil flushing requirement for over-irrigation to limit soil salt accumulation may make purely water-saving strategies unsustainable over the long term (e.g., [29, p. 47]). However, these issues are beyond the scope of the present analysis.

2.2. Productivity and food security

When the root-zone soil moisture decreases, transpiration and carbon assimilation are reduced [30–32], thus reducing crop yield (defined here as the marketable part of the total productivity). Hence, assuming no nutrient limitations and in the absence of crop diseases and pests, high yields are achieved when plant water stress is avoided throughout the growing season by means of irrigation (i.e., by performing stress-avoidance irrigation; see VPI). Nevertheless, irrigation investment planning should account for rainfall variability and risk tolerance level. In fact, a series of wetter-than-average seasons may render an irrigation investment redundant and thus not economically optimal, while long periods of extremely low rainfall may render a given irrigation strategy insufficient, with detrimental impacts on crop yields in terms of both quantity and reliability (i.e., food security).

2.3. Profitability

To be profitable an agricultural enterprise needs to effectively balance investments and costs required to achieve the expected yields and their related incomes. While capital costs for irrigation equipment, labor and ordinary-maintenance expenses, and water costs are relatively easy to account for, crop sale prices and water-related costs fluctuate considerably. Specifically, crop sale prices are influenced by governmental programs and pricing mechanisms of offer and demand, which in turn are vulnerable to weather conditions in production areas, availability of alternate crops, and demands for conflicting uses. As a result, crop sale prices tends to be highly volatile (for example, fourfold changes in prices paid to US farmers for staples like wheat and corn have been reported over the period 1999–2009 [33]). Water-related costs mainly depend on location (see, e.g., [34, Table 22]) and source of water (e.g., small-scale rain water harvesting, groundwater pumping, or surface water diversion). Moreover, costs of off-farm water may be significantly higher as a result of a particularly dry season, while the expense for water pumping may fluctuate with electricity or pump fuel prices. Some of these profit-related adverse effects may be limited by adjustments in irrigation strategy during the growing season: for example, implementation of deficit irrigation in place of stress-avoidance irrigation may significantly reduce water-related expenses, while limiting only in part the net return. Conversely, capital investments represent fixed costs, which are distributed over several years, and thus cannot be altered in the short term. Hence, investments in irrigation equipment must be accurately planned, with inclusion of uncertainties inherent in the system (chiefly, variability in rainfall amounts, crop sale prices, and water related costs [16]) and levels of tolerable risks in exchange for higher profits [9,24].

3. From ideal to actual irrigation water requirements

To facilitate the comparison of actual water requirements of a variety of demand-based irrigation strategies under a common framework, a quantitative description of application efficiency as a function of irrigation parameters is presented in this Section.

3.1. Irrigation application efficiency

Following Burt et al. [35], we define the irrigation application efficiency, η_A, as the ratio between the water volume effectively contributing to the target (here the water volume effectively increasing soil moisture to $\hat{s}$) and the total water volume necessary to reach such a target (including non-beneficial uses). As such, the application efficiency accounts for non-beneficial fluxes associated with an irrigation application. Typical examples of irrigation non-beneficial uses are evaporation from furrows, runoff from the field (particularly relevant in case of surface irrigation without tailwater recovery system), percolation below the root zone during the application, and wind drift and interception by vegetation (for sprinkler systems). Note that these types of non-beneficial uses should not be confused with increased transpiration and runoff/percolation fluxes due to irrigation, for the latter fluxes are already included in the solution of the stochastic soil water balance and in the related irrigation volumes under ideal conditions, as detailed in VPI. Even though irrigation application efficiency may be affected by a number of conditions, and thus be geographically dependent [36], the main factor determining η_A is the selected irrigation method. As discussed in VPI, it is possible to establish a correspondence between irrigation methods and irrigation parameters (intervention point $\tilde{s}$ and target level $\hat{s}$), and use the latter to parameterize the range of irrigation efficiencies. In particular, surface systems are suitable for infrequent and large irrigation applications (high values of $\hat{s}-\tilde{s}$), while continuous irrigation is attained through micro-irrigation ($\hat{s}-\tilde{s}\to 0$), and sprinkler systems are employed to cover intermediate irrigation strategies. In most settings, application efficiency does not exceed 50% for surface systems, is around 80% for sprinkler irrigation, and may reach or even be above 90% for drip irrigation (as, e.g., reported by Trout and Kincaid [37]). These figures indicate a first steep increase in η_A from surface irrigation to sprinkler systems, and a second less-pronounced one when switching to more sophisticated systems such as micro-irrigation. Because existing sprinkler systems are characterized by similar levels of non-beneficial uses (e.g., wind drift and canopy interception), it can be expected that they may attain similar values of η_A: hence, it is reasonable to assume a plateau in application efficiency, covering most of the parameter combinations pertaining to traditional irrigation achieved through sprinklers. We introduce the following efficiency surface to describe such behavior

$$\eta_A(\tilde{s},\hat{s}) = (\eta_{A,m}-\eta_{A,f})\varphi(\tilde{s},\hat{s})+\eta_{A,f}, \tag{1}$$

where $\eta_{A,f}$ is the minimum application efficiency (here assumed comparable with the one typical of furrow irrigation, i.e., $\eta_{A,f}$ = 0.5), and $\eta_{A,m}$ is the maximum application efficiency (corresponding to modern micro-irrigation; here $\eta_{A,m}$ = 0.9). The function $\varphi(\tilde{s},\hat{s})$ ranges from 0 (for no irrigation applications, i.e., $\tilde{s}=0$) to 1 (for micro-irrigation, i.e., $\tilde{s}=\hat{s}$), and describes the relationship between application efficiency and the different irrigation methods. A flexible function to describe the previously-mentioned dependence on irrigation parameters $\tilde{s}$ and $\hat{s}$ is

$$\varphi(\tilde{s},\hat{s}) = \begin{cases} \left(1+c_2-e^{-1}\right)^{-1}\left[1-\exp\left(-\left(\frac{\tilde{s}}{\hat{s}}\right)^{c_1}\right)+c_2\left(\frac{\tilde{s}}{\hat{s}}\right)^{c_3}\right], \\ \qquad \tilde{s}\geqslant 0,\ \hat{s}>0, \\ 0, \quad \tilde{s}=\hat{s}=0. \end{cases} \tag{2}$$

For positive values of the three parameters c_1, c_2, c_3, this functional form reproduces the observed behavior of efficiency with a steep increase from furrow to sprinkler irrigation methods (the lower c_1, the steeper this increase), a plateau covering most of the parameter combinations pertaining to traditional irrigation obtained through sprinklers, and a final increase for modern micro-irrigation (the higher c_3, the steeper the increase from traditional to micro-irrigation). The same functional dependence on irrigation parameters, $\varphi(\tilde{s},\hat{s})$, will be used to link irrigation investment costs to irrigation parameters under a unified framework, as discussed in Section 5. A robust estimate of the necessary parameters would require the knowledge of the application efficiencies (and/or installation costs) for several irrigation strategies (i.e., for several points in the irrigation parameter space). In absence of more specific data, here we

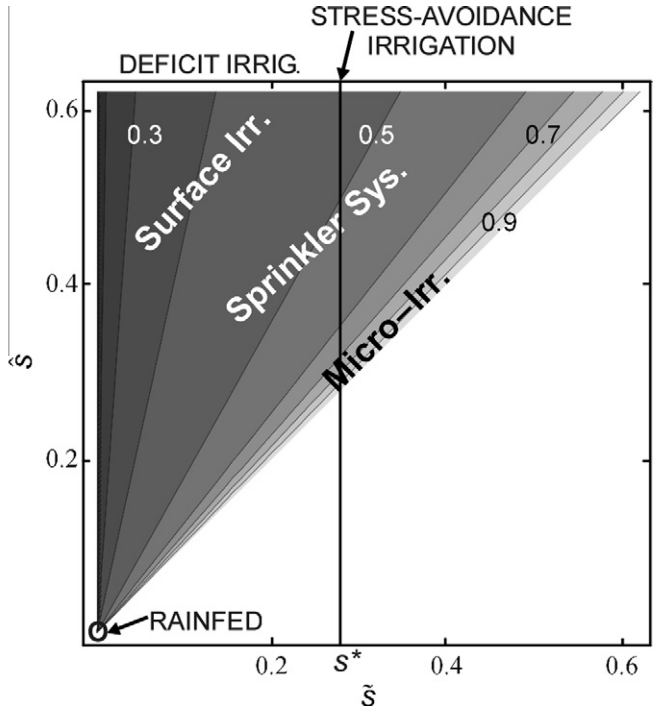

Fig. 1. Dependence of the function $\varphi(\tilde{s},\hat{s})$ (Eq. (2)) on the irrigation parameters, with $c_1 = 1/3$, $c_2 = 1/2$, and $c_3 = 8$. For reference, the corresponding irrigation methods are qualitatively reported in the irrigation parameter space (see Section 2 and Fig. 1 in VPI for details). Note that the irrigation parameter space is limited by the condition $\hat{s} \geqslant \tilde{s}$ (i.e., the target level needs to be larger than intervention point). The thin vertical line corresponds to $\tilde{s} = s^*$, i.e., stress-avoidance irrigation, with deficit irrigation on its left and over-irrigation on its right.

base our estimates on qualitative information available on application efficiencies (reported above) and installation costs (see Section 5). These result in values $c_1 = 1/3$, $c_2 = 1/2$ and $c_3 = 8$, which will be used in the following applications. A sensitivity analysis showed that, for parameter values resulting in a realistic dependence of application efficiencies (and installation costs) on irrigation parameters, the choice of c_1, c_2, c_3 plays a secondary role on the final results presented in Section 6. Fig. 1 shows the behavior of $\varphi(\tilde{s},\hat{s})$ as a function of the irrigation parameters (see Table 1).

3.2. Actual irrigation requirements

The ideal irrigation volumes, obtained in Eq. (15) of VPI, can now be corrected with the application efficiency defined in the previous section to provide an estimate of the actual average total required volume per unit area over a growing season of duration T_{seas} as

$$V(\tilde{s},\hat{s}) = \eta_A(\tilde{s},\hat{s})^{-1} V_{ideal}(\tilde{s},\hat{s}) = \eta_A(\tilde{s},\hat{s})^{-1} nZ_r(\hat{s}-\tilde{s})\rho(\tilde{s})p(\tilde{s})T_{seas}, \quad (3)$$

where n is soil porosity, Z_r is the active rooting depth, while the function $\rho(\tilde{s})$ represents evapotranspiration loss rate (ET) at $\tilde{s}$ normalized by nZ_r and $p(\tilde{s})$ is the probability density function (pdf) of soil moisture for the generalized demand-based irrigation scheme under stochastic steady-state conditions computed at $\tilde{s}$.

While Eq. (3) above is general and valid for any form of the loss function, in the following quantitative applications a piecewise linear function is assumed for $\rho(\tilde{s})$, with constant loss rate, η, for stress-avoidance irrigation (i.e., when the intervention point is set at or above the point of incipient stomatal closure s^*), and linearly decreasing loss rates from $\tilde{s} = s^*$ to zero at $\tilde{s} = 0$ (Eq. (2) in VPI). Recall also that in VPI rainfall events are modeled according to a marked Poisson process, with average frequency of occurrence λ, and exponentially distributed event depth with mean α (resulting in a total rainfall over the growing season $R_{tot} = \alpha\lambda T_{seas}$). With these assumptions, Fig. 2 represents the actual required irrigation volumes (as provided by Eq. (3)), for different choices of irrigation

Table 1
Summary of parameter values for the application to *Zea mays* grown on a sandy loam.

Parameter	Value (range)	Source
a (–)	2.57	Fitting of Eq. (4) to data in [38,43–45]
C_0 (\$ ha^{-1})	600	Intermediate irrigation capacity according to the calculations in [60] for NW Kansas
c_1 (–)	1/3	See Section 3.1 for details
c_2 (–)	1/2	See Section 3.1 for details
c_3 (–)	8	See Section 3.1 for details
c_c (\$ kg^{-1})	0.12 (0.06–0.21)	Average US corn sale prices in the period 1999–2009 (and observed range) [33]
$c_{I,m}$ (\$ ha^{-1})	658	See Section 5.2 for details
c_w (\$ m^{-1} ha^{-1})	148 (12–1932)	Average US expenses for irrigation water from off-farm suppliers in 2003 (and observed range of state-level expenses) [34, Table 22]
$ET_{\max}$ (cm d^{-1})	0.55	Seasonal-average daily ET from long-term average values in [60] relative to days 10–120 after emergence
$ET_{seas,50\%}$ (mm)	694	Fitting of Eq. (4) to data in [38,43–45]
n (–)	0.43	[64]
$s*$ (–)	0.28	Estimated from data in [65]
s_1 (–)	0.62	Chosen value, 10% higher than soil field capacity
T_{seas} (d)	110	Realistic duration of growing season
$Y_{\max}$ (ton ha^{-1})	26	Fitting of Eq. (4) to data in [38,43–45]
Z_r (cm)	50	After Dwyer et al. [66]
$\eta_{A,f}$ (–)	0.5	Estimated form data reported in [37]
$\eta_{A,m}$ (–)	0.9	Estimated form data reported in [37]

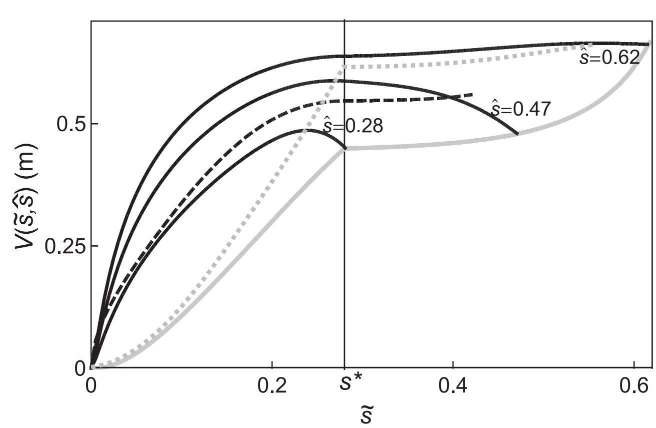

Fig. 2. Required irrigation volumes $V(\tilde{s},\hat{s})$ (Eq. (3)), as a function of intervention point $\tilde{s}$, for different choices of the parameter $\hat{s}$ (solid black lines) and for the case of $\hat{s}-\tilde{s} = 0.2$ (i.e., each irrigation application supplies a fixed water depth $nZ_r(\hat{s}-\tilde{s}) = 0.2nZ_r$; dashed black line), over a 110-day growing season. Gray lines refer to the extreme case of $\hat{s} \rightarrow \tilde{s}$, i.e., micro-irrigation, while the dotted gray line represents the values of that maximize $V(\tilde{s},\hat{s})$ for increasing $\hat{s}$. The thin vertical line corresponds to $\tilde{s} = s^*$. Average depth of rainfall events is $\alpha = 15$ mm and rainfall frequency is $\lambda = 0.15$ day^{-1}. Soil and crop parameter values are listed in Table 1.

parameters and given rainfall statistics (to be compared to the ideal volumes reported in Fig. 5 of VPI). The analysis is extended to all feasible combinations of parameters, i.e., $\tilde{s} \leqslant \hat{s}$, where the equality corresponds to the case of micro-irrigation (solid gray line in Fig. 2). Traditional irrigation water requirements are examined by changing the irrigation parameters in two ways, i.e., altering $\tilde{s}$ while keeping $\hat{s}$ fixed (black solid lines in Fig. 2), and altering $\tilde{s}$ while keeping a fixed application depth $nZ_r(\hat{s} - \tilde{s}) = 0.2nZ_r$ (black dashed line). In the second case, the value $\hat{s} - \tilde{s} = 0.2$ is chosen as an illustrative example, because it represents an intermediate application depth between soil saturating irrigation and very shallow applications, which would lead to results similar to micro-irrigation. As expected, the irrigation strategy markedly affects the required water volume. Micro-irrigation has the lowest water requirements for a given intervention point, because of its high application efficiency (solid gray line). From this limiting case, for any intervention point $\tilde{s}$, the amount of water required for irrigation purposes increases with application depth (i.e., with $\hat{s} - \tilde{s}$). This increase in required irrigation volumes was already apparent under ideal conditions (i.e., V_{ideal}, corresponding to unit application efficiency; Fig. 5 in VPI), and can be ascribed to the increased frequency of runoff and deep percolation due to higher $\hat{s}$ that cause the excursions of the soil moisture process at higher values. Furthermore, while V_{ideal} monotonically increases with the intervention point (Fig. 5 in VPI), accounting for the application efficiency produces a maximum in water requirements as a function of $\tilde{s}$ (dotted gray line in Fig. 2). Parameter combinations located to the right of the maximum require lower irrigation volumes for the same $\hat{s}$ (even though $\tilde{s}$ is higher), due to the higher application efficiency commonly associated with these irrigation schemes. Hence, irrigation parameter combinations located along the dotted gray line should be avoided when aiming at sustainable practices, because choosing irrigation strategies with the same $\hat{s}$ and slightly higher $\tilde{s}$ would results in lower water requirements and possibly higher yields (because of the higher intervention point; see Section 4.1). Nevertheless, higher investment costs may be associated with these more optimal irrigation strategies (see Section 5), thus making them less advantageous from a profitability standpoint.

4. Linking soil moisture dynamics to crop yield

4.1. Crop productivity function

When adequate soil nutrients are available, and in the absence of pests and diseases, yields per unit cultivated area are primarily controlled by water availability [31]. Several classes of empirical relationships (crop productivity functions) have been proposed to describe crop yield as a function of available rainfall and applied water, or plant transpiration (the latter has been shown to be well correlated with crop yield [38]; see [39] and references therein for a comparison of selected crop water functions). Even if the impact of water stress on crop yield may depend on both the phenological stage in which the water deficit occurs and the extent of the deficit itself [40], as a first approximation, it may suffice here to simply assume that crop yield depends on total seasonal transpiration. Such an assumption is supported by several experimental results, which explored the impact of irrigation timing over crop yields [38,39,41–45], by eliminating irrigation applications over one or more crop phenological stages, and measuring the corresponding total seasonal ET and yield. We compare these data relative to different cultivars of *Triticum aestivum* (wheat) and *Zea mays* (corn) in Fig. 3, where crop yields are plotted against total seasonal ET, for different irrigation treatments, as detailed in the data sources. Fig. 3 clearly shows that the effects of irrigation withdrawal timing are less important than changes in cumulative transpiration in determining crop yield, thus lending support to the use of a dependence on ET_{seas} to obtain an estimate of crop yield.

Other interesting observations can be drawn from the comparison of data collected in Fig. 3. First, the yield-ET_{seas} relationship is highly species-specific: the yield of *Triticum aestivum* (a relatively drought tolerant species) is not significantly impacted by a small decrease in ET_{seas} as long as ET_{seas} remains above 300 mm, while the yield of *Zea mays* (a more drought sensitive species) is markedly reduced by a small decrease in ET_{seas}, even at relatively high total seasonal transpirations. As a result, the more drought tolerant *Triticum aestivum* may adapt well to deficit irrigation, while the drought sensitivity of *Zea mays* makes stress-avoidance irrigation a better strategy to sustain crop productivity [40]. Second, the productivity function does not depend only on the selected crop, but also on crop cultivar, soil features and management, nutrient availability and climatic conditions, as evident when comparing data from different experiments (e.g., closed and open symbols in Fig. 3; see also [46]). Also, crop yield may be affected by irrigation method [47] and existing interactions with the water table [48].

The observed transpiration-yield patterns are well fitted by the following empirical crop water productivity function

$$Y = Y_{max} \frac{ET_{seas}^a}{ET_{seas,50\%}^a + ET_{seas}^a}, \tag{4}$$

where Y_{max} represents the maximum yield (i.e., the asymptotic yield for very high ET_{seas}), $ET_{seas,50\%}$ is the ET corresponding to a yield of $Y_{max}/2$, and the parameter a defines the steepness of the curve. These parameters are easily obtained through regression of experimental data (Fig. 3). Such a relationship is sufficiently flexible to describe, through a limited number of parameters, the observed features of productivity functions, i.e., existence of a minimum

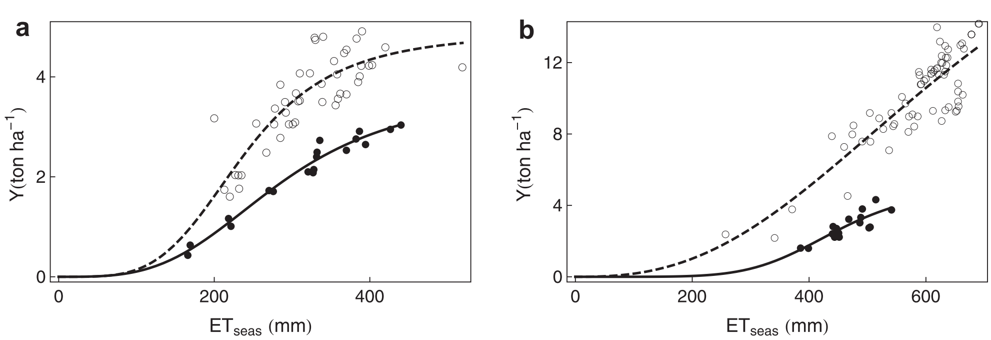

Fig. 3. Synthesis of crop yield data as a function of total seasonal transpiration (symbols) and model (Eq. (4); lines) for (a) *Triticum aestivum* (open symbols: data from [41], r^2 = 0.70; closed symbols: data from [42], r^2 = 0.97) and (b) *Zea mays* (open symbols: calculations by [38,43–45], r^2 = 0.75; closed symbols: data from [39], r^2 = 0.72). Points in each dataset refer to different irrigation treatments, consisting of irrigation withdrawal over different growth period and/or maintaining low, intermediate, or high soil water content throughout the season (see sources of data for more details on irrigation treatments).

transpiration below which yield is practically zero, nearly linear dependence of yield on transpiration over a range of intermediate ET_{seas}, and decrease in slope of the yield-ET_{seas} relationship towards high ET_{seas} corresponding to well-watered conditions [40]. We note that a saturating relationship, as the one employed here, is more realistic than previously proposed linear [49–52] and quadratic [41,53] dependences.

4.2. Water productivity

As discussed in Section 2, when focusing on water requirements, irrigation sustainability can be assessed by water needs either per unit cultivated area or per unit yield. This second approach revolves around the concept of water productivity, *WP*, i.e., the yield-to-water supply ratio, representing the yield per unit total applied water (both through irrigation, $V(\tilde{s},\hat{s})$, and rainfall, R_{tot})

$$WP = \frac{Y}{V(\tilde{s},\hat{s}) + R_{tot}}. \quad (5)$$

We point out that *WP* in Eq. (5) is different from the commonly employed irrigation (water use) efficiency. In fact, here we consider total supplied water (through both rainfall and irrigation) rather than the more customary supplied irrigation water alone (see, e.g., [35]). Thus defined, *WP* allows us to evaluate both the generalized irrigation scheme and rainfed agriculture under a common framework, whereas the commonly-employed irrigation efficiency would be unsuitable for extremely limited irrigation applications, where it would tend to infinity or be indeterminate.

4.3. Application to corn

In the following quantitative analyses, we focus on corn (*Zea mays*), a food staple and source of biofuels. This crop is currently irrigated mainly through surface and sprinkler systems (traditional irrigation), with micro-irrigation (e.g., drip irrigation) used only in research environments [54–56]. For the following applications, the crop productivity function (Eq. (4)) is parameterized by using the data presented by Payero et al. [38,43–45] (i.e., Y_{max} = 26 ton ha^{-1}, $ET_{seas,50\%}$ = 694 mm, a = 2.57; dashed line in Fig. 3b).

Fig. 4 illustrates the impact of the irrigation parameters on *Zea mays* yield *Y* (black lines) and water productivity *WP* (gray lines), for two families of irrigation strategies with adjustable intervention points, namely micro-irrigation and a case of generalized traditional irrigation (with each application delivering a fixed water depth $nZ_r(\hat{s} - \tilde{s}) = 0.2nZ_r$). Results presented in Fig. 4 are based

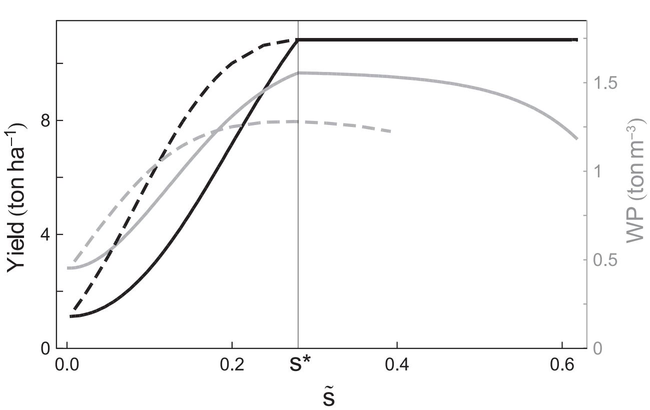

Fig. 4. Yield *Y* and water productivity *WP* (black and gray lines, respectively) as a function of the intervention point for micro-irrigation (solid lines) and traditional irrigation (with fixed application depth $nZ_r(\hat{s} - \tilde{s}) = 0.2nZ_r$; dashed lines) for *Zea mays* (T_{seas} = 110 days). The thin vertical line corresponds to $\tilde{s} = s^*$.

on stochastic steady-state conditions and the assumption of a piecewise linear function for the ET losses. The constant loss rate under well-watered conditions, ET_{max}, cause seasonal ET to be upper-bounded at $ET_{max}T_{seas}$, a fact that becomes apparent in the upper bound of the crop yield in Fig. 4 (black lines). Obviously, for yield maximization soil moisture should be kept at (or above) the point of incipient stomatal closure s^*, implying a stress-avoidance irrigation (or over-irrigation). Even mild deficit irrigation causes a decrease of yield for drought-sensitive crops such as *Zea mays*. This decrease is more significant for micro-irrigation (black solid line) than traditional irrigation (dashed black line). In fact, the jumps of soil moisture to $\hat{s}$ implied by the latter scheme result in periods of maximum transpiration rate even for deficit irrigation, thus limiting the negative effects of mild deficit irrigation on crop yield. Conversely, in the case of micro-irrigation, where the only jumps towards high soil moisture levels are caused by rainfall, even a mild deficit may cause soil moisture to stay below s^* for relatively long periods, negatively impacting yield (see Fig. 3 in VPI for examples of soil moisture time series for several choices of irrigation parameters).

Furthermore, for the drought-sensitive *Zea mays*, the reduction of yield with deficit irrigation is faster than the decrease in irrigation water requirements. Hence the water productivity *WP* decreases with progressive deficit irrigation, to reach a minimum for rainfed agriculture (Fig. 4, gray lines). The maximum *WP* occurs at mild deficit irrigation for the traditional scheme and at stress-avoidance irrigation for micro-irrigation. With the exception of extreme deficit irrigation, *WP* is higher for micro- than traditional irrigation (solid and dashed lines, respectively), as the former minimizes the amount of water lost to runoff and deep percolation, while supplying the vegetation with the necessary water [57]. Enhancing water use efficiency is one of the strategies often suggested to meet the increasing demand for food under scarce water resources [58,59]. Nevertheless, as apparent in Fig. 4, high water productivity *WP* may be obtained with intervention points corresponding to lower-than-maximum crop yields per unit cultivated area, thus potentially requiring cultivation of larger areas. Hence, there is the need to find a compromise between productivity and sustainability. The question is further complicated when the economic aspect is also taken into account, as discussed next.

5. Economic analysis: balancing incomes and costs

Crop yield maximization may not be the primary objective when water for irrigation purposes is scarce or expensive. In these cases, enhancing water productivity may be more profitable and sustainable. To fully assess the advantages of an irrigation strategy, the above considerations on crop yield and sustainability need to be complemented by an economic analysis including the crop sale price and the fixed and variable costs [8].

5.1. Economic balance

Gross income per unit cultivated area, *J*, is determined by yield, *Y*, times crop sale price (i.e., crop price received by the farmer) c_c, i.e., $J = c_cY$. Farmer's income may be increased by payments and other economic protection measures related to farm support governmental programs, which, however, are not included in the following analysis. Costs sustained by the farmer can be divided into three main types:

(i) Fixed costs per unit area for seeds, pesticides, fertilizer, field machinery, labor, and operation expenses (including crop harvesting), which the farmer would incur even in the absence of irrigation, here combined in the term C_0. For the sake of simplicity, it is assumed here that C_0 is independent of irrigation, even though some of these expenses (e.g., harvesting costs) may be partially dependent on crop yield and hence indirectly on irrigation [60].

(ii) Fixed irrigation costs, including irrigation equipment capital costs, maintenance, and irrigation-related labor, C_I. This cost term is primarily determined by the irrigation method (and hence by irrigation parameters). In general, irrigation technologies with higher application efficiencies have higher costs of installation and maintenance, while automation costs may be partially offset by lower labor expenses. Hence, as a first approximation, we assume that C_I exhibits the same dependence on irrigation parameters as the application efficiency $\eta_A(\tilde{s}, \hat{s})$, i.e.:

$$C_I(\tilde{s}, \hat{s}) = c_{I,m}\varphi(\tilde{s}, \hat{s}), \tag{6}$$

where $c_{I,m}$ is the fixed cost to apply modern micro-irrigation per unit cultivated area. The functional dependence on irrigation parameters, $\varphi(\tilde{s}, \hat{s})$, ranging from 0 to 1, is reported in Eq. (2).

(iii) Variable irrigation-related costs, in most cases mainly dependent on amount of applied water (e.g., fuel for pumping or price paid for off-farm water; application-specific labor), C_w. We assume a linear dependence of irrigation variable costs on applied irrigation water, i.e., $C_w = c_wV$, where c_w is cost per unit applied water. While such linear dependence on applied irrigation volumes is realistic in most cases, non-linear pricing schemes (e.g., resulting from flat fees for basic water allocations and non-linearly increasing costs for additional supplies) may be more appropriate in some contexts, and can be easily introduced in the model.

According to the above assumptions, net income per unit cultivated area, G, may be expressed as

$$G = J - [C_0 + C_I + C_w] = c_cY - [C_0 + c_{I,m}\varphi(\tilde{s}, \hat{s}) + c_wV]. \tag{7}$$

5.2. Application to corn

We now parameterize the above economic balance for the case of corn. Based on the fact that US corn sale prices ranged from 0.06 to 0.21\$ kg^{-1} over the period 1999–2009 [33], we assume an average crop sale price c_c = 0.12\$ kg^{-1}, but we also perform a sensitivity analysis over the entire observed range. Water costs are assumed to be c_w = 148\$ m^{-1} ha^{-1} (US average expense for irrigation water from off-farm suppliers in 2003 [34, Table 22]), and increased in a further analysis to simulate expected future costs (a possible consequence of increased water demand, declining aquifer levels and increasing fuel costs [36]). Average expense for seeds, fertilizers, and crop harvesting and hauling is taken as C_0 = 600\$ ha^{-1} (a value corresponding to the case of intermediate irrigation capacity according to the calculations of [60] for Northwestern Kansas). Finally, to quantify the irrigation-specific fixed costs, we consider the values reported by [61]. With an interest rate of 5% and an economic life expectancy ranging from 10 yr for drip/trickle irrigation to 15 yr for most of sprinkler and surface systems and including annual maintenance costs (ranging from 2 to 5% of the total cost of the system [62, p. 88]), the equivalent annual costs of equipment installation and maintenance are 166\$ ha^{-1} for flood irrigation, 365\$ ha^{-1} for sprinkler irrigation, and 658\$ ha^{-1} for drip irrigation. These costs are in good agreement with values reported elsewhere (e.g., [18,27]). Based on these calculations, the fixed cost to apply modern micro-irrigation over a unit area, $c_{I,m}$, is set to 658\$ ha^{-1} in Eq. (7).

6. Linking sustainability, productivity, and profitability

To assess the irrigation strategies under the criteria discussed previously, we combine Eqs. (3)–(7) with the results relative to generalized irrigation scheme and piecewise linear-loss function (presented in VPI). The resulting model allows us to quantitatively determine water requirements, crop yield, water productivity, and economic gain, for given climatic conditions, water costs, and crop sale prices. Fig. 5 reports these quantities as a function of the irrigation parameters $\tilde{s}$ and $\hat{s}$, for a total rainfall over the growing season equal to $R_{tot} = \alpha\lambda T_{seas}$ = 248 mm, average crop sale price (c_c = 0.12\$ kg^{-1}), and current water cost (c_w = 148\$ m^{-1} ha^{-1}). For completeness, the analysis is extended also to less-often employed parameter combinations, such as extremely low and high intervention points. As expected, there is no single irrigation strategy that simultaneously minimizes water requirements while also maximizing crop yield and economic gain. Hence, the choice of the best strategy depends on the importance associated with each of these criteria. If water supply is extremely limited (i.e., if minimization of water application is the most valuable criterion to guide irrigation choices), rainfed agriculture or extreme deficit irrigation are the best strategies (Fig. 5a), while deficit micro-irrigation allows the most efficient use of the scarce available water (Fig. 5c). The water savings associated with rainfed agriculture and deficit irrigation, however, cause a significant reduction in crop yield (Fig. 5b) and net gain, in particular if investment-intensive micro-irrigation is applied (Fig. 5d). In contrast, when larger amounts of water are available, stress-avoidance irrigation guarantees higher crop yields, and higher gross incomes, with net gain depending on the cost of the employed irrigation method. Hence, if economic gain maximization is the target, a mild deficit traditional irrigation with relatively infrequent but large irrigation applications (i.e., relatively high $\hat{s}$) is the most profitable strategy (Fig. 5d), at the same time leading to near-maximum crop yields (Fig. 5b). Micro-irrigation requires the smallest water volumes while preserving crop yield, a feature that may render this scheme optimal for water resources conservation but also problematic in case of salinization issues. Conversely, micro-irrigation is not the most profitable solution in this case, because current water cost and crop sale price are relatively low and thus high costs of installation of micro-irrigation are not offset by the limited savings associated with lower water requirements and by obtained yields. As discussed below, accounting for projected increases in water prices [36] may lead to different optimal solutions in terms of profits, favoring micro-irrigation over traditional irrigation. Furthermore, in the case of traditional irrigation, there is an ample plateau of net gain around the optimal $\tilde{s}$, while a significant decrease in net gain is apparent for micro-irrigation, when $\tilde{s}$ is set even slightly below s^*. These differences in the intervention point-economic gain relationships have clear repercussions on applicability of the two irrigation schemes. The expected steep decrease in profits when soil moisture drops slightly below s^* for micro-irrigation at current water costs clearly shows that successful irrigation depends on accurate soil water or plant stress sensing, to avoid counter-productive damages. Nevertheless, as pointed out by Jones [63], in practice it may be difficult to precisely measure soil water levels, and soil water actually available to crops may be not uniformly distributed in the field and along the soil profile. Thus, stress-avoidance micro-irrigation with $\tilde{s} = s^*$ could be risky, as a small underestimate of s^* may result in a significant decrease in crop yield and thus net income. In contrast, traditional irrigation presents a slower decrease in net profits with $\tilde{s} < s^*$ due to the excursions of soil moisture to $\hat{s} > s^*$. Hence, traditional irrigation with mild deficit and intermediate application depths may be the most suitable choice for a number

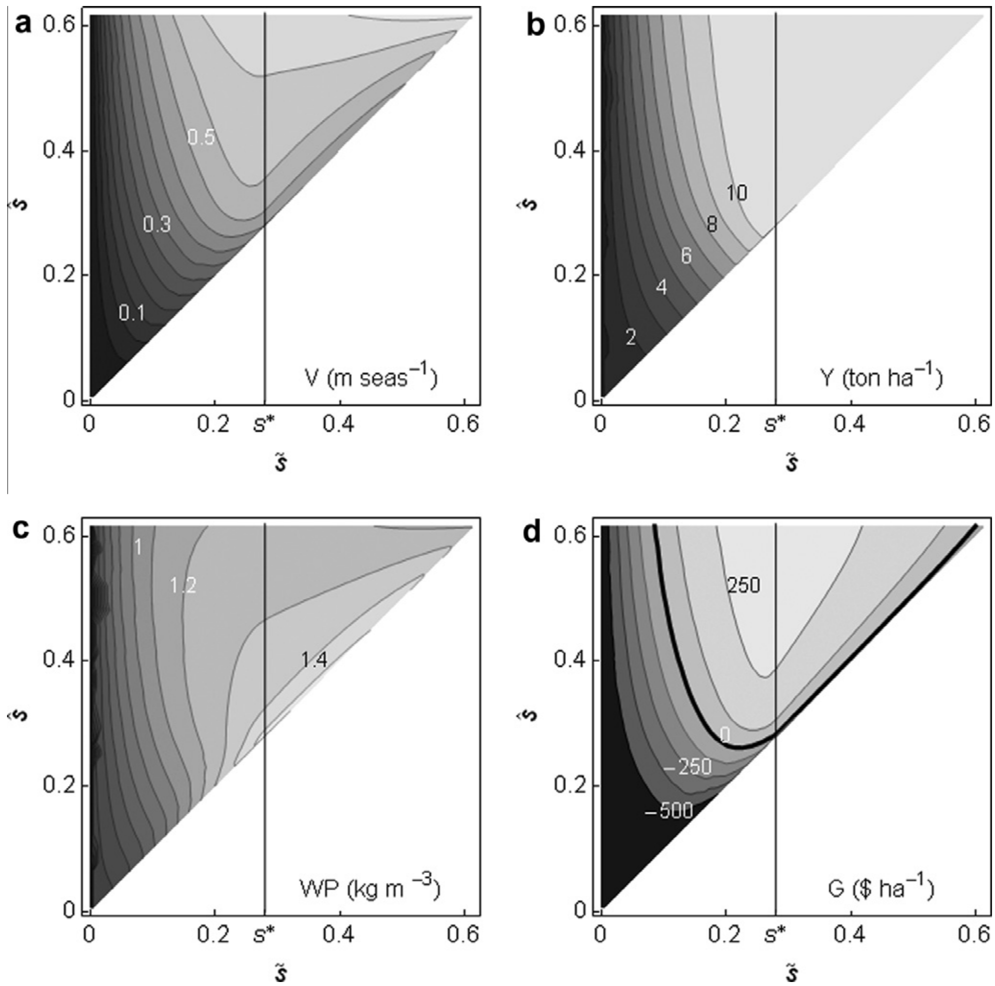

Fig. 5. Total water requirements (a), average crop yield (b), water productivity (c), and economic gain (d), as a function of irrigation parameters for *Zea mays*. For the economic analysis, water cost is set to c_w = 148$ m^{-1} ha^{-1} (average US expense for irrigation water from off-farm suppliers in 2003 [34, Table 22]) and crop sale price c_c = 0.12$ kg^{-1} (average US corn sale prices in the period 1999–2009 [33]). All the other parameters are as in Fig. 2. The thin vertical lines correspond to $\tilde{s} = s^*$. The thick black line in (d) represents irrigation parameter combinations leading to a zero net gain.

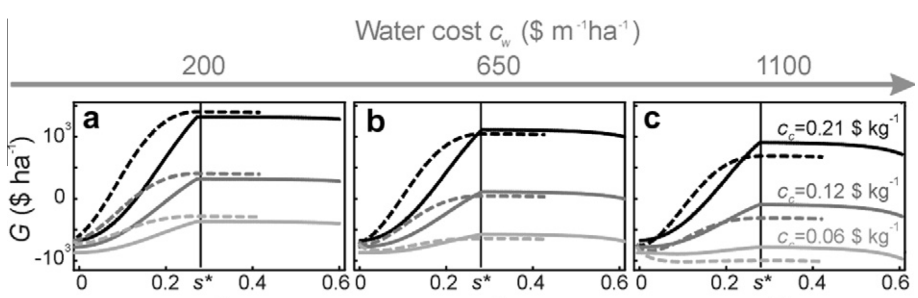

Fig. 6. Net income as a function of intervention point for the two irrigation schemes (micro-irrigation: solid lines; traditional irrigation with $\hat{s} - \tilde{s} = 0.2$ as in Fig. 4: dashed lines) for different crop sale prices and water costs. In each panel, crop sale price increases from bottom to top from minimum (0.06$ kg^{-1}), to average (0.12$ kg^{-1}) and maximum (0.21$ kg^{-1}) price paid to US farmer in the period 1999–2009 [33], as indicated in (c). From left to right, water cost c_w increases from 200, to 650, and 1100$ m^{-1} ha^{-1}. All the other parameters are as in Fig. 2, with the exception of rainfall (here, α = 10 mm and λ = 0.07 day^{-1}). The thin vertical lines correspond to $\tilde{s} = s^*$.

of practical applications, particularly when water costs and crop sale prices are relatively low.

With the climatic parameters used in Fig. 5 (corresponding to an average precipitation over the growing season of R_{tot} = 248 mm), water costs and crop sale prices do not significantly impact the choice of irrigation strategies, but rather they alter the net economic profits. This is generally not the case in more arid areas, where higher irrigation water volumes are required to offset effects of scarce rainfall. An example is presented in Fig. 6, where total rainfall over the growing season is reduced to R_{tot} = 77 mm, by altering both average event depth and frequency. When water costs are comparable to average current ones [34, Table 22], stress-avoidance or mild deficit irrigation remains the most profitable strategy (Fig. 6a) and crop sale prices only influence the attainable maximum economic return, which may be negative with extremely low crop sale prices. In contrast, when water costs are higher than current average ones, micro-irrigation is more profitable than traditional irrigation for higher intervention points. The value of $\hat{s}$ for which the two schemes have the same net gain decreases with decreasing crop sale prices (Fig. 6b and c). Also, for higher-than-current water costs, crop sale prices impact the position of the intervention point guaranteeing the optimal economic return, if a traditional irrigation is performed. Specifically, the optimal intervention point increases with increasing crop sale price, because, when the crop value on the market is high, the higher investments in water required by stress-avoidance irrigation are offset by returns from crop sales, while low crop values may not justify increased water expenditures associated with stress-avoidance irrigation. At extremely high water costs and low crop sale prices, the optimal intervention point goes to zero (i.e., rainfed agriculture is the best option in terms of profits). Hence, where water costs are elevated, irrigation planning must account for a crop-price forecast for the season, which represents a further source of uncertainty.

7. Conclusions

Linking an analytical stochastic model of soil moisture balance, including rainfall unpredictability and demand-based irrigation, to average crop yield and economic profit, we explored the impact of irrigation parameters on crop yield and net income. Irrigation parameters, such as intervention point (i.e., the level of soil moisture that triggers a water application) and applied water volume at each treatment ($nZ_r(\hat{s} - \tilde{s})$), have significant impacts on the resulting water requirements, crop yield, and associated profit. As expected, stress-avoidance micro-irrigation is the most convenient irrigation scheme for water requirement minimization and water use efficiency maximization, but it may not be the most profitable choice for medium-to-low water costs, due to its high costs of installation and maintenance. In contrast, a mild-deficit traditional irrigation scheme seems to balance sustainability, yield, and profitability in those cases. Also, the relatively weak dependence of crop yield and economic gain on the intervention point around its optimal value represents an advantage over micro-irrigation for practical applications. In fact, fine-tuned micro-irrigation may be difficult to apply in practice [8,63], and in this case even relatively small uncertainties in modeling and/or monitoring of soil water status may be responsible for a significant reduction in crop yield and profit.

Our analysis also quantifies how the most profitable irrigation strategy may shift with crop sale prices and water costs: higher crop sale prices and lower water costs encourage use of more water (in agreement with the conclusions of [25]), either through stress-avoidance micro-irrigation or traditional irrigation. Thus, high profitability and water productivity may be achieved through the same irrigation strategy under certain economic conditions, while opposite strategies would be advisable when water costs are low and/or crop sale prices are high. This is remarkable because a reduction in available water, and hence an increase in water costs, or an increase in the crop sale prices may lead farmers to adopt more sustainable strategies, which enhance water use efficiency.

In summary, the proposed theoretical framework allows us to assess different irrigation strategies with respect to different criteria, using a common framework and thus facilitating their comparison. The necessary parameters, characterizing soil and crop features, as well as the economic situation, have a clear physical meaning, and their estimates are often available in practice. By explicitly including random rainfall variability (in terms of stochastic precipitation frequencies and amounts), the proposed framework is also suitable to assess the effects of climate change on irrigation needs and profitability.

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