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Research Paper

Adaptability to future climate of irrigated crops: The interplay of water management and cultivars responses. A case study on tomato

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In the context of climate change strategies are needed towards sustainable agricultural production. The aim of this study is to identify crop adaptation options to face the expected changes in water availability by exploiting the existing intra-specific biodiversity of the tomato crop and accounting for irrigation management and the hydrological properties of soils. The biophysical dimension of crop adaptation is therefore addressed. A study is presented examining an irrigated district in southern Italy. Using as a climatic reference the period 1961–90 and as a future climate the period 2021–2050, a soil water availability indicator was determined by a soil water balance model, at optimal irrigation and at different deficit irrigation strategies, in 23 soil units. For five tomato cultivars, hydrological requirements were determined by means of yield response functions to soil water availability. Cultivar-specific hydrological requirements were evaluated against the soil water availability indicator to determine probabilities of adaptation of each cultivar. These cultivars are not currently being grown in the study area so their potential spatial distribution in the study area was estimated. For instance, with 60% of optimal irrigation, two cultivars were assessed as having probabilities of crop adaptation larger than 0.89, in 90% and 62% of the area. In the future climate, with limited water resources, a proper choice and combination of cultivars, irrigation strategies and soils would allow to maintain the current production system in a large part of the study area.

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Nomenclature

DOY	Day of year
ET_a	Crop actual evapotranspiration (mm)
ET_o	Reference evapotranspiration (mm)
ET_p	Crop potential evapotranspiration (mm)
h	Soil water pressure head (cm)
HS	Hargreaves and Samani method
IE	Irrigation effectiveness (–)
I_r	Seasonal water depth applied for each irrigation case (mm)
k	Hydraulic conductivity (cm d^{-1})
LAI	Leaf area index (m^2 m^{-2})
MPA	Median of probability of adaptation (–)
PA	Probability of adaptation (–)
Q	Quartile
$RSWD_{act}$	Relative soil water deficit – actual (–)
$RSWD_{calc}$	Relative soil water deficit – calculated (–)
$RSWD_{calc}^*$	Relative soil water deficit – calculated – averaged over time (–)
$RSWD_{req}$	Relative soil water deficit – cultivar-specific hydrological requirement (–)
S	Water extraction rate by plant roots (cm^3 cm^{-3} d^{-1})
S_{max}	Maximum possible water extraction rate by plant roots (cm^3 cm^{-3} d^{-1})
STU	Soil typological unit
SWAP	Soil – water-atmosphere-plant model
$T_{a\ ir}$	Seasonal crop actual transpiration for each irrigation case (mm)
$T_{a\ ir0}$	Seasonal crop actual transpiration with no irrigation (mm)
T_p	Crop potential transpiration (mm)
TWRC	Total water retention capacity of soil (mm)
Y_{act}	Actual yield (t)
Y_{max}	Maximum yield (t)
Yr	Relative yield (–)
Yr_{adapt}	Target relative yield for adaptation (–)
z_r	Effective rooting depth (cm)
α	Function of soil water pressure head (–)
$\delta_{RSWDreq}$	Standard error on cultivar-specific hydrological requirement (–)
Θ	Volumetric soil water content (m^3 cm^{-3})

1. Introduction

Food production is already being negatively influenced by climate change (Lobell, Schlenker, & Costa-Roberts, 2011) and climate trends are causing evident water shortages in many parts of the world, including southern Europe (Fereres, Orgaz, & Gonzalez-Dugo, 2011). Agriculture is heavily dependent on irrigation and water resources which are, in turn, tightly coupled to climate variability (Collet, Ruelland, Borrell-Estupina, Dezetter, & Servat, 2013). Water availability therefore mediates agricultural vulnerability to climate change and the potential for responses through crop adaptation.

Several studies on impacts of climate change and on adaptation are documented in literature. Reidsma, Ewert, Lansink, and Leemans (2010) evaluated the capacity of European agriculture to adapt to prevailing climatic conditions, climate change and climate variability over recent decades (1990–2003). They considered both impacts on crop yields and on farmers' income and evaluated the responses to spatial and to temporal climate variability. Olesen et al. (2011) illustrated perceived risks and foreseen impacts on European agriculture and described both observed and predicted adaptation responses. They documented crop adaptation responses, in a Mediterranean environment, by introducing new and more suitable cultivars. Supit et al. (2012) assessed climate change impacts on potential and water limited yield of four selected European crops under different emission scenarios, time scales and water regimes. They recognised that no information is available about future crop varieties and assumed that crop types and their characteristics do not change over time. Ventrella, Charfeddine, Moriondo, Rinaldi, and Bindi (2012) examined current cultivars of durum wheat and tomato crop and specifically identified the potential of irrigation and fertilisation as adaptation responses to climate change. Saadi et al. (2014) studied the impacts of climate change in the Mediterranean region on water and irrigation requirements on the yield of tomato crops; no adaptation measures were examined.

Vulnerability can be defined as having three elements: exposure (to climatic stress), sensitivity and adaptive capacity (Reidsma et al., 2010; Xu et al., 2012). Therefore, a framework can be defined in which climate can be regarded as an independent, external forcing factor (i.e. stressor) with potential impacts being modulated by the sensitivity of each production system: *potential impacts = sensitivity x stressor*. Potential impacts occur without considering adaptive measures. Adaptation interventions, according to the illustrated framework, lead from potential to actual impacts by reducing or removing sensitivity. In this study sensitivity is regarded as a determinant of impacts that can be regulated by operating, among others, on crop and cultivar selection and on irrigation management, accounting for soil hydrological properties.

In Mediterranean environments, a very significant determinant of the sensitivity of a production system is crop response to water stress. The sensitivity of a farming system can be reduced by interventions on crops, and intra-specific differences in yield response to water availability need to be investigated to identify options for adaptation to projected climatic conditions. In fact the intra-specific biodiversity of agricultural crops is very significant (Elia & Santamaria, 2013) and can provide a major opportunity to cope with the effects of the changing climate on agricultural systems (Aspinwall et al., 2015).

Moreover, in irrigated agriculture, sensitivity can be reduced, and adaptation achieved, through changes in irrigation management. In a future (foreseen as warmer) climate, if water availability is not limited, the increase in crop water demand could be fully met by increasing irrigation, and the influence of a (moderately) warmer and drier climate on production could be offset by higher irrigation volumes. The climate change signal would thus be translated into higher water consumption. In a more realistic future scenario, water availability will be limited and a sub-optimal quantity of water will be delivered to crops, i.e. the climate change signal would thus translate into a soil water deficit. The irrigation strategy, therefore, determines the signature of climate change, i.e. whether and how climate signal is observed.

The effects of irrigation and precipitation on crop water availability are modulated by soil hydrological properties (Taylor & Ashcroft, 1972). An accurate description of local variability of soil hydrological properties is thus needed, as reported by Monaco et al. (2014) and by Bonfante et al. (2015). However, many studies on the impacts of climate change on agricultural productivity by means of numerical experiments, do not account for the variability in soil hydrological properties (White, Hoogenboom, Kimball, & Wall, 2011), although adaptation measures are recognised as being place-specific (IPCC, 2014).

As regards processing tomato, Italy is the 7th largest world producer and production amounts to $5132 \cdot 10^3$ t and is valued $1897 \cdot 10^6$ US$ (FAOSTAT, 2012). This crop is among those with the most intensive use of agricultural land, with a high input of water and fertilisers (Ronga et al., 2015; Vazquez, Pardo, Suso, & Quemada, 2006) and proper water management is a key factor in obtaining high fruit yields (Kinet & Peet, 1997; Rinaldi, Garofalo, Rubino, & Steduto, 2011).

The overall objective of this study is to explore the interplay of cultivars responses to water availability and irrigation management strategies to assess the potential for adaptation of a processing tomato crop to future climate, accounting for spatial variability of soils hydrological properties. The following are analysed: i) the impact of climate change on water consumption, irrigation water requirements and soil hydrological conditions; ii) the probability of adapting the cropping of five processing tomato cultivars in different irrigation management scenarios to optimise water use. These cultivars are not currently being grown in the study area, thus the study is an evaluation of their potential value as options for adaptation. Therefore, an approach has been modified and applied (see Section 2.1) in an irrigated district in southern Italy.

2. Material and methods

2.1. The approach

The approach that was developed was to remove, or at least reduce, the vulnerability of current production systems by identifying alternate cultivars optimally adapted to expected climate conditions, without altering the pattern of current species and production systems (Menenti et al., 2008, 2015). Previous applications of this approach have been documented by Reyer et al. (2013) and Monaco et al. (2014).

The approach involved the following steps:

a) Evaluating the impacts of climate change on soil hydrological conditions by means of an indicator of expected conditions (i.e. *the hydrological indicator* Relative Soil Water Deficit), as determined by different irrigation schedules within a specific area, across a range of soil types (Fig. 1a).

The adaptation interventions that can be undertaken, relying on the intra-specific biodiversity of the tomato crop, are then identified in two further steps:

b) Determining the hydrological conditions required to achieve the target yield (i.e. the cultivar-specific *hydrological requirements*) of a set of cultivars relevant to the crop under consideration (Fig. 1b);
c) Identifying, as options for adaptation, the cultivars for which expected hydrological conditions match the requirements (Fig. 1c).

In our approach the indicator of hydrological conditions was calculated using a mechanistic simulation model of water flow in the soil-plant-atmosphere system. Numerical experiments were thus performed to determine the soil water regime as influenced by climate, soils physical properties, irrigation management and a growing crop (Fig. 1a). Crop yield was not calculated by the mechanistic model; instead, empirical functions (based on field trials) of cultivars yield response to water availability were used to determine required hydrological conditions to attain the target yield (Fig. 1b).

Our assessment of cultivars adaptability was performed by estimating the probability that a given cultivar attains the target yield under a specific combination of climate, soil and irrigation. This led to maps of potential extent and distribution of cultivars, i.e. locations where each cultivar is expected to be compatible with the future climate (Fig. 1c).

2.2. The study area

The irrigated district Destra Sele (22,000 ha) was located in the Sele river plain (southern Italy). The altitude ranged between 15 and 32 m a.s.l. Destra Sele was characterised by four different geomorphic systems (conoids, dunes, hills/foothills, fluvial terraces) with heterogeneous parent material (Fig. 2). Very different soil types were formed: phaeozems, luvisols, cambisols, vertisols, and the soil spatial variability was found to be very high. Soil information was derived from a soil map at 1:50,000 scale (Regione Campania, 1996); twenty three soil typological units (*STUs*) were identified. The irrigated area (15,000 ha) was managed by the consortium Destra Sele, a government-controlled association of farmers. Irrigation water was conveyed by a pressurised pipeline network, and delivered on-demand. There were sufficient water resources available at present to fulfil farmers' water demands. Vegetable crops (tomato, melon, fennel, cauliflower) and maize are grown in the Destra Sele and the district belongs to the Province of Salerno, where tomato is cropped in 1100 ha and mainly drip irrigated; the yearly production amounts to 88,000 tons (I.Stat, 2011).

2.3. Climate

Climate data was produced within the Italian project "Agroscenari" (www.agroscenari.it). In this study two climatic cases are studied: a reference climate case, i.e. the current WMO reference period 1961–1990, and future climate case, consisting in 50 simulations of a year representative of the period from

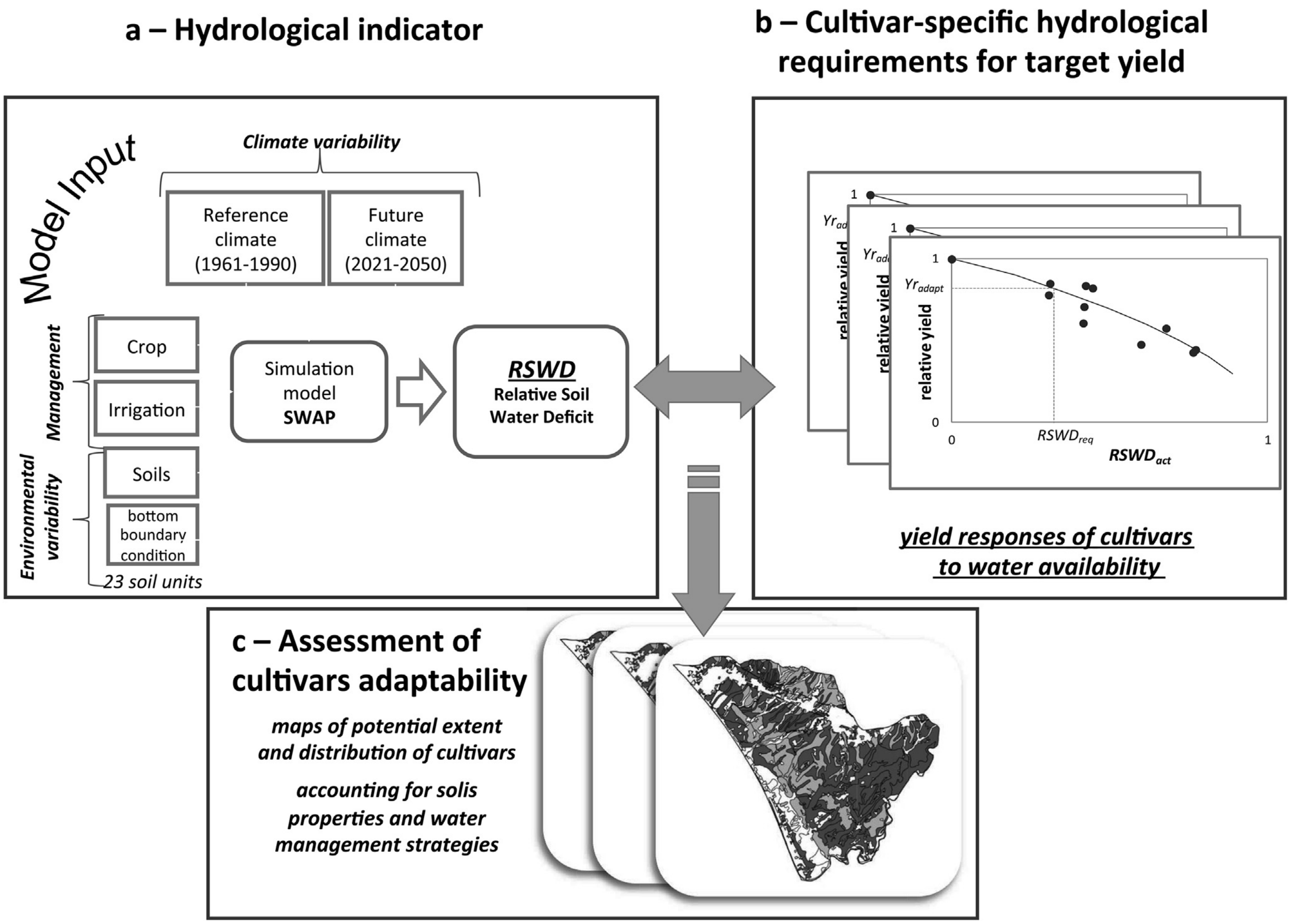

Fig. 1 – Conceptual scheme of the approach to assess the adaptability of cultivars to climate evolution by evaluating hydrological indicators against cultivar-specific hydrological requirements.

2021 to 2050, under the A1B scenario.[2] Climatic data consists of daily time series of maximum and minimum air temperature and rainfall. Data apply to a 35 km by 35 km resolution grid covering the entire Italian territory. Monaco et al. (2014) described in detail how the data sets representing reference and future climates were produced. In this work, the data at the grid node 1179 (40°39′19″ N, 14°53′13″ E) that includes our study area, was used.

2.4. *Soil hydraulic properties*

Hydraulic properties of all 23 *STUs* were determined in order to calculate soil hydrological conditions by means of a mechanistic model. The model is illustrated in Section 2.5. The equations proposed by van Genuchten (1980) were used to parameterise i) soil water retention, i.e. the relationship between the soil water content (Θ) and the soil water pressure head (h), and ii) hydraulic conductivity (k), i.e. the relationships between hydraulic conductivity and Θ or h. Soil hydraulic properties were derived applying the pedotransfer function HYPRES (Wösten, Lilly, Nemes, & Le Bas, 1999), the reliability of which was preliminarily tested on experimentally determined water retention and hydraulic conductivity functions. Eight $\Theta(h)$ and $k(\Theta)$ relationships were determined in the laboratory in undisturbed soil cores (volume ≈ 750 ml), collected in some representative soils of the area (Bonfante et al., 2011). Details on the tests and overall calculation procedures were described by Basile, Coppola, De Mascellis, and Randazzo (2006) and Bonfante et al. (2010).

Total water retention capacity (*TWRC*) of each soil unit was calculated as the difference between the soil water content at field capacity ($h = -33$ kPa) and at wilting point ($h = -1500$ kPa); the difference was integrated over the soil depth of interest.

2.5. *Modelling of soil hydrological conditions*

2.5.1. *The SWAP model*

A mechanistic model of the water flow in the Soil-Water-Atmosphere-Plant system (SWAP v3.26; Kroes, Van Dam, Groenendijk, Hendriks, & Jacobs, 2009) was used to describe the soil hydrological conditions in response to climate and irrigation. SWAP calculates the soil water flow by integrating the Richards' equation, assuming one-dimensional vertical flow processes.

[2] The A1B scenario depicts a future world characterised by very rapid economic growth, increase in global population and rapid introduction of new and more efficient technologies. The energy system relies on a balanced combination of energy sources.

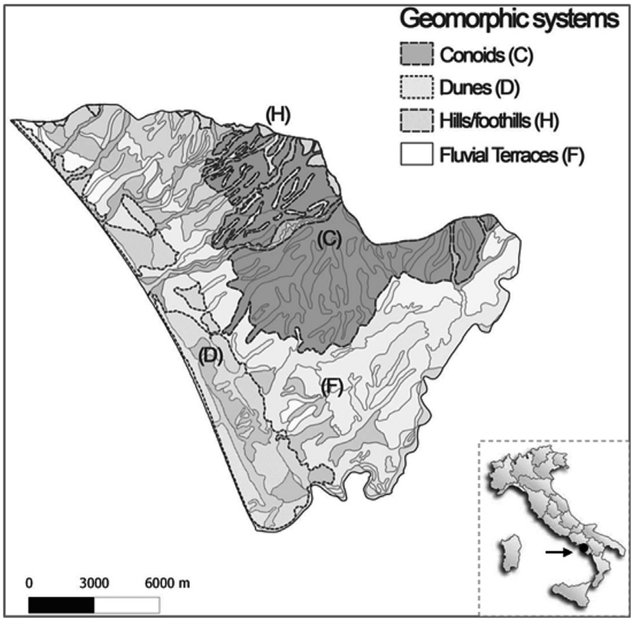

Fig. 2 – The study area Destra Sele: location and map with geomorphic systems layer.
Reprinted from Advances in Agronomy, Vol. 133, Antonello Bonfante, Eugenia Monaco, Silvia M. Alfieri, Francesca De Lorenzi, Piero Manna, Angelo Basile, Johan Bouma, Climate Change Effects on the Suitability of an Agricultural Area to Maize Cultivation: Application of a New Hybrid Land Evaluation System, pp. 33–69, 2015, with permission from Elsevier.

The *SWAP* model applies daily crop potential evapotranspiration (ET_p), daily precipitation and irrigation to prescribe the upper boundary condition. ET_p is calculated from reference evapotranspiration (ET_o) and a crop factor (as described by Kroes et al., 2009). Reference evapotranspiration (ET_o) was estimated, for the reference and future climate case, from daily time series of air temperature by means of the Hargreaves and Samani (1985) method (*HS*). The *HS* model is a simplified method which requires solely air temperature data. This was used since only air temperature was known in the future climate case. Fagnano, Acutis, and Postiglione (2001) report that in the area under study the *HS* method underestimated the seasonal (May–September) values of ET_o, calculated by the Penman–Monteith equation (Allen, Pereira, Raes, & Smith, 1998), by 4%. Commonly used climate scenarios at much lower spatial resolution (e.g. 200 km by 200 km) include a richer set of climatic variables, but such low spatial resolution did not meet the requirements of our analysis in a small area. Daily time series of rainfall data concur in defining the upper boundary condition. *SWAP* does not describe exactly how irrigation water is applied to the soil and irrigation is assumed to be applied uniformly to the surface, likewise precipitation. Soil evaporation is calculated using a soil-dependent maximum evaporation rate and time-dependent reduction factors estimated according to Boesten and Stroosnijder (1986). The lower boundary condition was prescribed as unit gradient in hydraulic head.

The *SWAP* model was calibrated and validated for several crops (e.g. maize, alfalfa, tomato, aubergine, snap beans, artichoke, fennel, cauliflower) in the Sele plain (Basile & Terribile, 2008; D'Urso, Menenti, & Santini, 1999; Tedeschi & Menenti, 2002). In addition, *SWAP* has been used to assess the impacts of climate change and evaluate various adaptation options (Bonfante et al., 2015; Droogers, Loon, & Immerzeel, 2008; Martínez-Ferri, Muriel-Fernández, & Díaz, 2013; Menenti et al., 2015; Monaco et al., 2014). Simulations were carried out for all *STUs* and the daily soil water balance was calculated for each *STU* and year of the reference and future climate cases.

2.5.2. *Simulation of crop water use*

Crop water use was simulated by the "simple crop module" option in *SWAP* which prescribes crop development; the main function of the crop is to provide a proper upper boundary condition for soil water movement. The simple model does not calculate either the potential or actual crop yield.

The soil water balance was simulated in a 2-year rotation scheme typical of the area (tomato, fennel, melon and cauliflower). Numerical experiments were performed for an *exemplary* tomato cultivar, assumed to be representative of the species under study and defined by a temporal profile of leaf area index (*LAI*), rooting depth and crop factor, as described by Kroes et al. (2009). Crop input data were estimated based on local experiments and the scientific literature. Several experimental and literature data sets were examined in order to describe the phenology of the exemplary cultivar. Maximum leaf area index was set to 2.8 $m^2\ m^{-2}$ (Onofri, Beccafichi, Benincasa, Guiducci, & Tei, 2009; Patanè unpublished data). Maximum rooting depth and density were set, respectively, to − 0.8 m and between − 0.15 and − 0.50 m (Battilani, Henar Prieto, Argerich, Campillo, & Cantore, 2012; Patanè unpublished data). Crop factor at mid-season growth stage was set to 1.25, in agreement with Rinaldi and Rana (2004). The growing season was assumed to last 101 days, from May 10th to August 18th (i.e. from Day of Year, *DOY*, 130 to *DOY* 230), which is the ordinary cropping season for tomato in the area. For processing tomato Battilani et al. report a length of the growing season varying from 95 to 115 days.

Actual transpiration was calculated by *SWAP*, according to Feddes, Kowalik, and Zaradny (1978), representing water extraction by plant roots as a sink term S defined as:

$$S = \alpha(h) \cdot S_{max} = \alpha(h) \cdot T_p / |z_r| \quad [\mathrm{cm^3 cm^{-3} d^{-1}}] \tag{1}$$

where S is the water extraction rate, α is a non-dimensional function of soil water pressure head (h) with values between 0 and 1, S_{max} is the maximum possible water extraction by plant roots, T_p is the potential transpiration rate and $|z_r|$ is the effective rooting depth, defined as the soil depth where approximately 75% of the roots are found. T_p is calculated by partitioning ET_p into soil potential evaporation and potential transpiration, taking into account *LAI* evolution and rainfall interception (Kroes et al., 2009). The light extinction coefficient for the soil cover fraction was set to 0.45 (Cavero et al., 1998).

Under non-optimal conditions S_{max} was reduced by means of the pressure-head dependent function α and the actual transpiration rate of the crop was equal to the integral of the sink term over the effective rooting depth. The function *α(h)* defines limiting points of the root extraction rate. Water uptake was assumed to be maximal (and transpiration to attain its potential rate) when $\alpha(h) = 1$, i.e. in an interval of pressure head values between h_2 and h_3. When soil water pressure head was lower than h_3, then $\alpha(h) < 1$ and transpiration decreased less than its potential rate. The limiting point h_3 can have two different values ($h_{3\ high}$ and $h_{3\ low}$) according to potential transpiration rate. $h_{3\ high}$ shifts towards lower values of h (i.e. $h_{3\ low}$) for decreasing potential transpiration, since insufficient root uptake is less likely under reduced evaporative demand. The limiting points of root extraction rate were set according to Kroes et al. (2009). (A more detailed description of the function *α(h)* is given in supplementary file 1).

2.5.3. *Simulation of irrigation scheduling*

Five irrigation strategies were defined and scheduled using the *SWAP* model, from optimal irrigation to different levels of deficit irrigation. Irrigation amounts and schedules were distinctly designed for each *STU* and for each simulation of the reference and future climate cases.

Optimal irrigation (100%) was scheduled on the basis of the soil water pressure head. The limiting point h_3 was set as the threshold value to trigger irrigation. Namely, $h_{3\ high}$ and $h_{3\ low}$ values were set to −800 cm and −1500 cm, respectively (Kroes et al., 2009). Irrigation was applied, in each *STU*, at any time when the threshold value h_3 was attained at −0.3 m depth, i.e. within the soil layer where root density was maximum at full crop development. In our calculated optimal schedule, irrigation events were thus triggered by pressure head reaching the same threshold value for all soil units. The dates of irrigation events and the corresponding soil water deficit, however, varied across soil units. Irrigation water depths were calculated to restore to field capacity the soil water content in the rooting depth.

Deficit irrigation schedules were defined by keeping the same dates as the optimal irrigation schedule just described, but reducing water depths to 80%, 60%, 40% and 20% of the optimal ones. The case with no irrigation was simulated as well. Between consecutive irrigation events, a minimum interval of 3 d was prescribed.

Next, for each irrigation schedule, *STU* and simulation of the climate cases, the effectiveness of irrigation and indicators of soil hydrological conditions were determined, as explained in Sections 2.5.4 and 2.5.5.

2.5.4. *Effectiveness of irrigation*

The effectiveness of each irrigation schedule was calculated as the marginal increase of transpiration for a given irrigation water depth:

$$IE = (T_{a\ Ir} - T_{a\ Ir0})/Ir \quad [-] \tag{2}$$

where *IE* is irrigation effectiveness, $T_{a\ Ir}$ (mm) is the seasonal crop actual transpiration for each irrigation case (i.e. 100%, 80%, 60%, 40% and 20%), $T_{a\ Ir0}$ (mm) is the seasonal crop actual transpiration with no irrigation (0) and *Ir* (mm) is the seasonal water depth applied for each irrigation case.

2.5.5. *Indicator of soils hydrological conditions*

Water availability in each *STU* was described by means of a hydrological indicator, i.e. the calculated relative soil water deficit ($RSWD_{calc}$) (Menenti et al., 2008, 2015; Reyer et al., 2013), calculated from *SWAP* numerical experiments as follows:

$$RSWD_{calc} = 1 - ((\Theta_{calc} - \Theta_{WP})/(\Theta_{FC} - \Theta_{WP})) \quad [-] \tag{3}$$

where Θ ($m^3\ m^{-3}$) is the volumetric soil water content in the layer explored by roots, namely: Θ_{calc} is calculated soil water content (numerical experiments), Θ_{WP} is soil water content at h = −1500 kPa (wilting point) and Θ_{FC} is soil water content at h = −33 kPa (field capacity).

The daily values of the hydrological indicator $RSWD_{calc}$ were calculated in each *STU* for each simulation of the reference (1961–90) and future (2021–50) climate cases. Daily $RSWD_{calc}$ were then averaged over the entire cropping season or part of it, as explained in Section 2.7.

2.6. Cultivars hydrological requirements

Cultivar-specific requirements on water availability of five cultivars of tomato (*Solanum lycopersicum* L.) were derived from yield response functions to water availability. Several experimental data sets in the scientific literature and unpublished, that included concurrent measurements of yield and soil water availability under field conditions that spanned well-watered to water-stressed conditions, were analysed. Data on yield and water use for two tomato cultivars were derived from literature: *Brigade* (Patanè & Cosentino, 2010) and *H3044* (Machado & Oliveira, 2005). Data on three cultivars were unpublished: *Design*, *Season* and *Solerosso* (Patanè; unpublished data). In the selected data sets the start of the irrigation treatments occurred in the same phase of the growing season as in the numerical experiments. Some characteristics of the cultivars are listed in Table 1.

To determine yield response functions, the yield of each cultivar was expressed as relative yield (*Yr*) defined as:

$$Yr = Y_{act}/Y_{max} \quad [-] \tag{4}$$

where Y_{act} is actual yield and Y_{max} is maximum yield under given climate and soil conditions, i.e. the yield at non-limiting soil water availability.

From the experimental data sets, soil water availability was determined, and described, by the actual (observed) Relative Soil Water Deficit ($RSWD_{act}$):

Table 1 – Characteristics of the tomato cultivars analysed in the present study.

Cultivar	Fruit shape	Fruit weight (g)	Cycle length[a] (d)	Disease resistance[b]
Brigade	Plum square	60–70	99	V, F, ASC
Design	Plum	50–60	105	V, F, N
Season	Long	60–70	105	V, F, N, ST
Solerosso	Plum	40–50	99	V, F, P
H3044	Plum blocky	75	100	V, F, N

[a] From transplant to harvest.
[b] ASC = Ascomycetes; F = Fusarium Wilt; N = Nematodes; P = Pseudomonas; ST = Stemphylium; V = Verticillium Wilt.

$$RSWD_{act} = 1 - ((\Theta_{act} - \Theta_{WP})/(\Theta_{FC} - \Theta_{WP})) \quad [-] \tag{5}$$

where Θ ($m^3\ m^{-3}$) is the volumetric soil water content in the layer explored by roots, namely: Θ_{act} is actual (observed) soil water content, Θ_{WP} is soil water content at h = −1500 kPa (wilting point) and Θ_{FC} is soil water content at h = −33 kPa (field capacity).

$RSWD_{act}$ (Eq. (5)) was defined similarly to the hydrological indicator $RSWD_{calc}$ (Eq. (3)), however the water availability variables in Eq. (5) were derived by experimental data (e.g. Machado & Oliveira, 2005; Patanè & Cosentino, 2010), not by simulations.

Yr values were plotted against values of $RSWD_{act}$ and the yield response function was defined by a curve fitting the experimental data. The yield set point for adaptation (Yr_{adapt}), i.e. *the target relative yield*, and the corresponding value of $RSWD_{act}$ (i.e. the cultivar-specific requirement, $RSWD_{req}$) were estimated as described below.

Crops may respond linearly (Payero, Melvin, Irmak, & Tarkalson, 2006) or non-linearly (Moriana & Orgaz, 2003) to changes in water availability, therefore in our study cultivar-specific yield response functions were represented by means of linear or threshold-slope regression models. In the threshold-slope model the value of $RSWD_{act}$ at which a decrease of the response function is initiated (breakpoint) was set as $RSWD_{req}$. In the linear model, the yield set point for adaptation was set as $Yr_{adapt} = 0.9$, as per a comprehensive analysis on adaptation measures by Montesino - San Martin, Olesen, and Porter (2014); the value of $RSWD_{act}$ corresponding to $Yr_{adapt} = 0.9$ was set as the cultivar-specific hydrological requirement ($RSWD_{req}$). In both cases, the standard error ($\delta_{RSWDreq}$) of each cultivar-specific requirement ($RSWD_{req}$) was estimated. Both $RSWD_{req}$ values and the slope of the response functions are cultivar-specific and they represent a measure of sensitivity to the reduction of soil water availability (Doorenbos, Plusje, Kassam, Branscheid, & Bentvelsen, 1986; Rizza et al., 2004).

2.7. Adaptability assessment

The probabilities of crop adaptation, i.e. the probability that a given cultivar attains the target relative yield, were evaluated for all cultivars, simulations of climate cases, *STU*s and three irrigation levels (100%, 80% and 60%) by comparing the cultivars requirements ($RSWD_{req}$) with *RSWD* values calculated from *SWAP* outputs ($RSWD_{calc}$). In the yield response functions, the $RSWD_{act}$ values were derived from measurements performed through the whole crop growing season or through a part of it, according to the data set available for the cultivar. Therefore, cultivar requirements ($RSWD_{req}$) were evaluated against $RSWD_{calc}$ values averaged over the same period of time. The averaged values of $RSWD_{calc}$ are indicated by $RSWD_{calc}^*$.

The evaluation of the cultivars hydrological requirements ($RSWD_{req}$) against the averaged hydrological indicator ($RSWD_{calc}^*$) was done for each cultivar in each year, *STU* and irrigation level. A cultivar was considered adaptable when $RSWD_{calc}^*$ was lower than $RSWD_{req}$, and this assessment was done taking into account the standard error ($\delta_{RSWDreq}$) of the estimate of $RSWD_{req}$. To this purpose a probability distribution function was associated with each cultivar-specific hydrological requirement, assigning to each $RSWD_{req}$ a normal distribution with standard deviation equal to $\delta_{RSWDreq}$. The probability of adaptation (*PA*) of the cultivar was then estimated by calculating the probability of $RSWD_{calc}^*$ being lower than the given random value of $RSWD_{req}$. *PA* was calculated for each cultivar, year, *STU* and irrigation level. Figure 3 shows an example of a cultivar-specific hydrological requirement, its associated distribution and how the probability *PA* (the shaded area) is quantified. It should be noted that the *PA* value indicates the probability of attaining the target relative yield (Yr_{adapt}), since the latter determined the value of the hydrological requirement $RSWD_{req}$. This approach makes less critical the accuracy of Yr_{adapt}, since the uncertainty of the requirement was considered by comparing each value of the hydrological indicator $RSWD_{calc}^*$ with a range of $RSWD_{req}$, and consequently of Yr_{adapt} values, to calculate the probability of adaptation.

Subsequently, for each cultivar, *STU* and irrigation level, the medians (*MPA*) of the distributions of *PA* values were calculated over the years in either climate case (reference and future). A unique distribution of medians was then set up by pooling all *MPA* values. The quartiles (Q) of the unique distribution were determined and used to set adaptability ranges; then the medians of the distributions of *PA* values (*MPA*) of each cultivar, for each *STU* and irrigation level, in the reference and future climate, were evaluated on the quartiles of the unique distribution of *MPA*. For instance, an adaptability range could be set between the first and second quartile of the distribution (Q_1 and

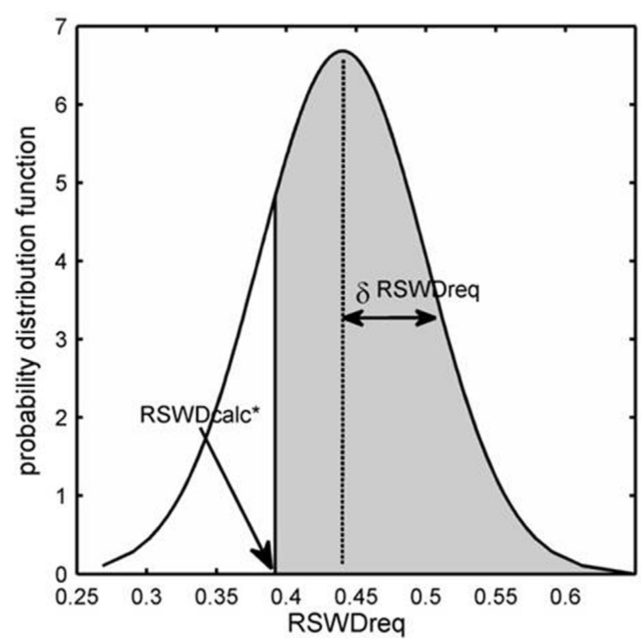

Fig. 3 – Cultivar-specific hydrological requirement ($RSWD_{req}$, dashed black line) and its probability distribution function determined through the standard error ($\delta_{RSWDreq}$) associated with $RSWD_{req}$. The shaded area indicates the probability of adaptation, in one year and *STU*, at a given irrigation level.

Q_2, respectively). Then, for one cultivar and irrigation level, in one climate case, the *STUs* in which $Q_1 < MPA \leq Q_2$ were determined. Maps of locations where the *MPA* of the cultivar lay within the range could be drawn. The adaptability ranges were thus used to define the potential spatial extent and distribution of each cultivar in the study area.

2.8. Statistical analysis

Data values were expressed as medians and inter-quartile ranges. Data were processed by two-way analysis of variance (*ANOVA*) to test the effects of climate case and of irrigation schedules. The significance of the relationships of cultivar yield responses was tested by calculating *p*-values. The results were accepted as significant at $P < 0.05$.

3. Results

3.1. Climate

The predicted changes in precipitation and mean temperature are shown in Fig. 4; variations in annual and seasonal (May–August) values are shown, as well as those during the growing season of tomato (*DOY* 130–230). In the reference climate case (1961–90) the median of the distribution of mean daily temperatures, from January to December, was 14.6 °C and is expected to increase by 1.5 °C in 2021–50. For the May–August period the median was 21.4 °C and is likely to increase by 1.8 °C in 2021–50. For the growing season of tomato, the median was 21.6 °C and it is expected to increase by 1.6 °C in 2021–50. Hence, projected variations in mean temperature over the tomato growing season were consistent with seasonal and annual ones. However, variations in precipitation were quite different when considering annual, seasonal and growing season trends. In 1961–90 the median of annual rainfall was 1052 mm, the median of seasonal rainfall (May–August) was 157 mm and the median of rainfall during the growing season of tomato was 121 mm, although distributions were characterised by quite high inter-quartile ranges (i.e. the differences between the third and the first quartile) (data not shown). Projected changes for rainfall varied widely between −23% and −2%, respectively for annual and May–August values; projected rainfall variation in the tomato growing season was −7.4%.

The number of rainy days slightly decreased in 2021–50 (−2 days). In the 1961–90 climate case reference evapotranspiration (ET_o) was 513 mm and increased by 18 mm (+3.5%) in 2021–50.

While the median of total precipitation over the tomato growing season was predicted to decrease (−7.4%) in the future climate case, the distributions of 10-days precipitation, over the same period, were different. Figure 5 shows that in the 1st and 3rd decades the rainfall in 1961–90 was higher than in 2021–50; in all other decades the rainfall was higher in 2021–50.

3.2. Water requirement under optimal and deficit irrigation

3.2.1. Crop and irrigation water requirements: reference versus future climate

Seasonal actual crop evapotranspiration (ET_a) and irrigation depths were calculated using the SWAP model in the two climate cases for different irrigation schedules and are shown in Table 2. ET_a and irrigation depths for the optimal, 80% and 60% irrigation levels are shown; medians were calculated over the distributions of the variables in the 23 *STUs*.

Simulated ET_a ranged from 407 to 463 mm in the reference climate, according to the irrigation levels, while in the future climate ET_a varied from 420 to 483 mm. The two-way *ANOVA* at significance level 0.05 showed that climate case and irrigation schedules were the main source of variation for ET_a and seasonal irrigation depths. From reference to future climate ET_a, averaged over the irrigation levels, increased by 3.5% (i.e. by 20 mm under optimal irrigation). Seasonal irrigation depths increased on average by 2.4% (i.e. by 8 mm at optimal

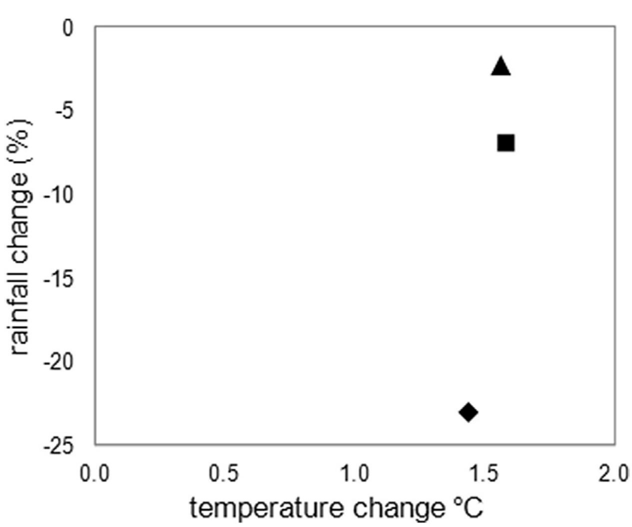

Fig. 4 – Changes in rainfall and mean temperature in 2021–50 relative to the reference period (1961–90). Changes are shown for annual (diamond), seasonal (May–August, triangle) and for the tomato growing season (*DOY* 130–230, square) projections.

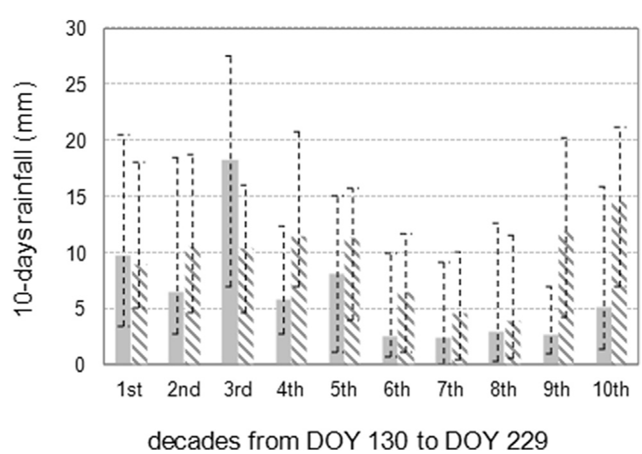

Fig. 5 – Medians of 10-days rainfall from *DOY* 130 to *DOY* 229 in the reference (1961–90, solid bars) and future (2021–50, striped bars) climate case. Dotted lines indicate the range from the first to the third quartile.

Table 2 – Seasonal actual crop evapotranspiration and irrigation water depths (medians and inter-quartile ranges of the distributions) in the two climate cases, at different irrigation levels (optimal irrigation and water depths reduced to 80% and 60% of the optimal one). Data were calculated over the 23 Soil Typological Units.

Climate	Seasonal actual crop evapotranspiration (mm)			Seasonal irrigation depths (mm)		
	Optimal	80%	60%	Optimal	80%	60%
1961-90	463 (19)	448 (21)	407 (31)	327 (71)	262 (57)	196 (43)
2021-50	483 (19)	464 (23)	420 (31)	335 (51)	268 (40)	201 (30)
2021–50 vs. 1961–90	+20 (3.9%)	+16 (3.6%)	+13 (3.2%)	+8 (2.4%)	+6 (2.3%)	+5 (2.5%)

irrigation level). The increase in ET_a was thus more than twice the variation of irrigation depths. The start of irrigation treatments, in the future climate, is expected to occur on average at *DOY* 161 (31 days after planting), i.e. four days earlier than in the reference climate.

The relatively small increase of irrigation water depths from reference to future climate was due to the trend of 10-days rainfall that was predicted in the future climate case, as discussed in Section 3.1. During the irrigation period, i.e. from *DOY* 160 (4th decade of the growing season) onwards, increased rainfall partly compensated for the increase in crop evapotranspiration.

3.2.2. *Irrigation requirements in different soil typological units*

To assess the influence of soils hydrological properties on irrigation water requirements, the variability in irrigation water depths in the *STUs* was analysed under optimal irrigation. Figure 6 shows, for the reference climate case, box-and-whisker plots of seasonal irrigation depths in the *STUs*, ranked by increasing median. Irrigation depths were lower in *STUs* in the fluvial terraces (*F*) where vertisols prevail, and higher in conoids (*C*) and hills/foothills (*H*) where phaeozems dominate.

Future climate irrigation depths, evaluated over all *STUs*, increased by 8 mm under optimal irrigation (Table 2); variations in irrigation depths, however, were different between *STUs* (Fig. 7). Irrigation depths increased mainly in *STUs* in the fluvial terraces (*F*), and in some cases the variation was ~40 mm. In several *STUs*, both in the fluvial terraces and in the other geomorphic systems, the variation was very small or slightly negative. Differences in seasonal irrigation depth were much higher, however, between soils within the same climate case (Fig. 6). Considering *STUs* 48 and 20, respectively in the highest and lowest rank of Fig. 6, the differences between their seasonal irrigation depths were 143 and 123 mm, in the reference and future climate case, respectively.

An example of the differences in irrigation water depth and frequency in different soils is given for *STUs* 20 and 48, the two extreme cases in Fig. 6, under optimal irrigation. Table 3 shows the amounts of irrigation in two growing seasons, within each climate case, characterised by contrasting rainfall amounts and crop potential evapotranspiration values (ET_p); the differences between ET_p and rainfall amount provide an estimation of gross irrigation requirements. In the given example rainfall varied from 46 mm (low rainfall season in the 1961–90 climate) to 167 mm (high rainfall season in 2021–50), ET_p varied from 544 mm (high rainfall season in 1961–90) to 594 mm (low rainfall season in 2021–50). The differences in seasonal rainfall between high and low rainfall cases were similar within each climate case (i.e. approximately 95 mm). Gross irrigation requirement in the low rainfall case was about 140 mm higher than in the high rainfall case, in both climate cases.

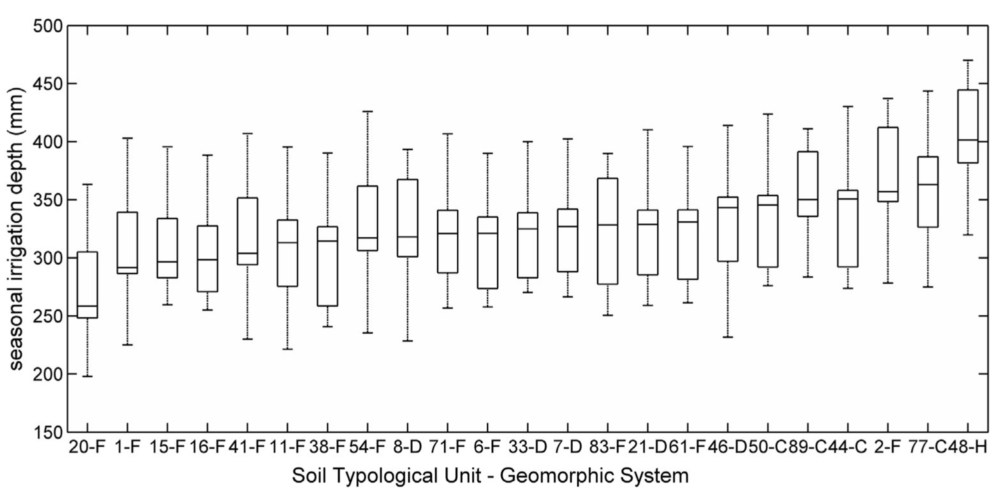

Fig. 6 – Distributions of seasonal irrigation depths under optimal irrigation scheduling for all soil typological units (*STUs*), in the reference climate case (1961–90). Boxes are delimiting the first and the third quartile with the median inside; whiskers indicate the minimum and maximum values. Number and geomorphic system of each *STU* are indicated; C represents conoids, D represents dunes, F represents fluvial terraces and H hills/foothills.

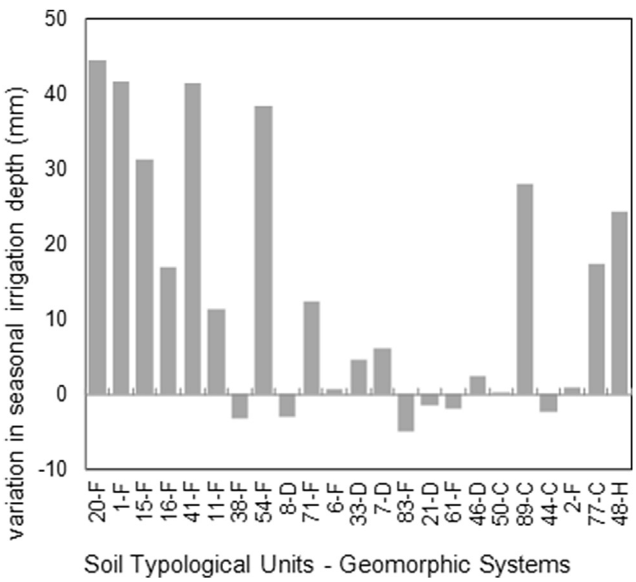

Fig. 7 – Variations in seasonal irrigation depths under optimal irrigation for all soil typological units (*STUs*) from the reference (1961–90) to future (2021–50) climate case. Number and geomorphic system of each *STU* are indicated; C represents conoids, D represents dunes, F represents fluvial terraces and H hills/foothills.

In *STU* 48 the differences in seasonal irrigation water depths between the low and high rainfall cases were quite similar (≅ 55 mm) in the two climate cases. On the contrary, in *STU* 20 the difference was much higher in 1961–90 than in 2021–50 (i.e. ≅110 mm in 1961–90 versus ≅ 45 mm in 2021–50). This could be due to the interaction between the hydraulic properties of *STU* 20 and the variation in the temporal distribution of daily precipitation in the low rainfall cases in 1961–90 and 2021–50. The number of rainy days was lower and the percentage of wet days following dry days was higher in the low rainfall case in 2021–50 than in 1961–90 (data not shown). In the high rainfall case the number of rainy days was the same in the two climate cases. Therefore, over the period 2021–50, in the low rainfall case rainfall was more efficient in soils with low *TWRC*, like *STU* 20, leading to lower seasonal irrigation depths.

In *STU* 48 seasonal irrigation depths were quite similar between the two climate cases, both at high and low rainfall. The high *TWRC* of *STU* 48 smoothed out the impact of different rainfall amounts and distributions in the two climate cases. *STU* 20 had a different behaviour due to its low *TWRC*. *STU* 20 and 48 received the same number of irrigations (7) only in the low rainfall case in the reference climate. In all other cases *STU* 20 received one irrigation less than *STU* 48. The differences between *STU* 20 and 48 with respect to irrigation depths and frequencies are due to their different hydraulic properties, which are discussed in detail in supplementary file 2.

3.2.3. *Effectiveness of irrigation*

To evaluate the feasibility of deficit irrigation we have analysed its effectiveness (using the indicator *IE*, defined by Eq. (2)) and crop response to water stress. The latter is evaluated for different cultivars in the next section, while here we focus on irrigation effectiveness. Table 4 shows *IE* at different irrigation levels, in the two climate cases. Medians and interquartile ranges of the distributions of *IE* calculated over all *STUs* are reported.

The two-way *ANOVA* at significance level 0.05 showed that climate case and irrigation schedules were the main source of variation for irrigation effectiveness. In the future climate case irrigation effectiveness was higher at all irrigation levels; this indicates that, for a given irrigation water depth, the marginal increase of actual transpiration was higher. This was due to the different temporal distribution of rainfall in the two climate cases: the predicted lower number of rainy days in the 2021–50 climate case increased the effectiveness of irrigation. In both climate cases irrigation effectiveness was highest at 60% of optimal irrigation, and declined both towards higher and lower irrigation levels. In the two climate cases *IE* had a quite similar trend due to the criteria used to define irrigation schedules.

3.3. *Water saving by deficit irrigation: climate versus cultivars*

3.3.1. *Hydrological indicator*

Soil water availability in *STUs* was described by $RSWD_{calc}$ (Eq. (3)), determined by the numerical experiments with the *SWAP* model. Due to the definition of the irrigation strategies (i.e. optimal irrigation and proportional reduction of water depths in deficit irrigation schedules), $RSWD_{calc}$ values for each soil, calculated through the irrigation season, were similar, in the two climate cases, for the same irrigation strategy. However higher irrigation depths were needed to maintain similar values of $RSWD_{calc}$ in the future climate.

Table 3 – Rainfall, crop potential evapotranspiration (ET_p), gross irrigation requirement (ET_p - rainfall), seasonal irrigation depth under optimal irrigation scheduling. Data refer to two soil typological units (*STU*), in two growing seasons, within each climate case, with contrasting rainfall amounts.

Climate	*STU*	Rainfall (mm)	ET_p (mm)	ET_p – rainfall (mm)	Seasonal irrigation (mm)
1961–90	*STU* 20	46 (low)	587	541	364
		141 (high)	544	403	255
	STU 48	46 (low)	587	541	455
		141 (high)	544	403	402
2021–50	*STU* 20	69 (low)	594	525	306
		167 (high)	553	386	260
	STU 48	69 (low)	594	525	448
		167 (high)	553	386	396

Table 4 – Irrigation effectiveness (*IE*) in the reference (1961–90) and future (2021–50) climate case at different irrigation levels (optimal irrigation and water depths reduced, with respect to optimal one, from 80% to 20%). Medians (and inter-quartile ranges) of the distributions of *IE* over 23 soil typological units (*STUs*) are reported.

Climate	Irrigation effectiveness				
	Irrigation level				
	Optimal	80%	60%	40%	20%
1961–90	0.62 (0.10)	0.70 (0.09)	0.73 (0.10)	0.71 (0.09)	0.59 (0.12)
2021–50	0.64 (0.10)	0.73 (0.09)	0.75 (0.09)	0.73 (0.09)	0.62 (0.11)

Some examples of the trend and spatial distribution of $RSWD_{calc}{}^*$ are thus presented for one climate case (2021–50). In the given examples, in each *STU*, $RSWD_{calc}{}^*$ values were averaged through the *DOY* 190–223 period, in the soil layer 0–0.4 m.

The variability of $RSWD_{calc}{}^*$ at three irrigation levels (100%, 80% and 60% of optimal volume) is shown in Fig. 8. Each probability distribution function describes the frequency of $RSWD_{calc}{}^*$ values in all *STUs* and simulations of the climate case. The differences in soils hydrological properties among *STUs* translate into different probability distribution functions of $RSWD_{calc}{}^*$ at different irrigation volumes. At the optimal irrigation level (100%) values of $RSWD_{calc}{}^*$ were higher than zero (range 0 ÷ 0.1) due to the criterion adopted for irrigation start, i.e. detection of soil water pressure head at a specific depth in the soil layer, and to the time required for water infiltration. The differences in hydrological properties among *STUs* determined the much higher variability of $RSWD_{calc}{}^*$ at lower irrigation volumes. Moreover, the inter-annual variability of precipitations affected more soils hydrological conditions at lower irrigation volumes.

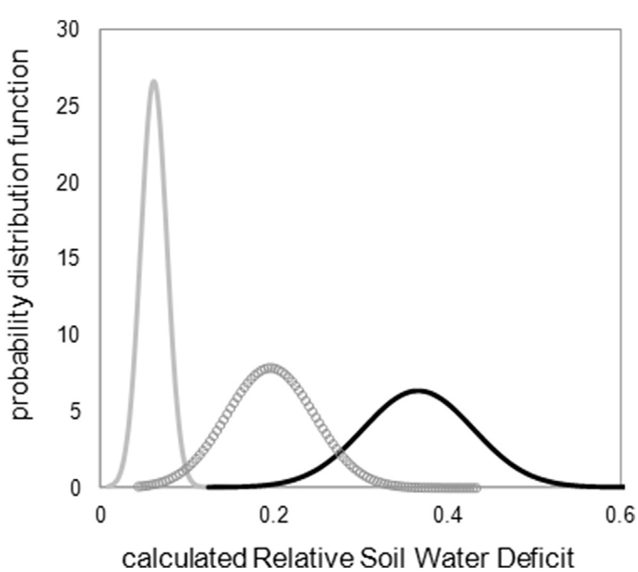

Fig. 8 – Probability distribution functions of the calculated hydrological indicator relative soil water deficit, averaged over the *DOY* 190–223 period, in all Soil Typological Units of the study area, at three irrigation levels, in the 2021–50 climate case. Grey line represents 100% irrigation level, circles represent 80% irrigation level and black line represents 60%.

Figure 9 shows the spatial distribution of the indicator $RSWD_{calc}{}^*$ at two irrigation levels (80% and 60% of optimal volume). In each *STU*, $RSWD_{calc}{}^*$ values were averaged over the simulations of the period 2021–50; the ranges plotted are the quartiles determined on the distribution of the values of $RSWD_{calc}{}^*$.

$RSWD_{calc}{}^*$ values do not correlate well with the total water retention capacity (*TWRC*) of the layer (0–0.4 m), i.e. most $RSWD_{calc}{}^*$ values in Fig. 9 correspond to very similar *TWRC* of about 50 mm. Moreover *STU* 83 has similar $RSWD_{calc}{}^*$ values to most *STUs* but a lower *TWRC* (≅ 40 mm). There is only one exception i.e. *STU* 20 where higher $RSWD_{calc}{}^*$ values correspond to a lower *TWRC* (= 40 mm). Differences in hydraulic conductivity help explaining differences in $RSWD_{calc}{}^*$ across soils having $TWRC \cong 50$ mm. Let us take *STU* 21, with an $RSWD_{calc}{}^* = 0.28$ and $TWRC = 54$ mm, and *STU* 71, with $RSWD_{calc}{}^* = 0.44$ and $TWRC = 50$, in both cases at 60% irrigation level. The hydraulic conductivity of *STU* 71 remains rather constant and about one order of magnitude higher than the hydraulic conductivity of *STU* 21 up to $|h| \cong 5000$ cm (data not shown). Vertical water transport, and losses in *STU* 71, were much higher than in *STU* 21, thus explaining the higher $RSWD_{calc}{}^*$.

3.4. *Hydrological requirements of tomato cultivars*

Cultivars requirements ($RSWD_{req}$) were determined through yield response functions, by applying linear or threshold slope regression models, as described in Section 2.6. The choice between the models was determined by the available data, i.e. for each cultivar the model which fitted best the experimental data was chosen. A range of values around $RSWD_{req}$ was considered in the assessment of the probabilities of adaptation, since the latter was done taking into account the standard error associated with the cultivars requirements ($\delta_{RSWDreq}$, as described in Section 2.7). Figure 10 shows the experimental data and the yield response function for the cultivar *Brigade*.

Hydrological requirements, and their associated errors of estimate, were determined for five processing tomato cultivars. They are reported in Table 5, together with their associated errors of estimate and the *p*-values, i.e. the probability of $RWSD_{req}$ values such that the relationship would not be significant. The yield response function for cultivar *H3044* was derived from observed values of soil water availability ($RSWD_{act}$) referred to the whole tomato cultivation period, whereas $RSWD_{act}$ values of all other cultivars were derived from measurements performed through the last part of the

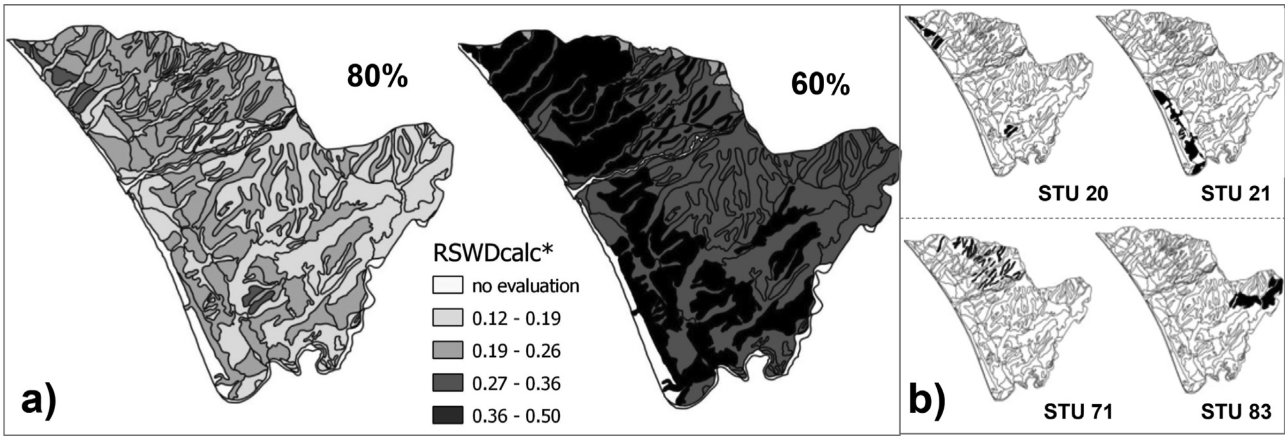

Fig. 9 – a) Spatial distribution of the calculated hydrological indicator $RSWD_{calc}^*$ in the 2021–50 climate case at two irrigation levels: 80% (left) and 60% (right) of optimal irrigation volume; b) Position of soil typological units (*STU*) discussed in the text (in black).

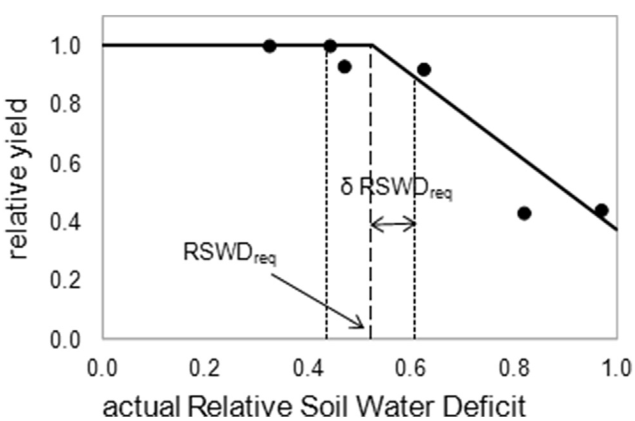

Fig. 10 – Experimental data on tomato cv. *Brigade* and its yield response function represented by a threshold-slope regression model. The cultivar-specific hydrological requirement ($RSWD_{req}$) and its standard error ($\delta_{RSWDreq}$) are shown.

crop cycle, approximately from 1st fruit set to harvest (DOY 190–223). The $RSWD_{req}$ of cultivar *H3044* was lower than the requirements of the other four cultivars, indicating a higher sensitivity of the cv. to soil water deficit. The values of the hydrological indicator $RSWD_{calc}^*$ for both climate cases were in a range significantly lower than the requirements for cultivars *Brigade, Season* and *Solerosso*. This would give high probabilities of adaptation, except for a few cases in the tail of the $RSWD_{req}$ distribution determined by the standard error values. Therefore, very high values of the medians of the distributions of the probability of adaptation (*MPA*) were expected, given the large difference between $RSWD_{calc}^*$ and $RSWD_{req}$. The *MPA* were expected to be lower for the cultivar *H3044*, because of the lower value of $RSWD_{req}$.

3.4.1. *Adaptability assessment*

The probabilities of adaptation of the cultivars, i.e. the probability of attaining the target relative yield (Yr_{adapt}), were assessed for the 23 *STUs* at irrigation levels 100%, 80% and 60%, for both climate cases (see Section 2.7).

Figure 11 shows the distribution functions of the probabilities of adaptation (*PA*) of cultivar Season in the future climate case: *PA* calculated in all soil typological units of the study area, at three irrigation levels (80%, 60% and 40% of optimal volume), are shown. Probabilities of adaptation decreased at decreasing irrigation levels and, similarly to the trend of $RSWD_{calc}^*$ in Fig. 8, the variability of *PA* was higher at lower irrigation levels, due to the differences in hydrological properties among *STUs* and to the inter-annual variability of precipitation, as discussed previously with respect to the hydrological indicator.

The medians of the distributions of *PA* values (*MPA*) were calculated (as explained in Section 2.7) and the adaptability ranges were set according to the quartiles determined on the unique distribution of the medians. For the cultivars examined in this study, the quartiles Q_1 and Q_2 of the distribution of *MPA* were 0.894 and 0.992, respectively. A large number of cases fell in the high tail of the probability distribution function of *MPA*, i.e. there was a large fraction of total cases with

Table 5 – Cultivars hydrological requirements ($RSWD_{req}$), their standard errors ($\delta_{RSWDreq}$), *p*-values and the model used to determine requirements.

Cultivar	$RSWD_{req}$ ($\pm\delta_{RSWDreq}$)	*p*-value	Model	Source
Brigade	0.52 (±0.08)	0.003	Threshold slope	Patanè and Cosentino (2010)
Design	0.41 (±0.07)	0.004	Threshold slope	Patanè (unpublished data)
Season	0.53 (±0.16)	0.032	Threshold slope	"
Solerosso	0.54 (±0.13)	0.014	Threshold slope	"
H3044	0.26 (±0.07)	0.068	Linear	Machado and Oliveira (2005)

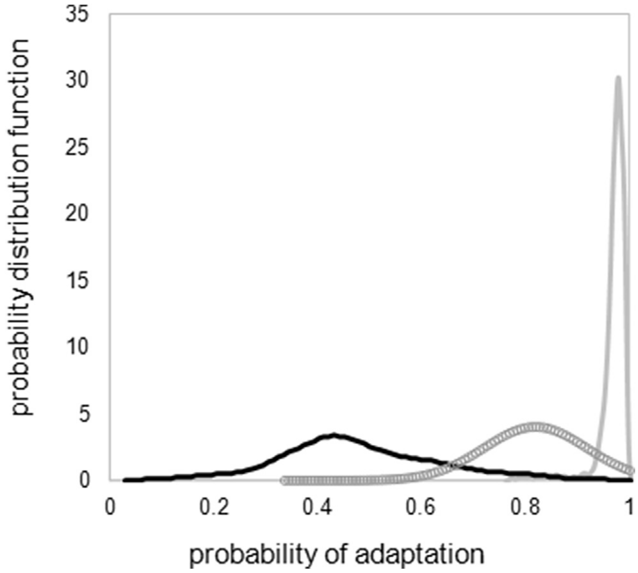

Fig. 11 – Climate case 2021–50: distribution functions of the probabilities of adaptation of cv. Season in the soil typological units of the study area at three irrigation levels. Grey line represents 80% irrigation level, circles represent 60% irrigation level and black line represents 40%.

MPA ≅ 1, with a very small inter-quartile range between Q_3 and 1. The *MPA* values higher than Q_2 were grouped, being the Q_2 value quite close to Q_3 and to the maximum value. The *MPA* of a 75% subset lay in a range of probabilities higher than 0.894, therefore the probabilities of adaptation, for the cultivars, soils and climate cases examined in this study, were quite high.

Table 6 shows the potential spatial extent of the cultivars within the adaptability ranges for different irrigation schedules. Only the case 2021–50 is shown in Table 6, since, due to the definition of irrigation schedules, the values of the probabilities of adaptation in each *STU* were similar, for the same irrigation strategy, in the two climate cases, as discussed previously with respect to the hydrological indicators (Section 3.3.1). However, in the future climate higher irrigation water depths were needed to determine *MPA* values similar to those assessed in the reference climate.

With optimal irrigation schedule, cultivars *Brigade, Design, Season* and *Solerosso* had *MPA* higher than 0.992 in all *STUs*, whereas the *MPA* of cultivar *H3044* had lower values. Cultivars *Brigade, Design* and *Solerosso* proved to be resistant to moderate water shortages, since at 80% irrigation water depth their *MPA* were higher than 0.992 in 98%, 95% and 89%, respectively, of the study area. *MPA* of cultivar *Season* were higher than 0.894 in 98% of the area. In the case of cultivar *H3044* reduced water availability led to a shift of the entire area towards lower *MPA*. At 60% irrigation volumes *MPA* of *Brigade* and *Solerosso* were higher than 0.894 in 95% and 62%, respectively, of the area. All other cultivars had lower *MPA* in at least 95% of the area. As expected, the potential spatial extent was related to cultivar-specific hydrological requirements and their associated errors (Table 5). Cultivar *Brigade* had the highest extent and the value of its hydrological requirement ($RSWD_{req}$ = 0.52) was among the higher ones. $RSWD_{req}$ values of cultivar *Season* and

Table 6 – Potential spatial extent, expressed as percentage of the surface of the Destra Sele, of tomato cultivars at different irrigation schedules in the 2021–50 climate case. Extent is expressed within each adaptability range, defined by quartiles Q_1 and Q_2 of the *MPA* distribution (see text for explanation).

Cultivar	*Brigade*			*Design*			*Season*			*Solerosso*			*H3044*		
Irrigation schedule	Optimal	80%	60%	Optimal	80%	60%	Optimal	80%	60%	Optimal	80%	60%	Optimal	80%	60%
MPA ranges															
MPA > Q_2 (0.992)	100%	98%	5%	100%	95%	0%	100%	0%	0%	100%	89%	0%	58%	0%	0%
Q_1 (0.894) < *MPA* ≤ Q_2 (0.992)	0%	2%	90%	0%	3%	5%	0%	98%	5%	0%	11%	62%	42%	57%	0%
MPA ≤ Q_1 (0.894)	0%	0%	5%	0%	2%	95%	0%	2%	95%	0%	0%	38%	0%	43%	100%

Solerosso were quite similar to that of *Brigade*, but, being the standard errors higher, their potential spatial extent was smaller. Cultivar *Design* had an intermediate value of $RSWD_{req}$, associated to a low standard error. This led, in 95% of the area, to $MPA > 0.992$ at 80% irrigation level and to a shift to the lower adaptability range ($MPA \leq 0.894$) at 60% irrigation level. The lower $RSWD_{req}$ values of cultivar *H3044* led to a lower potential spatial extent in the highest adaptability range ($MPA > 0.992$).

A moderate reduction of water availability would not impair tomato crop productivity in the study area, since, at 80% irrigation level, three cultivars had $MPA > 0.992$ in at least 89% of the study area.

Figure 12 shows an example of the potential spatial distribution, at different adaptability ranges, of the cultivars *Brigade* and *Solerosso* if water availability would severely decrease, and irrigation depth would be 60% of optimal. *MPA* of *Brigade* and *Solerosso* would be higher than 0.894 in 90% and 62% of the area, respectively. The spatial pattern of probabilities of adaptation was related to soils hydrological properties; adaptability was higher in soils which can store higher water contents in a favourable range of pressure head values. Even though, at 60% irrigation level, a small decrease of the probability to attain optimal yield (i.e. $MPA = 0.894$ vs. 0.992) had to be considered, the combination of properly chosen cultivars and location in relation with *STUs* would allow to maintain the potential extent of tomato crop in at least 60% of the study area. Moreover, at 60% irrigation level, the irrigation effectiveness calculated over all *STUs* was highest ($IE = 0.75$, Table 4). As a consequence, the combination of soils and cultivars would allow to effectively exploit limited water resource.

4. Discussion

4.1. *Climate change impacts*

Climate change impact on crop water consumption, irrigation water requirements and soil water availability was analysed. In the reference climate ET_a, under optimal water supply, is in good agreement with data reported by Katerji, Campi, and Mastrorilli (2013) and Patanè, Tringali, and Sortino (2011); our estimated irrigation amounts compare well with those reported by literature (Machado & Oliveira, 2005; Ozbahce & Tari, 2010; Patanè & Cosentino, 2010; Rinaldi et al., 2011). As regards future water requirements, the variations in irrigation depths we have found are consistent with other studies in southern Italy. For instance Ventrella et al. (2012) simulated irrigation amounts of a tomato crop under a baseline climatic condition (1975–2005) and a future climate scenario (A2) centred over years 2030–2060. Under optimal irrigation scheduling irrigation water depths increased by 4% in the future climate case, a figure quite close to the one calculated in this work, although predicted climate scenarios were different, as well as the criteria for irrigation scheduling. It should be noted that studies on impacts of climate change often differ by climate scenarios, time horizon and assessment methodologies; therefore, it is difficult to directly compare results with those from other studies (Kassie et al., 2015).

In this study the predicted evolution of climate variables leads to higher crop evapotranspiration that, in turn, requires higher irrigation depth. Therefore, to maintain the target yield levels, the amount of the irrigation water should be increased; the climate signature would thus be reflected by higher irrigation water demand. However, the relatively small increase of irrigation water depths from reference to future climate indicates that the climate signature on irrigation of the tomato crop is rather weak. This is due to the temporal distribution of precipitation predicted in the future climate: the rainfall increases during most part of the tomato growing season, as shown by the higher medians of the distributions of 10-days rainfall (Fig. 5).

It has been shown that irrigation water depths can vary among *STUs*, in relation to their hydrological properties. Similarly, the impacts of varying amounts and distributions of precipitations on soil water regime are strongly dependent on

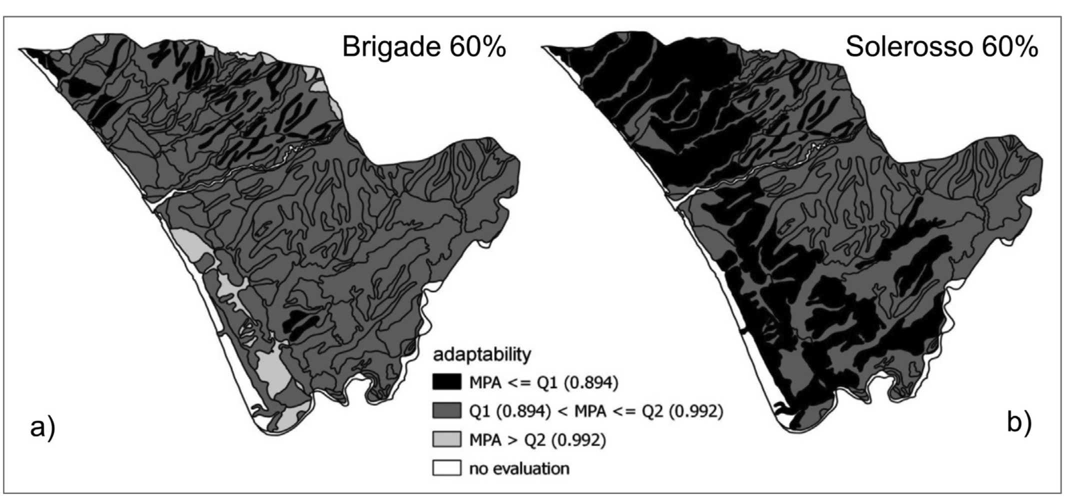

Fig. 12 – Potential spatial distribution, as determined by adaptability ranges, of tomato cultivars *Brigade* (a) and *Solerosso* (b) at 60% irrigation level in the future climate (2021–50). The adaptability ranges are set according to quartiles (see text for explanation).

soils properties. Particularly in soils with low *TWRC*, seasonal irrigation water requirements were strongly influenced by the temporal distribution of precipitation. These results stress the importance of site-specific assessment of climate impacts related to agricultural water management. Moreover, besides description of spatial variability of soil types, reliable climate predictions at adequate resolution in time and space are necessary to determine consequences of climate evolution in a specific location. The predicted trends of seasonal and annual temperature were shown to be quite similar, whereas precipitation trends can differ a lot (Fig. 4). Improved rainfall prediction is therefore a key target for the analysis of site-specific impacts on agriculture. It should be noted that the uncertainties in climate projections are higher at higher resolution in time and space, and such shortcomings need to be considered. The use of multiple climate models allows the range of uncertainty (Gualdi et al., 2013) to be estimated; in our case the analysis was repeated for 50 simulations of a year representative of the 2021–50 period, derived by an ensemble of climatic models.

4.2. Cultivars adaptability

The cultivar-specific hydrologic requirements were determined. That is, the intra-specific variation in the ability of five genotypes to respond to changes in water availability were specifically quantified. The requirements of these five cultivars were used in the adaptability assessment, therefore the potential spatial extent of each cultivar was related to its requirement and the associate error of estimate. The phrase "potential spatial extent" is used since these cultivars are not presently being cultivated in the study area. The combination of cultivar requirements and soils hydrological indicators provided an assessment of the likelihood of the persistence of the tomato crop and of cultivar substitutions within the area. Cultivar *Brigade*, which is known to maintain its productivity when subjected to moderate drought (Lowengart-Aycicegi, Manor, Krieger, & Gera, 1999; Patanè & Cosentino, 2010), has a very large spatial potential within the study area even at severely reduced water availability. Hence, it can be seen that the effects on yield of moderate and severe reductions of water resources can be counterbalanced by an appropriate combination of cultivars and soils, thus leading to effective use of scarce water for irrigation.

The approach used in our study has strengths and limitations, both of which are discussed below.

Challinor et al. (2014) examined the benefit on yield of different adaptation practices. They indicated that cultivar adjustment is the most effective adaptation strategy; i.e. switching from currently grown to better adapted cultivars (cultivated elsewhere) is more effective than adjusting planting dates, optimising irrigation and enhancing fertilisation. Moreover Aspinwall et al. (2015) stressed that the utilisation of intra-specific variation in species responses to climate change may support agricultural and forest productivity.

In the study area expected thermal conditions are likely to be compatible with tomato growing since tomato vegetative and reproductive development can be sustained at their maximum rates up to 28 °C (Boote, Rybak, Scholberg, & Jones, 2012). However, in southern Europe summer crops are predicted to experience water shortages, and their cultivation will depend on the competition between various water consuming sectors (Supit et al., 2012). Thus, among abiotic factors, the focus in this study was on water availability to assess climate impacts and thereafter identify possible adaptation options.

On the basis of these assumptions, our analysis focused on cultivar biodiversity in the response to water availability. Crop yield was not simulated by means of a mechanistic model, since there is little knowledge on cultivar-specific values of model parameters (Asseng et al., 2015; Craufurd, Vadez, Krishna Jagadish, Vara Prasad, & Zaman-Allah, 2013; Estes et al., 2013) and this severely constrains the use of mechanistic models to model cultivars yield response to water availability. Instead, the study relied on experimental and cultivar-specific yield response functions, thus the intra-specific biodiversity of crops can be evaluated towards a more robust assessment of crop adaptation to climate evolution.

Therefore, the results of this study face several sources of uncertainty. The experimental yield response functions do not account for the effects of elevated CO_2 on crop growth and yield since data and knowledge on cultivar-specific responses to elevated CO_2 are sparse and uncertain. A number of studies (e.g. Bishop, Betzelberger, Long, & Ainsworth, 2015) have demonstrated that C_3 crop yield responses to elevated CO_2 shows a large intra-specific variation. Moreover, a key finding from elevated CO_2 experiments is that the effects of elevated CO_2 on plant productivity are highly dependent on interactions with temperature, availability of nutrients and soil moisture (Leakey, Bishop, & Ainsworth, 2012; O'Leary et al., 2015). For most crops these interactions have not yet been studied. Decisions on adaptation, however, need to be taken before these advancements in crops and cultivars physiology are made.

Likewise, thermal times for tomato crop growth and development are cultivar-specific (Boote et al., 2012) and are not known for most cultivars; this impairs the prediction of their growth and development as a function of thermal regime. Therefore, the soil water balance was simulated using a fixed length of crop cycle, which has been set according to the ordinary cultivation period for tomato in the area and to the characteristics of the cultivars analysed in this study (see Table 1). Indicators $RSWD_{calc}^*$ were averaged through the entire crop cycle or through a part of it; the averaged value, and therefore the adaptability assessment, would be scarcely influenced by limited variations in the length of the growing cycle. In the future climate, the difference between the $RSWD_{calc}^*$ values calculated for a 93 d crop cycle and the ones for the 101 d crop cycle was non-significant (data provided as supplementary file 3). Other adaptive measurements, such as changing the planting dates, can be evaluated, and combined, by performing the analysis according to the approach used in this work.

5. Conclusions

It has been shown that the issue of the adaptability of irrigated crops to climate change and variability has to be addressed by accounting for spatial variability of soil types and choosing one or more scenarios on local water availability for irrigation. Here, a mechanistic model evaluated five different irrigation strategies, ranging from optimal irrigation water depths, timed and calculated on the basis of soil water deficit in the root zone, to water depths reduced to 20% of the optimal. By calculating the optimal irrigation water depths for the reference and future climate case it was observed that the impact of higher air temperature on water requirements was mitigated by changes in the temporal distribution of precipitation. For a tomato crop, when considering the whole study area, optimal irrigation water depths increased slightly, due to the interaction between crop growing period and the temporal distribution of precipitation. Irrigation water requirements varied much with the different soil types analysed and their relative increases with respect to future and reference climates was also soil dependent.

The adaptability of five tomato cultivars was examined for a reduction of irrigation water depths to 80% and to 60% of optimal. Adaptability was shown to be strongly dependent on cultivars biodiversity and on soils hydrological properties. Our results, even with just five cultivars, show that cultivar biodiversity in response to climate is so large that the probability of adaptation of a cultivar can only be assessed for paired cultivars and soil hydrological properties. This implies that to assess the potential of either a new or a known cultivars for use in a region, soil hydrological properties and their spatial variability must be taken into account in addition to cultivar characteristics. This would allow sustainable current crop production systems under conditions of reduced water resource availability and greater irrigation effectiveness.

To our knowledge this is the first study that examines alternate tomato cultivars as adaptation options. The strengths and limitations of our study are discussed. However, our results show that the existing crop biodiversity is a viable tool to identify options for adaptation to climate change, at least in the short term. Decisions on adaptation need to be taken before the gaps in our knowledge are closed, and before new suitable crops are developed. Improving crop performance through genetics can be regarded as a longer term solution for sustaining agricultural productivity.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biosystemseng.2017.02.007.

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