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Assessment and modelling of crop yield and water footprint of winter wheat by aquacrop

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Abstract. Agriculture has a considerable impact on water resources and it is strongly affected by climate change. It is important to determine and forecast crop water use for controlling and planning water resources while ensuring agricultural sustainability. Crop Water Footprint (WF) is an indicator of water consumed for crop production. The aim of the study is to calculate WF of winter wheat using Water Footprint Assessment (WFA) and to simulate future WFs by means of AquaCrop model for the Thrace region in Turkey. Although winter wheat does not require irrigation, the estimation of the WF is of importance due to its extensive production throughout the country. The WFs is estimated using meteorological and CORDEX data. The emerging findings indicate an increase in average temperature between 0.9 and 4.0°C. Precipitation is expected to increase by 15% under the optimistic scenario (RCP 4.5) and decrease by 17% under the worst-case scenario (RCP 8.5) by 2099. Winter wheat yield will positively be affected by increasing temperatures by up to 17% under RCP 4.5 and 26% under RCP 8.5 scenarios.

Keywords. Climate Change, Green Water Consumption, Crop Productivity, Crop Growth Simulation Model, Cereal.

INTRODUCTION

Climate projections emphasize that water scarcity will be one of the most important problem in the future. Therefore, determination of water consumption of crops has a crucial importance especially in arid and semi-arid countries in the world. To determine direct and indirect water use, the water footprint is widely used (Hoekstra, 2003). The WF represents the volume of freshwater used to production process and it is measured on all levels of the supply chain. Showing water consumption and polluted water volumes by source and type of pollution, WF comprises of components like blue, green and grey WFs. Blue WF is estimated in crop production with irrigated agriculture while green WF is determined in rainfed agriculture conditions. Grey WF involves the information about groundwater pollution because of fertilization.

Crop-climate models indicate that crop production may decrease because of high temperatures, while crop yield may increase as a consequence of rising CO_2 concentrations in the atmosphere (Caldag and Saylan, 2005; Nakagawa et al., 2007; Özdoğan, 2011). Moreover, agricultural activities consume nearly 70% of global water resources (Huang et al., 2018; Taheri et al., 2019). In this study, WF of winter wheat is estimated and WF's future projections are realized by means of AquaCrop model developed by Food and Agriculture Organization (FAO). AquaCrop bases on soil-water balance method and it is one of the most common used models to determine crop yield and WF (Raes et al., 2009; Steduto et al., 2009). The input requirements of the model are soil, climate, crop and agricultural management data.

There are many applications of the AquaCrop model for estimating the WF and yield. For instance, Gobin et al. (2017) have analyzed variability of arable crop production in some parts of Europe. Results showed that WF of cereals was much bigger than WF of tuber and root crops and the biggest part of WF belongs to green WF. Variability of arable crops was mainly related to variability of crop yield and variability of crop water use. Others, Chouchane et al. (2018) assessed the WF of wheat, barley, potatoes, dates, olives and tomatoes for the period 1981-2010. The model is better in explaining net virtual water import (NVWI) of wheat, barley and potatoes than NVWI of dates, olives, and tomatoes. Alvarez et al. (2016) estimated the green and blue WF of maize in Argentina, observing a WF decrease with an increase in irrigation and fertilization. They have determined that green WF represented 92% of total WF. Zhuo and Hoekstra (2017) have analyzed the effect of different agricultural applications on green and blue WF, irrigation efficiency and of crop water usage efficiency. The results indicated that the deficit irrigation improved irrigation efficiency by 5% and decreased blue WF by 38%. Zhou et al. (2016) simulated WF of winter wheat production considering only water stress. According to their findings, the WF for irrigated winter wheat was 8-10% larger than rainfed winter wheat and the WF criteria for rainy years were 1-3% smaller than the dry years, 7-8% for the WF criteria for the hot years. Moreover, it was mentioned that WF criteria showed 10-12% differences in different soil types. Karandish and Hoekstra (2017) have predicted WF of 26 crops by means of AquaCrop in Iran. In the 1980-2010 period, it was determined that crop production, total crop production WF and blue WF have increased by 175%, 122%, 20%, respectively. During this period, the population has increased by 92%, while the crop consumption per person has grown by 20%, whereas the total crop consumption and total WF by 130 and 110%, respectively. Additionally, Lalic et al. (2018) have investigated monthly forecast of green water components and summer crops yield in Serbia and Austria using AquaCrop model and ensemble weather forecast. Tsakmakis et al. (2018) analyzed the effects of different irrigation schedules on WF of cotton with AquaCrop and CROPWAT for the north of Greece. The results showed that the effect of irrigation technology and strategy in green, blue and total WF were better predicted by the AquaCrop model, while the CROPWAT model can only evaluate changes in the irrigation strategy. Nouri et al. (2019) examined the reduction of WF with different soil mulching and drip irrigation methods. In the previous study, AquaCrop model and global Water Footprint Assessment (WFA) was used for estimating blue and green WF of ten major crops. The results showed that WF of crop production was more sensitive to climate and soil type. They have found that that the annual blue WF of the summer season was highest when water availability was lowest. Mulching has reduced the blue WF by 3.6% and mulching with drip irrigation have decreased the WF by 4.7%. Bakanogullari et al. (2017) used AquaCrop model and estimated that sunflower is more sensitive to soil water content than winter wheat.

For the estimation of winter wheat WF, different models such as linear and nonlinear regression model (Ye et al., 2019), Agro-Ecological Zones model (Wang et al., 2015), Soil and Water Assessment Tool (Luan et al., 2018), AquaCrop (Gobin et al., 2017; Zhuo and Hoekstra, 2017; Chouchane et al., 2018), Markov chain (Feng et al., 2017), CWUModel (De Miguel et al., 2015), global gridded crop model (Deryng et al., 2016), CROPWAT (Muratoglu, 2019), DSSAT (Ventrella et al., 2018), crop models

within ensemble approach (Palosuo et al., 2011; Garofalo et al., 2019) and WFA methodology have been used (Ababaei and Etedali, 2017; Santos et al., 2017; Huang et al., 2019; Zhai et al., 2019).

The aim of this study was to investigate WF and yield of winter wheat for northwestern part of Turkey (for Edirne, Kırklareli and Tekirdağ cities) using WFA and AquaCrop model. Firstly, WF of winter wheat was calculated by means of WFA with meteorological variables. Secondly, AquaCrop model was performed under RCP (Representative Concentration Pathway) 4.5 and 8.5 scenarios to forecast potential WFs and yields in the future. As input EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment) data, HadGEM2-ES global climate model data and HIRHAM5 regional climate model data were used. Finally, WF and yield from calculations and simulations were compared and evaluated.

MATERIALS AND METHODS

Study Area

This study covers the agricultural areas of the Edirne, Kırklareli and Tekirdağ provinces of Thrace region, in the northwestern part of Turkey. As shown by elevation data reported in figure 1, Istranca mountains are the highest ones of the region with 1032 m and locate in the north of the Kırklareli city. The blue dots and red triangles on the map represent the locations of the meteorological stations used to correct CORDEX data. AquaCrop was performed according to RCP 4.5 and 8.5 scenarios in grids (0.11° horizontal resolution) with the red triangles. AquaCrop was not performed in grids with blue dots because necessary input data such as meteorological, soil and crop phenological data for the model were insufficient. For this
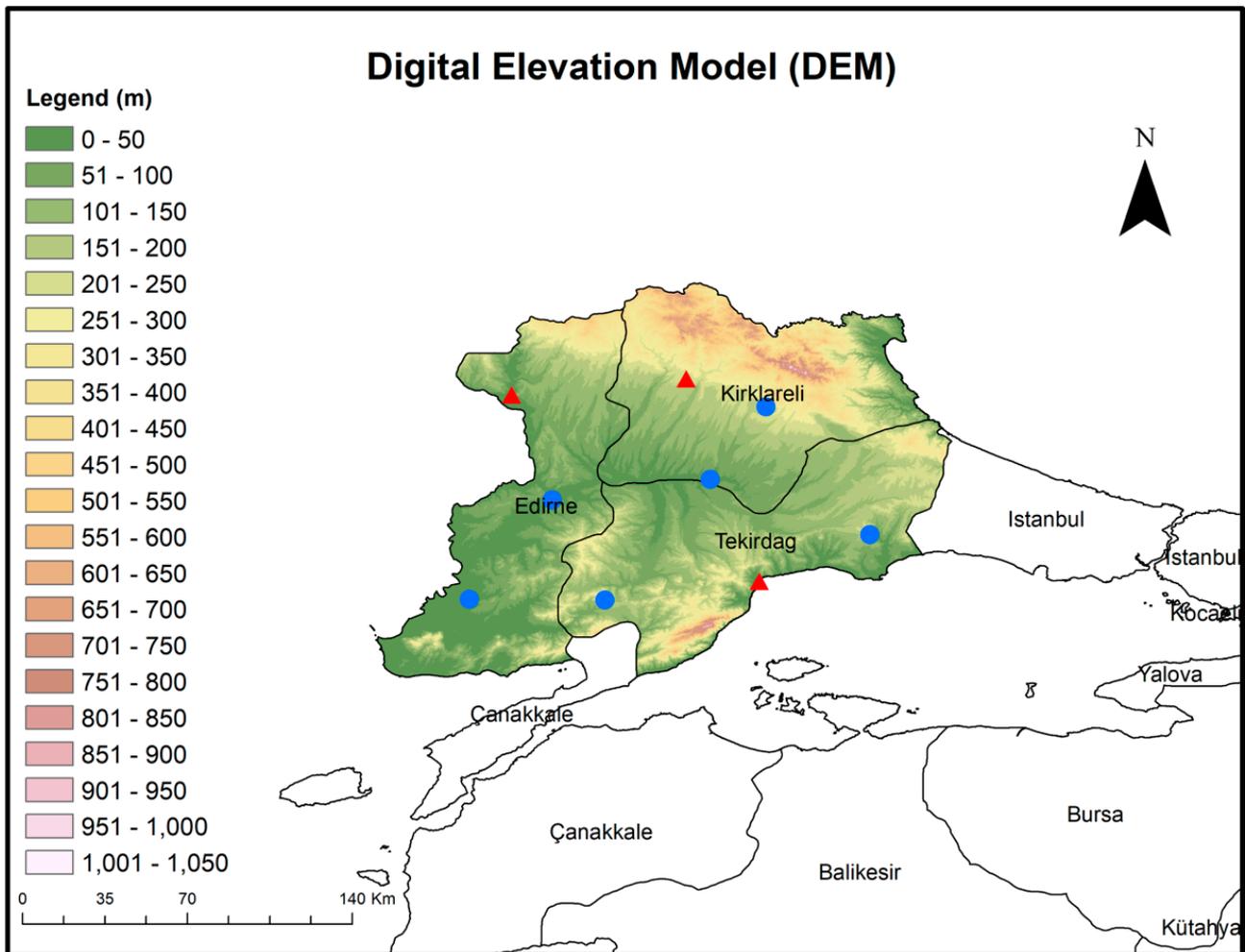
Fig. 1. Study area.

reason, AquaCrop model results were examined for each grid in 3 locations.

Data

Meteorological Data

Daily temperature (mean, maximum, and minimum), precipitation, global solar radiation, relative humidity and wind speed measurements were obtained from meteorological stations located in Edirne, Kırklareli (connected to Atatürk Soil Water and Agricultural Meteorology Research Institute, AMRI) and Tekirdağ (connected to Turkish State Meteorological Service, TSMS). Besides, meteorological data in between the reference years (1971-2000) were used for correction of CORDEX data. Table 1 contains the longitude, latitude, and mean sea level (msl) information of meteorological stations.

In Fig. 2, annual mean air temperature and total precipitation maps are illustrated for reference years (1971-2000).

The annual mean air temperature was 13.2°C and the annual total precipitation was 588 mm. Mean temperature and precipitation values of southwestern part of Thrace were about 0.5°C and 100 mm higher than the region average, respectively. In the reference years, Kırklareli had about 60 mm lower precipitation and about 0.5°C lower than the region's mean precipitation and temperature, respectively. Similarly, Fig. 3 shows the mean air temperature, precipitation and effective precipitation in the growing season of winter wheat.

Tab. 1. Locations of Selected Meteorological Stations.

Stations	Longitude (°)	Latitude (°)	Msl (m)
Pınarhisar (TSMS)	27.52	41.63	225
Edirne (TSMS)	26.55	41.68	48
Kırklareli (TSMS)	27.22	41.74	232
Çorlu (TSMS)	27.92	41.14	153
Tekirdağ (TSMS)	27.50	40.96	14
Lüleburgaz (TSMS)	27.31	41.35	45
İpsala (TSMS)	26.39	40.89	73
Uzunköprü (TSMS)	26.71	41.27	22
Malkara (TSMS)	26.91	40.89	202
Kırklareli (AMRI)	27.21	41.70	170
Edirne (AMRI)	26.64	40.73	30

During the winter wheat growing season, the Thrace region recorded an annual temperature of and precipitation of were 9.9°C and 463 mm, respectively. Moreover, effective precipitation was calculated as 217 mm. The mean temperature and the precipitation during the growing period in the southwestern part of the region were higher than the region average.

According to TSMS measurements, Average temperatures of wheat during growing season between 1971-2000 were measured in Edirne, Kırklareli and Tekirdağ as 10.4, 10.0 and 10.9°C, respectively. However, after 2000s, the average temperature in wheat growing season increased by 1°C in the region (Fig. 4).
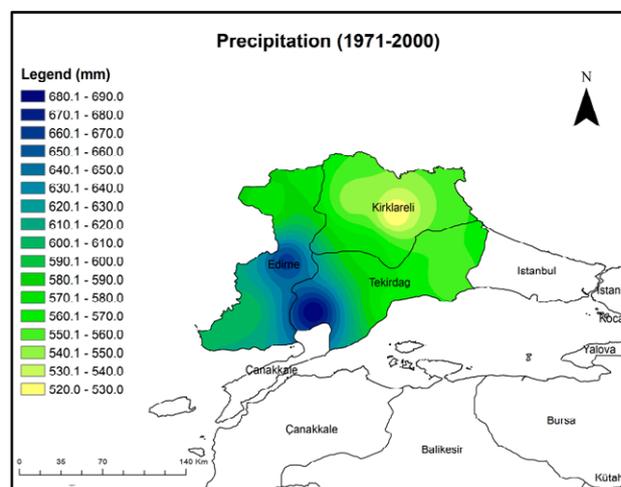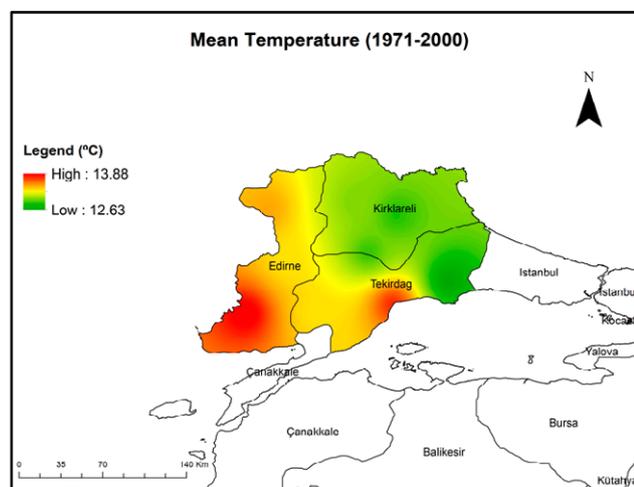
Fig. 2. Annual Mean Temperature and Total Precipitation Maps.
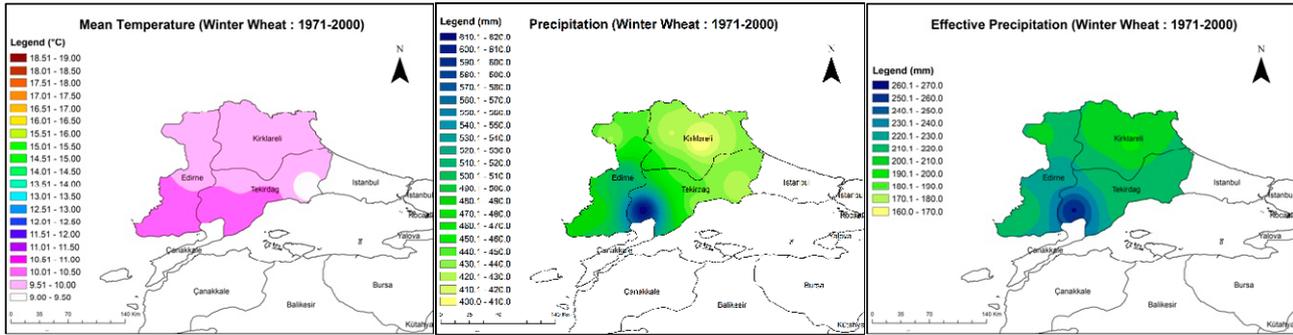
Fig. 3. Mean Temperature, Precipitation and Effective Precipitation in Winter Wheat Growing Season (Reference Years).

Soil and Crop Data

Physical properties of locations' dominant soils are given in table 2 (Gobin et al., 2017; Gürbüz et al., 2019). Table 3 shows the reference sowing and harvest data for winter wheat (Gelibolu cultivar) cultivated in the region in 2015-2016 and 2017-2018 agricultural years.

CORDEX Data

In the study, projection data of RCP 4.5 (optimistic) and RCP 8.5 (worst-case) scenarios were provided between the years of 1971 and 2099. Developed with the Hadley Meteorology Office and designed for the scenarios in the IPCC's 5th Assessment Report (AR5), the HadGEM2-ES global climate model, whose outputs are downscaled with HIRHAM5 (Christensen et al., 2007) regional climate model with a horizontal resolution of 0.11° (~12.5 km) and EURO-CORDEX temperature, precipitation, relative humidity, global radiation, and wind speed data were provided in the daily time interval.

Bias Correction

The data produced by climate models generally do not match the measurement data in the reference period. These errors affect the simulations for the future. Future reliability of climate models is increased with bias correction. Due to the nature of meteorological variables, their distributions are different and different bias correction methods are used (Feigenwinter et al., 2018; Soriano et al., 2019; Zapata et al., 2020).

Simple Mean Seasonal Bias Correction

Climate projection data require bias correction (Teng et al., 2015; Qian et al., 2015; Macadam et al., 2016; Mostafa et al., 2019). In the study, simple mean seasonal bias correction was used for daily mean, maximum, and minimum temperature data. Differences between measured and modelled data for both RCP 4.5 and 8.5 were corrected as computed as follows:

Tab. 2. Texture and hydrological parameters of dominant soils in the Thrace region.

Location	Soil Type	Field Capacity (%)	Wilting Point (%)
Edirne	Clay	37	23
Kırklareli	Sandy Loam	35	17
Tekirdağ	Loamy	39	28

Fig. 4. Time Series of Mean Temperature of Winter Wheat Growing Seasons from 1971 to 2018.

Tab. 3. Sowing and harvest date for winter wheat cultivation.

Practice	Edirne	Kırklareli	Tekirdağ
Planting	20-October	20-October	20-October
Harvest	20-June	25-June	20-June

$$T_{i,cor} = T_i + \Delta T_i, \tag{1}$$

where T_i is the temperature (mean, max, min) in a given month i, ΔT is the difference between the mean temperature of the climate model and the observations in a given month i, and $T_{i,cor}$ is the corrected temperature in month i.

Quantile Mapping Bias Correction

Quantile Mapping (QM) method is a widely used method for correcting projection data not only precipitation but also global solar radiation, relative humidity, wind speed correction (Themeßl et al., 2011; Teutschbein and Siebert, 2012; Gudmundsson et al., 2012; Chen et al., 2013; Feigenwinter et al., 2018). This method is based on the application of the measurement values of the cumulative distribution function (CDF) of the reference years from the models to the projection distribution functions by mapping them over the cumulative distribution functions (Heo et al., 2019; Soriano et al., 2019). Bias corrected data was calculated by using the following Eq. 2.

$$Q_m(t) = F_0^{-1}[F_s[Q_s(t)]] \tag{2}$$

where $Q_m(t)$ and $Q_s(t)$ are the bias corrected and simulated data from the regional climate model (RCM) during the reference period, F_s and F_0^{-1} are the CDF of the raw data from the RCM and the inverse CDF of the observed data, respectively.

AquaCrop Model

The AquaCrop model has been developed by the FAO, based on the principles of soil-water balance method and widely used by researchers, and was preferred in determining the WF and crop parameters (Alvarez et al., 2016; Zhuo et al., 2016; Gobin et al., 2017; Karandish and Hoekstra, 2017; Zhuo and Hoekstra, 2017; Chouchane et al., 2018; Lalic et al., 2018; Tsakmakis et al., 2018; Nouri et al., 2019). Input data required in this model are soil (soil type, field capacity, wilting point, initial soil water content etc.)-crop (phenological date, seed number etc.)-climate parameters (max and min temperature, global solar radiation, precipitation, relative humidity, ET_0) information on agricultural practices (fertilizer, cultivation etc.) with particular reference to irrigation (Raes et al., 2009; Steduto et al., 2009). In this study, AquaCrop model v6.1 was used in order to model of yield and WF of winter wheat.

Water Footprint Calculations

The WF [m³ ha⁻¹] has 3 different components: blue, green and gray WF. The blue WF shows irrigated agriculture, while the green rainfed conditions (Mekonnen and Hoekstra, 2011), and the grey the amount of groundwater contaminated by fertilization. The WF of crops is the sum of blue and green WFs (Eq. 3). In this study, the amount of green WF was calculated since the winter wheat is grown in rainfed conditions in Thrace Region.

$$WF = WF_{Blue} + WF_{Green} \tag{3}$$

Blue and green WFs are calculated with Equations 4 and 5 (Hoekstra et al., 2011; Bocchiola et al. 2013).

$$WF_{Blue} = 10 \, x \frac{ET_{Blue}}{Yield} \tag{4}$$

$$WF_{Green} = 10 \, x \frac{ET_{Green}}{Yield} \tag{5}$$

The coefficient 10 is used to convert the specified ET quantity unit from mm to m³ ha⁻¹, yield (t ha⁻¹) and WF is used in m³ t⁻¹. Blue and green ET calculations from WF components are calculated with Equations 6 and 7, respectively.

$$ET_{Blue} = \max(0, ET_c - P_{eff}) \tag{6}$$

$$ET_{Green} = \min(ET_c, P_{eff}) \tag{7}$$

where ET_c, crop evapotranspiration (mm); P_{eff}, efficient precipitation (mm). In order to determine P_{eff}, USDA SCS method (Nearing et al., 1989) is used in daily time step (Eq. 8 and 9).

$$P_{total} < 8.3 \, mm, \; P_{eff} = \frac{P_{total}(4.17 - 0.2P_{total})}{4.17} \tag{8}$$

$$P_{total} \geq 8.3 \, mm, \; P_{eff} = 4.17 + 0.1P_{tota} \tag{9}$$

ET_c is calculated from modified Penman&Monteith (P&M) ET0 approach (Allen et al., 1998), detailed information can be found in Raes et al. (2009) and Steduto et al. (2009). Using soil water content measurements, the actual ET values of winter wheat are determined by the Soil Water Balance (SWB) method (Allen et al., 1998).

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RESULTS

Yield and Water Footprint

The calibration of AquaCrop for winter wheat was performed on the basis of grain yield of 2015-2016 and 2017-2018 growing seasons. Measured mean temperature, total precipitation and effective precipitation during the growing seasons are also shown in Tab. 4.

According to Table 4, the daily mean temperature in the wheat development period in the reference years (1971-2000) was 9.9°C, while the mean temperature in the periods of model calibration was calculated as 12.9°C. The total precipitation in the years when the model was calibrated and in the reference years were 481.8 and 462.9 mm (approximately 19 mm lower in reference years), respectively. Although the amount of precipitation in the years when model calibration was performed is higher than the reference years, the effective rainfall amount is approximately 5 mm lower. When the actual and predicted yields were compared, the average relative errors (REs) in the cities of Edirne, Kırklareli and Tekirdağ were -2.4%, -1.6% and 5.6%, respectively.

Figure 5 shows the green WFs calculated from the measurements and estimated by the AquaCrop model. According to Figure 5, the REs between the WF calculated with SWB and the modelled green WF were 17.1%, -28.7% and -52.4% in Edirne, Kırklareli and Tekirdağ, respectively. The average green WF of the region was calculated as 452.7 m3 t⁻¹ with SWB method and it was 359.0 m3 t-1 for modelled green WF. The reason of this difference is that the ET values were calculated using the P&M method through meteorological variables while the SWB method uses the changes of soil water content values. Besides, infiltration and runoff were not taken into account in the calculation of SWB. WF differences between the provinces may be resulted from these assumptions and differences of the soil structure.
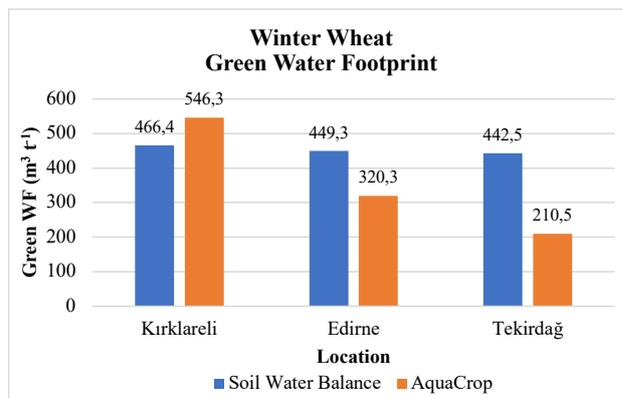
Fig. 5. Comparison of Winter Wheat Water Footprints.

Future Scenarios

While making simulations for the future with the AquaCrop model, the concentration amount of RCP 4.5 and 8.5 scenarios was used as atmospheric CO_2 concentration. It is projected that the increase in temperatures in recent years will continue in the RCP 4.5 and 8.5 scenarios. The mean temperature in the region is expected to increase by 0.9-1.6°C and 2.0-4.0°C under the RCP 4.5 and 8.5, respectively, by 2099. Variation of mean temperature for different scenarios in three periods (P1: 2020-2040, P2: 2041-2070, P3: 2071-2099) during the winter wheat growing seasons are shown in Figures 6 and 7, respectively.

The analysis of future precipitation (RCP 4.5) trends show that precipitation during the winter wheat season will increase 15% compared to baseline scenario, while a decrease of 17% is expected in the worst-case scenario (RCP 8.5). Effective precipitation changes in winter wheat growing season is expected to increase by 12% in the RCP 4.5 and 21% decrease in the RCP 8.5. In Figure 8, there are projected effective precipitation maps according to the RCP 4.5 scenario.

According to the RCP 4.5, effective precipitation is increased between 3% and 22% in P1. The lowest

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Tab. 4. Statistics of 2015-2016 and 2017-2018 Winter Wheat Growing Seasons.

	Actual Yield (t ha⁻¹)	AquaCrop Yield (t ha⁻¹)	Mean Temperature (°C)	Precipitation (mm)	Peff (mm)
Edirne	4.86	4.74	12.5 (10.8*)	518.8 (499.2*)	225.4 (234.9*)
Kırklareli	4.67	4.59	12.2 (10.4*)	503.0 (492.1*)	218.9 (231.7*)
Tekirdağ	3.85	4.06	13.1 (11.3*)	423.7 (495.7*)	191.7 (232.1*)
Region Average (1971-2000)	-	-	9.9	462.9	216.9

*Average of 1971-2019 in winter wheat growing seasons.
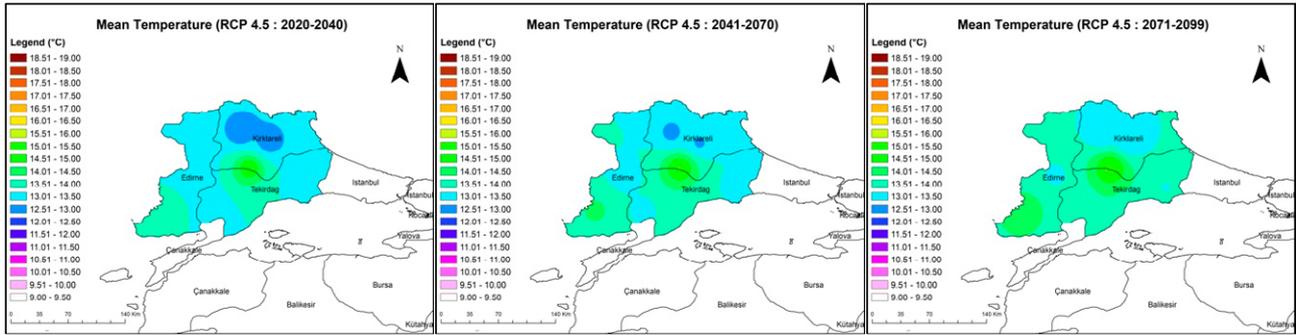
Fig. 6. Mean Air Temperatures in Winter Wheat Growing Season (RCP 4.5 Scenario).
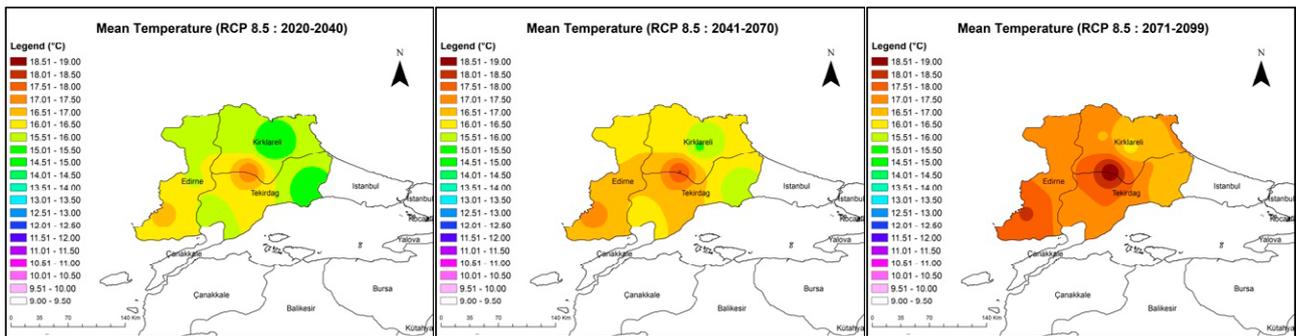
Fig. 7. Mean Air Temperatures in Winter Wheat Growing Season (RCP 8.5 Scenario).

increase is expected to be in the northeast and southwest of the region whereas the highest increase is expected to occur in Tekirdağ city center and some parts of Edirne. The changes in the effective precipitation that occurred in the P2 and P3 periods have similar increase patterns. In P2, the increases in effective precipitation are between 0.3% and 20%. Moreover, the increases in the period of P3 are between 5% and 26%. In Fig. 9, it can be seen maps of the effective precipitation according to the RCP 8.5, with the effective precipitation decreasing in con-

trast to the RCP 4.5. The percentage of such changes were estimated in a range of -14% and -26% in P1, -18% and -28% in P2, and 20% and -30% in P3.

Potential Yield and Water Footprint Estimations

Potential yields and WF calculations of winter wheat in Edirne, Kırklareli and Tekirdağ are reported in Tab. 5.

According to Tab. 5, winter wheat yields show an upward trend in all scenarios except in P1 period in
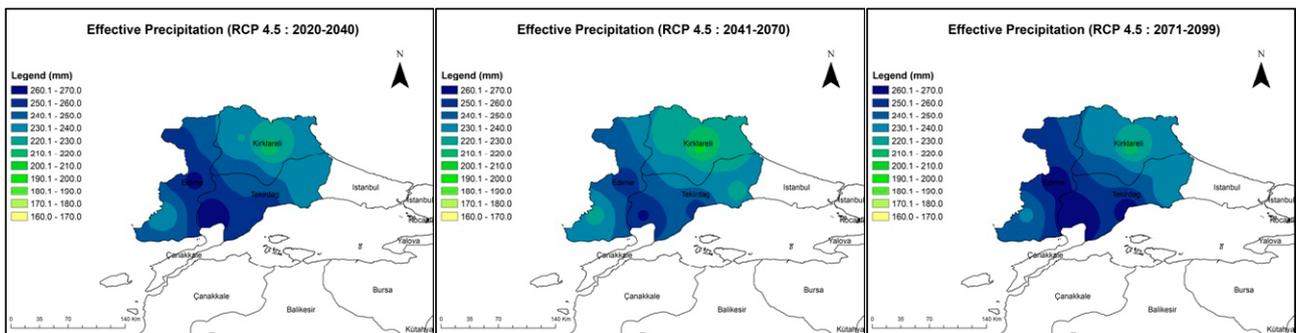
Fig. 8. Effective Precipitation Amount in Winter Wheat Growing Season (RCP 4.5 Scenario).
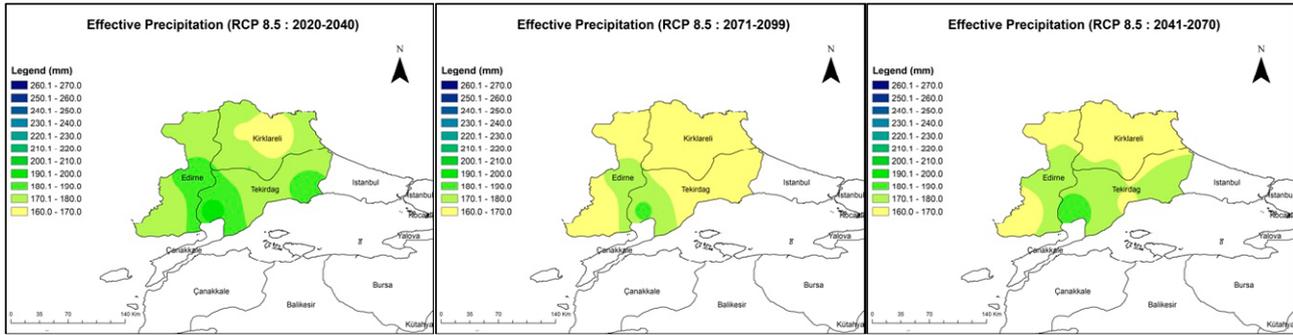
Fig. 9. Effective Precipitation Amounts in Winter Wheat Growing Season (RCP 8.5 Scenario).

Tab. 5. Potential Crop Yield of Winter Wheat by AquaCrop.

Years	Winter Wheat Yield for RCP 4.5 (t ha⁻¹)			Winter Wheat Yield for RCP 8.5 (t ha⁻¹)		
	Edirne	Kırklareli	Tekirdağ	Edirne	Kırklareli	Tekirdağ
Actual Yield	4.86	4.67	3.85	4.86	4.67	3.85
2020-2040	5.46 ± 0.72	4.61 ± 0.24	4.52 ± 0.45	5.23 ± 0.77	4.72 ± 0.27	4.48 ± 0.44
2041-2070	5.94 ± 0.80	4.96 ± 0.26	4.88 ± 0.45	6.13 ± 0.82	5.29 ± 0.35	5.11 ± 0.41
2071-2099	6.28 ± 0.86	5.11 ± 0.30	5.05 ± 0.39	7.53 ± 0.84	6.19 ± 0.34	5.89 ± 0.44

Kırklareli. In this period, the decrease in the yield is estimated as 1.3%. Winter wheat yield was positively affected by the increase of temperatures and atmospheric CO2 concentrations. The decrease in precipitation did not have a considerable effect on yield. The largest increase in wheat yield was reported under RCP 4.5 in Tekirdağ. Average yield increases in Edirne, Kırklareli and Tekirdağ were calculated as 21%, 5% and 25%, respectively. When yields were analyzed by periods, it was predicted that the winter wheat yields in the region will increase by 9% in P1 (4.86±0.79 t ha-1), 18% in P2 (5.26±0.26 t ha-1) and 23% in P3 (5.48±0.42 t ha-1).

Additionally, winter wheat yield may increase more in RCP 8.5 than in RCP 4.5. The reason of this situa-

tion can be explained by the fact that the atmospheric CO_2 concentration and the temperatures will be about 1-2.5°C higher for RCP 8.5 than the RCP 4.5. Average yield increment in Edirne, Kırklareli and Tekirdağ were calculated as 29.6%, 15.6% and 34.0%, respectively. When the yields were analyzed by periods, it is predicted that the winter wheat yields in the region will increase by 8.3% in P1 (4.81±0.81 t ha-1), 24.0% in P2 (5.51±0.32 t ha-1) and 46.8% in P3 (6.54±0.42 t ha-1). In addition to the yield of winter wheat, WF were also calculated with the AquaCrop model and shown in Tab. 6.

According to Tab. 6, the potential WFs of winter wheat decreases in all scenarios and for different time horizons. This is explained by an increase in win-

Tab. 6. Forecasted WF of Winter Wheat by AquaCrop.

Years	Winter Wheat WF for RCP 4.5 (m³ t⁻¹)			Winter Wheat WF for RCP 8.5 (m³ t⁻¹)		
	Edirne	Kırklareli	Tekirdağ	Edirne	Kırklareli	Tekirdağ
SWB Method	449	466	442	449	466	442
2020-2040	169.7 ± 28.4	177.6 ± 32.8	212.9 ± 37.1	140.5 ± 29.7	143.6 ± 31.2	143.1 ± 26.7
2041-2070	147.0 ± 28.4	153.7 ± 27.7	179.4 ± 41.9	105.5 ± 31.1	109.6 ± 29.5	109.0 ± 28.0
2071-2099	137.6 ± 24.2	145.5 ± 29.6	166.4 ± 32.9	73.1 ± 18.1	77.9 ± 18.4	86.8 ± 22.0

ter wheat yield. The winter wheat WF decrease throughout the region in the periods of P1, P2 and P3 by 58.7% (186.7±0.27 m^3 t^{-1}), 64.6% (160.1±0.30 m^3 t^{-1}) and 66.9% (149.9±0.37 m^3 t^{-1}) in RCP 4.5, respectively. When compared the result of increases in yields between RCP 4.5 and 8.5, it can be said that the WFs in RCP 8.5 is lower than WFs in RCP 4.5. WFs of winter wheat decrease as 68.5% in P1 (142.4±0.29 m^3 t^{-1}), 76.1% in P2 (108.0±0.26 m^3 t^{-1}) and 82.5% in P3 (79.3±0.25 m^3 t^{-1}). The reason for this situation in WF can be explained not only by the increase in yield and atmospheric CO_2 concentration in RCP 8.5, but also with the decrease in the effective precipitation.

CONCLUSION

In this study, actual crop yield and WF of winter wheat grown under rainfed conditions were compared by using AquaCrop model for two growing seasons.

RCP 4.5 and 8.5 scenario results produced by HadGEM2-ES model were used as input data to estimate the crop yield and water footprint of the future by AquaCrop. According to the AquaCrop simulation results, it is predicted that winter wheat yield would increase for the future in the Thrace part of Turkey. Although the precipitation decreased and temperature increased in the RCP 8.5 scenario, crop yield would be affected positively. On the other hand, increases in the crop yield would cause decreasing WF of winter wheat.

The results of our study were compared with other related studies. In the Kersebaum et al. (2016) study, the total WF of wheat (556 m^3 t^{-1}) is 23% more than our WF (452 m^3 t^{-1}) and their wheat yield was 28% higher (5.78 t ha^{-1}) than our research area (4.46 t ha^{-1}). Similarly, estimated WF by Zhuo et al. (2016) for winter wheat (1074±133 m^3 t^{-1}) in China is higher than our WF. Additionally, green WF of wheat determined by Zhuo and Hoekstra (2017) is also higher than our WF. As can be seen from these studies, dissimilarity of yield and WF of winter wheat can be attributed to the climatic characteristics, soil hydrological parameters, cultural genotype and management practices.

In future studies, current and potential crop yield and WF of winter wheat can be evaluated comparatively using different regional climate model results and crop growth simulation models in this study area. Performing the same processes in different regions and crop types are also important in terms of effective use of water in agricultural ecosystems. In order to enhance such studies, the input and output data required for the models must be continuously monitored and recorded in the countries. Data infrastructure should be created for better results.

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An agrometeorological analysis of weather extremes supporting decisions for the agricultural policies in Italy

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Abstract. The future European Common Agricultural Policy foresees Strategic National Plans founded on recognised needs for intervention and indicators in order to select the more effective policy measures. The Strategic plans start from a "context analysis", describing the current-starting conditions. In support to the policy theme on climate change, the authors proposed a context analysis on the main agrometeorological variables and weather extreme events, both at national and subnational (NUTS1) level. This paper describes the methodological choices made and the results obtained, considering the contents required by the European Commission for the context analysis (agrometeorological indicators and an indicator of economic damages due to natural disasters). The data source chosen is ERA5, the climate reanalysis dataset produced within the Copernicus project. The study demonstrates the importance of cross-reading data on hazards and data on vulnerability for policy decisions. In particular this is shown for the resulted most impacting weather condition: the drought, measured through the SPEI index, affecting all the country. There are also other hazards frequent and quite impacting, first of all heavy rain. Further improvements of the analysis are programmed in terms of spatial scale, time scale (seasonal approach) and in terms of correlation hazard-vulnerability.

Keywords. Agrometeorology, climate indices, decision support systems, ETCCDI, climate-related risks.

INTRODUCTION

The Common Agricultural Policy (CAP) was launched in 1962 as a strategy to provide affordable food for European citizens and a fair standard of living for farmers[1]. During the last decades, several reforms have been necessary in order to ensure the general goals of the policy in a changing context, in particular referring to the main issues of the environmental protection, the globalization and the challenges posed by climate change (CC), in general covering almost all the United Nations Sustainable Development Goals (SDGs). Given the importance of these global issues for the future CAP 2021-2027, in the new proposal of regulation, the European Parliament introduced, among other innovations, the realization of strategic national plans that reflect a comprehensive intervention logic, a "policy cycle concept" founded on identified and recognised intervention needs, deriving objectives and indicators (at all levels of evaluation) and consequent selected measures that can effectively contribute to reach the targets (European Parliament, 2018). The strategic plans need to start from a "context analysis", describing through objective studies the current conditions, strengths, weaknesses, opportunities and threats (SWOT analysis) with respect to the objectives of the CAP. The context analysis has a core role for the rural development policy, of the CAP, in which the choice of the measures is linked to specific goals to be pursued (environment, climate change, etc.) and to local conditions.

In Italy, the rural development policy has always been programmed and applied at administrative regional level (21 regional programmes, NUTS2), while the new CAP cycle requires a national programming phase, based on a context analysis at national level. This innovation represents an important step forward to have a more coherent and consistent programming phase compared with the past 21 separate regional programmes, nevertheless it also represents a challenge because of the heterogeneity of environmental and agricultural conditions of the Italian territory. For these reasons, a task force has been established by the Italian Ministry of Agricultural and Forestry Policies (MIPAAF), which involves representatives from the Regions, with the idea of a common work path, identifying the analyses to be carried out at national and regional level. The task is supported by technical analyses performed by research institutions, including the Council of Agricultural Research and Economics (CREA) with its researchers involved in the National Rural Network project[2].

As a starting point, it was agreed to deal with the proposal of regulation containing context indicators and with the thematic documents produced by the European Commission (EC) on the objectives of the future CAP (policy briefs), which provides guidance on how to set the contents required for the context analysis.

A specific thematic policy brief has been proposed by the EC on the general objective 2 "*to strengthen environmental protection and action for the climate and contributing to the achievement of the Union's environmental and climate objectives*", among whose a specific objective 2.1 is "*contributing to the mitigation of climate change and adaptation to them, as well as to the development of sustainable energy*" (EC, 2019; EEA, 2019). The article describes the specific study carried out to contribute to the Italian policy brief on climate change and to the context analysis for future CAP. The objective of the study is also a first attempt to assess the relationships between the agrometeorological context and the impacts on agricultural productions and practices, considering the scenarios currently taking shape, showing an increase in uncertainty of climate conditions directly influencing the agricultural production. The sector is indeed the most exposed and vulnerable to climate change referring to the higher likelihood of weather events extreme and non-extreme leading to natural disasters (IPCC, 2012). At last, the study intends to contribute in exploring the potentialities in agrometeorological analyses of new data sources offered by the European project Copernicus[3].

MATERIALS AND METHODS

General criteria adopted for the context analysis

Referring to the objectives of the study, the first step has been to analyse the EC requirements regarding the contents needed in the context analysis with reference to the climate and the impact of CC in agriculture. As explained in the introduction, the reference documents are the proposal of regulation and the EC policy brief on climate change.

The policy brief reports what it is expected from the context indicators in terms of information: a) changes in precipitation; b) changes in temperatures; c) frequency and intensity of extreme events; d) other references, such as changes in agricultural yields, the period of flowering and in the agricultural calendar.

Moreover, in the proposal of regulation, an impact indicator is requested in the "climate" section: the indi-

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[1] https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-glance_en.
[2] https://www.reterurale.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1.

[3] https://www.copernicus.eu/en.

cator c.45 "Direct losses in agriculture attributed to disasters".

The methods for this study were chosen so as to reflect both the EC expectations for the context analysis of the National strategic plan, and the need to ensure a good agrometeorological analysis at national and sub-national level, with a specific and new focus on extreme events connected to climate-related disasters risks in agriculture.

The main choice criteria were the following:
- availability of data for the calculations;
- descriptive capacity of the relations between agriculture and weather-climate conditions;
- possibility of representing the indicators with respect to the climate ("changes" of temperature and precipitation);
- preference for statistical distributions at a local scale (percentiles) and not for fixed value thresholds for the estimation of extreme events. This choice is linked to the climatic and agricultural heterogeneity of Italy, which makes the fixed thresholds unsuitable to adequately describe the different conditions.

In addition to the EC approach to the context analysis, the main references for the study are the works of the Intergovernmental Panel on Climate Change (IPCC) and of the Expert Team on Climate Change Detection and Indices (ETCCDI)[4]. Following the IPCC approach, the indicators are divided into: context indicators, corresponding to the indicators of "hazard" and "exposure"; impact indicators, representing the "vulnerability" (IPCC, 2007 and 2012). The context and hazard indicators chosen for the information on "extreme events" derive from the work of ETCCDI, that proposed a set of 27 main indices, based on daily temperature (maximum and minimum) and precipitation values.

Moreover, two specific indices have been added to improve the context description, in relation to the drought conditions and the changes of the phenological calendar, respectively.

As above explained, in relation to the objectives of the analysis, it has been proposed to enrich the analysis of hazards and climatic conditions with an impact indicator, a "vulnerability" indicator in the IPCC approach, defined as "Direct losses in agriculture attributed to disasters" in the proposal of regulation. In fact, the concept of "climate extremes" discussed within the IPCC works is particularly important in agriculture, because the increase of climate extremes likely will lead to more "disasters" defined as *severe alterations in the normal functioning due to hazardous physical events interact-* *ing with vulnerable conditions, that require immediate emergency response*" (IPCC, 2012). In the context of climate change, the disaster risk is influenced not only by hazard, but also by exposure and vulnerability, where the exposure refers to the presence of productive systems where hazard may occur, while the vulnerability is the predisposition to be adversely affected (economic damages due to lack of resilience and low capacities to cope with/adapt to). In the IPCC approach, the climate-related risks should be faced through the improvement of two components of risk management: measures of risk reduction (more stringent where the vulnerability is high) and disaster management (more stringent where the hazard is high). For these reasons, it is important to start changing the approach in policy decisions, integrating the weather and climatic analyses with a vulnerability component (IPCC, 2012; UNISDR, 2015; EEA, 2017). This study is also a first attempt to introduce these integrated concepts in the policy analyses in the agricultural sector.

The indicators have been calculated at sub-national scale, using the classification of territorial units for statistics (NUTS), a geocode standard for referencing the administrative divisions of countries for statistics, developed by the European Union[5]. The first-level NUTS regions (hereinafter also called "areas"), based on major socio-economic areas, has been adopted, precisely for Italy: North-West (Aosta Valley, Liguria, Lombardy, Piedmont); North-East (Emilia-Romagna, Friuli Venezia Giulia, Trentino-Alto Adige/Südtirol and Veneto); Centre (Lazio, Marche, Tuscany and Umbria); South (Abruzzo, Apulia, Basilicata, Calabria, Campania and Molise); Islands (Sardinia and Sicily). Although aware that the agrometeorological analyses poorly adapt to areas on administrative basis, this choice seemed the most suitable compromise to be used in this kind of analysis with institutional purposes at national scale.

The climate reference period (hereinafter referred to as "climate period") is 1981-2010, according to the World Meteorological Organization (WMO) that defines the "normal standard climates" as the averages of climatic variables calculated for a uniform period of 3 consecutive decades. In 2017, the WMO established that, in addition to the 1961-1990 period, which remains the standard reference period for long-term assessments of climate change, it is possible and recommended to use the new "climatological standard normal" 1981-2010, able to describe more coherently the current climate (WMO, 2017). The need to provide a description as representative as possible of the current climate variability led to choose 1981-2010 as the climate reference period.

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[4] http://etccdi.pacificclimate.org/list_27_indices.shtml.

[5] https://ec.europa.eu/eurostat/web/nuts/nuts-maps-.pdf-.

The period chosen for the analysis is 2003-2018, covering enough time (16 years) to describe the current context of the application of a mid-term policy like CAP (7 years cycles).

Data

All the elaborations and analyses of data here presented are original and are based on data from three main sources: a climate reanalysis dataset, for meteorological data, a phenological observation dataset, a database on damages on agriculture due to adverse events derived from the Italian ministerial decrees on damages.

The data source chosen for the meteorological analysis, is ERA5, the hourly climate reanalysis data, available on a regular grid at a resolution of 0.25°. ERA5 is the latest climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), providing hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty (C3S - Copernicus Climate Change Service, 2017).

The choice of the ERA5 dataset is due to several reasons:

- climate reanalysis combines past observations with weather models to generate gridded datasets of consistent and complete time series of multiple climate variables at sub-daily intervals, which are currently the most used datasets in the climate extreme studies (Donat et al., 2014);
- the data are public, produced by a European institutional project (Copernicus);
- the available dataset starts from 1979, covering a good time period for climatic analysis;
- the dataset will maintain continuity over time, allowing analyses able to be updated (this is important also for supporting the policies evaluation through indicators); moreover, data are released every two days, overcoming problems of availability of other datasets;
- further improvements and enrichment of the variables provided in the Copernicus project are planned.

The variables selected in ERA5 (atmosphere) are described in table 1.

The phenological database of the IPHEN network[6] has been used to extract weekly observational data of the grapevine phenological phases on 33 sites, distributed all over the country, for the period 2006-2018.

The data used for the impact indicator derive from damages declarations recognized by the State as due to

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[6] https://www.reterurale.it/fenologia.

Tab. 1. Variables selected in ERA5 for the context analysis.

Name of variable in ERA5	Abbreviation	Measure unit	Transformation of derived variables
2m temperature	2T	K	°C
2m dewpoint temperature	2D	K	Relative umidity min and max (%)
10m u-component of wind	10U	m s-1	Wind speed (m s-1)
10m v-component of wind	10V	m s-1	
Surface solar radiation downwards	SSRD	J m-2	MJ m-2
Total Precipitation	TP	m	mm
Orography	OROG	m2 s-1	Altitudine (m s.l.m.)

natural disasters, as assigned by the National solidarity fund for disasters in agriculture of MIPAAF (legislative decree 102/2004). Information from Italian ministerial decrees of damages due to "adverse events" is collected in a database now managed by CREA, reporting data from the 1980s on the date and the kind of event, the location (at level of municipalities) and the declared economic damages on production (at least 30% of losses), farm structures (such as irrigation systems, animal shelters, greenhouses, etc.) or infrastructures connected to agricultural activities (mostly collective drainage and irrigation channels, rural roads, etc.). For the present study, only the weather adverse events have been considered (for instance, earthquakes and volcanic eruptions have been not included). The definition of "adverse event" in the Italian law is an adverse weather such as frosts, storms and hail, ice, heavy rains or severe droughts that destroy more than 30 percent of the average annual production calculated on the basis of the previous three years or a three-year average based on the previous five years, excluding the lowest value e the highest one (legislative decree n. 102/2004). The general criteria used by the Ministry to declare a disaster due to adverse events are the aforementioned threshold of damages and the statistical exceptionality of the event (not the same in the previous 5 years in the same territory), but each case can be differently evaluated. The declara-

tion assigns also an economic damage associated to the event in order to compensate farmers.

Moreover, the ISTAT data of the "Surveys on the structure and production of agricultural holdings (SPA)" have been used for the UAA data available for the analysis period[7].

Methods

With reference to the context analysis, among the ETCCDI core indices, four "extreme events" indicators have been selected (warm and cold spell duration indices, a modified version of frost days and very wet day fraction). Moreover, the standardized precipitation evapotranspiration index - SPEI has been calculated because of the importance of monitoring drought events in agriculture. This indicator covers also the issue "changes in precipitation and in temperatures" proposed by the EC policy brief, being the two variables strictly linked in its definition and calculation. An increasingly widespread use of these indicators and indices can be found in the scientific literature, also referred to risk assessment and adaptation policies support (EEA, 2017; Klein Tank et al., 2009; Donat et al., 2013a, b; Russo et al., 2014; Zhang et al., 2011; Zolina et al., 2009). Less references can be found in the agricultural sector, most of them referring to drought indices, although a general increase of the studies in this field has been observed in the last decade (EEA, 2019; Cogato et al. 2019; Blauhut et al. 2015).

A further context indicator is the First flowering date, very important for agricultural productions and practices. Basing on the data availability, the chosen indicator has been calculated for the Grapevine Chardonnay variety.

Finally, an original impact-vulnerability indicator has been defined, mainly based on the economic value of damages affecting production, farm structures and infrastructures.

All the indicators have been aggregated at the NUTS1 region level using the official administrative boundaries from the Italian National Institute of Statistics (ISTAT), updated to the 1st of January 2019[8] and transformed from the projected EPSG: 32632 to the geographical EPSG: 4326 reference system[9], the same adopted by the data distributed through Copernicus climate data store. Data have been spatially aggregated, using the median value of the cells intercepted by the administrative boundaries, unless for the SPEI index, for which the

10th percentile has been adopted (Bachmair et al., 2015), with the aim to investigate the link with the impact-vulnerability indicator values.

Data processing has been performed through specific libraries of the R software ("climdex.pcic" and "SPEI"). R is an open source statistical software released under the GNU general public license (GPL)[10].

Warm spell duration index - WSDI

The warm spell duration index is the yearly number of days belonging to warm spells, defined as at least 6 consecutive days with maximum temperature higher than the 90th percentile of the distribution of maximum daily temperatures in the same period of the year over the 30 years of climate. Recently, the negative correlation between wine quality and the incidence of heat waves has been investigated by Blanco-Ward et al., 2017.

Cold spell duration index - CSDI

The cold spell duration index is the yearly number of days belonging to cold spells, defined as at least 6 consecutive days with minimum temperature less than the 10th percentile of the distribution of minimum daily temperatures in the same period of the year over the 30 years of climate. This index is generally calculated within a set of indices (see references above), in some cases strictly associated to WSDI (Song et al., 2018).

Late frost days - LFD

Starting from the original indicator FD of ECCTDI, this indicator is based on the count of the frost days limited to the period March -April, when most of crops are in the phenological phase most sensitive to frost (flowering), with reference to the area study and as reported by Gobin (2018), who analysed the spring frost days during the sensitive crop stages. The indicator is expressed as the yearly deviation from the climate values [LFD_{year} - $LFD_{Climate}$], which correspond to the median of the distribution of the annual values during the climate period.

As frost days are considered all the days with a minimum temperature equal to or less than 0 °C. This generic threshold of 0 °C is due to the purpose of the analysis, that doesn't consider local conditions and specific crops. Furthermore, to detect the wheat's frost-susceptibility, this threshold has also been adopted by Zheng et al. (2015).

[7] http://dati.istat.it/.
[8] https://www.istat.it/it/archivio/222527.
[9] https://www.epsg-registry.org/.
[10] https://cran.r-project.org.

Very wet day fraction - R95pTOT

This indicator represents the yearly amount (in millimetres) of the daily precipitation above the 95th percentile of the distribution of daily rainfall of the wet days (greater precipitation than 1 mm) in the climate period. The values are also expressed as percentage contribution of R95pTOT to annual total precipitation. This index has been already used to investigate the impacts of heavy rains on wheat (Li et al., 2016) and rice (Subash et al., 2011).

For this indicator, an additional analysis has been carried out to compare the mean value resulted in the analysis period to the mean value calculated for the previous not-overlapping period 1981-2002.

Standardized precipitation evapotranspiration index at time scale of 6 months – 6-month SPEI

SPEI represents a simple climatic water balance (CWB), also known as "effective precipitation", calculated as difference between total precipitation and potential evapotranspiration (PET), here estimated through the Penman-Montheit equation (Allen et al., 1998).

The indicator has two important peculiarities. The first is that it can be computed at different time scales, incorporating the influence of the past values (Vicente - Serrano S.M. et al., 2010). Thus, the value calculated for each month considers the values of the previous months, with a different time scale (from 1 to 48 months) which depends on the aims of the analysis (assessment of meteorological, agricultural or hydrological drought). In the study, the time scale chosen is 6-month, considered more suitable to describe water stresses during the agricultural season. The second peculiarity is that the SPEI calculation is based on the comparison between the CWB recorded in an interval of t months (where $t = 1, 2, ..., 48$ months) with the distribution of the CWB in the climate period for the same interval. For each cell, the time series of cumulative effective precipitation is interpolated by means of a log-Logistic theoretical probability distribution with the unbiased fitting method probability weighted moments (Vicente - Serrano S.M. et al., 2010), assuming a rectangular kernel that assigns the same weight to all months of the interval of 6 months. The tail values of SPEI <-2.5 and SPEI> +2.5 have been cut according to what suggested in literature, mainly when short time series are considered (Vicente-Serrano S. M. et al., 2016).

The SPEI drought index is classified by the scientific community in different classes of intensity[11] (WMO and GWP, 2016) (Tab. 2).

Tab. 2. Classes of values of SPEI.

Classes of intensity	SPEI values
EW - Extreme wet	≥ 2.00
SW - Severe humidity	1.50 ÷ 1.99
MW - Moderate humidity	1.00 ÷ 1.49
N - Near normal	-0.99 ÷ 0.99
MD - Moderate drought	-1.00 ÷ (-1.49)
SD - Severe drought	-1.50 ÷ (-1.99)
ED - Extreme drought	≤ (-2.00)

The elaborations are here reported with the values of March as representative of the recharge seasons (October-March) and with the single values from April to September, useful to monitor the drought during the growing seasons.

Grapevine first flowering date -FFD (cv. Chardonnay)

The indicator is expressed as yearly deviation from the climate values [FFD_{year} - $FFD_{Climate}$], which corresponds to the median of the first flowering dates during the climate period. The first flowering corresponds to the 61 value of the BBCH scale (Meier, 2001). The FFD indicator is calculated using the IPHEN phenological model for the estimation of grapevine flowering dates for each year both of the analysis and climate periods. The model, adopted by CREA for producing a weekly phenological bulletin at a national scale[12], has been developed within the IPHEN project (Mariani et al., 2013; Cola *et al.,* 2012). It is based on the calculation of normal heat hours (NHH) (Wang and Engel, 1998; Weikai and Hunt, 1999). The accumulation of NHH is converted to phenological phases, according to the BBCH scale, through empirical equations obtained by regression on both historical NHH and phenological data detected in the field.

To check the IPHEN model performance in simulating flowering dates, the mean absolute error-MAE between the flowering dates simulated and those observed in the field has been calculated.

Considering that the altitudes of ERA5 cells and phenological observation sites may be dissimilar, the

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[11] https://spei.csic.es/home.html.

[12] https://www.reterurale.it/bollettinofeno.

link between the differences of elevation and those of flowering date (MAE errors) has been investigated, by a linear regression, with the aim of verifying whether this uncertainty source can affect the model performance.

Damages attributed to natural disasters

Referring to the impact-vulnerability indicator, the chosen indicator "Economic damages attributed to disasters on utilized agricultural area" (euro/hectare of UAA) is based on the above-mentioned database on data of damages recognized by the State as due to natural disasters, as assigned by the National solidarity fund for disasters in agriculture of MIPAAF.

The calculation of the economic value of impacts on production is based on the UAA involved and the official prices at the time of the event of the affected crops, while for structures and infrastructures is based on the physical damages and the prices of rebuilding/repairing. These data produced with the same criteria are an important point of reference to assess the impacts in different periods and areas. Nevertheless, it is important to specify that they are slightly underestimated in terms of absolute values because of the exclusion of insured crops (foreseen by the law, but less than 18% of national production in 2015) (Pontrandolfi et al., 2016).

The UAA data from ISTAT have been used for creating a complete series from 2003 to 2018. As original data cover only the years 2003, 2005, 2007, 2010, 2013, 2016[13], missing annual data have been covered by the nearest previously available value: e.g. 2003 data applied also to 2004 and so on.

The geographical reference units for the elaborations are the NUTS1regions and the indicator has been calculated as yearly values of total damages per hectare of UAA.

Further elaborations are presented referring to the kind of damages (on production, farm structures or infrastructures) and to the kind of events producing damages.

RESULTS

The SPEI data in figure 1 show two cases of widespread severe and extreme drought phenomena: 2003 and 2017, with extreme drought in 2003 in Centre and North and in 2017 in Centre, South and Islands. Another similar phenomenon, although of lower intensity, is noticeable for 2007 and 2012; it involved almost

all NUTS1 regions, unless the Islands. This latter region was instead affected by a moderate/severe drought during 2016. In some cases, drought conditions, at least moderate, affected the recharge periods (March) almost all over the country, mainly in 2007, 2012 and 2017. A prolonged drought condition interested the Northern regions from 2003 to 2007 and 2011-2012 in northern and central Italy but with less intensity. As regards wetness events during the observed period, only few cases are remarkable: South in 2009, Centre in 2010, Centre and North-East in 2013, Centre in 2018 show wetness conditions from moderate to severe. These phenomena resulted to affect mainly Centre.

The results of warm and cold spell indices are reported in the figure 2. Referring to the warm spells, the most critical years result to be 2011 and 2003, followed by 2007 and 2015. In details, in 2011 the maximum values were reached in the northern and central regions, with a peak of 45 in North-East. In 2003, warm spells were widespread all over the country, with WSDI values of at least 30 in 4 of the 5 NUTS1 regions. On the contrary, the years less interested by warm spells were 2004, 2005, 2008 and 2010. In general, the second half of the analysis period results to be more continuously affected by these phenomena.

The cold spells are in general less widespread all over the country and the values result to be lower than warm spells in terms of days. Few years show the occurrence of these phenomena: the most relevant in the North-West, with peaks of 15 days in 2012 and 10 in 2005; single events of cold spells occurred in northern regions (2003), South (2006, 2009 and 2017), Islands (2005 and 2009). It is noticeable that almost all events are concentrated in the first 10 years of analysis.

The results on late frost days are shown in the figure 3. The data show positive anomalies in 2005 in all the regions and in 2010 in the North. The number of late frosts is below average in 2007-2009 and after 2013 there is a clear tendency to reduction of late frosts (each year below the average), most accentuated in the north-eastern and central areas. A different behaviour is present in the Islands, where the late frost days are near normal, except a weak positive anomaly in 2005.

In figure 4, the indicator R95pTOT (very wet days) is represented in millimeters and as the percentage fraction of the total annual precipitation, in order to allow a better comparison among the different cases. The distribution of these phenomena shows that, even though different rainfall regimes are present within the country, a heavy rain fraction is always represented among the years and the areas, with an average of 20% and a range between 10 and 31%. In general, the percentage

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[13] http://dati.istat.it/.
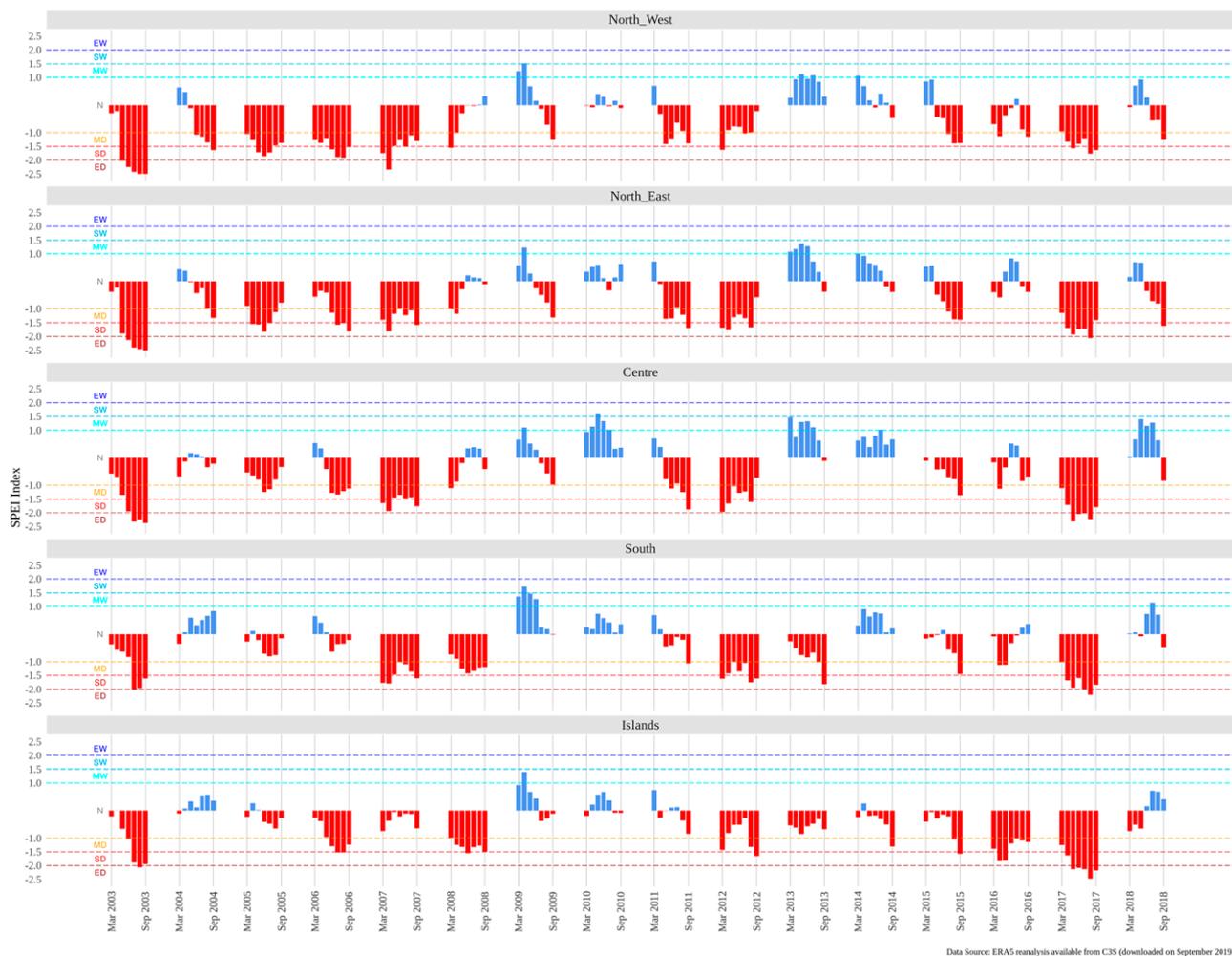
Fig. 1. Standardized precipitation evapotranspiration index – 6-month SPEI, monthly values in the period 2003-2018 (class description in Tab. 2).

values vary among regions, but they all show high values, from 24% in the Centre to 30% in North-West and Islands, in the year 2010 (the second rainiest year in the period). Another important indication is that in the 16 years period the heavy rain amounts have been most relevant in South and Islands, with a mean value significantly higher than in the previous period 1981-2002: the increase is equal to 42.4% (*p.value* 0.0006) and 44.7%, (*p.value* 0.003) in South and Islands respectively.

At last, the indicator of first flowering date shows between-year variability in terms of deviation from average (Fig. 5). Anomalies can be observed in 2004 with generalized late flowering around 7–12 days and in 2007 with generalized early flowering around 10-16 days. From 2012, Centre, South and Islands present a widespread advanced flowering until 16 days. In 2013 and 2016 a significant latitudinal gradient of temperatures

divided Italy in two parts, with the northern regions presenting a late flowering while the central, southern and island regions an advanced one. The median MAE value has resulted to be equal to 5 days at a national scale and significantly affected by the differences in elevation between gridded and site dataset. In fact, the relationship between MAE and differences in elevation has showed that the 65% of FFD variability can be explained by these differences (adjusted r-squared= 0.65, *p.value* <2.2e^{-16}).

Referring to the indicator of impacts, the results show significant damages due to natural disasters meteorological-related all over the country in 2003 and 2017, corresponding to the most severe droughts, followed by 2012 (Fig. 6). In these years, the highest values range from 300 to 600 euro of damages per hectare of UAA. The most affected region is North-East, with highest

damages per hectare in 2003 and 2012 and the second highest in 2017, after Centre (with 614 €/ha). The persistent conditions of drought in the period 2004-2007 in the North of the country (Fig. 1) don't correspond to the damages, less pronounced. On the contrary, in 2003-2007, South and Islands show relevant damages although with no or moderate and less persistent drought than in North.

In total, it has been calculated a damage of 27.837 billion euros declared in the 16 years, 76% of which are damages on productions, 18% on farm structures and 8% on infrastructures connected to the agricultural activities (Tab. 3). The highest absolute values of damages affected the Islands and the South, followed by the North-East. The Islands also suffered the major damages on productions and on farm structures and the South on infrastructures. These data, comparing to the intensity of the events, in terms of hazard showed before, seem define the Islands and the South of Italy more vulnerable to damages than exposed to the hazards.

The kind of event affects differently areas and type of damages (Fig. 7). The number of events declared as natural disaster classified per type of damage show that the episodes of heavy and/or prolonged rain are frequent and affect all three productions, structures and infrastructures (these ones almost exclusively hit by heavy rain), while several strong winds and tornados mainly hit the farm structures. The damages on productions are due to several kind of events, mainly drought, hail and heavy rain.
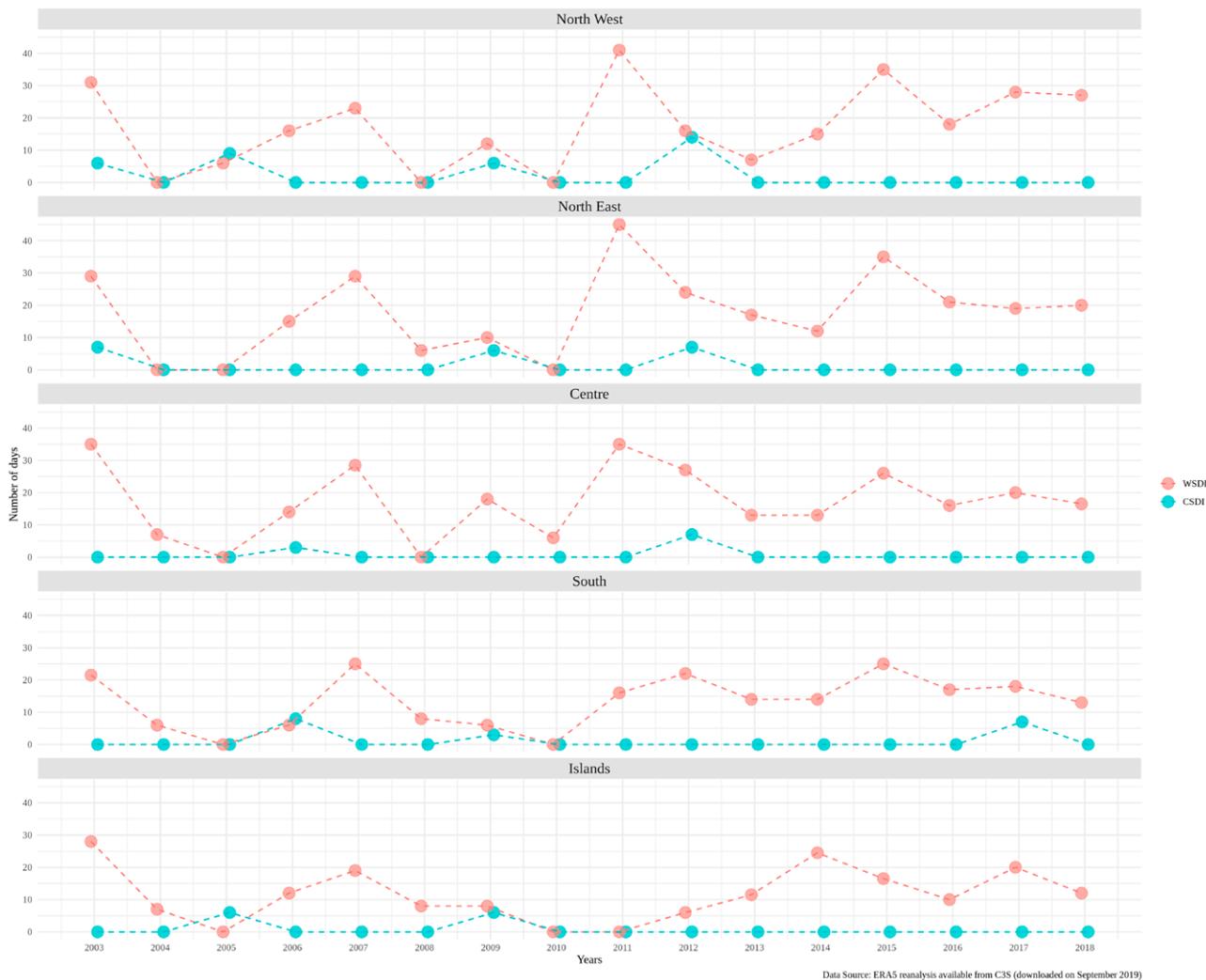
Fig. 2. Warm spells and cold spells, number of days per year in the period 2003-2018.
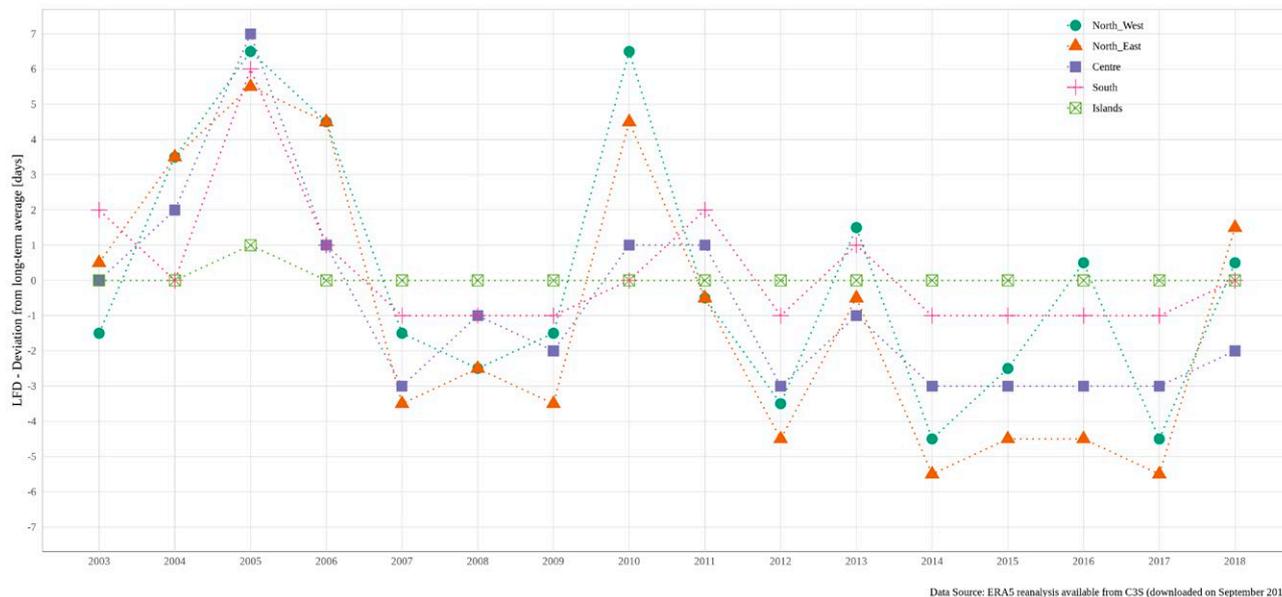
Fig. 3. Late frosts days, deviation from the climate per year in the period 2003-2018.

DISCUSSION

The context analysis here presented provides a first description of the relationships between damages on agriculture and weather-climate conditions, despite the small scale necessary for the National Strategic Plan.

In particular, the results show that drought has been the most impacting hazard and a frequent condition affecting all the country around every 4-5 years, with extreme peaks in 2003 and 2017. Moreover, considering the climatic characteristics of the different areas of the country, in South and Islands the drought events are less extreme than in North, in terms both of hazard and impacts (see Figg. 1 and 7). The positive relationship between drought and damages did not occur everywhere: for example, lower damages have been recorded for the persistent drought occurred in the northern areas in the period 2004-2007 (Fig. 1), while relevant damages occurred in South and Islands in 2003-2007, although these areas showed no or moderate and less persistent drought in relation to North. These results confirm that the link between drought and impacts is time variant and region specific (as already noticed by EEA, 2017; Bachmair et al., 2015 and Blauhut et al., 2015). In the investigation of this link, it would be also important to consider other factors such as the level of spatial aggregation (i.e. NUTS1), mainly in climatically heterogeneous areas, and the type of agricultural production (Parsons et al., 2019; Gobin, 2018).

The second most important event is heavy rain: the results show that the country has a general intense and concentrated precipitation hazard. The concentrated precipitation in average is equal to 20% of annual total precipitation. Overall, there is a variability of this phenomenon during the analysis period and among the different NUTS1 regions. In particular, the heavy rain amounts have been most relevant in South and Islands, with a mean value for the analysis period significantly higher than in the previous period 1981-2002, meaning a change of pattern in precipitation distribution in time.

Heavy rain is the hazard that affects at the same time productions, farm structures and infrastructures and in some cases, as in Islands for 2012 and 2015, these phenomena during the year are associated to drought events, with potential huge impacts on entire agricultural seasons.

Another significant indication comes from the warm spells, which affected the whole period, with a major frequency in its second half, while the cold spells are rarer, with few events concentrated in the first 10 years of analysis, even though the general threshold adopted for this index (0 °C) is not suitable to investigate the different hazards due to late frosts, which vary with the site, the season and the crops.

The late frost days after 2013 show a clear tendency to reduction (all the years below the average), most accentuated in the north-eastern and central areas.

The results on the indicator of first flowering show a generalized early flowering from 2012 in the Centre, South and Islands.
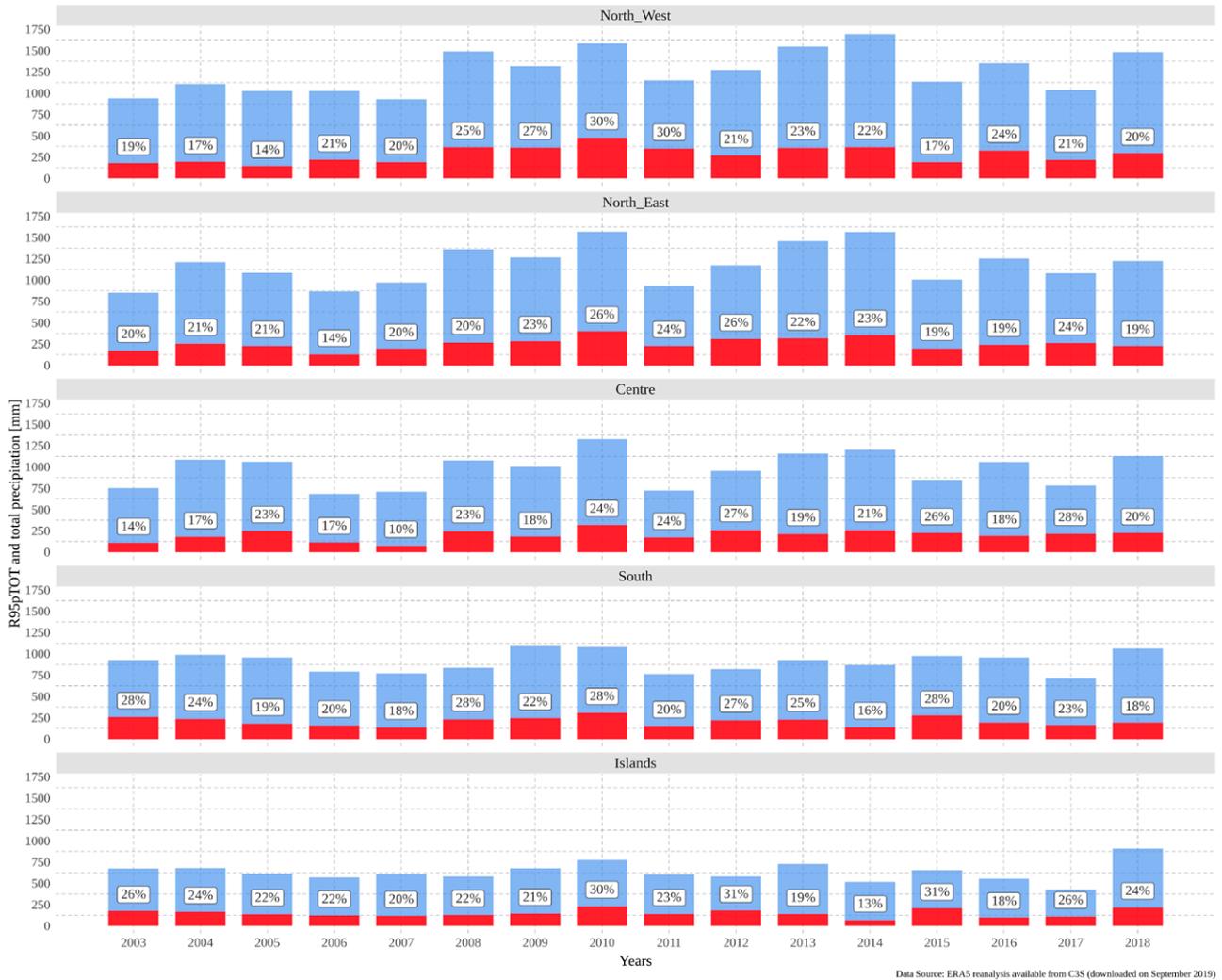
Fig. 4. Annual total precipitation (blue bar) and precipitation fraction due to very wet days (red bar and %) per year in the period 2003-2018.

The joint analysis of some hazard indicators highlights some consistent signals in relation to particular years or sub-periods. In 2004, the relevant delay of first flowering is consistent with the almost absence of warm spells, on the contrary, a negative link between flowering and warm spells is evident, all over the country in 2007 and mainly for northern regions in 2011. In addition, a persistent advanced flowering in the second part of the analysis period is consistent with a general increase of warm spells, especially in South and Islands.

As regards the choice of indicators, some of them need to be assessed at a more detailed spatial scale and to be focused on the specific requirements of the different crops. In addition, local specific thresholds could improve the analyses.

The results of SPEI, late frost days, first flowering date and warm spells seem strictly linked to the undisputed increase of average temperatures in the last years also in Italy (ISPRA, 2019).

In general, the country shows a high vulnerability to weather events leading to disasters, with a huge amount of damages declared (almost 30 billion euros) in these 16 years and frequent high values, normalized to the hectares of UAA, which are greater than about 300 up to 600 euros. The highest absolute values of damages affected the Islands and the South, followed by the North-East and these data, cross-read with the intensity of the events, seem define the Islands and the South of Italy more vulnerable to damages than exposed to the hazards. For instance, in terms of kind of event, the highest damages are due to drought events, while the most

frequent events are others, such as hail and heavy rain (both frequent and damaging), while other events are more frequent and less damaging (strong wind).

A crucial point in this analysis is the choice of metrics (i.e. median or 10th percentile) for spatial aggregation: in fact, it is important to choose the most effective metric to highlights the phenomena, particularly in a very orographically complex area like Italy. Some uncertainties are due to the resolution of input data, as in the case of first flowering: the correlation of phenological model errors (MAE) with differences in elevation between the ERA5 cells and observation sites confirms such uncertainty, as suggested by Fehlmann et al. (2019).
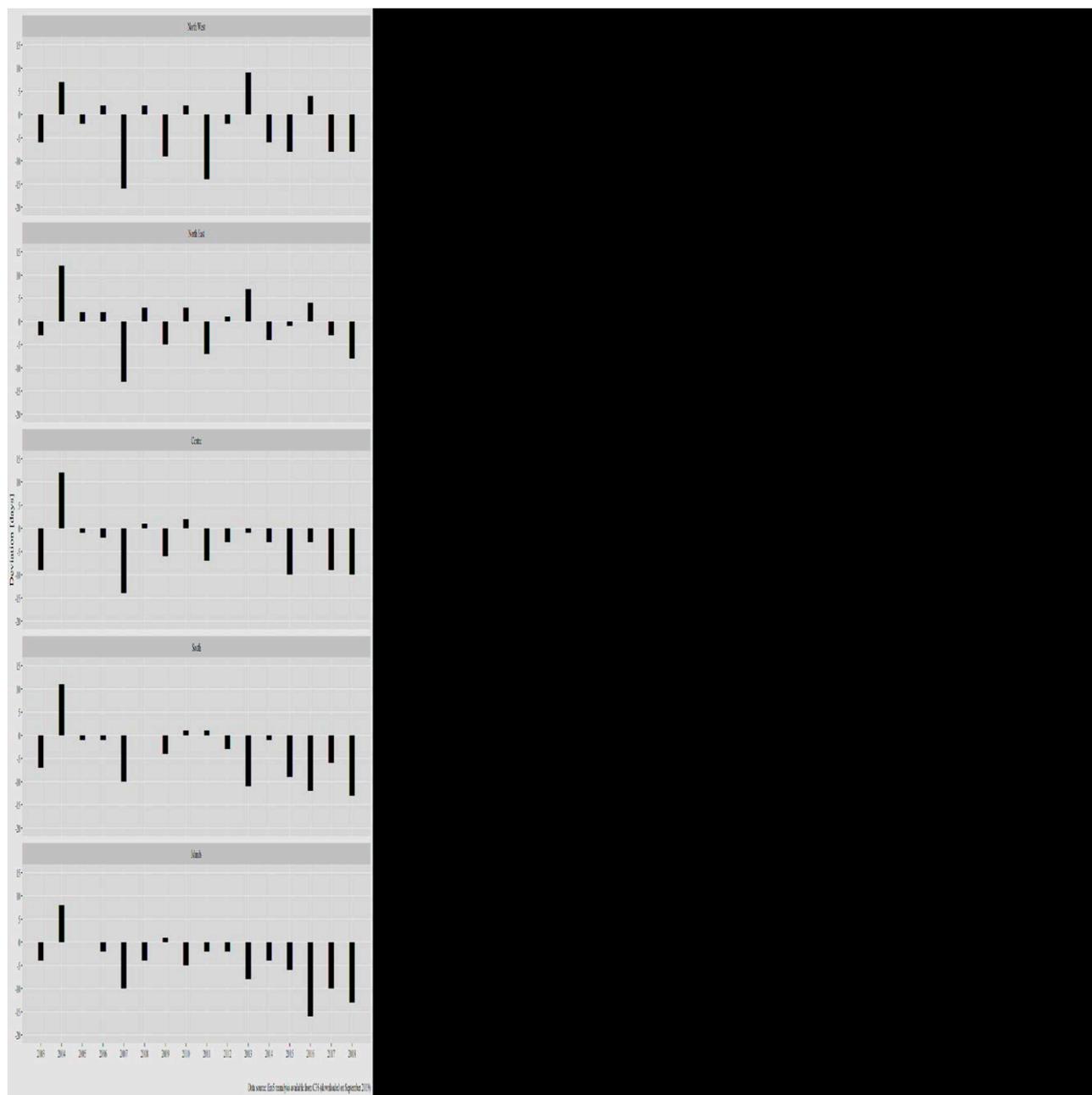
Fig. 5. Annual deviation of first flowering dates from the median (corresponding to 0 value on the y axis) of the climate period. The median dates correspond to 3 of June (DOY, day of the year = 154) for the North West, 27 of May (DOY=147) for the North-East, 28 of May (DOY=148) for Centre, 25 of May (DOY=145) for the South and 16 of May (DOY=136) for the Islands.
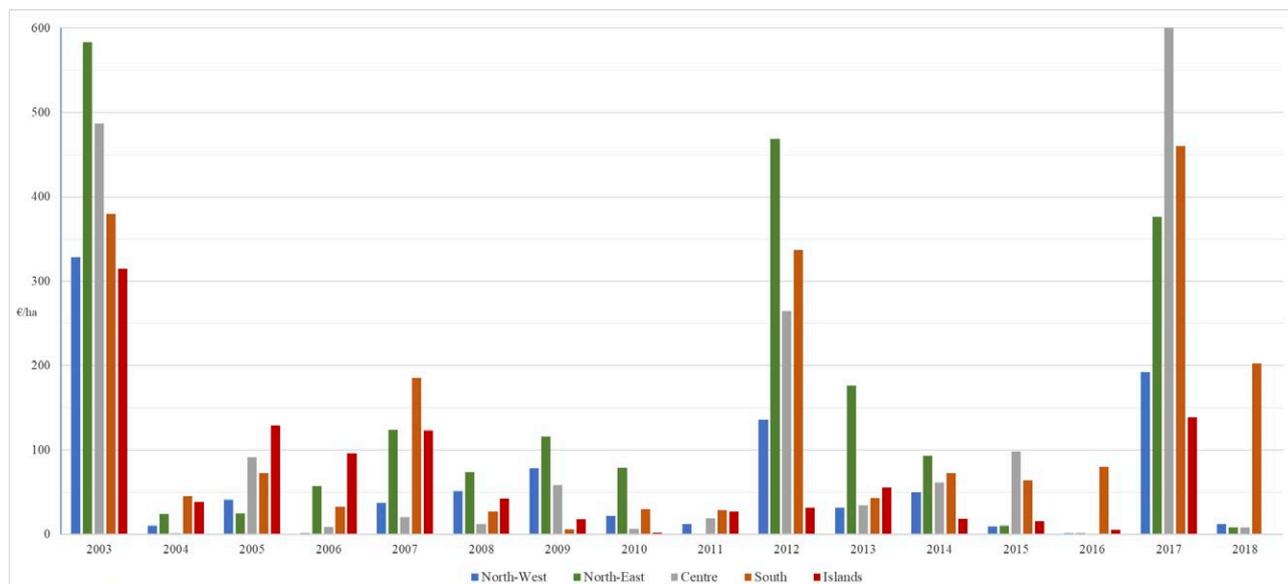
Fig. 6. Damages attributed to natural disasters per NUTS 1 region per year in the period 2003-2018 (values in €/ha UAA).

CONCLUSIONS

Referring to the aims and the context of the study, the results suggest the adoption of policy measures designed through objective analyses instead of simple "perception" of hazard and risks. This aspect has emerged by cross-reading the results of the hazard indicators in terms of intensity and occurrence in time and space and those of the impact indicator (damages due to natural disasters), that in some cases confirm, but not in others, the relationship between hazard and impacts. Moreover, the policy measures need to be enhanced at local level in terms of risk reduction where the agricultural systems are highly vulnerable (the hazard and the impacts are not aligned) and in terms of

adaptation to CC and disaster management where the impacts are linked to objective high hazards. For future studies it will be important also to consider indicators for events such as hail and strong wind and some indicators correlating more directly the hazards and the vulnerabilities at territorial level for each kind of adverse event.

A possible weakness of the study is the spatial resolution of the input meteorological data, that could be not completely suitable for agrometeorological analyses. In addition, the NUTS1 spatial aggregation chosen due to the needed synthesis for the national context could flatten the phenomena too much; better indications for policy choices could derive from a regional/sub-regional aggregation (NUTS2/NUTS3).

Nevertheless, the study indicates good potentialities of the ERA5 data source for the purpose above explained (Italian national context analysis). In order to give more specific indications for agricultural policy decisions other options will be explored for future studies, such as ERA5-Land which provides higher resolution[14], but shorter time series (from 2001 onwards).

Further improvements are also planned in terms of time scale, for instance using a seasonal approach, important for programming adaptation actions of the agricultural activities.

Tab. 3. Damages attributed to natural disasters in the period 2003-2018 per NUTS 1 region (values in billion euros).

NUTS 1 Region	Damages on productions	Damages on farms structures	Damages on infrastructures for agriculture	Total
North-West	1,542	0.298	0.290	2,131
North-East	4,716	0.433	0.350	5,499
Centre	3,088	0.629	0.232	3,950
South	5,566	1,201	0.447	7,214
Islands	6,369	2,350	0.323	9,043
Italy	21,283	4,912	1,642	27,837

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[14] https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview.
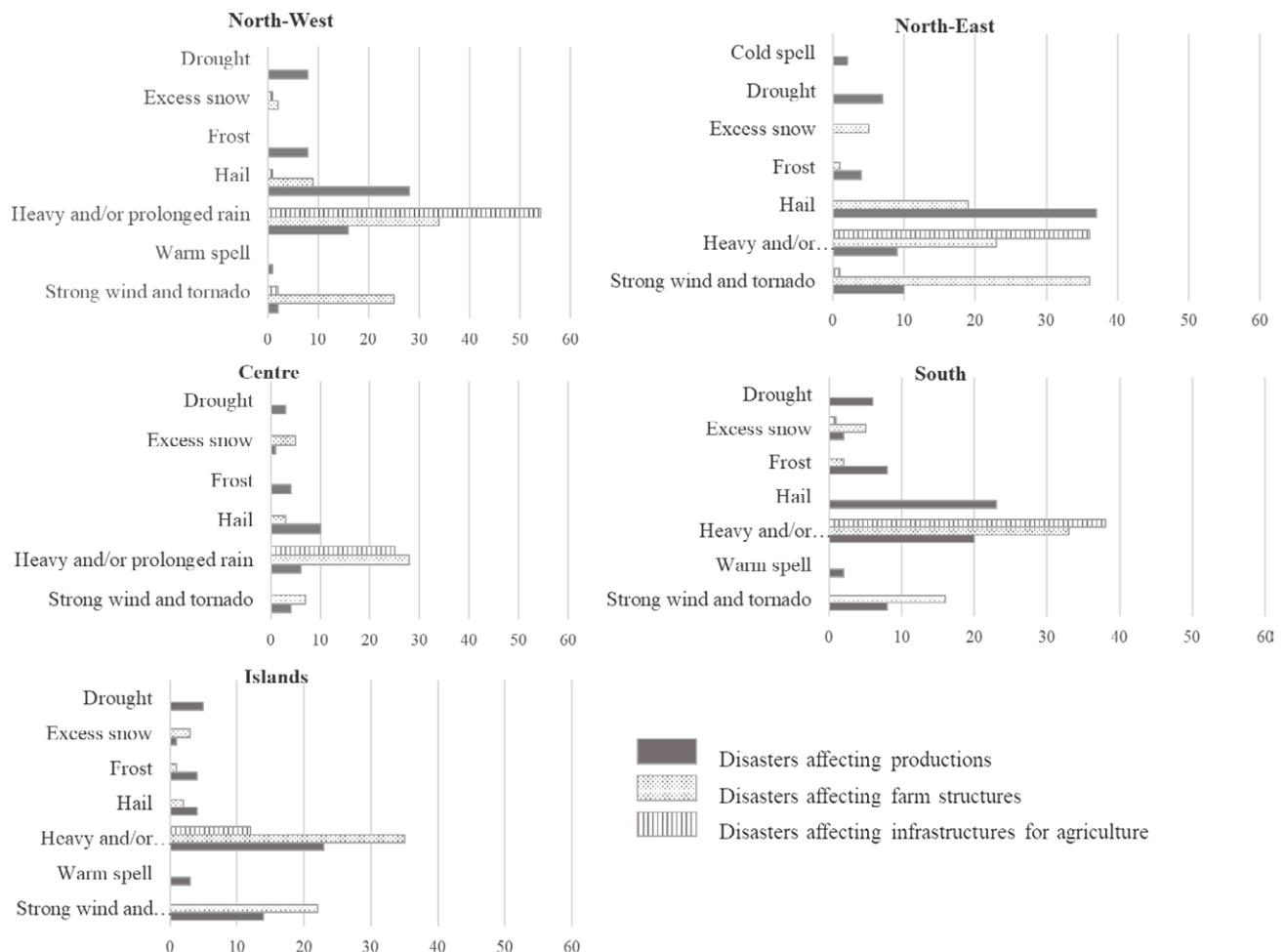
Fig. 7. Number of disasters declared per NUTS 1 region, type of event and type of damages in the period 2003-2018.

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Evaluation of forage Amaranth (*Amaranthus hypochondriacus* l.) yield via comparing drought tolerance and susceptibility indices

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Abstract. In orther to investigate the influence of different drought stress levels on the quality and quantity yield of forage Amaranth, a set of split-plot analysis were carried out in randomized blocks design with three replicates during the 2018 and 2019 growing seasons. The main factor of this study was different irrigation levels (50, 60, 70, and 80 % of the plant available water depletion) and the sub-factor was considered to be three different forage Amaranth genotypes, including Cim, Kharkovski, and Loura. The results revealed that an increase in irrigation intervals especially in 80 % water-deficit condition, will lead to a decrement in the fresh and dry yields (62 and 50 %), a reduction of WP factor (50 %) and an increase of the dry matter and crude protein percentages regarding the control treatment. Furthermore, to specify the most significant stress indices from Principal Component analysis in different drought stress levels, Harmonic Mean was chosen as the best index to examine the tolerance of Amaranth cultivars to the drought condition. According to the 3D graph of the opted index correlation with the yields, it was concluded that while Loura presents a better yield under mild stress conditions, the Cim genotype has the highest performance under moderate and severe drought stress conditions.

Keywords. Amaranthus hypochondriacus, Forage, Drought, Stress tolerance indices.

INTRODUCTION

Amaranth (*Amaranthus spp.*) which is originally a native plant in Mexico and Central America is considered as a weed in many regions (Khan et al., 2019). However, for many others, it has proved to be a highly tolerant and valuable plant which brings about many different human usages. Since the Spanish conquest, it has been considered as cuisine and the main ingredient for various beverages due to the high rich content of protein, and the dietary minerals such as calcium, magnesium, phosphorus, and potassium (Adhikary et al., 2020; Svirskis, 2003). Moreover, not only because of the plant's excellent tolerance in harsh climates and its short growth period but also due to the relatively high yields compared to the seeding rate, there is a worldwide trend for using it as a forage crop for ruminants, rabbits, pigs, and poultries (Leukebandara et al., 2019; Obua et al., 2012; Peiretti, 2018; Purwin et al., 2019).

In Nigeria, the effects of intercropping and fertilizer applications on the yield and nutritive value of Amaranth and maize were studied as a forage crop. The study revealed that the fertilizer which is used augments the Dry Matter yields and Crude Protein concentration of Amaranth and Amaranth/maize intercropping mixtures (Olorunnisomo and Ayodele, 2009). In another study, Sokoto and Johnbosco (2017) examined the yield and growth of Amaranths also in Nigeria. They applied 2 varieties of the plant with four different seed rates. Their findings indicated that although the plant height is not severely affected by the seed rates at 2 Weeks After Planting but at 4, 6, and 8 WAP the plants with a higher seed rate were obviously taller than the others. The effect of organic fertilizers on the same factors (yield and growth) also was investigated by Dlamini et al., (2020), they recommended stillage as a good choice for the farmers who prefer organic fertilizers in planting Amaranths.

On the other hand, ever since there was agriculture, drought was always considered a problem in the hot and dry regions of the world. The drought stress can affect the plant from morphological, physiological and biochemical aspects (Anjum et al., 2011; Gao et al., 2020). A study was conducted by Liu and Stützel (2002) to observe the leaf water relations and osmotic adjustment of Amaranth in dry soil conditions. Two years later in another research, they examined biomass production, partitioning, and water use efficiency of four different genotypes of Amaranth. They stated that the Specific Leaf Area and Water Use Efficiency of the plant were affected by the lack of water in all types but not with identical behavior (Liu and Stützel, 2004).

Despite Amaranths mentioned outstanding applications, research on the responses of forage Amaranths to the drought stresses was not carried out, adequately. But in other species of Amaranth, for example, grain for human consumption, a study was conducted in Brazil on the response of two Amaranth species (*Amaranthus caudatus* and *Amaranthus cruentus*) to water deficit stress. The results showed that with increasing the stress the amount of root dry mass decreased while the shoot part augmented. Also in the *A. cruentus* specimen water productivity decreased with increasing water stress (Da Silva et al., 2019).

In Japan, four vegetable Amaranth cultivars were examined under the drought stress conditions. It was seen that due to its fine supply of the necessary elements under stress conditions, the plant could be an appropriate crop in semi-arid and dry regions and also during dry seasons, but it was highly dependent on the genotypes (Sarker and Oba, 2018). In Russia, also Amaranth responses to the soil drought in a greenhouse were investigated by Valdayskikh et al. (2019). Furthermore, Jamalluddin et al. (2019) tried to evaluate the Transpiration Efficiency of Amaranth in response to drought. They explored the TE factor for 9 accessions belonging to Amaranths and stated that the TE factor was much higher in the water-deficient plants compared to the water-sufficient plants. In another investigation Grantz et al., (2019) examined the tolerance to ozone and drought in *Amaranthus tuberculatus*. Although in their study, Amaranth was considered as a weed, but according to their results, the plant productivity, Leaf mass per unit area, and root mass per unit leaf area were not significantly affected by the drought.

Due to the increasing demand for animal feed and the lack of fodder Amaranth scientific investigations, it seems essential to study different qualifications and specifications of the plant. Thereby, regarding the inadequacy of awareness about the drought stress on the Amaranth as forage, this study aimed to investigate the quantity and quality of leaves and stems of three Amaranth cultivars for forage usage and it was tried to evaluate the resistance and performance of this plant when sown under different levels of water deficit, via comparisons of stress tolerance and susceptibility indices. Also, in this research, we sought to achieve maximum water productivity with a non-significant statistical reduction in forage yield.

MATERIALS AND METHODS

Plant materials and growth conditions

Seeds of three forage Amaranth cultivars were used in this study namely Cim, Kharkovski and loura. Seeds

Tab. 1. Meteorological data of the experimental sites. (During the experiments).

Month	Temperature (°C)				Relative Humidity (%)	Evaporation Rate (mm)	Monthly Rainfall (mm)
	Mean of Max.	Mean of Min.	Daily ave.	Mean of soil (0-30 cm)			
May 2018	34.9	21.0	28.3	30.1	19.7	12.6	7.8
June 2018	39.8	24.7	33.1	36.1	8.5	15.9	0
July 2018	39.2	25.8	33.0	37.4	11.2	16.3	0
May 2019	30.7	18.3	24.7	27.4	28.7	9.8	8.5
June 2019	39.0	25.2	32.4	35.5	12.6	15.0	0
July 2019	39.3	24.3	32.9	35.8	7.4	16.0	0

Tab. 2. physicochemical properties of the soil in the field before planting (0–30 cm depth).

Year	K (p.p.m)	P (p.p.m)	N (%)	O.C (%)	S.A.R	pH	EC (dS/m)	FC Θ_V	PWP Θ_V	Soil texture
2018	157	13.6	0.017	0.205	3.63	7.2	4.9	24.4	10.8	Sandy clay loam
2019	138	7.3	0.021	0.254	2.8	7.2	4.5	-	-	Sandy clay loam

O.C: Organic Carbon, S.A.R: Sodium Adsorption Ratio, EC: Electrical Conductivity, FC: Field Capacity, PWP: Permanent Wilting Point, Θ_V: Volumetric Humidity.

were planted at Agricultural Research Station located in Yazd, Iran (31°54′30′′N and 54°16′20′′W). The station is located at 1215 m above the sea level and according to Koppen climate classification (Kottek et al. 2006), it has summers with dry and warm climates (See Table 1). The genotypes were planted in the first week of May during 2018 and 2019 in 40m^2 plots (fifteen 4-meter-long rows). The spacing was 10 cm and 60 cm between the plants and the rows, respectively (Planting density =166000 plants.ha^{-1}). In addition, the soil properties of the study site are listed in Table 2.

Treatments

One of the factors was devised to be the four levels of soil moisture: 1. No drought stress (i.e. 50 % moisture depletion of plant available water, normal condition), 2. Mild water deficit (60 % moisture depletion), 3. Medium water deficit (70 % moisture depletion) and 4. Severe water deficit (80 % moisture depletion). Soil moisture was checked with TDR (Connector and Buriable Probes, 6050X1 TRASE System I Analyzer, Soil-moisture Equipment Corp., United States). In the first step, Field Capacity (FC) and Permanent Wilting Point (PWP) were calculated in the field and the pots, respectively (table 2), and afterwards, Plant Available Water

(PAW) was computed from PAW=FC-PWP (Kirkham, 2005).

Firstly, all test cases were irrigated at the same time from planting to the seedling establishment stage as designed in the control conditions (50% moisture depletion of plant available water). Afterwards, the stress treatments were applied (60, 70 and 80 % moisture depletion of plant available water). The amount of irrigation was determined by the irrigation meter of each plot, and Table 3 presents the number of irrigation times and the amount of irrigation in two years.

Another factor was the three different Amaranth genotypes used in this study. All of the specimens belong to the *Amaranthus hypochondriacus* specie. It is worth mentioning that these cultivars were selected, according to the available species of Amaranth in Iran recommended by the Iranian state organization (AREEO)[1], and also due to the conservation of genetic diversity. Seeds of all cultivars had a yellow cream color, and unlike Kharkovski's green color; the Loura and Cim plants were a spectrum of the red color (Rahnama and Safaeie, 2017).

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[1] Agricultural Research, Education and Extension Organization

Tab. 3. The number of irrigation times and the amount of irrigation in two years.

Irrigation treatments	Number of irrigation times		The cumulative amount of irrigation (m³ ha⁻¹)	
	Year: 2018	Year: 2019	Year: 2018	Year: 2019
Normal condition (50% moisture depletion)	12	12	12307	12000
Mild stress (60% moisture depletion)	11	11	11282	11000
Medium stress (70% moisture depletion)	10	10	10256	10000
Severe stress (80% moisture depletion)	9	9	9230	9000

Tab. 4. Various drought stress index equations.

Mean Production	$MP = (Y_P + Y_S)/2$	(Rosielle and Hamblin 1981)
Tolerance Index	$Tol = Y_P - Y_S$	(Rosielle and Hamblin 1981)
Geometric Mean Productivity	$GMP = \sqrt{Y_S \cdot Y_P}$	(Fernandez 1992)
Stress Index	$SI = 1 - (\overline{Y}_S/\overline{Y}_P)$	(Fischer and Maurer 1978)
Stress Susceptibility Index	$SSI = (1 - Y_S/Y_P)/SI$	(Fischer and Maurer 1978)
Stress Tolerance Index	$STI = (Y_S \cdot Y_P)/(\overline{Y}_P)^2$	(Fernandez 1992)
Yield Stability Index	$YSI = Y_S/Y_P$	(Bouslama and Schapaugh 1984)
Harmonic Mean	$HM = (2 \cdot Y_P \cdot Y_S)/(Y_P + Y_S)$	(Fernandez 1992)
Yield reduction ratio	$Yr = 1 - (Y_S/Y_P)$	(Gavuzzi et al. 1997)
Relative Drought Index	$RDI = (Y_S/Y_P)/(\overline{Y}_S/\overline{Y}_P)$	(Bidinger et al. 1987)

Yield parameters

Plants per experimental plot were harvested to obtain biologic yield at 50 % flowering. The Sampling process was carried out from four middle lines of each sub-plot with 4 m² by removing the marginal effect. Then, in order to obtain the dry weight of the plant, the samples were incubated for 48 hours in the oven at 75 ° C. At the same time, fresh and dry weights of the leaves and stems of some random bushes were measured (Rahnama and Safaeie, 2017).

For agricultural systems, Water Productivity (WP) is a factor that indicates the production rate of a plant with respect to the consumed water. In this survey, water productivity was calculated by the following equation.

$$WP = \frac{fresh\ forage\ yield}{consuming\ water} \text{ (kg m}^{-3}) \text{ (Cook et al., 2006)}$$

Also, the Leaf to Stem Ratio (LSR) in Amaranth is obtained from the division of fresh leaf to fresh stem weight (Rahnama and Safaeie, 2017). Likewise, the dry matter (DM) content of the crop represents the amount of residual dry material when the water content of the plant has been deducted, which is obtained from the ratio of dry plant yield to fresh plant yield (Olorunnisomo and Ayodele, 2009). The Kjeldahl method was applied to calculate the total nitrogen content for the plants with a ratio of 1: 1 leaf and stem (Kjeldahl, 1883). Then the amount of Crude Protein (CP) was calculated based on the nitrogen value (Onyango, 2010).

Drought indices

Various stress indices were applied in this study to carry out the drought stress analysis in different fodder genotypes of Amaranths. The plants' drought stress sensitivity and tolerance are investigated using the following equations.

In the above equations, and are the mean yields of a given genotype evaluated under the drought stress and non-stress conditions, respectively. Also, and are the mean seed yields overall genotypes evaluated under the drought stress and non-stress conditions, respectively.

Experimental design and data analysis

A split-plot analysis was applied in some randomized complete blocks design in two successive years. The main factor was four levels of water stress and the sub-factor was three cultivars of forage Amaranth. Each treatment was repeated three times and wherever significant differences were obtained by the ANOVA, a comparative Duncan test (P≤0.05) was carried out. Bartlett test was applied to ensure the homogeneity of error variances (Bartlett, 1937). All of the traits were analyzed by combined analysis because of homogeneous error variances for two consecutive years. Furthermore, the obtained data were analyzed using SAS v 9.4 (SAS Institute Inc. USA), and the principal component analysis

was done using the Statgraphics 18 Software (Statgraphics Technologies, Inc. The Plains, Virginia).

RESULTS AND DISCUSSION

Yield Parameters

According to table 5, no significant difference was observed in the studied behaviors of the cases in the two test years (i.e. 2018 and 2019). Moreover, amongst all other active parameters of the main factor (various levels of the drought stress) a significant difference (p<0.01) was observed. Besides, the forage fresh and dry yields, as well as the water productivity in the Control condition (50 % of the plant available water depletion) were clearly higher than those of other treatments, which was also reported by several other researchers (Alvar-Beltrán et al., 2019; Jaleel et al., 2009). Since our target product was the leaves and stems of the plants and the plant's life cycle was relatively short, therefore the drought stress durations after the establishment of the seedlings were quite short, which leads to a decrement of WP with an increment of the drought stress levels. However, in the 3 other parameters (LSR, DM, and CP) the results in the 80% water-depletion treatment were relatively higher than the other treatments.

Also in the genotypes factor, differences (p<0.05) were obtained in the LSR, CP and fresh yield parameters between treatments, which is due to the genetic diversity of the genotypes. According to the field experiments, the LSR and fresh yield parameters of Cim and Loura genotypes were remarkably higher than Kharkovski but on the other hand, the Crude Protein percentage of the Kharkovski genotype was significantly higher than the others.

The interactions of drought stress levels and cultivars revealed that in the control condition Cim and Loura genotypes offered the best results in the fresh and dry yield parameters, while they had a significant difference with Kharkovski. But, it was interesting to see, although Loura had the highest result in the control condition, the genotype was quite weak facing the drought stress. It was seen that the rate of decrement in the fresh and dry yields of the genotypes subjected to the drought stress was much steeper for Loura. Meanwhile, Cim offers an acceptable productivity level in the control condition and also it shows a better tolerance to the water deficit under moderate and severe drought stresses. The reduction of plants' yields under drought stress conditions has been reported vastly by other researchers in the open literature (Bidinger et al., 1987; Da Silva et al., 2019; Sarker and oba, 2018). Under mild drought stress, Loura water productivity did not show any significant difference to

Cim and Loura genotypes in the control condition. With the augmentation of the drought stress level, we witness a decrease in water productivity in all cultivars which is also verified by other researchers (Da Silva et al., 2019). In this parameter also Cim presented a better performance facing the drought stress, regarding Loura and Kharkovski genotypes.

However, the three different genotypes of Amaranth show different behaviors from the fresh weight of leaves to the stem ratio per plant parameter point of view. As was observed in the control condition, Cim cultivar offers the highest LSR, but Loura didn't show a distinguishable difference between its control and the 80 % water deficit conditions. It goes without saying that LSR is a division of two independent parameters (leaf to stem). In the control condition due to the maximum growth and competition of the plants, the numerator (fresh leaf weight) of the fraction exceeds the denominator. On the other hand, in the 80% water-deficit case, despite remarkable leaf and stem weight drops, the stem weight decreased more drastically. Hence, the denominator reduces and it causes the no-significance difference level between the control and severe stress conditions.

Furthermore, Kharkovski cultivar offered a relatively higher percentage of crude protein in the 80% water-deficit condition with respect to the other genotypes×drought stress levels. The CP behavior with a mild variation rate decreases from the severe stress to control condition in all genotypes. This trend also was reported by others (Kuchenmeister et al., 2013). Besides, Nabhan (1986) stated that in some wild cultivars of the canopy, the nitrogen levels are increased but prolonging the drought condition can cause a decrement in the nitrogen content of leaves due to the nitrogen transport to the foliage and seeds. Also, the dry matter percentage did not show any significant difference between the cases.

Comparison of the genotypes based on tolerance indices

The most popular tolerance and susceptibility index equations which are presented in Table 4 were applied to investigate the resistance of Amaranths different genotypes to the drought stress. It is also worth mentioning that the best usage of Amaranths plant is as fresh or silage fodder (Stordahl et al. 1999), thus in this research the stress indices are used for the fresh forage, only and the results can be seen in table 6.

It is known that for RDI, SSI, TOL, and Yr indices, lower values represent higher resistance of the plant to the drought stress, while for YP, YS, GMP, MP, YSI, STI, and HM indices higher values are representing higher tolerance. However, for a better understanding of the

Tab. 5. Effect of water stress on the yield parameters of three genotypes of forage Amaranth in the two successive years.

Treatment	Fresh Yield (ton ha^{-1})	Dry Yield (ton ha^{-1})	Water Productivity (kg m^{-3})	Leaf to Stem Ratio	Dry Matter (%)	Crude Protein (%)
			Year			
2018	35.52	5.63	3.21	0.51	16.56	15.27
2019	36.71	5.56	3.39	0.50	15.76	15.16
significance	ns	ns	ns	ns	ns	ns
			Drought stress level			
water-deficit 50%	53.65 a	7.59 a	4.42 a	0.51 b	14.16 c	13.50 d
water-deficit 60%	41.72 b	6.30 b	3.74 b	0.50 bc	15.11 c	14.62 c
water-deficit 70%	28.98 c	4.78 c	2.86 c	0.49 c	16.66 b	15.66 b
water-deficit 80%	20.12 d	3.74 c	2.21 d	0.54 a	18.75 a	17.11 a
significance	**	**	**	**	**	**
			Genotype			
Cim (C)	38.55 a	5.91	3.54	0.53 a	15.81	14.66 b
Kharkovski (Kh)	31.99 b	5.04	2.94	0.46 b	16.22	15.94 a
Loura(L)	37.82 a	5.86	3.44	0.54 a	16.47	15.07 b
significance	*	ns	ns	*	ns	*
			Interaction			
water-deficit 50%×(C)	56.24 a	8.08 a	4.63 ab	0.60 a	14.38	13.02 h
water-deficit 50%× (Kh)	46.32 bc	6.56 bc	3.81 c	0.35 g	14.15	14.35 f
water-deficit 50%×(L)	58.40 a	8.14 a	4.81 ab	0.58 b	13.93	13.13 h
water-deficit 60%×(C)	42.19 c	6.20 cd	3.79 c	0.46 f	14.67	13.95 g
water-deficit 60%× (Kh)	36.24 d	5.56 de	3.25 d	0.53 c	15.41	14.86 e
water-deficit 60%×(L)	46.74 b	7.13 b	4.19 bc	0.49 de	15.26	15.05 e
water-deficit 70%×(C)	33.15 d	5.23 e	3.27 d	0.50 de	15.79	14.79 e
water-deficit 70%× (Kh)	27.51 e	4.86 ef	2.72 e	0.46 f	17.71	16.56 c
water-deficit 70%×(L)	26.28 ef	4.25 fg	2.59 ef	0.52 d	16.47	15.65 d
water-deficit 80%×(C)	22.62 fg	4.15 fg	2.48 ef	0.55 c	18.42	16.88 b
water-deficit 80%× (Kh)	17.88 h	3.16 h	1.96 g	0.49 e	17.61	17.98 a
water-deficit 80%×(L)	19.85 gh	3.92 gh	2.18 fg	0.58 b	20.21	16.47 c
significance	*	*	*	**	ns	**
CV (%)	12.02	12.98	12.86	14.56	7.04	5.02

Values within one column followed by different letters are significantly different at P<0.05 according to Duncan's test. ns, no significance (P<0.05). *, **, significance at P<0.05, P<0.01, respectively.
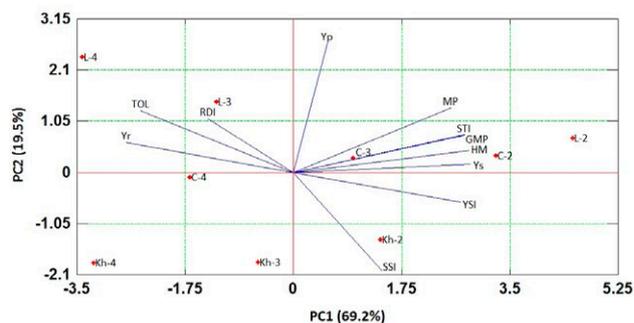
Fig. 1. Biplot principal component analysis (PCA) of various drought resistance indices in three forage Amaranth cultivars. Note: PC1 and PC2; First and second principal component respectively. C: Cim, KH: Kharkovski, L: Loura. 2, 3 and 4: 60, 70 and 80% plant available water depletion, respectively.
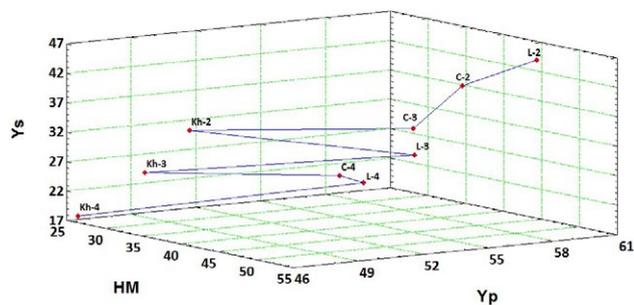
Fig. 2. Graphic display 3D biplot of the best genotypes for Harmonic Mean and potential (control) yield and fresh forage yield under drought stress. Note: C: Cim, KH: Kharkovski, L: Loura. 2, 3 and 4: 60, 70 and 80% plant available water depletion, respectively.

results of table 6, it is required to investigate the mutual relationship of these indices together.

Principal Component Analysis simplifies complex data via converting several associated variables into a smaller number of variables as main components. The first component indicates the maximum variability in the data as compared to the others. This is while in this study, Component 1 and 2 accounted for approximately 89% of the variation (Supplementary Table 7).

Table 8 presents the correlation results of the average values for the three genotypes in two successive years between the fresh forage yield and stress indices in the normal and stress condition, independently. In the mild stress condition HM, STI, GMP, TOL, MP indices and in the moderate stress condition Yr, Ysi, MP, TOL indices had the highest correlation with the yield of the no-stress condition Yp. Also in the severe stress condition, Tol and Mp indices presented the strongest correlation to the control yield. On the other hand, while in

Tab. 6. Tolerance and susceptibility indices three genotypes of forage Amaranth under conditions of drought stress in the two successive years.

Genotype	Yp	Ys	MP	TOL	GMP	SSI	STI	YSI	HM	Yr	RDI
					Tolerance and susceptibility indices under mild drought stress						
Cim	56.24	42.19	49.21	14.05	48.65	0.98	2370.16	0.76	48.09	0.24	1.01
Kharkovski	46.32	36.24	41.28	10.08	40.81	0.94	1671.91	0.80	40.36	0.20	1.02
Loura	58.40	46.74	52.57	11.66	52.16	1.00	2735.08	0.81	51.76	0.19	1.00
					Tolerance and susceptibility indices under moderate drought stress						
Cim	56.24	33.15	44.70	23.09	43.08	0.99	1861.41	0.59	41.54	0.41	1.01
Kharkovski	46.32	27.51	36.91	18.81	35.65	0.99	1282.43	0.60	34.43	0.40	1.01
Loura	58.40	26.28	42.34	32.12	38.73	0.80	1515.89	0.46	35.56	0.54	1.02
					Tolerance and susceptibility indices under severe drought stress						
Cim	56.24	22.62	39.43	33.63	35.32	0.98	1270.19	0.41	31.81	0.59	1.00
Kharkovski	46.32	17.88	32.10	28.44	28.66	0.99	833.49	0.39	25.64	0.61	1.01
Loura	58.40	19.85	39.13	38.55	33.46	0.99	1144.34	0.35	28.88	0.65	1.02

Yp, fresh mean yield of the genotype under non-stress conditions; Ys, fresh mean yield of the genotype under stress conditions; MP, mean productivity; TOL, tolerance; GMP, geometric mean productivity; SSI, stress susceptibility index; STI, stress tolerance index; YSI, yield stability index; HM, harmonic mean; Yr, Yield reduction rate; RDI, relative drought index.

all drought stress levels Tol, SSI, YSI, Yr, RDI indices did not have any significant correlation with the yield of the stress condition (Ys), other indices of Mp, GMP, STI, HM demonstrated a positive correlation (P<0.01) to Ys.

In order to specify the most applicable indices, the Principal Component Analysis (PCA) was carried out. According to the biplot graph of figure 1, the first and second components represented 69.2 and 19.5 % of the variation with the different attributes, respectively. Additionally, since Ys and HM indices in the first component and Yp index in the second component can probe the variations in the best way, they were applied in this study.

Also for a precise study of the cultivars, their Harmonic Mean (HM) index is investigated in the no-stress and under-stress conditions. The result is illustrated in figure 2, in which the horizontal axis indicates the cultivars' priority from the HM index point of view. It is obvious at the first look, that Loura possesses the highest yield in the mild stress condition, but it can be seen that its tolerance to the drought stress is much weaker regarding other genotypes. On the other hand, not only Cim offers the highest HM index in the severe stress condition, but also its performance in the moderate stress condition is higher than Kharkovski in the mild stress condition. This can prove that Cim cultivar provides much better resistance to drought stress with relatively high productivity.

CONCLUSIONS

Despite its tolerance to the harsh weather and wonderful applications in both food and forage industries in

Tab. 7. Principal component analysis of stress tolerance indices in three genotypes of forage Amaranth under conditions of drought stress.

Indices	Component				
	1	2	3	4	5
Yp	0.069	0.628	-0.319	0.180	0.311
Ys	0.361	0.039	0.080	-0.043	-0.120
MP	0.321	0.313	-0.079	0.046	0.043
TOL	-0.311	0.300	-0.249	0.139	0.283
GMP	0.349	0.184	-0.031	0.075	-0.033
SSI	0.181	-0.477	-0.416	0.747	0.006
STI	0.348	0.181	-0.057	-0.036	-0.597
YSI	0.340	-0.145	0.254	-0.053	0.464
HM	0.358	0.108	0.002	0.071	-0.063
Yr	-0.340	0.145	-0.254	0.053	-0.464
RDI	-0.175	0.261	0.720	0.607	-0.119
Eigenvalue	7.604	2.142	1.106	0.132	0.014
Percent of Variance	69.126	19.476	10.054	1.200	0.144
Cumulative Percentage	69.126	88.602	98.656	99.856	100

the world, it seems that the forage Amaranth plant is not appreciated by many researchers. In the present study, the growth and yield of three different genotypes of forage Amaranth were investigated under various drought stress levels in Yazd - Iran in two successive years. The results revealed that the plant is highly affected by water deficit and the water productivity parameter (WP) expe-

Tab. 8. The correlation coefficient between the different levels of tolerance and susceptibility to water deficit in the average of three genotypes of forage Amaranth in the two successive years.

	YS	MP	TOL	GMP	SSI	STI	YSI	HM	Yr	RDI
Tolerance and susceptibility indices under mild drought stress										
YP	0.52*	0.91**	0.72**	0.88**	0.43ns	0.88**	-0.58*	0.84**	0.58*	-0.48*
YS		0.82**	-0.21ns	0.86**	-0.31ns	0.86**	0.38ns	0.9**	-0.38ns	0.28ns
MP			0.38ns	0.99**	0.14ns	0.99**	-0.21ns	0.99**	0.21ns	-0.19ns
TOL				0.31ns	0.74**	0.31ns	-0.97**	0.24ns	0.97**	-0.77**
GMP					0.09ns	0.99**	-0.14ns	0.99**	0.14ns	-0.13ns
SSI						0.09ns	-0.82**	0.04ns	0.82**	-0.97**
STI							-0.13ns	0.99**	0.13ns	-0.13ns
YSI								-0.07ns	-1**	0.83**
HM									0.07ns	-0.07ns
Yr										-0.83**
Tolerance and susceptibility indices under moderate drought stress										
YP	-0.04ns	0.82**	0.83**	0.54*	0.16ns	0.54*	-0.66**	0.28ns	0.66**	-0.39ns
YS		0.82**	-0.21ns	0.86**	-0.31ns	0.86**	0.38ns	0.9**	-0.38ns	0.28ns
MP			0.36ns	0.93**	-0.11ns	0.92**	-0.11ns	0.78**	0.11ns	0.06ns
TOL				-0.01ns	0.37ns	-0.01ns	-0.96**	-0.3ns	0.96**	-0.69**
GMP					-0.24ns	0.99**	0.27ns	0.96**	-0.27ns	0.34ns
SSI						-0.23ns	-0.47*	-0.32ns	0.47*	-0.87**
STI							0.26ns	0.96**	-0.26ns	0.33ns
YSI								0.52*	-1**	0.78**
HM									-0.52*	0.52*
Yr										-0.78**
Tolerance and susceptibility indices under severe drought stress										
YP	0.09ns	0.83**	0.8**	0.48*	-0.36ns	0.48*	-0.4ns	0.23ns	0.4ns	-0.28ns
YS		0.82**	-0.21ns	0.86**	-0.31ns	0.86**	0.38ns	0.9**	-0.38ns	0.28ns
MP			0.33ns	0.88**	-0.43ns	0.88**	0.18ns	0.73**	-0.18ns	0.24ns
TOL				-0.15ns	0.14ns	-0.15ns	-0.87**	-0.4ns	0.87**	-0.73**
GMP					-0.36ns	0.99**	0.61**	0.96**	-0.61**	0.61**
SSI						-0.36ns	-0.11ns	-0.29ns	0.11ns	-0.37ns
STI							0.6**	0.96**	-0.6**	0.61**
YSI								0.79**	-1**	0.9**
HM									-0.79**	0.76**
Yr										-0.9**

ns, no significance (P<0.05). *, **, significance at P<0.05, P<0.01, respectively.

rienced a significant drop of 15, 35, and 50 % for mild, moderate and severe drought stress conditions, respectively. It was also observed that despite its short life cycle, Amaranth plant offers acceptable quantity and quality of fodder which is why it is considered an excellent forage in many regions of the world. Moreover, the Principal Component analysis indicated that the HM index is one of the main components for the genotypes and according to this index, while Cim cultivar yield was higher than the other two genotypes, Kharkovski showed the weakest results. Since in this study the irrigation treatments were chosen according to the customary farming of the region. It seems that applying milder treatments in future researches could be effective in increasing water productivity. It may also lead to an increment in the yield.

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Effect of shading on photosynthesis of greenhouse hydroponic cucumber crops

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Abstract. In this work an attempt was made to investigate the effect of shading on photosynthesis rate, transpiration rate and stomatal conductance of a cucumber cultivation in a greenhouse. To this end, autumnal hydroponic cultivation of cucumbers was installed in three same arched greenhouses with lateral ventilation openings at the University of Thessaly experimental farm in Velestino, Greece. One of the greenhouses was used as a control (without shading), the other two were shaded using two different shading nets (shading intensity of 35% and 50%). In the hydroponic cucumber cultivation, a series of crop photosynthesis measurements were performed for two months on leaves of randomly selected plants per greenhouse under natural illumination and using artificial illumination conditions of 1000 μmol m^{-2} s^{-1} with the LCpro+ instrument. Statistical processing of the results showed that shading reduced photosynthesis of the cucumber leaf almost linearly. Furthermore, artificial illumination measurements allowed us to conclude that shaded plants do not acclimate to shade conditions and respond directly to lighting conditions which practically enhances the usefulness of periodic shading as a tool for improving the microclimate in greenhouses.

Keywords. Photosynthesis, greenhouse, shading, hydroponic crops, cucumber.

INTRODUCTION

Various methods can be used to cool the greenhouse. The use of nets or screens is a typical practice in the whole Mediterranean basin. It is considered a low-cost method of decreasing radiation and the concomitant energy load during warm periods (Kitta, 2014). Mobile shading allows improvement of greenhouse climate, especially during the noon hour. It reduces canopy transpiration and water uptake, and increases remarkably water use efficiency (Lorenzo et al., 2006). The use of shading screens in greenhouses became a common practice during the last decade (Cohen et al., 2005; Castellano et al., 2008) because it is a flexible and efficient method of reducing the energy load inside the greenhouse (Teitel and Segal, 1995), especially in climates characterized by high evaporative demand and limited water resources (Lorenzo et al., 2006). The optical properties of the screens (mainly shade factor) can modify the diffuse-to direct radiation ratio (Baille et al., 2001; Raveh et al., 2003; Cohen et al., 2005) and cooling performance (Willits, 2001), while reducing air and crop temperature (Smith et al., 1984; Fernandez-Rodriguez et al., 2000). The modifications arising from the optical properties of the screens can affect radiation absorbed by the crop, stomatal conductance, and net CO_2 assimilation, and consequently crop growth and productivity. Nevertheless, adaptation of plants to light conditions depends also on the specific behavior of the plant species grown in greenhouses (Raveh et al., 2003; Barradas et al., 2005; Romacho et al., 2006). Shade can increase total and marketable yield of tomato grown in hot climates. Depression of crop yield is frequently observed under Mediterranean conditions when high solar radiation and low air humidity conditions prevail. El-Gizawy et al. (1993) mention that the highest tomato crop production was obtained under 35% shading, while increasing shading intensity decreased by up to 100% the incidence of sunscald on fruit. Concerning the effect of shading on cucumber crop, Naraghi and Lofti (2010) observed that increasing shading density up to 35% led to an increase in the number of fruits per plant. However, the number of fruits tended to decrease as shading density increased to 60%. Furthermore, the above authors mention that shading intensity greatly influenced the physiological disorders like sun-scald of cucumber fruits.

A better understanding of plant responses to shading is of great interest for greenhouse crops. With respect to the Mediterranean greenhouses, more information is needed mainly on plant responses to the time of application, including both commencement and termination of shading dates. So, an important issue not yet fully investigated in shaded greenhouses concerns plant acclimation to the light regime imposed by the screen.

Therefore, in this paper we are trying to investigate the effect of shading on photosynthesis rate and plant acclimation of a hydroponic cucumber crop, which is of great economic interest for the Mediterranean countries.

MATERIAL AND METHODS

Greenhouses and plant material

The experiments have been performed in three similar arched roof greenhouses, with vertical side walls, covered with a single sheet of 180 μm thick PE film, N-S oriented, located at the University of Thessaly near Volos, (Velestino: Latitude 39º 22′, longitude 22º 44′, altitude 85 m), Eastern Greece. The geometrical characteristics of the greenhouses were as follows: eaves height of 2.4 m; ridge height of 4.1 m; total width of 8 m; total length of 20 m; ground area of 160 m², and volume of 572 m³. The soil of each greenhouse was totally covered by double-side coloured plastic mulch. The greenhouses were equipped with two side roll-up vents controlled automatically and ventilation set point temperature was set at 23ºC. An autumn hydroponic cultivation of cucumber (Cucumis sativus cv. Stamina) was planted, which was transplanted on September 1 and expired on November 12. The plants were grown in slabs (1 m long, 0.3 m wide) filled with perlite sacks (1 m long, 0.3 m wide, 0.2 m high) and planting density was 2.4 plants / m².

Plants were arranged in four duplicate rows, spaced between the lines 0.33 m and 0.80 m apart. . The supply of a standard nutrition solution for cucumber (Sonneveld, 2002) was automatically controlled by a fertigation computer and pH set point was at 5.6 with small fluctuations aimed to maintain the pH between 5.5 and 6.5 in the drainage solution. The plants were pruned according to the umbrella training system (Klieber et al., 1993) and all other cultural practices inside the greenhouse (plant protection, harvesting, etc.) were similar to those practiced commonly by local greenhouse cucumber producers.

Three levels of greenhouse shading were tested in the greenhouses, obtained using no net in one of the greenhouses and shade nets made by polypropylene strips (C. Vellis S.A., Piraeus, Greece) differing in hole size. The fixed nets were installed over the external surface of the cover in the two shaded greenhouse. In particular, the three shading treatments were as follows:
- 0% shading ($Gr_{0\%}$), greenhouse transmission to solar radiation approximately 79%).

- 35% shading (Gr$_{35\%}$) (net hole size 2X 8 mm), greenhouse with 35% shading intensity (SI) and transmission to solar radiation of approximately 50% and
- 50% shading (Gr$_{50\%}$) (net hole size 2 X 8 mm), greenhouse with 50% shading intensity (SI) and transmission to solar radiation of approximately 38%.
- The values of greenhouse transmission to solar radiation are the mean values calculated using the ratio of inside to outside solar radiation during the experimental period.

Shading was installed immediately after transplanting and maintained up to the end of the experiment.

Measurements

Climate measurements

For the purpose of the experiment total solar radiation (W/m^2) was recorded by means of pyranometers (model Middleton EP08-E, Brunswick Victoria, Australia), located 2 m above the ground in the center of each of the three greenhouses (Control greenhouse Gr$_{0\%}$, 35% shaded greenhouse Gr$_{35\%}$, and 50% shaded greenhouse Gr$_{50\%}$) and outside (Out) 15 m away from the greenhouse on a mast 3.5 m above the ground.

Photosynthesis Parameters Measurements

For the photosynthesis measurements in the experiment, a closed type LCpro+ photosynthesis system (model LCpro+, ADC BioScientific Ltd., Hertfordshire, England) was used, and the photosynthesis rate (A, µmol.m^{-2}.s^{-1}), transpiration rate (E, mmol.m^{-2}.s^{-1}) and stomatal conductance (gc, mol.m^{-2}.s^{-1}) were measured. The photosynthesis measurements were done for two months, October and November. For photosynthesis measurements, 16 plants/greenhouse were randomly selected. The photosynthesis measurements were carried out approximately every 10 days on a random healthy, well-developed leaf that was about the middle of the total plant height each time. A total of 48 photosynthesis measurements were made every ten days. Two sets of measurements were made. The first series was in sunny days under natural light conditions inside the greenhouses. The second one was made over cloudy days, with artificial constant illumination conditions to evaluate whether cultures in different shading conditions (control, 35% shading and 50% shading) were adapted (acclimated) and reacted differently or not. Constant irradiation measurements, were performed with the use

of the integrated PAR control and adjustment mechanism using LED diodes provided by the LCpro+ measuring device. The illumination intensity was set at the intensity level of 1000 µmol.m^{-2}.s^{-1} for both the control greenhouse and the two shaded greenhouses in the PAR area.

Six (6) complete sets of measurements were made during the experiment, four (4) in sunshine conditions and two (2) in cloudy conditions.

Calculation of Vapor pressure deficit

Furthermore, Vapor Pressure Deficit (VPD$_C$) in the leaf chamber air of the LCpro+ device can be calculated from (Allen et al., 2005):

$$VPD_C = e_{sat,c} - e_{ref} \tag{1}$$

Where:
VPD$_C$ = Vapor Pressure Deficit in leaf chamber, kPa
e$_{sat,c}$ = saturation vapor pressure in air temperature, kPa

e$_{ref}$ = partial pressure of the water vapor in the air in leaf chamber, kPa

e$_{sat,c}$ and e$_{ref}$ can be calculated from the following relations (Howell and Dusek, 1995):

$$e_{sat,c} = 0.611 * e^{\frac{(17,27*T_{a,c})}{((T_{a,c}+73)-36)}} \tag{2}$$

$$e_{ref} = \frac{RH}{100} * e_{sat,c} \tag{3}$$

where: T$_{a,c}$= air temperature in the leaf chamber (°C) and RH= relative humidity of the air in the leaf chamber.

Collection, storage and processing of measurements

Solar radiation measurements were collected on four (4) data loggers (ZEN0®3200, Coastal Environmental Systems, Inc., Seattle, Wash.) Measurements were taken every 30 s and averaged 10 min.

With regard to photosynthesis, transpiration and stomatal conductance measurements, the closed type LCpro+ photosynthesis measurement system had its own recording and storage system.

Descriptive and inferential statistics were performed with SPSS 25.0. One way ANOVA was used for comparisons, along with Fisher's Least Significant Difference (LSD) test for post-hoc analysis. Level of statistical significance was set at p=0.05.
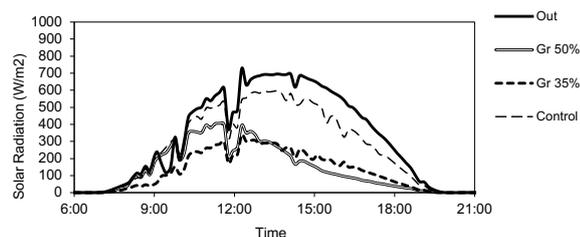
Fig 1. Daily sunlight outside the greenhouses, in the control greenhouse (Gr$_{0\%}$), in the 35% shaded greenhouse (Gr$_{35\%}$) and in the 50% shaded greenhouse (Gr$_{50\%}$), on 19 September.

RESULTS

Solar radiation measurements

Fig. 1 shows the daily course on 19th September of the incident and incoming solar radiation in the three greenhouses. The mean values of solar radiation are 275 W.m^{-2}, 231 W.m^{-2}, 129 W.m^{-2} and 111 W.m^{-2} for the external environment, the control greenhouse, the 35% greenhouse and the 50% greenhouse respectively. Similar results were found throughout the experiment.

Photosynthesis parameters measurements

As already described, photosynthesis rate (A), transpiration rate (E) and stomatal conductance (g$_c$) measurements concerned leaf measurements of plants exposed to different shading conditions.

Measurements in natural solar radiation conditions

Processing of measurements made during September- November in natural conditions, gave the following results.

Tab. 1. Results of Analysis of Variance (ANOVA) for Photosynthesis Rate A measurements in Gr$_{0\%}$, Gr$_{35\%}$ and Gr$_{50\%}$ during September-November.

Greenhouse	Mean μmol.m^{-2}.s^{-1}	SD μmol.m^{-2}.s^{-1}	F	p
Control	14.50	3.76		
Shading 35%	11.74	4.06	12.54	0.000
Shading 50%	9.51	2.87		

SD= Standard Deviation.
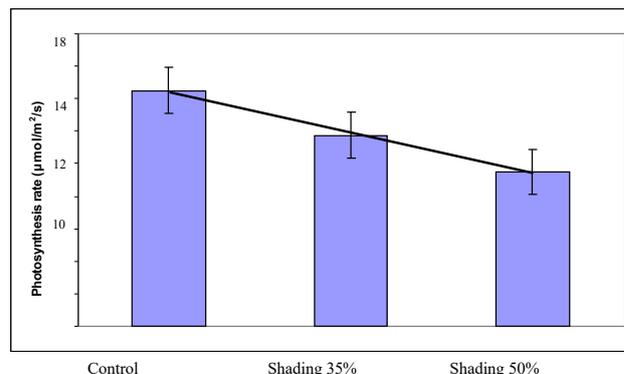
Fig 2. Mean values of Leaf Photosynthesis Rate in greenhouses Gr$_{0\%}$, Gr$_{35\%}$ and Gr$_{50\%}$.

Effect of shading on photosynthesis rate

One- way ANOVA results for the photosynthesis rate A in greenhouses appear in Table 1. From this Table is concluded that photosynthesis rate A differ statistically between the 3 greenhouses.

Fig. 2 shows, also, the descriptive statistics of photosynthesis rate A for the three greenhouses. It can be seen from this Figure that photosynthesis rate decreases as shading intensity increases.

Furthermore, Post Hoc analysis with LSD test for the dependent variable A, showed that the three greenhouses differ statistically from each other, for a significance level of 0.05, with the control greenhouse having the highest photosynthesis rate and the greenhouse with the highest 50% shading having the least photosynthesis (Table 2).

Effect of shading on leaf transpiration rate

Table 3 shows the results of ANOVA analysis of the leaf transpiration rate E in greenhouses.

Tab. 2. Results of multiple comparisons for the depended variable Photosynthesis Rate A in Gr$_{0\%}$, Gr$_{35\%}$ and Gr$_{50\%}$ according to Least Significant Difference (LSD) test for significant level 0.05 for measurements during September- November period

	Greenhouse (I)	Greenhouse (II)	Mean Difference (I-II)	p
LSD	Control	Shading 35%	2.75	0.007
		Shading 50%	4.98	0.000
	Shading 35%	Control	-2.75	0.007
		Shading 50%	2.23	0.028
	Shading 50%	Control	-4.98	0.000
		Shading 35%	-2.23	0.028

Tab. 3. Results of Analysis of Variance (ANOVA) for Transpiration Rate E measurements in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean mmol.m^{-2}.s^{-1}	SD mmol.m^{-2}.s^{-1}	F	p
Control	6.29	1.74		
Shading 35%	4.64	1.55	8.29	0.001
Shading 50%	5.12	1.05		

SD= Standard Deviation.

Tab. 5. Results of Analysis of Variance (ANOVA) for Vapor Pressure Deficit, VPDc in the leaf chamber at the three greenhouses $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean mol.m^{-2}.s^{-1}	SD mol.m^{-2}.s^{-1}	F	p
Control	3.32	0.46		
Shading 35%	2.73	0.85	6.39	0.003
Shading 50%	3.19	0.48		

SD= Standard Deviation.

Tab. 4. Results of multiple comparisons for the depended variable Transpiration Rate E in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ according to Least Significant Difference (LSD) test for significant level 0.05 for measurements during September- November period.

	Greenhouse (I)	Grenhouse (II)	Mean Difference (I-II)	p
LSD	Control	Shading 35%	1.65	0.000
		Shading 50%	1.17	0.006
	Shading 35%	Control	-1.65	0.000
		Shading 50%	-0.48	0.253
	Shading 50%	Control	-1.17	0.006
		Shading 35%	0.48	0.253

Tab. 6. Results of multiple comparisons for the depended variable Vapor Pressure Deficit, VPDc in the leaf chamber at $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ according to Least Significant Difference (LSD) test for significant level 0.05 for measurements during September- November period.

	Greenhouse (I)	Grenhouse (II)	Mean Difference (I-II)	p
LSD	Control	Shading 35%	0.59	0.001
		Shading 50%	0,13	0.462
	Shading 35%	Control	-0.59	0.001
		Shading 50%	-0.46	0.006
	Shading 50%	Control	-0.13	0.462
		Shading 35%	0.46	0.006

It can be seen that there are statistically significant differences between the E averages. Post Hoc analysis with LSD test (Table 4) found that the unshaded greenhouse had a statistically greater transpiration rate than shaded greenhouses.

For no statistical differences in transpiration E between 35% and 50% shading greenhouses it should be considered whether there were differences in the air saturation deficit in the leaf chamber between 35% and 50% greenhouses.

Calculating from the experimental measurements data, vapor pressure deficit (VPDc) in the leaf chamber according to the previous equations (1), (2) and (3), we performed an ANOVA analysis for the dependent variable VPDc to determine if there were differences in the three greenhouses. The results are presented in the following Tables 5 and 6.

Vapor pressure deficit appears to be lower in the greenhouse with 35% shading than the 50% shaded greenhouse and the control. Given that cucumber leaves were in good condition, out of stress, the greater vapor

pressure deficit in the leaf chamber under the 50% shaded greenhouse chamber probably explains the higher transpiration values in this greenhouse in relation to the corresponding transpiration values in the 35% shaded greenhouse, despite the greater intensity of the incoming radiation load in this greenhouse.

Effect of shading on leaf stomatal conductance

Concerning the values of stomatal conductance g_c for the three greenhouses, it was found that the mean g_c values of the hydroponic cucumber leaves were almost similar for the three greenhouses and there are no statistically significant differences between the greenhouses (Table 7).

Measurements in artificial lighting conditions. Effect of shading on photosynthesis rate

The purpose of these measurements was to investigate how plants in the three greenhouses exposed to

Tab. 7. Results of Analysis of Variance (ANOVA) for leaf Stomatal Conductance g_c measurements in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean mol.m^{-2}.s^{-1}	SD mol.m^{-2}.s^{-1}	F	p
Control	0.97	0.46	0.51	0.950
Shading 35%	1.04	0.82		
Shading 50%	0.98	1.02		

SD= Standard Deviation.

Tab. 8. Results of Analysis of Variance (ANOVA) for photosynthesis rate A measurements under constant illumination conditions in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean μmol.m^{-2}.s^{-1}	SD μmol.m^{-2}.s^{-1}	F	p
Control	11.58	4.29	1.43	0.245
Shading 35%	12.09	2.81		
Shading 50%	10.58	2.79		

SD= Standard Deviation.

different shading conditions responded to the same incident light intensity of 1000 μmol.m^{-2}.s^{-1}. That is, whether they were adapted or not to shading conditions.

The following Table 8 shows the ANOVA results for photosynthesis rate A with constant illumination in the three greenhouses.

From this Table it appears that no statistical differences exist for photosynthesis rate between the three greenhouses. So, under constant illumination conditions of 1000 μmol m^{-2} s^{-1} the photosynthesis of cucumber leaves grown on a perlite substrate is not affected by shading for a significance level of 0.05.

DISCUSSION

Photosynthesis rate

The value of the photosynthesis rate in the control greenhouse (Table 1) is almost the same as this found by Mavrogiannopoulos et al. (1999) for melon cultivation in a greenhouse in Heraklion, Crete, Greece and by

Lykoskoufis et al. (2005) on hydroponic greenhouse pepper cultivation in Athens area. The results of the experiments on the effect of shading on photosynthesis rate showed that shading affects almost linearly the photosynthesis of cucumber leaves (Figure 1). Thus from A = 14.5 μmol m^{-2}s^{-1} in the control greenhouse it fell to A = 11.7 μmol.m^{-2}.s^{-1} in the 35% shading greenhouse and to A = 9.5 μmol.m^{-2}.s^{-1} in the 50% shading greenhouse It, therefore, appears that 35% shading reduces the rate of photosynthesis by 20% and 50% shading reduces it by 34%. Thus the ratio of photosynthesis-shading is almost linear, which allows us to conclude that a 10% increase in shading induces a decrease in the rate of photosynthesis by 0.80 μmol.m^{-2}.s^{-1}. Similar results were also found by Schwartz et al. (2002) when they made photosynthesis measurements in a hydroponic tomato culture in a growth chamber at the University of Georgia, USA, and found that a reduction in radiation level of 35% resulted in a decrease in leaf photosynthesis by 0.84 μmol.m^{-2}.s^{-1}.

Furthermore, although photosynthesis rate measurements showed a clear difference between the three greenhouses, at the same time leaf stomatal conductance was statistically the same in all three greenhouses. The reduction in the rate of A under shading is reasonable, since the radiation regime inside the non-shaded greenhouse during September and October was relatively high but below the saturation point for cucumber crop, which ranges between 800-1000 μmol.s^{-1}.m^{-2} (Turcotte and Gosselin, 1989; Drew et al., 1990). The restriction of net photosynthesis in the shaded greenhouses was not due to limitations in the diffusion of CO_2 to the mesophyll through the stomata aperture, as indicated by the lack of any effect of shading on g_c. Hence, it is reasonable to conclude that in the shaded greenhouses net photosynthesis was inhibited at the chloroplast level due to limitations in light energy perception by the photosystem I. A similar response on net photosynthesis owing to suboptimal light availability was also reported by Robbins and Pharr (1987) and by Hao and Papadopoulos (1999).

Transpiration rate and stomatal conductance

The leaf transpiration values presented in Table 3 are greater than the values found by Lykoskoufis et al., 2005, for pepper cultivation. These values, however, are very close to the values found by Medrano et al., 2005, who found transpiration values per m^2 of leaf in a greenhouse with autumn cucumber cultivation in perlite, from 10:00 to 14:00 of the order of 250-300 g.m^{-2}.h^{-1}, corresponding to a transpiration rate of 4.6 - 5.6 mmol.m^{-2}.s^{-1}, which are similar to our values from Table 3. The same researchers found that transpiration rate

values were linearly affected by the levels of incoming solar radiation, thus confirming the effect of shading on the transpiration rate found in our experiment. Also, close to the values of Table 4 are the results of Nederhof et al., 1992, who found for sweet pepper cultivation mean leaf transpiration rate values around 200 W.m^{-2}, that is, about 4.5 mmol.m^{-2}.s^{-1} (Hanan, 1998).

For stomatal conductance g_c the values found in the greenhouses of our experiment are similar to those found by Mavrogiannopoulos et al, (1999) in hydroponic melon culture and higher than those found by Lykoskoufis et al. (2005) in pepper cultivation.

The values in Table 7 show leaf stomatal conductance values for our experiment conditions of the order of 1 mol.m^{-2}.s^{-1}, corresponding to stomatal conductance of about 22.3 mm.s^{-1} (Rosenberg et al., 1983). This value is close to the values of Katsoulas et al. (2001), who found values for the stomatal conductance of the order of 20 mm.s^{-1} for rose cultivation in a shaded roof greenhouse in Volos-Greece region. Similar values were given by Nederhof et al. (1992) who gave values for stomatal conductance of 15-20 mm.s^{-1} for hydroponic sweet pepper cultivation in a greenhouse in the Netherlands.

It is well known that stomatal conductance values above 20 mm.s^{-1}, such as g_c values for cucumber leaves in our three experimental greenhouses in autumn, correspond to normal state of free transpiring plants that are outside stress and their stomata are open (Hanan, 1998). Since, in such conditions their transpiration rate is a function of the incident solar radiation on the leaves and the air vapor pressure deficit in the leaf chamber (Katsoulas, 2002), greater transpiration in the control greenhouse is justified by the higher solar radiation intensity.

Photosynthesis acclimation

Finally, the lack of any difference in photosynthesis rates A between plants from the three shading treatments when the measurements were conducted at light saturation with a constant illumination conditions of 1000 µmol.m^{-2}.s^{-1}, despite the long term exposure to different light conditions shows that shading up to 50% does not affect permanently the leaf photosynthetic apparatus (Table 8). These results indicate that greenhouse cucumber does not adapt to reductions in light up to 50%. Hence, automated application of intermittent shading depending on current solar radiation intensity does not seem to affect the photosynthetic potential of greenhouse cucumber due to acclimation. This is in accordance with the results of Smith et al. (1993) for tomato crop who found that leaf photosynthetic capacity along a fruit-bearing shoot is mainly driven by the sink demand of the most proximal fruit, and not by light acclimation.

CONCLUSIONS

The analysis of photosynthesis measurements made during autumn hydroponic cucumber cultivation showed that photosynthesis rate is reduced proportionally by shading while, shading does not seem to have a permanent effect on leaves and this illustrates the usefulness of the periodic shading by placing shading for periods of high solar radiation (summer) and removing shading when the intensity of solar radiation decreases (mid-autumn-winter) without photosynthetic cost.

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An empirical framework for modelling transpiration use efficiency and radiation use efficiency of biomass sorghum in Mediterranean environment

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Abstract. In this experimental-modelling research, the potential biomass achievable by sorghum to be converted in bioethanol was assessed and then formalized into the radiation use efficiency (*RUE*) and transpiration use efficiency (*TUE*). Dry above-ground biomass (harvested at the flowering stage) ranged between 22.6 t ha^{-1} and 28.34 t ha^{-1} over two growing seasons with a total water consumption of 382 mm and 504 mm, respectively. Starting from sampling measurements, the empirical framework allowed to reproduce daily data of dry biomass, canopy development, intercepted photosynthetically active radiation and transpiration related efficiencies. *RUE* and *TUE* resulted 4.98 g MJ^{-1} and 7.45 kg m^{-3}, respectively. Their robustness (as stable parameters) was assessed through the validation process. Finally, the multiple linear regression approach, was applied to screen among limiting factors. It was pointed out that although sorghum was grown under irrigated regime, water demand resulted not fully fulfilled to achieve the full performance of the crop.

Keywords. Energy crop, crop modelling, bioethanol, biomass, water consumption.

INTRODUCTION

In the search for renewable energy sources, also promoted by the recent European directives (Renewable Energy Directive, RED I and RED II) sorghum (Sorghum bicolor L. (Moench) is seen as one of the main crops to produce bio (ethanol) energy.

Sorghum is highly efficient in using the available soil water, nitrogen and growing inputs. Indeed, in Mediterranean environment the crop showed higher efficiency respect to the agro-energy inputs, improving the energy performance and energy use efficiency of the bioethanol supply chain (Garofalo et al., 2015).

To assess the suitability of a crop for energy purpose, the potential biomass needs to be estimated, considering the consequences of the pedo-climatic context coupled to the soil-crop management on yield. This allows to screen and to rank the crops deputed to feed the energy supply chain and their requirements in water, solar radiation, nutrients.

Indeed, the growth and development of a crop is driven by several environmental components such as water availability, intercepted solar radiation and temperature. These factors affect all the hierarchically structured processes involved in the leaf gas exchange (CO_2 and H_2O), the storage of photosynthates, the accumulation of biomass and finally the yield (Garofalo and Rinaldi, 2015).

The strong relationship among crop water transpiration, solar radiation interception and biomass accumulation is made explicit by two empirical parameters: transpiration use efficiency (*TUE*) and radiation use efficiency (*RUE*). The photosynthetically active radiation (*PAR*; 400-700 nm waveband) is intercepted at canopy level to provide the radiant energy at chloroplast level to drive both CO_2 assimilation and H_2O transpiration processes.

The correlations between aboveground dry plant matter (*ADM*) and water used by the crop, as well as the radiation intercepted by the canopy, tend to remain linear in both well-watered and water deficit conditions (Hsiao, 1993; Hsiao and Bradford, 1983; Monteith, 1977; Tanner and Sinclair, 1983). The robustness of *RUE* and *TUE* resulted in their implementation (individually or both) in most of the crop simulation models as conservative parameters. A group of these models uses a crop growth module relying on *RUE* (*i.a.*, CERES, Ritchie et al. 1985; Jones and Kiniry 1986; Jones et al. 2003; EPIC, Jones et al. 1991; and STICS, Brisson et al. 2003).

TUE represents the driving parameter for another group of crop simulation models. It is the case of PARCH (Hess et al., 1997) and AquaCrop (Steduto et al., 2009). While CropSyst (Stöckle et al., 2003) estimates

the crop biomass accumulation on the basis of both *TUE* and *RUE* parameters.

The estimation of *RUE* and *TUE* should be carried out under optimal-growing conditions, since their values are estimated based on the potential biomass accumulation and canopy development under a specific environment. Heat and/or water stresses that can occur during the growing period, negatively impact on the canopy development resulting in a reduction of the intercepted radiation, water transpired and anticipated senescence and as a result, on biomass.

Under Mediterranean environment, soil water shortage and high air temperature do occur during the spring-summer period, determining a high variability of estimated *RUE* and *TUE*.

Indeed, different values were reported for estimated *RUE* in Mediterranean environment, ranging from 3.4 g of *ADM* per MJ^{-1} of intercepted PAR (*iPar*; Mastrorilli et al., 1995) to 4.7 g MJ^{-1} (Perniola et al., 1996) or between 1.89 g MJ^{-1} and 3.81 g MJ^{-1} (Garofalo and Rinaldi, 2011).

On the other hand, further investigations on the water use efficiency in sorghum (*WUE*) reported values that ranged from 4.4 to 5.5 kg of *ADM* per m^{-3} of water used by the crop (Steduto and Albrizio, 2005) or from a minimum of 4.0 kg m^{-3} to a maximum 8.49 kg m^{-3} (Garofalo and Rinaldi, 2013).

In addition, uncertainty in *RUE* and *TUE* may arise according to the methods applied for their estimation.

Although *RUE* and *TUE* are commonly recognized as the slopes of the linear predictor function between the explanatory variable (*iPAR* or *Tr*) and the response variable (*ADM*), the extent of approximation is strictly dependent on the number of observations of such variables. The more data available, the better the estimate is.

In this context *ADM*, canopy cover (*CC*), *iPAR* and *Tr* collected on daily basis, would represent the optimal dataset, but technical, human or environmental constrains could not allow for daily sampling. In the light of that, most of the researches to estimate *RUE* and/or *TUE* relied on time-spaced samples or even on the data collected at harvest (Rinaldi and Garofalo, 2011; Kemanian et al., 2004; Kiniry et al., 2005, Garofalo and Rinaldi, 2015; Yimam et al., 2015; Liu and Stützel, 2004).

Dataset coming from samplings spared in time may not adequately draw the dynamics of growth, leading to an incorrect estimate of *RUE* and *TUE*.

However, empirical models can render a gradual transition from one phase of the growth to the next, at daily scale, by smoothing within a certain extent of approximation any sampling flaws (Yin et al., 2003).

Thus, in this paper is reported an empirical approach to develop a framework to artificially repro-

duce daily data on growth and development of sorghum. The experimental dataset collected over two growing years was functional to both calibration and validation process of the algorithms provided for the empirical approach. The artificial data at daily scale shaped by the system, allowed us to estimate *RUE* and *TUE* of sorghum. Finally, the multiple linear regression statistics allowed to assess if solar radiation or soil water availability were the main constraint for achieving the potential crop performance.

MATERIALS AND METHODS.

Experimental site

The field experiment was carried out over 2-year period from 2013 to 2014 in Rutigliano (lat: 40° 59' N, long: 17° 01' E, alt: 147 m a.s.l.), Southern Italy, in the experimental farm belonging to the Council for Agricultural Research and Economics (CREA).

Soil texture was classified as clay-loam (USDA, 2010) with physical-chemical characteristics of soil were reported in Table 1. At 0.6 m in depth, the parent rock reduces the capacity of the root systems to expand beyond this layer and the capillary rise from deeper soil layers. As a consequence, the impact of the groundwater to the rooting zone is totally negligible.

The experimental site is under the Mediterranean climate (UNESCO-FAO classification, 1963), characterized by warm and dry summers, with daily minimum air temperature ranging from 0-5°C and daily maximum temperature from 32 to 43°C. Annual rainfall (average 535 mm) is mostly concentrated during the winter months and class 'A pan' evaporation exceeds 7.5 mm day^{-1} during the summer months. Daily meteorological data - temperatures, humidity, rainfall, wind velocity and solar radiation - were recorded by the local meteorological station.

Finally, initial soil water content at sowing time was of 0.324 m^3 m^{-3} and 0.312 m^3 m^{-3} (0-0.6 m depth) in the first year and second year, respectively.

Field experiment

Biomass sorghum (cv. Bulldozer) was sown at the beginning of June in 2013 and in late May in 2014, in rows 0.45 m apart and 0.1 m between seeds in each row (7 kg of seeds per hectare). Sorghum was harvested before heading (when the crop achieved the maximum dry matter yield) or the second half of September in both years. The experimental trial was arranged a single plot of 80 m^2 size, 14 rows per plot. Water distribution was supplied by drip irrigation system: one line for each plant row; 4 L h^{-1} per dripper; 0.3 m dripper spacing. Irrigation volumes were measured by flow meters (one per plot). Before sowing, 120 kg ha^{-1} of N and 90 kg ha^{-1} of P$_2$O$_5$ were supplied as diammonium phosphate. Mouldboard plow, disk harrow and rotary tiller were used to prepare the soil for the sowing, similarly to local farmer practices. Weeds were controlled by herbicides before sowing and by hand-hoeing during the first part of growing cycle. The health of the plants was ensured by chemicals when required.

During the experimental seasons, weather data were measured by means of a meteorological station located in the experimental farm. Maximum and minimum temperatures, global solar radiation (*Rg*), precipitation, wind speed and relative maximum and minimum air humidity were collected on a daily basis.

Growth analysis

Plants from 1- linear meter were sampled eight times during both sorghum seasons and each sample was replicated three times. The above ground biomass was obtained by adding stems and leaves. The plant material was dried at 80 °C until the weight was constant. At harvest, biomass samples covered a surface area of 2 m x 2 m and dry weight of stem and leaf determined accordingly.

To investigate the dynamic of the dry matter accumulated during the growing period, the sigmoid model

Tab. 1. Main physical-chemical characteristics of soil of the experimental site.

Parameter	Unit	Average	Standard deviation (±)
Sand	g 100g^{-1}	21	0.6
Silt	g 100g^{-1}	37	2.9
Clay	g 100g^{-1}	42	3.6
Soil electrical conductivity 1:1	dS m^{-1}	0.6	0.05
Field Capacity	m3 m^{-3}	0.36	0.03
Wilting Point	m3 m^{-3}	0.22	0.02
Soil Organic Content	g kg^{-1}	14	1.1
Total Nitrogen	g kg^{-1}	1.5	0.2
Available Phosphorus	mg kg^{-1}	71	3.1
Exchangeable Potassium	mg kg^{-1}	540	61

(Vannella, 1998) was calibrated on the observed data of the most favourable (in terms of accumulated biomass and canopy development) growing season (2014):

$$ADM_i = \frac{ADM_{max}}{(1 + e^{(t_i - t_h)/b})} \tag{1}$$

where ADM_i is the above dry biomass (t ha^{-1}) at day i, ADM_{max} the maximum achievable value of ADM, t_i the time expressed in days after sowing, t_h represents the time between sowing and time to reach 50% of the ADM_{max} and b the fitting parameter of the model.

The green leaf area index (GAI, m^2 m^{-2}) was measured at each sampling date with a LI-COR 2000 portable area meter (LI-COR Biosciences, Lincoln, NE, USA). For each sampling, figures were derived by the average of six measurements carried out below the plant canopy, during the 12:00 to 02:00 p.m. daytime and for each of the three replications within the main plot.

Daily green leaf area index (GAI_i) was estimated by fitting the field data with a beta function (Yin et al., 2003):

$$GAI_i = GAI_{max} * (1 + \frac{t_e - t_i}{t_e - t_m}) * (\frac{t_i}{t_e})^{\frac{t_e}{t_e - t_m}} \tag{2}$$

where GAI_{max} is the maximum GAI, t_m represents the time between sowing and time to achieve GAI_{max}, t_e the time at the end of canopy growth.

The values of the parameters involved in Eqs (1, 2) were achieved by iterative procedure implemented in Excel (Solver add-in program) using the Generalized Reduced Gradient (GRG) Nonlinear algorithm as solving method.

Daily canopy cover (CC_i; 0-1) was estimated with the equation:

$$CC_i = 1 - e^{(-k * GAI_i * cf)} \tag{3}$$

where k is the light extinction coefficient (-0.75; Rinaldi and Garofalo, 2013) and cf is the clumping factor (Nilson 1971; Lang 1986, 1987), as follow:

$$cf = 0.75 + (0.25) * (1 - e^{(-0.35 * GAI_i)}) \tag{4}$$

Intercepted radiation and radiation use efficiency

The fraction of PAR intercepted by the canopy at daily scale ($iPAR_i$; MJ m^{-2}) was estimated as:

$$iPAR_i = CC_i * Rg_i * 0.48 \tag{5}$$

where Rg_i (daily global radiation) was measured with a thermophile pyranometer (305–2800-nm wavelength range) and 0.48 the fraction of solar radiation photosynthetically active.

RUE (g MJ^{-1}) was calculated as the slope of the linear regression between the cumulated daily values of ADM and $iPAR$ by forcing the intercept (b) to zero:

$$RUE = \frac{ADM_{ipar}}{\sum_{i=sowing}^{i=harvest} iPAR_i} \tag{6}$$

Irrigation, transpiration and transpiration use efficiency

The reference evapotranspiration (ET_0, in mm), was calculated using the FAO-Penman-Monteith model (Allen et al., 1998).

Irrigations were scheduled according the crop evapotranspiration (ETc, mm), restoring the water used by sorghum whenever the 30 mm threshold was reached (subtracting rainfall).

ETc was calculated as follow:

$$ET_c = ET_0 * Kc \tag{7}$$

where Kc is the crop coefficient as reported by Rinaldi and Garofalo (2011) and ET_0, the reference evapotranspiration

Daily transpiration at day i (Tr_i) was calculated as:

$$Tr_i = CC_i * (Kc * ET_0) \tag{8}$$

Finally, TUE (kg m^{-3}) was calculated as the slope of the linear regression between cumulative ADM and water consumed by transpiration (Eq. (9)):

$$TUE = \frac{ADM_{itr}}{\sum_{i=sowing}^{i=harvest} Tr_i} \tag{9}$$

with b (intercept) forced to 0.

Temperature limitation on growth

To account for the effect of temperature on growth and canopy development, the "T_{lim}" factor was calculated which describes the effect of daily average temperature T_m on biomass accumulation, as reported by Montieth (1977). T_{lim} was assessed as follow:

$$T_{\lim} = 0 \;\; when \;\; \begin{matrix} T_m < T_b; \\ T_m > T_x \end{matrix}$$

$$T_{\lim} = 1 \;\; when \;\; T_m = T_{opt}$$

$$T_{\lim} = \frac{T_m - T_b}{T_{opt} - T_b} \;\; when \;\; T_b \leq T_m \leq T_{opt}$$

$$T_{\lim} = \frac{T_{opt} - T_b}{T_m - T_b} \;\; when \;\; T_{opt} \leq T_m \leq T_x$$

(10)

where T_b is the base temperature (8 °C), T_{opt} the optimal temperature for growth (25 °C) and T_x the maximum temperature threshold for growth (33 °C; Alagarswamy and Ritchie 1991; Hammer et al. 1993; Rinaldi and Garofalo, 2011; Djanaguiraman et al., 2014).

Thus, the fitting of the parameters reported in Eq (1) occurred in two steps. The first one, involved a preliminary estimate of ADM_{max}, t_m and b on observed data, after which ADM_i and GAI_i resulting from Eqs. (1-2) were recalculated multiplying their values by T_{lim}. Finally, a second fitting procedure of parameters was carried out based on daily ADM_i and GAI_i corrected for T_{lim} to refit their figures to the values observed at sampling date.

The plant development rate was expressed by the growing degree days, GDD (°C) which measures that measured the heat accumulation calculated as the difference between the daily mean temperature and T_b.

Validation of the framework

To check the robustness of the framework, Eqs. (1) and (2) were replicated on the 2013 growing season, keeping the values of their parameters, unchanged. The outcomes were adjusted by T_{lim} calculated based on the climatic pattern of 2013 and compared with the observed data.

Finally, for 2013 $iPAR_i$ was estimated with Eqs. (3-5) and Tr_i with Eqs. (8) and (9) to validate ADM radiation-dependent and ADM transpiration-dependent adjusted by T_{lim} by means of RUE and TUE values assessed in the calibration step, when the 2014 data-set was used.

Biomass-RUE dependent and biomass-TUE simulated with this approach, were compared with the 2013 observed data to validate the reliability of RUE and TUE computed with the calibration step.

RESULTS

Meteorological patterns

In 2013, during the first part of growing period, climate was characterized by peaks of maximum temperature (*Tmax*) up to 33 °C, up to 19 °C for minimum temperature (*Tmin*). Cooler temperatures characterized the period from late June until the third decade of July, where *Tmax* remained below 28 °C and *Tmin* below 18 °C (Fig. 1).

Except for some very hot days (daytime temperature up to 37 °C), the second part of the growing peri-
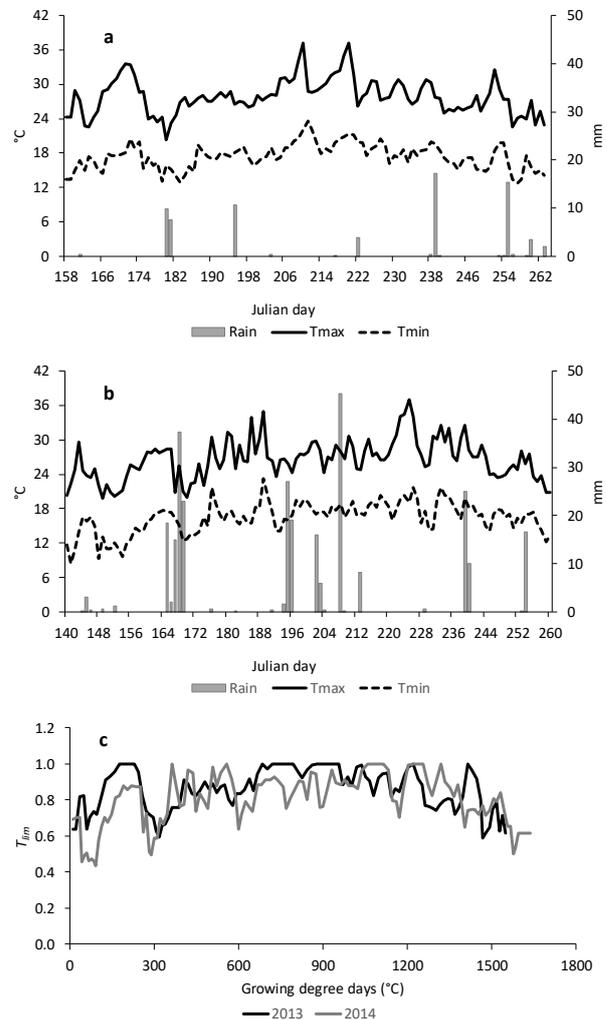

Fig. 1. Maximum temperature (Tmax; continuous line), minimum temperature (Tmin; dashed line), rain (grey columns) recorded in 2013 (a) and 2014 (b) growing season and Tlim (see text) behaviour.

od recorded temperature below 30 °C (*Tmax*) and 19 °C (*Tmin*) in August, to remain below 25 °C and 18 °C in September (hotter temperature in some days at the beginning of September, were observed).

Total rainfall in 2013 growing season was 72.4 mm, spaced over time, with two fairly rainy events, one at the end of August and the other in mid-September (Fig. 1).

The crop growing period of 2014 was warmer than in 2013, especially from 16th to 51st day after sowing (from June 4th to July 10th) with peaks of *Tmax* that exceeded 31 °C for several days and some events of *Tmin* above 20 °C.

Conversely, the middle part of the growing period was cooler in 2014 than in 2013, with *Tmax* rarely above 30 °C as well as Tmin which remained below 18 °C.

However, for the most of the second part of the growing season, temperature reached maximum peaks of 2-3 degrees above 30 °C, whereas *Tmin* was cooler than the first period of the growing period; the last part of the growing cycle in 2014, was slightly hotter than 2013, with *Tmax* that ranged from 23 to 27 °C and *Tmin* below 15 °C.

Rainfall in 2014 cultivation time frame was much higher than 2013 (157 mm vs 72 mm) with 96 mm falling on four consecutive days in June and 76 mm recorded from from 21st July to 1st.

Two following events for a total of 35 mm of rainfall characterized the end of August, whereas a single event of 17 mm concluded the growing period in 2014.

Crop growth and development analysis

The daily growth and canopy development curves of the 2014 growing season, resulting from the calibration of Eq. (1) and Eq. (2), were well fitted to the observed values of *ADM* (R^2 = 0.976) and *GAI* (R^2 = 0.97; fig. 2). It should be pointed out that the values of parameters of both models were preliminary calibrated to fit the estimated *ADM* and *GAI* to the observed values and recalibrated on daily values of *ADM* and *GAI* corrected by T_{lim}. In this way, parameters of Eq. (1) and (2) were predicted net of the effect of temperature on growth.

Over the 2014 growing season (year used for the calibration of the empirical models), the average temperature rarely achieved optimal values and T_{lim} was close to 1.

This trend was particularly noticeable from the middle to the final part of the growing season, where T_{lim} showed values between 0.9 and 0.7 or even below 0.7, mainly due to mean temperatures which remained below the optimal value (25 °C) rather than above the maximum threshold (33°C).

From 300 GDD to 1000 GDD, was observed a first growing phase characterized by an exponential convex growth, followed by a second phase (between 1000 GDD and 1500 GDD) identified by a concave senescent growth. The inflection point (transaction between the first and second growing phase) at which the development rate reached its maximum value (t_h) was formalized 78 days after sowing. Finally, the potential dry biomass achievable at harvest (net of limitations due to temperatures not optimal for the crop) was estimated as 32 t ha^{-1}, whereas the actual *ADM* at harvest was 28.32 t ha^{-1}. Such figure is consistent with the yield values reported in the international literature: in Greece (from 17 t ha^{-1} to 31 t ha^{-1}; Dercas and Liakatas, 2007), in Spain (18.38 t ha^{-1}, Farrè and Faci, 2006), in Italy (from 40.97 t ha^{-1} to 23.22 t ha^{-1}, Rinaldi and Garofalo, 2011)

As regards the development of canopy (*GAI*), the beta function curve highlighted the highest expansion rate in the first period of growing season (from 300 GDD to 700 GDD) with *tm* achieved at 65 days after sowing. After that, followed a near-linear development of the canopy (from 700 GDD to 1050 GDD) to reach the maximum value of 6.8 m[2] m^{-2} (5.2 m[2] m^{-2} when accounting for T_{lim} during the growing cycle) at 92 days after sowing (*te*), time to end the plant growth.

Fig. 2. Dynamic of total above dry matter (ADM a; line), green area index (GAI b; line) and experimental data (circle) observed during 2014 growing season. Vertical bars indicate ± standard deviation. The values of parameters of the empirical models are shown (see text).

Canopy radiation interception and radiation use efficiency

Sorghum reached a high value of *CC* (0.9) quite rapidly, or 64 days after sowing.

Basically, this value was reached with *GAI* of 3.34 m² m⁻² keeping a high efficiency in radiation interception for more than 50% of its growing cycle (Fig. 3**a**) with performance in line with Fletcher et al. (2013) but slightly lower than Rinaldi and Garofalo (2013).

At the end of growing season, cumulative *iPAR* was of 568 MJ m⁻², with a linear increment of intercepted radiation from emergence to harvest (Fig. 3**b**), consistent with the value indicated by Narayanan et al. (2013) but less than that reported by Ceotto et al. (2013).

The strong correlation between dry biomass accumulated during the growing season and the radiation intercepted by the canopy is drawn by figure 3**c**. The slope of the linear regression between *iPAR* and *ADM* was equal to 0.0481, confirming the sorghum high efficiency (4.81 g MJ⁻¹) in converting the intercepted solar energy in photosynthates.

Our results pointed out a higher *RUE* compared to recent studies (e.g. 3.48 g MJ⁻¹ reported by Ceotto et al., 2013; 3.23 g MJ⁻¹ found out by Garofalo et al., 2011) but consistent with previous investigations (4.7 g MJ⁻¹, Perniola et al., 1995).

Obviously, the forcing to reproduce a logistic growth pattern through a linear regression model produces bias. A polynomial fitting would have matched the growth curve more accurately but would not have led to the formalization of a single parameter (*RUE*) of quick understanding and easy application.

Fig. 3. Trend of the intercepted radiation (iPAR; a), canopy cover (CC; b) during the 2014 growing season and linear regression between iPAR and aboveground dry matter (ADM; c).

Plant transpiration and transpiration use efficiency

Total water supplied with irrigation in 2014 amounted to 225 mm, split in one application (15 mm) before sowing to restore the water field capacity and seven applications (30 mm each) over the 2014 growing season.

Rainfall plus water supply indicated a total water consumption (soil evaporation, drainage and crop, drainage and crop transpiration) equal to 475 mm (Fig. 4 a), in line with the finding (489 mm-517 mm) reported by Hao et al. (2014), or (446 mm-683 mm) indicated by Yimam et al. (2015) both calculated under well-watered regimes. It should be pointed out that to account for the effect of closed canopy on rainfall interception, a 22% reduction of water amount from precipitation in calculating *WU* (Kozak et al., 2007) was applied after *CC* reached 0.9.

The water daily transpired by the crop raised rapidly from 28 days after sowing to reach peaks of 7-10 mm between 80 and 100 days after sowing (Fig. 3**a**).

The reported value of Tr_i was due to combined effect of the rapid expansion of canopy (in the early phenological stages) and the evaporative demand of the atmosphere (Fig 3**a**). On the other hand, the cumulative water transpired by the crop (see Eq. (8)) was 399 mm, with a trend synchronized with the canopy development (Fig. 3**b**). The discrepancy between *Tr* and the total water consumption represented the loss of water by evaporation and drainage, otherwise called not productive water, which was estimated to range between 61 mm and 280 mm in sorghum (Garofalo and Rinaldi, 2013).

Most of the abovementioned difference was accounted in the first part of the growing season, due to the evaporation from bare soil or partially covered by the canopy other than the crop transpiration. Once achieving *GAI* of 3.0 m² m⁻² or a *CC* close to 0.9, *WU* was due to the plant transpiration, if the soil was completely shaded by canopy and so evaporation was negligible (Ritchie, 1972).
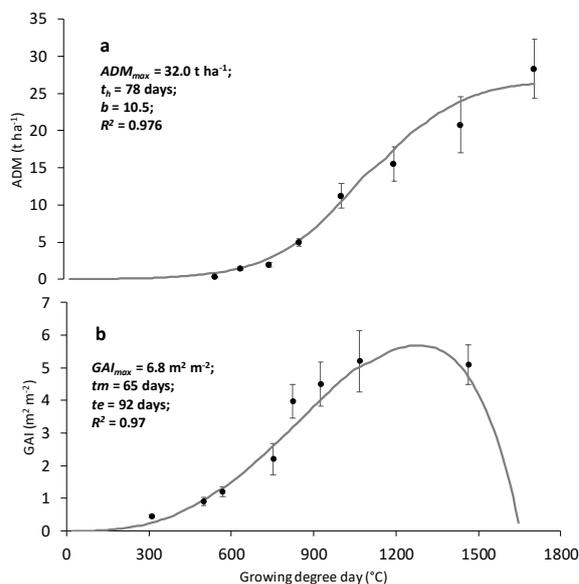
Fig. 5. Dynamic of total above dry matter (ADM a; line), green area index (GAI b; line) and experimental data (circle) observed during the growing season. Vertical bars indicate ± standard deviation.

Fig. 4. Daily transpiration and reference evapotranspiration (Tri, ET0 a), cumulative transpiration (Tr_cum, continuous line) vs total water consumption (WU, dashed line; b) and linear regression between Tr and aboveground dry matter (ADM; c), in 2014 growing season.

At the end of the growing period the gap between the total water consumption and water transpired by the canopy was 76 mm.

The slope between the transpiration (net of water loss by evaporation or drainage) and cumulative dry biomass on daily basis was of 0.072 t mm^{-1} or 7.2 kg m^{-3} (Fig. 3**c**) a value higher than those reported by other researches (Thapa et al., 2017; Reddy and Angira, 2015) but consistent with other investigations (Garofalo and Rinaldi, 2013).

Validation of the empirical framework

To check the robustness of this framework, from the formalization of biomass accumulation and canopy
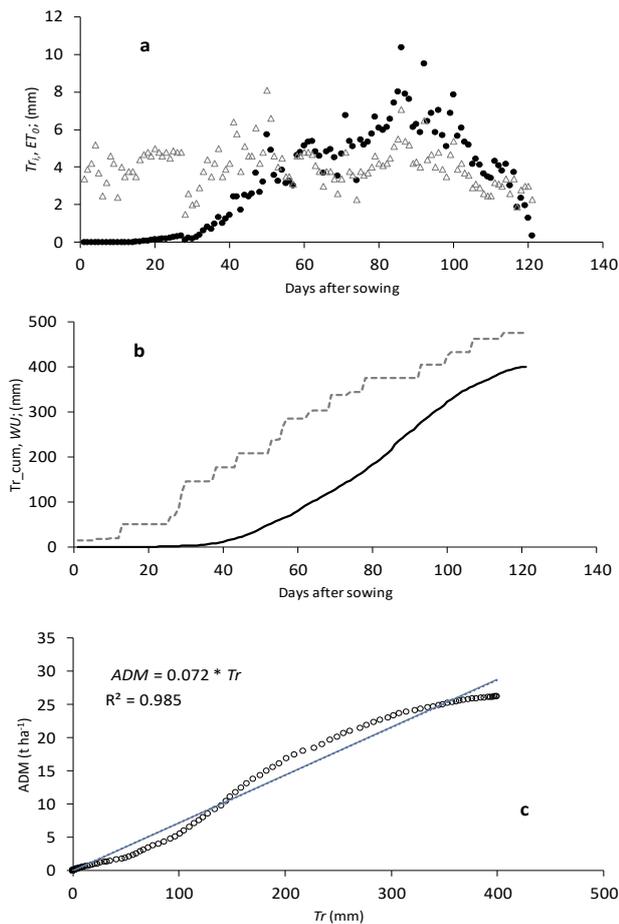
development to the accuracy of the estimated *RUE* and *WUE*, the empirical structure was verified on experimental data collected over the 2013 growing season.

Basically, the parameters of Eqs. (1-5) and Eqs. (7-8) remained unchanged excepting for *Rg* and *ET$_0$*, as well as *T$_{lim}$*, that varied according to 2013 climate trend.

Validation process pointed out a satisfying matching between the experimental data of *ADM* and *GAI* with figures replicated by the empirical model (R^2 = 0.96 for *ADM*, Fig. 5**a**; R^2 = 0.839 for *GAI*; Fig 5**b**).

Water transpired by the crop in 2013 had a pattern close to that computed in 2014; indeed, the daily transpiration grew up rapidly from 30 to 80 days after sowing, passing from 1 mm to 6 mm and then settle between 6-8 mm at maximum canopy expansion and decline rapidly once reached the reproductive phase (Fig. 6**a**).

Cumulative *Tr* in 2013 was slightly lower than 2014 (- 29 mm), but *WU* was 22% lesser compared to the first growing season (Fig. 6**b**). A shorter distance between *WU* and *Tr* in 2013 was due to a lower amount of rainfall in this year compared to 2014 (reduced water loss by drainage) and lower evaporative demand of the environment (*ET$_0$*; Fig. 6**a**).

Once it was established that the framework was suitable to replicate the growth of the crop and development of the canopy, *ADM* of 2013 was estimated on the basis of computed *Tr* and *iPAR* (2013) and *TUE* and *RUE* of 2014.
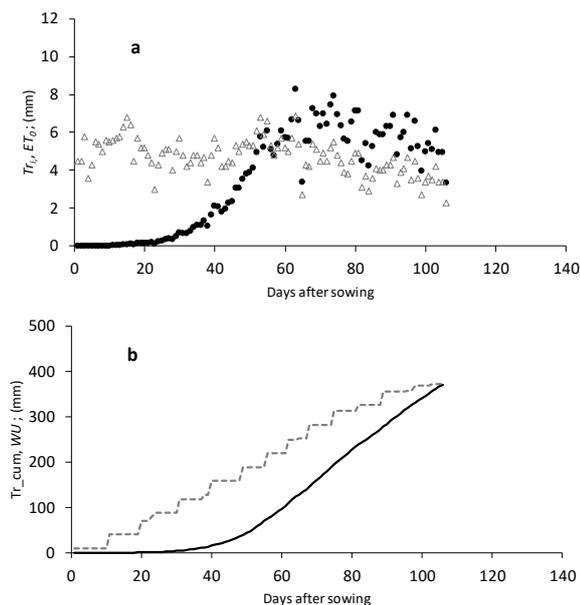
Fig. 6. Daily transpiration and reference evapotranspiration (Tri, ET0 a), cumulative transpiration (Tr_cum, continuous line) vs total water consumption (WU, dashed line; b) in 2013 growing season.

Fig. 7. Comparison between the trend of observed (full circle) aboveground dry matter (ADM) and ADM dependent on RUE (ADM-RUE; grey line, a) and ADM dependent on TUE (ADM-TUE, b) in 2013 growing season.

This procedure (validation step) allowed us to assess the stability and effectiveness of these parameters (*RUE* and *TUE*) as well as the empirical approach here proposed, in estimating the potential productivity of sorghum.

Formalization of *ADM* dependent on *RUE* (*ADM-RUE*) as well as *ADM* dependant on *TUE* (*ADM-TUE*) and T_{lim} acting on potential *ADM*, was congruent with the experimental data collected in 2013 (Fig. 7).

Effect of available water and radiation on plant performance

A sensitivity analysis was aimed at assessing whether the biomass accumulation was mainly affected by the intercepted radiation or by transpiration or by both drivers interacting each other, or again, if both parameters had the same weight. Specifically, the standardized multiple linear regression (Myers, 1990) was applied, with cumulative ADM_i as dependent response variable and cumulative Tr_i and cumulative $iPar_i$ as predictors for both years, as single factors and in interaction. In this way, it was assessed whether the daily increase in biomass was more sensitive to the daily amount of water used by the crop or to the intercepted radiation or, in other words, which was the limiting factor (if any).

The standardized regression coefficients (β) pointed out that transpiration was the main driver in regulating the accumulation of biomass and that interaction between *Tr* and *iPar* was not significant (Fig. 8).

DISCUSSION

Our experimental data confirmed the high capability of sorghum to produce high amount of biomass under well-watered irrigation regime, as reported in other investigations (Zegada-Lizarazu and Monti, 2012). However, the ability of this crop to thrive also under suboptimal conditions is well documented (Garofalo and Rinaldi, 2013) where other crops would struggle (Woods, 2001).

In addition, sorghum is known for being a low demanding N crop, even compared to other C4 crops. For example, it was highlighted that sorghum requires up to 40% less nitrogen fertilization than maize (Smith and Buxton, 1993), whereas Garofalo et al. (2015) pointed out the lack of statistical differences between the biomass productivity of sorghum under well-fertilized regime compared to halved N doses (150 kg N ha^{-1} vs 75 kg N ha^{-1}) or even no N fertilization. The same authors also indicated comparable performance between sor-
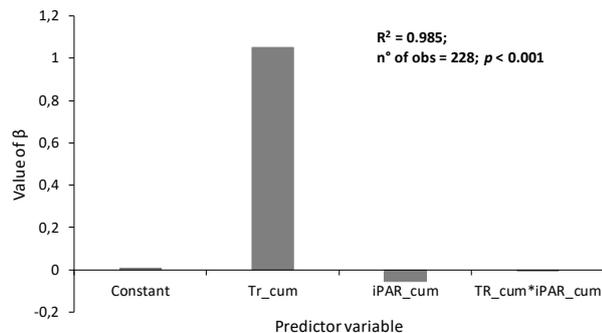
Fig. 8. Standardized regression coefficients (β) of cumulative transpiration (Tr_cum), cumulative intercepted solar radiation (iPAR_cum) and the combined effect on biomass accumulation. The higher the value, the higher their contribution.

ghum cultivated under conventional soil practices compared with no-tillage soil management.

High biomass productivity even with reduced agro-inputs result in a high energy efficiency and energy performance of a specific energy crop, which are the key points to make the sorghum suitable for energy purposes (Garofalo et al., 2018).

However, the assessment of the performance (e.g. biomass, yield or energy harvest) of a crop using only the "productivity" (biomass or yield) parameter, net of the environmental impacts that lead to its value, may determine assessment bias.

Radiation, available water and air temperature are the main weather-related variables affecting the biophysical processes related to the growth and development of a crop. If these processes are recognized as a hierarchical pyramid structure in which the complexity is reduced as we move from the base to the tip, *RUE* and *TUE* are located at top, including and integrating the mechanisms and climatic constrains for plant growth and development (Garofalo and Rinaldi, 2015).

Although, *RUE* and *TUE* are known to be crop-specific parameters (Hughes et al., 1987; Russell et al., 1989; Monteith, 1994), other studies pointed out as these variables can vary according to environmental factors and management (i.e. nitrogen and water supply, plant density, cultivars; Sinclair and Horie, 1989; Rosenthal and Gerik, 1991; Cosentino et al., 2016).

However, here we assume that *RUE* and *TUE* should be easy to read and quick to understand and maintain their robustness and effectiveness inside the modelling frameworks or modelling solutions as stable parameters.

This implies the calculation of *TUE* and *RUE* as fixed indices of the potential crop performance, on which "limiting factors" afterwards act.

In the Mediterranean environment the factors constraining the plant growth are the water scarcity and heat waves, especially in spring-summer cropping systems, not the solar radiation.

Thus, in this experimental-modelling research drought conditions were mitigated through irrigation; as for temperature, the T_{lim} correction allowed to separate its effect when *RUE* and *TUE* were estimated.

As previously stated, in other investigations, the data of biomass used for the estimation of *RUE* or water use efficiencies were collected from sampling during the growing season; out-of-scale values could lead to overestimation or underestimation of these parameters.

Thus, in this research the empirical framework was set up to replicate daily biomass accumulation of sorghum, starting from sampling data. Although flaws in sampling may occur, the proposed approach is adequate to dampen such biases, since it models the growth dynamics between two figures through a curvilinear instead of a linear transition.

The approach proposed in this research led to results that can also be considered valid in other pedo-climatic and management contexts comparable to those from which the data for this research were obtained. Significant variations in terms of canopy development and/or biomass accumulation, intercepted radiation and transpiration can occur with crop and soil management substantially different from our field trials (i.e. sub-optimum fertilization, sprinkler system instead of drip irrigation, no-tillage instead of conventional tillage, etc.)

In other researches, the efficiency to convert water in biomass was estimated without partitioning the water consumption in soil evaporation and crop transpiration or accounting for the rainwater intercepted by the closed canopy, whose amount is not gathered from soil and not available for the transpiration process (Moroke et al., 2011; Hao et al., 2014; Chimonyo et al., 2016). Water loss by evaporation as well as rainfall intercepted by closed canopy and not available for the water requirement of the crop are not involved in the bio-physical processes of the plant and their inclusion in water use efficiency may lead to underestimation of this parameter.

In this paper is indicated a procedure that reproduce the daily canopy development (Eqs. (2-4)) and the water daily transpired by the canopy itself (Eqs. (7-8)) taking into account the effect of closed canopy on rainfall interception. Thus, water transpired by the crop fitted linearly with daily biomass accumulation, led to the estimation of *TUE*.

The replicability of this empirical structure has proved feasible through the validation step and *RUE* and *TUE* calibrated in 2014 accurately formalized the bio-

mass accumulation observed in 2013 (validation year).

This let us to discuss on the most suitable index (*RUE* or *TUE*) to replicate the growth of the crop as a function of intercepted radiation or water transpired by the canopy.

If the available water or radiation are alternatively the limiting factors, the choice of the parameter to simulate the plant growth should be linked to the limiting factor itself; *RUE* if radiation is limiting for the optimal growth or *TUE* if the crop is under sub-optimal watered regime.

In the experimental trials carried out for this investigation, the water management was aimed at maintaining the crop under well-watered condition to avoid possible water stresses. On the other hand, in the Mediterranean environment, solar radiation did meet the energy demand for photosynthesis.

Results from the standardized multiple linear regression suggested that the accumulation of crop biomass over the two growing seasons, was mainly driven or affected by the water used by the sorghum rather than by the intercepted radiation as a single factor or in interaction with transpiration. Such result paves the way to three hypothesises: i) solar radiation was not a limiting factor; ii) during the two growing seasons, the sorghum crop experienced the soil water shortage; iii) all the biophysical processes are water-dependent. For the latter, some authors reported that *RUE* was strongly correlated to the water consumed by the crop (Derkas and Liacatas, 2007; Rinaldi and Garofalo, 2011). However, we assumed that *RUE* (as well as *TUE*) should be a stable parameter as a predictor of potential sorghum performance
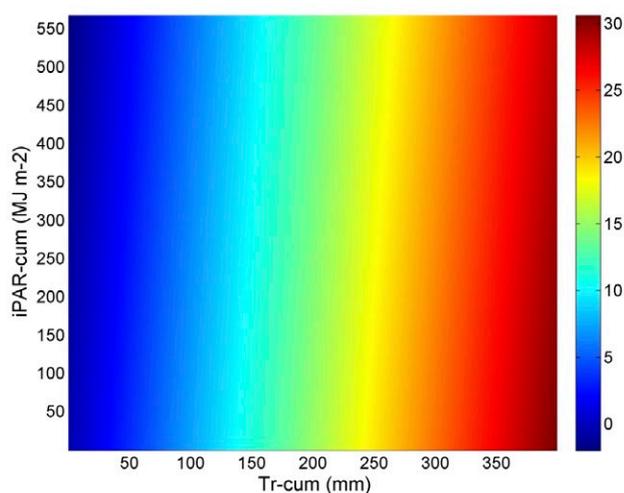
and that limiting factors (such as the water availability) should act in reducing the potential biomass computed by *RUE* and/or *TUE*. This assumption is further evidenced by the surface response plot (Fig. 9) which pointed out that the accumulation of biomass occurred mainly in response to *Tr*_cum rather than *iPar*_cum.

CONCLUSIONS

Our experimental-modelling research proposes an empirical framework to formalize the daily growth and development of sorghum as well as *RUE* and *TUE* as a function of intercepted radiation and transpiration on daily basis. Under well-watered regime and in Mediterranean pedo-climatic conditions (as in our experimental trials), sorghum proved to be high performant in biomass yielding even with less water requirements respect to other energy crops (Triana et al., 2014), such as giant reed (1161 mm) or miscanthus (991 mm). This turned in the capability of sorghum to fully take advantage from solar radiation and water supply, providing high values of *RUE* and *TUE*, thus making this crop suitable for energy purposes (high energy yield in response to the agro-inputs management).

The estimate of *RUE* and *TUE* was the conclusive step in the whole empirical procedure, which starting from sampling carried out over the growing season, led to the projection of data at daily scale involved in the estimation of the efficiency of the plant to convert radiation and water into biomass.

This framework is easy to replicate also in other pedo-climatic contexts and for other crops, since few inputs are required for specification and parametrization (i.e. weather data and crop coefficient of the species under investigation).

The modelling approach used for this research was empirical and all the relationship among the analysed parameters (biomass and canopy development as a function of temperature, and intercepted radiation and transpiration) were quantified by means of regression models. Therefore, this approach excluded any process-based analysis underlying these relationships which could be deepened through mechanistic crop simulation models.

In addition, for the experimental trials the crop was grown under optimal level of nitrogen fertilizer as well as conventional soil tillage; by varying these two conditions the results and discussions reported so far could also undergo significant changes. Changes that could also be induced by climate change scenarios, where prolonged or repeated drought or heat waves conditions could undermine the crop growth-water or the crop

Fig. 9. Interaction response surface of the cumulative ADM (right bar) as it depends on cumulative intercepted solar radiation (iPAR-cum) and cumulative transpiration (Tr-cum).

growth-radiation dependence, which in turn are *TUE* and *RUE*.

Although the water supply was aimed at satisfying the water demand of sorghum, the regression analysis highlighted that the water requirement was likely not fully met.

This leads to the final considerations: i) in our experimental trials, sorghum did not reach its full performance and that; ii) other irrigation scheduling and distribution methods in addition with investigations on different soil tillage schemes, different nitrogen doses, plant densities or sowing times should be assessed to attain also at the farm scale the findings collected so far.

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Quinoa's response to different sowing periods in two agro-ecological zones of Burkina Faso

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Abstract. The Soudano-Sahelian and Soudanian agro-climatic zones of Burkina Faso extent over 150,000 km^2 and 55,000 km^2, respectively, equivalent to 75 % of the country's total surface area. Food security throughout the country is constantly threatened due to inter/intra annual fluctuations on crop production. Climate resilient and highly nutritional crops (*Chenopodium quinoa* Willd.) are of increasing interest in regions exposed to environmental stresses and having high undernourishment rates. This study examines quinoa's adaptability in two agro-ecological zones of Burkina Faso (Soudano-Sahelian and Soudanian zones). Four quinoa genotypes (Pasankalla, Negra Collana, Titicaca and Puno) are tested for different sowing periods (from October to January) in two agro-ecological zones, and their effect on crop growth is evaluated. Results show a significant effect of sowing dates on plant phenology in both agro-climatic zones. Photoperiod, temperature and wind speed are the major environmental factors explaining variation in terms of crop growth and development between sowing dates. Emerging findings show that short cycle varieties (Titicaca and Puno) can be highly performing (above 3 t ha^{-1}) when sowing between November-December and October-December in the Soudano-Sahelian and Soudanian zones, respectively. Other genotypes (Pasankalla), can respond better to strong Harmattan winds, besides having similar yields to those reported for Titicaca and Puno. Pasankalla and Negra Collana tend to be susceptible to heat-stress conditions occurring in March-April because of their long cycle (around 120 days).

Keywords. Quinoa, agrometeorology, adaptability, climate-resilient crops, abiotic factors, Sahel.

INTRODUCTION

In recent years, the expansion of quinoa beyond traditionally grown agro-ecological zones has increased scientific attention. Portrayed as a highly nutritional crop, quinoa's spread is the result of an optimal adaptation to adverse environmental conditions. High tolerance to heat and drought-stress conditions, and great performance under saline and unfavourable soils have been reported within the Mediterranean, Middle East and North African (MENA) and Sahel regions (Hirich *et al.,* 2012; Coulibaly and Martinez, 2015; Bazile *et al.,* 2016; Dao *et al.,* 2016; Habsatou, 2016; Mosseddaq *et al.,* 2016). The great adaptability of quinoa to abiotic stresses is the result of a wide genetic diversity (Bazile, 2015). The recent discover of the quinoa genome sequence has open new opportunities for identifying desirable genotypes for specific regions (Jarvis *et al.,* 2017). The great genetic diversity of quinoa shows that there is space for developing new and more productive varieties that can cope with more intensified and recurrent environmental stresses (Gandarillas *et al.,* 2015).

To optimize the productivity of the crop, it is important to identify the most suitable sowing dates by adjusting ontogenesis (chronology of phenological stages) to the best environmental conditions. Sometimes, environmental stresses are unavoidable; therefore, minimizing the effects of adverse environmental conditions at plant's most sensitive stages (flowering and seed germination) becomes imperative. However, determining the most appropriate sowing dates of highly sensitive crop's to photoperiodicity is more complex. This is the case of quinoa, with genotypes ranging in cycle from 80 days to more than 200 days (Bertero, 2001; Rojas *et al.,* 2015). For this crop, it is widely accepted that the shorter the photoperiod the more rapid the plants flower, being its sensitivity to photoperiod and temperature a function of origin (Jacobsen, 2003). It is accepted that genotypes growing in the tropics are more sensitive to photoperiod and have a longer vegetative phase when compared to genotypes grown by the sea and at the Andean altiplano (Jacobsen, 2003). However, other experiments, under controlled environmental conditions, have shown that different genotypes are highly sensitive to day length, with very little differences on the time to flowering; but having great variances on time to maturity (Christiansen, 2010; Bertero, 2015a). Also, some affirm that day lengths over 12 hours tend to have an undesirable effect on the development of the plant (Jacobsen, 2015). This is the case of genotype Titicaca, with a time to maturity of 134 days in Germany (34 °N) and less than 90 days in Burkina Faso (11 °N) (Präger *et al.,* 2018; Alvar-Beltrán *et al.,* 2019a).

Quinoa is a new crop recently introduced in Burkina Faso (Dao *et al.*, 2016) and up until now, there has not yet been a study examining the adaptation of quinoa to the different agro-ecological zones. Hence, this study was carried out with the objectives to evaluate the effect of sowing dates on phenological and agronomic traits of quinoa, to evaluate plant growth and grain yield performance of quinoa varieties in two agro-ecological zones and to determine the optimal growing calendars in Burkina Faso.

MATERIALS AND METHODS

Experimental set-up and statistical analysis

These trials were conducted simultaneously in two agro-climatic zones of Burkina Faso between October 2017 and June 2018 (Figure 1). The Institut de l'Environnement et Recherches Agricoles (INERA)-Farako-Ba research station (11º05' N and 4º20′ W; 405 masl) was characterised for having a tropical savannah climate (Soudanian agro-climatic zone). While, INERA-Saria research station (12º16' N and 2º09′ W; 311 masl) was located within hot-semi arid climates (Soudano-Sahelian agro-climatic zone), with a well-defined rainy season (from June to October). Four sowing dates were

Fig. 1. Location of Farako-Ba (Soudanian zone) and Saria (Soudano-Sahelian zone) research stations within Burkina Faso.

tested, every month from 17th October 2017 until 17th January 2018, while four genotypes of quinoa were examined, namely Titicaca, Puno, Pasankalla and Negra Collana. Each treatment contained three replicates, with a total of 12 experimental plots per research site and sowing date. To test the different factors (sowing dates and genotypes), a completely randomized block-Fisher experimental design was used, with plots sizing 9 m², with 7 rows spacing each other by 0.50 m and with plants separated by 0.10 m. The ANOVA and the Student-Newman-Keuls post-hoc tests were used to assess the differences between means. All the statistics were done using the Statistical Analysis Software (SAS, version 9).

The soil was prepared manually and prior to sowing the soil was amended using compost at a rate of 5 t ha^{-1} (1.1 % N content). NPK fertilization (14-23-14) was applied during sowing at a rate of 100 kg ha^{-1}, while 30 days after sowing (DAS) urea, $CO(NH_2)_2$ (46 % N content), was spread at a rate of 100 kg ha^{-1}. Prior to sowing, the seeds were treated with insecticides (Permethrin 25 g kg^{-1} and Thirame 250 g kg^{-1}), and 3 to 5 seeds were introduced per hole at 10 mm depth. At 15 DAS, quinoa plants were thinned to leave 1 plant per hole, giving a plant density of 20 plant m^{-2}. Both trials were fully irrigated twice a week using a drip-irrigation system.

Measurements

Different crop parameters were selected to test the effect of different agro-climatic regions and latitude on crop development and performance. For each plot, 10 plants were selected and the following parameters were measured: days after sowing to flowering (Flo_{50} in days) and days after sowing to physiological maturity (PM in days), branches per plant (BP in number), plant height at harvest (PH in m), grain yield (GYP in g plant^{-1}) and thousand grain weight (TGW in g). All the plant measurements were taking from the middle rows to avoid side effects.

The Agence National de la Météorologie (ANAM) provided this research with the necessary meteorological information to compare both research sites. Maximum, minimum and mean air temperatures (°C), just like precipitation (mm) and average wind speeds (km h^{-1}) were recorded daily to evaluate the effect of weather phenomenon's on plant growth and development in both experimental sites. The day length information, for each day of the growing season, was adjusted according to the latitude and longitude of interest using an excel spreadsheet provided by the National Atmospheric and Oceanic Administration (NOAA).

RESULTS

The soil texture is characterised for being sandy-loam at both research stations (0-0.20 m), while turning into sandy-clay-loam at lower depths (0.20-0.40 m) (Table 1). In both locations, the soils are acidic (pH value

Tab. 1. Physic-chemical properties of the soil at different depths (0-0.2, 0.2-0.4 and 0.4-0.6 m) at Saria (Soudano-Sahelian zone) and Farako-Ba (Soudanian zone).

Parameter	Units	Saria			Farako-Ba		
		0-0.2	0.2-0.4	0.4-0.6	0-0.2	0.2-0.4	0.4-0.6
Sand	%	78.4	60.8	39.2	73.5	56.8	46.0
Silt	%	13.7	15.7	13.7	16.0	15.1	13.1
Clay	%	7.9	23.5	47.1	10.5	28.1	40.9
USDA class		Sandy-Loam	Sandy-Clay-Loam	Clay	Sandy-Loam	Sandy-Clay-Loam	Clay-Loam
pH (H_2O)		5.4	5.2	6.8	5.5	5.2	5.3
C	%	0.34	0.28	0.21	0.31	0.30	0.26
Org. matter	%	0.58	0.48	0.36	0.52	0.51	0.54
N	%	0.034	0.031	0.022	0.029	0.030	0.23
C/N		10.0	9.0	9.0	10.0	10.5	10.5
P total	mg kg^{-1}	146	120	137	108	121	123
P $_{Bray1}$	mg kg^{-1}	11.5	2.4	0.6	8.3	1.2	0.4
K total	mg kg^{-1}	940	1380	1575	1575	1941	2307
K available	mg kg^{-1}	41.4	29.5	44.4	80.7	86.6	62.8

of 5.5), with a slightly higher organic matter and nitrogen (N) content in Saria when compared to Farako-Ba. Low carbon nitrogen ratios (C:N 10 at 0-0.20 m) have been reported in both sites, showing showing a fast rate of decomposition of in the soil due to high temperatures. The availability of Phosphorus (P) in the first layer of the soil is higher in Saria than Farako-Ba (11.5 mg kg^{-1}

and 8.3 mg kg^{-1}, respectively); whereas the availability of Potassium (K) in the top layer is double at Farako-Ba than in Saria (80.7 mg kg^{-1} and 41.4 mg kg^{-1}, respectively).

Warm mean-temperatures (between 24 °C and 33 °C) have been consistent during the growing period of quinoa in both sites and for all sowing dates, with slightly higher mean-temperatures at Saria than Farako-
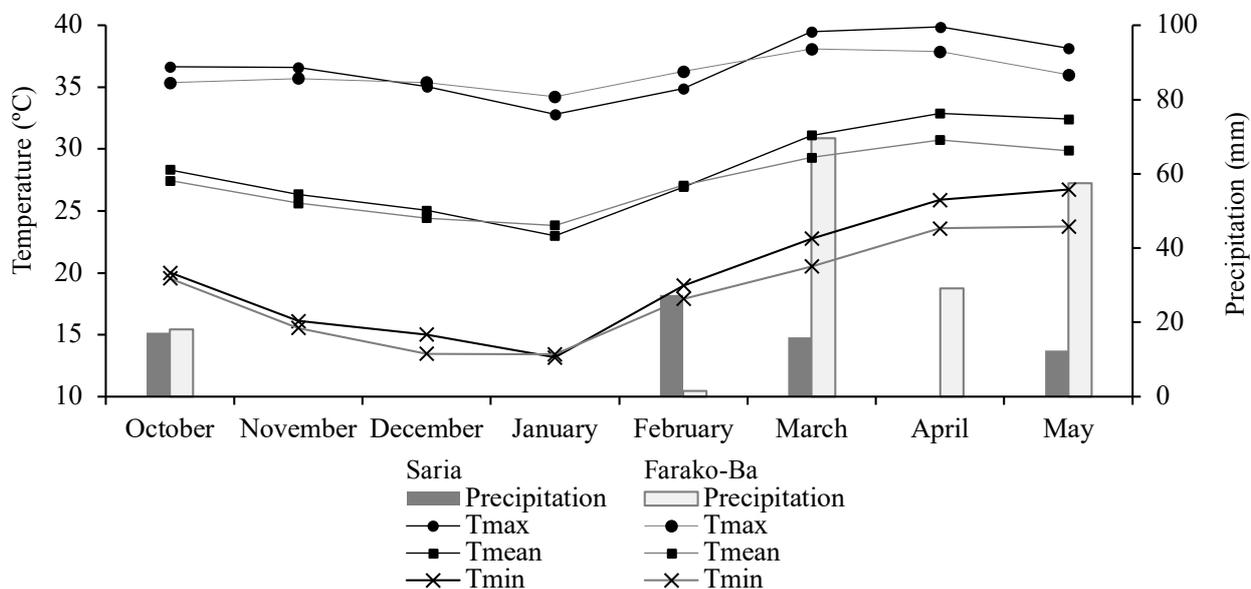

Fig. 2. Maximum/minimum mean monthly and average monthly temperatures (°C) and precipitation (mm) at Saria (Soudano-Sahelian zone) and Farako-Ba (Soudanian zone).
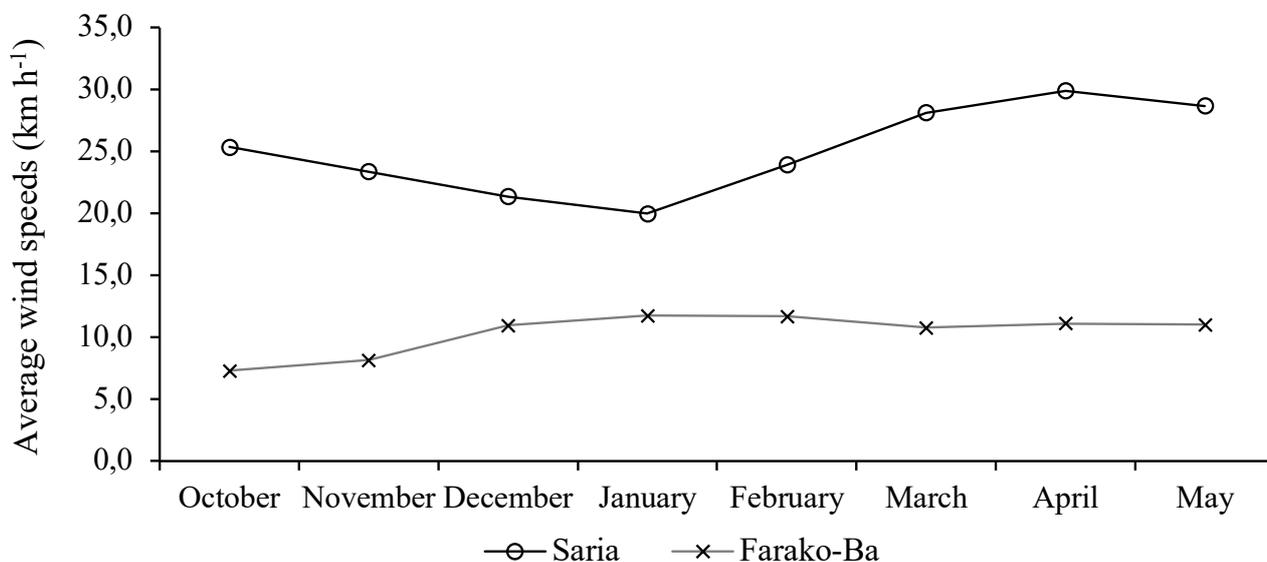

Fig. 3. Monthly average wind speeds (km h^{-1}) at Saria and Farako-Ba research stations.
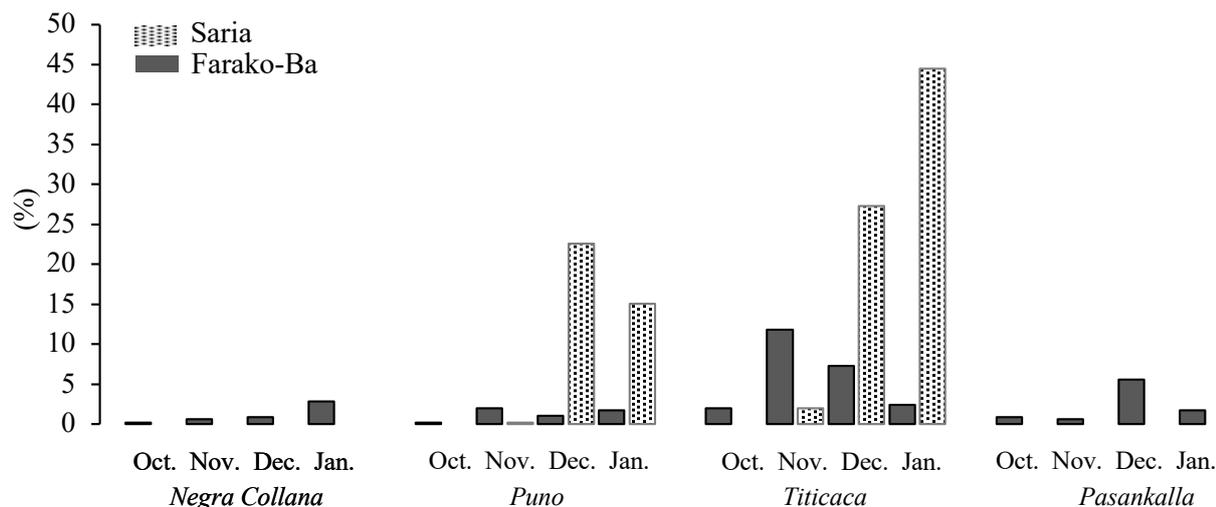
Fig. 4. Percentage of plants flattened by wind gusts for the different sowing dates (October, November, December and January), genotypes (Negra Collana, Puno, Titicaca and Pasankalla) in both experimental sites (Farako-Ba and Saria research stations).

Ba (Figure 2). Maximum monthly mean temperatures oscillated between 35 °C and 40 °C, particularly between October-November and February-May. Atypical precipitation for the time of the year has been reported in both sites, being exceptional the values recorded in March at Farako-Ba (70 mm) and during February and March at Saria (27 mm and 16 mm, respectively). Strong Harmattan winds (prevailing winds from the north) have been observed in both sites, being more intense in Saria during the warmest months of the year (March and April). Much higher average wind speeds have been reported in Saria than Farako-Ba, with mean wind speeds of 25 km h^{-1} and 10 km h^{-1}, respectively during the growing period (Figure 3). The impact of high wind speeds at Saria has resulted in a high number of plants flat-

tened by winds (Figure 4). The most affected genotypes by wind have been Titicaca and Puno at Saria, with 45 % of the Titicaca plants flattened in January and 23 % of the Puno plants flattened in December. These genotypes are characterised for having a smaller stem diameter, root development and lower number of branches than Pasankalla and Negra Collana (Alvar-Beltrán *et al.*, 2019a, Dao *et al.*, 2019).

Even though quinoa is a highly sensitive plant to changes in photoperiodicity, this research trials have been conducted in two sites with small differences in latitude (Farako-Ba at 11°N and Saria at 12°N). Therefore no impact on time to reach physiological maturity has been reported among sites (Figure 5). However, there is a positive correlation between sowing dates and time

Tab. 2. Over all means (± SE) of six traits for the four quinoa genotypes in both experimental sites (Farako-Ba and Saria).

Site	Variety	Crop parameters					
		Flo50 (days)	PM (days)	BP (number)	PH (m)	GYP (g plant^{-1})	TGW (g)
Saria	Puno	38.7±7.4c	78.7±20.7c	27.1±7.2a	0.86±0.12b	7.6±6.8a	1.9±0.6c
	Titicaca	36.2±8.2d	76.9±21.7d	22.4±7.1b	0.76±0.14c	7.0±7.2a	2.4±0.7a
	Pasankalla	48.1±6.8a	113.4±20.0b	21.7±8.1b	1.11±0.16a	9.4±5.1a	2.1±0.7b
	Negra Collana	47.4±6.8b	125.1±23.0a	21.1±8.3b	0.92±0.16b	0.5±1.5b	1.7±0.7c
Farako-Ba	Puno	39.5±13.1b	78.3±25.1c	14.1±4.3a	0.61±0.18a	3.2±2.2b	1.6±0.5a
	Titicaca	38.3±13.4b	77.5±25.5c	16.1±4.2a	0.62±0.19a	4.7±2.2a	2.0±0.5a
	Pasankalla	53.6±12.7a	113.5±24.9b	9.9±4.3b	0.71±0.19a	1.3±2.3c	1.6±0.5a
	Negra Collana	53.7±12.8a	125.8±26.6a	11.2±4.2b	0.65±0.19a	1.1±2.3c	1.6±0.5a

Legend: means that do not share a letter are statistically significant different (p<0.05).
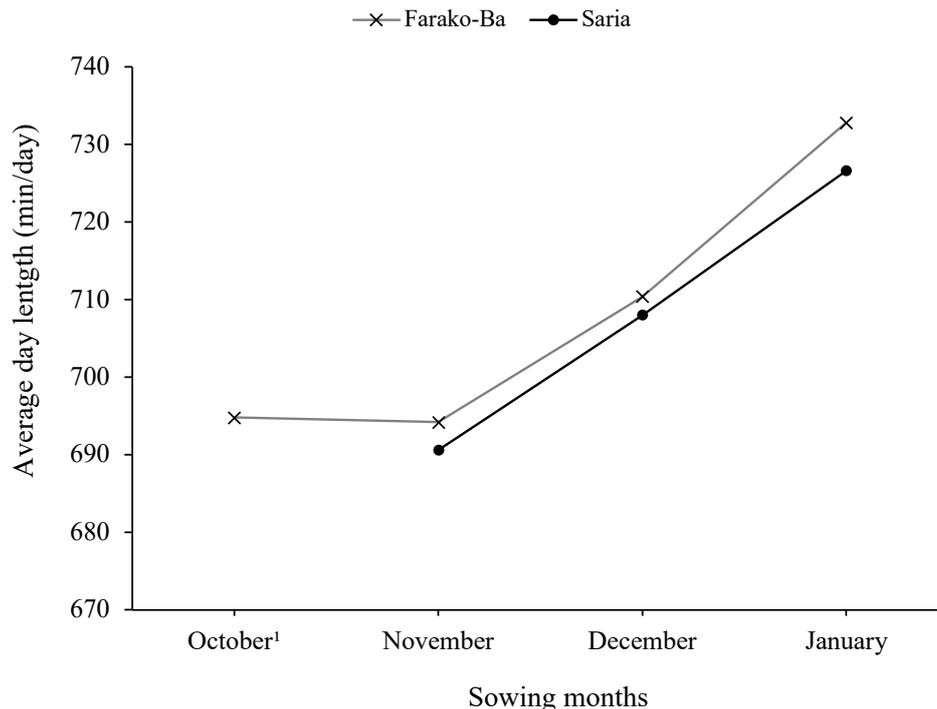
Fig. 5. Average photoperiodicity (minutes day-1) during the growing cycle for the four sowing dates at Farako-Ba and Saria research stations.

to maturity, with a similar observed pattern in both sites (Table 3). For instance, at Farako-Ba, a shorter time to maturity has been noticed among plants sown in October, and which have been exposed to average (from sowing to maturity) day lengths of 695 min day^{-1}. On the opposite, if sowing in January, the average (from sowing to maturity) day lengths are of 733 min day^{-1} and have resulted in a mean time to maturity of 125 days. Statistical differences on time to maturity have been depicted between short and long cycle genotypes, with Puno and Titicaca reaching maturity at 80 DAS, while Pasankalla and Negra Collana after 113-125 DAS (Table 2).

The time for reaching flowering of diverse genotypes of quinoa is significant different (Table 2). While Negra Collana and Pasankalla have attained flowering 50 DAS, Titicaca and Puno have only taken 40 DAS. In Saria, significant differences in time to flowering have been reported between all genotypes, being longest for Pasankalla (48 DAS) and shortest for Titicaca (36 DAS). Whereas for Farako-Ba statistical differences have only been reported between short cycle (Titicaca and Puno) and long cycle varieties (Negra Collana and Pasankalla), but not amongst them.

The number of primary branches varied among genotypes, and is affected by sowing dates and sites (Tables 2 & 3). The average of four sowing dates shows

that the number of primary branches of the early maturing genotypes (Puno, Titicaca) tend to have a high number of primary branches than the late maturing genotypes (Pasankalla, Negra Collana) (Table 2). Difference between the two sites in plant branching was also found, with a twofold increase between Farako-Ba and Saria from 12.8 to 23.1 branches plant[-1], respectively (Table 3). There has been significant differences in terms of plant height between genotypes. For instance, at Saria, Pasankalla had had an average height of 1.11 m, Negra Collana 0.92 m, Puno 0.86 m and Titicaca 0.76 m. A similar genotype-height order has been reported at Farako-Ba. Nevertheless, much smaller plants have been reported at Farako-Ba (0.65 m) than Saria (0.91 m), average of all genotypes, with a 30 % difference between sites. In addition, in both locations, there is a positive relationship between sowing dates and plant height, with higher plants found in December and January (Table 3). The average day length, from the sowing to maturity of the plants, is longer during the sowing of these months (December and January) than in October and November, resulting in a longer vegetative stage among plants exposed to longer photoperiods (Figure 5).

Results are displaying significant differences in yield (average of all genotypes) between sowing dates and locations (Table 3). For the differences between

sites, results show a twofold increase in terms of yield between Farako-Ba and Saria, from 2.57 g plant[-1] to 6.13 g plant[-1], respectively (average of all genotypes). More in detail, Pasankalla, Puno and Titicaca have shown a high performance in Saria with 9.4 g plant[-1], 7.6 g plant[-1] and 7.0 g plant[-1]. For the sowing dates (Table 2), remarkable differences are observed in Saria, with average yields dropping from 16 g plant[-1] to 1.3 g plant[-1], respectively between November and December sowing dates (Table 3). High temperature conditions occurring at flowering are responsible for non-fertilised plants, particularly in Saria where temperatures are higher than in Farako-Ba (Figure 2). In both sites, the most affected genotype by extreme temperatures, in terms of yield per plant, has been Negra Collana (0.8 g plant[-1], average of the two sites), which had the longest cycle out of the four geno-

types in study. In fact, long cycle varieties (Negra Collana and Pasankalla) sown in December and January have been the most affected by temperatures occurring at flowering, 50 DAS. For the previous sowing dates, flowering has occurred when temperatures are highest in the Soudanian and Soudano-Sahelian zone (March and April). However, at Farako-Ba, with milder temperatures than Saria, small differences in yield have been reported between October and December sowing dates, with yields starting to drop from January onwards (Table 3).

Finally, genotype Titicaca has shown the greatest kernel weight (mass of 1000 seeds) in both sites with 2.2 g (Table 2). For both locations, there is a positive relationship with significant differences among sowing dates and kernel weight, having a much higher seed weight plants sown in October/November than in January/Feb-

Tab. 3. Means (± SE) and mean squares of six traits for the different sowing dates in both experimental sites (Farako-Ba and Saria).

Site	Sowing date	Crop parameters					
		Flo50 (days)	PM (days)	BP (number)	PH (m)	GYP (g plant[-1])	TGW (g)
Saria	October[1]	-	-	-	-	-	-
	November	37.3±4.3c	85.8±18.6c	22.9±3.2b	0.85±0.12b	16.4±2.7a	2.8±0.4a
	December	43.1±3.7b	100.8±30.9b	28.3±4.6a	0.98±0.17a	1.3±0.6b	1.6±0.9b
	January	47.5±9.2a	109.0±17.4a	18.7±9.8c	0.96±0.17a	3.1±2.1b	1.4±0.1c
	Sowing date	317.2 ***	1669.5 ***	243.0 ***	541.3 **	477.2 ***	6.9 ***
	Variety	330.0 ***	5375.7 ***	68.9 **	1633.9 ***	3.30 NS	1.5 ***
	Sowing date x Variety	49.8 ***	250.6 ***	156.0 ***	117.9 NS	9.6 *	0.9 ***
	Residual error	0.47	0.47	2.99	7.96	1.52	0.17
	μ	42.61	98.53	23.14	0.93	7.19	2.06
	CV (%)	1.11	0.48	12.94	8.57	21.09	8.11
Farako-Ba	October	41.6±6.3c	84.0±14.7d	12.0±3.5b	0.56±0.15c	2.4±1.2b	2.0±0.6a
	November	40.7±3.7c	89.2±17.6c	10.0±4.1c	0.46±0.12d	2.7±1.4ab	2.1±0.2a
	December	43.4±4.4b	101.4±31.1b	15.0±2.6a	0.72±0.13b	3.7±3.1a	1.4±0.6b
	January	59.3±18.0a	120.6±26.3a	14.8±3.9a	0.84±0.08a	0.2±0.2c	1.3±0.1b
	Sowing date	928.6 ***	3172.8 ***	60.4 ***	3440.8 ***	7.9 **	1.8 ***
	Variety	873.4 ***	7277.9 ***	84.3 ***	350.9 *	13.6 ***	0.4 NS
	Sowing date x Variety	180.1 ***	236.8 ***	4.9 *	268.6 *	4.9 **	0.2 NS
	Residual error	1.78	1.23	2.31	9.89	1.00	0.41
	μ	46.25	98.79	12.98	0.64	2.36	1.70
	CV (%)	3.86	1.24	17.80	15.35	42.39	24.09

Legend: [1]No data has been collected in October sowing date at Saria due to external factors.
Legend: means that do not share a letter are statistically significant different (p<0.05).
Legend: p < 0.001 (***), p < 0.01 (**), p < 0.05 (*), no significance (NS).

ruary (Table 2). Significant differences have been noticed between genotypes in Saria, having Titicaca a kernel weight of 2.4 g, Pasankalla 2.1 g, Puno 1.9 g and Negra Collana 1.7 g (Table 2). However, for Farako-Ba no differences have been depicted between the different genotypes. Overall, the genotype Negra Collana has had the lowest performance, in terms of kernel weight, out of all genotypes, with just 1.65 g (average value of both sites).

DISCUSSION

Pasankalla, Puno and Titicaca are displaying great production, with yields of 16.4 g plant^{-1} (potential yield of 3.28 t ha^{-1}) when sown in November at Saria (Soudano-Sahelian zone). These potential values are similar to the observed yields for Pasankalla in the altiplano and coastal areas of Peru (4.5 t ha^{-1}) (Mujica, 2015). All genotypes of study have shown a strong negative relationship with lower yields under higher temperatures at flowering, notably when sown in January at Farako-Ba (0.2 g plant^{-1}) and in December and January at Saria (1.3 g plant^{-1} and 3.1 g plant^{-1}). Therefore, this research results are not in line with Hinojosa's et al., 2019, findings using cultivars from Chile; but rather in line with experiments affirming that quinoa is highly susceptible to temperatures above 35 °C, which result in pollen sterility (Bertero et al., 1999b; Bertero, 2015b; Pulvento, 2015; Alvar-Beltrán et al. 2019b). In addition, differences in soil characteristics could have been responsible for differences in yield between sites. Razzaghi et al., 2012, have reported higher yields under sandy-loam soils when compared to sandy soils. However, in this research, the main differences in yields between sites are attributed to a higher nitrogen and organic matter content in the soil at Saria than in Farako-Ba. In this line, Alvar-Beltrán et al., 2019b, reported a high bulk density (1.66 x 10^{-3}g/mm^3) at Farako-Ba research station, being a restrictive factor for root development.

Overall, the behaviour of genotype Titicaca under Soudanian environmental conditions is similar to that observed by Alvar-Beltrán et al., 2019a. For instance, the average observed kernel weight of this research (2.2 g) is similar to that observed in the previous experiment in November and December (1.9 g). The values for genotype Titicaca are also in harmony with those observed (2.1 g) in the Mediterranean region when sown in May (Pulvento, 2015). Whereas this research's kernel weight for Negra Collana is higher (1.6 g) to that previously reported in the Soudanian agro-climatic zone (1.0 g) (Alvar-Beltrán et al., 2019b). Other growth parameters, such as plant height and yield, are in line with those

reported by Coulibaly and Martinez, 2015, Dao, 2016, and Habsatou, 2016, under similar agro-climatic conditions (Mali, Burkina Faso and Niger, respectively). For instance, the reported plant height is around 0.80 m for Puno and Titicaca, whereas yield varies from 4 t ha^{-1} to 3 t ha^{-1}, respectively. Emerging findings have shown that these two varieties can attain 18.8 g plant^{-1} (Titicaca) and 16.8 g plant^{-1} (Puno) if sown in November at Saria (potential yield of 3.8 t ha^{-1} and 3.4 t ha^{-1}, respectively). In Kenya, significant differences are reported in the number of branches between 24 cultivars (Khaemba, 2015); whereas in this research, very few differences have been reported between genotypes.

Although, Hirich et al., 2014, have reported longer growing periods among plants exposed to shorter photoperiods and lower solar radiations, our research is in line with the following studies (Bertero, 2001; Jacobsen 2003; Noulas, 2015; Rojas et al., 2015). In fact, quinoa has had a more rapid growth and reached flowering faster under shorter photoperiods. Several studies have observed that time to flowering under different photoperiods does not vary much among genotypes. In fact, quinoa's response to different day lengths is reported after, at time to maturity and on plant height (Fuller, 1949; Christiansen, 2010; Bertero, 2015a). In both cases, plant height and time to maturity is positively affected by day length. Other plant parameters that react positively to longer day lengths are the number of leaves, but this parameter has not been considered in the present study (Bertero, 1999a). The present investigation has also observed significant differences when genotypes interact with sowing dates, having different photoperiods (particularly between November, December and January). These differences are depicted in terms of time to flowering, time to maturity and plant height, showing a positive relationship between time and height with the duration of the day.

CONCLUSION

The different genotypes of quinoa tested in this research have been exposed to a range of adverse conditions and have consequently responded differently. The multiple cultivars of quinoa have shown a high sensitivity to photoperiodicity, adapted to its ecotype of origin, just like differing between them: Puno and Titicaca from Denmark (maturity 80 DAS), while Negra Collana and Pasankalla from Peru (maturity 113-125 DAS). High-temperature stresses have had a major impact on long cycle varieties (Pasankalla and Negra Collana), when compared to short cycle varieties (Titicaca and Puno). Wind gusts have had devastating consequences in the

Soudano-Sahelian zone, often more exposed to strong Harmattan winds than the Soudanian agro-climatic zone. Genotypes with a less developed aboveground biomass and architecture of its root system (Titicaca and Puno) have been more exposed to winds than those fully developed and robust plants (Pasankalla and Negra Collana).

Emerging findings are important for developing crop calendars and need to be tailored according to the different agro-climatic zones. Selection of the most suitable crop varieties and improving existing crop management practices are also crucial. This research results bring to light the need to grow during the coldest period of the year (December and January) in order to avoid heat-stress at flowering and benefit the most of optimal temperatures for growth. Also, because the growing of quinoa during the rainy period (June to September) in these regions has not yet been successful (unpublished data). For this reason, sowing dates should target October and November in the Soudano-Sahelian zone and from October to December in the Soudanian zone. The previous genotype, together with Titicaca and Puno are more performing than Negra Collana under given agro-climatic conditions and therefore should be prioritized. Finally, considering the direction of the furrows with regards to the prevailing winds (North to South) in this time of the year is critical for diminishing the effect of strong winds on crop development and for maximizing plant density at harvest.

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Response of maize yield under changing climate and production conditions in Vietnam

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Abstract. This study concerns rainfed maize (Zea mays. L) grown in two different (winter and spring) growing seasons under current and future climate conditions in north-east of Vietnam. The yield response of rainfed maize was investigated by applying the DSSAT CERES-Maize crop model and two climate scenarios according to Representative Concentration Pathways (RCPs), RCP 4.5 and RCP 8.5. The results show that maize responds with a wide range of yield-levels due to the different climatic and production conditions. On average, under RCP 8.5 climate scenario, annual maize yield (including both winter and spring maize yields) increases by 1.1% while under RCP 4.5 the increase is 3.6%. The annual balanced maize yield increase under both RCPs is based, however, on significant changes in the simulated winter and spring maize yields, respectively. Winter maize yield was simulated to rise up to 33.3% and 31.9% under RCP 4.5 and RCP 8.5, respectively. In contrast, simulated spring maize yield decreases under both RCP 4.5 and RCP 8.5 by 30.3% and 33.9%, respectively. From those findings, it can be concluded that rainfed maize yields under future changing climatic conditions maybe positively affected in winter growing season while it will be reduced in the spring growing season, mainly due to increasing drought stress. Therefore, irrigation will be crucial key for spring maize production in the future to mitigate the effects of changing climate on crop water availability.

Keywords. Maize production, crop model, DSSAT, CERES-Maize, climate scenario, drought, adaptation, Vietnam

INTRODUCTION

An increase in the frequency and intensity of drought events is considered a consequence of climate change impact in many regions of the world (Baldock et al., 2000; Powell and Reinhard, 2015; Steffen et al., 2015). In the north of Vietnam, the decrease in precipitation by 5 to 10% throughout the year (IMHEN, 2011) has recently been considered as the main reason for increasing drought events, causing negative effects on crop production such as for grain maize (Thi-Minh-Ha et al., 2011).

Maize originated in South America (Mangelsdorf, 1947) and the highlands of Mexico (Tenaillon and Charcosset, 2011; Mickleburgh and Pagán-Jiménez, 2012). Maize is the third largest crop after wheat and rice globally and is cultivated around the world under a wide range of climatic conditions, from the temperate to tropical zones (Hardacre and Turnbull, 1986). However, changing climate conditions, such as increasing droughts, could become limiting factor that negatively influence maize growth.

Concerning water requirement, maize shows a wide range of responses in different production and climatic regions, depending on factors such as potential evapotranspiration and cultivar specific characteristics (e.g. phenological development). For example, over a province in the north of Iran, the total water requirement for maize cultivation, derived from satellite and meteorological data, ranges from 345 to 384 mm (Kamali and Nazari, 2018)there's a need for further investigation on various crops to identify the optimum water requirements to avoid water wasting in regions that are already facing water shortage. The focus of this work is to determine water requirement maize farming Mazandaran Province in Northern Iran, located on the southern side of the Caspian Sea, using Landsat satellite data. In order to use SEBAL algorithm, the images were atmospheric calibrated. Evapotranspiration maps with RMSE values equals to 0.73, 1.38 and 0.74 mm/day were produced and compared to Reference Book (RB while it is approximately 423 mm in a region of Ethiopia (Araya et al., 2015) and gets much higher in another region near the river basin in Northwest China with 618 mm (Zhao et al., 2010) six methods for estimating ETc have been applied to maize field in the middle Heihe River basin, China. The ETc was estimated by the soil water balance and Bowen ratio-energy balance methods while the Priestley–Taylor, Penman, Penman–Monteith and Hargreaves methods were used for estimating the reference evapotranspiration (ET0. These differences in water requirement for maize indicate that the response of maize not only depends on local weather conditions but also on genetics

and other factors, such as crop management, prevailing soil and topographic conditions.

To identify and analyze climate change or weather impacts on crop growth dynamics, crop yields and effects of different crop management options, process-oriented crop models are widely used (e.g. Devkota et al., 2013; Ebrahimi et al., 2016; Eitzinger et al., 2013a, Jones et al., 2003).

As a decision support system of several crop-specific simulation models, the DSSAT (Decision Support System for Agrotechnology Transfer) shell (MacCarthy et al., 2017) has been used for more than 30 years worldwide for various purposes (e.g. Kadiyala et al., 2015). In most studies, DSSAT has been approved that it is a useful tool for crop simulation (Soler et al., 2011). DSSAT crop models' performance and sensitivity analysis were carried out for the most important crops in many studies (Eitzinger et al., 2013b; Kisekka et al., 2017)However, calibration and validation do not cover all cultivars, weather conditions as well as soil conditions all over the world. The DSSAT crop model for maize used in our study, CERES-Maize, has been used in other studies to simulate grain yield, maximize the maize yield, and help to avoid yield losses (Iyanda et al., 2014; Jing et al. 2017; MacCarthy et al., 2017). However, DSSAT models have some limitations, for example Ngwiraet al. (2014) proved that it performed well for no-till and crop residue impacts but poor for crop rotation effects.

Being the first crop simulation study on the impact of climate change on maize production in the central north of Vietnam, we first tested the performance of CERES-Maize model for simulating seasonal maize growth under local conditions. We then applied the model to simulate maize yields for 100 years from 2001-2100 under two climate change scenarios (CCSs) of RCP 4.5 and RCP 8.5, respectively, in order to determine the response of maize yields to climate change conditions in Thai Nguyen province, a mountainous region in the north of Vietnam.

MATERIAL AND METHODS

To run process-based crop models for a specific location, a set of minimum data is required (MacCarthy et al., 2017). These include daily meteorological data (from Thai Nguyen center for Hydro-Meteorological Forecasting), soil data (from Thai Nguyen Department of Environment and Resources), field experiment data (from field experiment by Nguyen(2008)) and crop management data (from The Department of Agriculture and Rural Development, Thai Nguyen).

Material

The meteorological data were obtained from two local weather stations covering together 55 years from 1961 to 2015, namely Dinh Hoa station and Thai Nguyen station. They both record daily maximum temperature, minimum temperature, solar radiation, rainfall, and relative air humidity. The observed daily weather data from Dinh Hoa weather station was only available for 30 years from 1961-1990 while the daily data from Thai Nguyen weather station were recorded for 25 years from 1990-2015. However, the monthly weather data from Thai Nguyen weather station was available for 35 years from 1980-2015, providing an overlapping period from 1980-1990 of both weather stations to support the observed trend of climate change in Thai Nguyen province.

Soil properties involving soil textures, pH (acidic water-based solution), OM (organic matter), total N (total nitrogen), CEC (Cation exchange capacity) were examined by additional soil profilesfrom maize fields to ensure the accuracy of crop simulation. Three main soil types were chosen to simulate maize yields based on the main local soil types namely Ferralsols, Acrisols and Fluvisols (Tab. 1). Generally, Ferralsols and Acrisols are the two main soil types in Thai Nguyen province, with Ferralsols occupying approximately 75% of the total land area (TNDNRE, 2015). However, according to the FAO soil classification, local soil properties in some regions may fit to Acrisol classification. In addition, Ferralsols and Acrisols, Fluvisols and Gleysols are commonly found near the river banks and are strongly affected by flooding in the rainy season in the case of a poor water-drainage system; however, they only occupy tiny proportions.

Field experimental data, used for crop model calibration of 3 selected maize cultivars, were collected from a report published in Thai Nguyen scientific journal in 2008. In the field experiment, three maize cultivars (SX2010, SX5012, and LVN 47) were grown in spring and winter season in 2007/2008 under irrigated condition and optimized fertilizer application (Nguyen, 2008) (Tab. 2). Each field was planted by different maize hybrid cultivars in the area of 1 ha. The field experiment provided statistical significant data (P-value < 0.05) for five main genetic plant coefficients for cop model calibration for each cultivar, including total number of leaves per stem (LAIH), beginning peg stage (days after sowing) (R2AT), day of physiological maturity (harvest day) (MDAPs), leaf area index (LAIXS) and grain yields (HWAMS), (Nguyen, 2008).

For model validation de-trended reported annual yields from regional yield statistics of recent past 15 years were used, to meet recommended validation setups (e.g. Grassini et al., 2017). For this baseline period of 2000-2014, additional information on current crop management practices (common planting date, fertilizer dose and application schedule, irrigation system, irrigation schedule, pest management) was collected by the author, provided by 10 local agricultural experts from the Department of Agriculture and Rural Development, Thai Nguyen.

Tab. 1. Soil properties of examined soil profiles in the study region (Thai Nguyen province, Vietnam).

Profile	Depth (bottom) (cm)	Texture (%) < 0.002	Texture (%) 0.02-0.002	pH (KCl)	OM (%)	Total N (%)	CEC (cmol/kg)	Drained Lower limit	Drained Upper limit	Bulk density g/cm³
Profile A – Dong Hy	0-20	15.1	49.8	5.2	1.49	0.05	11.5	0.064	0.143	1.2
GleyicAcrisol	20-90	23.7	9.8	4.2	0.44	0.04	5.7	0.052	0.078	1.56
	90-120	23.7	9.1	4.3	0.37	0.03	4.3	0.051	0.075	1.58
Profile B - Vo Nhai	0-20	15.2	33.3	4.5	0.6	0.03	11.5	0.065	0.132	1.42
Calcic-Acric-Ferralsols	20-80	16.5	30.1	4.2	0.3	0.01	5.7	0.07	0.135	1.48
	80-120	16.9	30.9	4.4	0.1	0.01	4.3	0.057	0.11	1.51
Profile D - Phu Binh	0-20	18.2	33.5	6.0	1.7	0.06	18.1	0.147	0.283	1.29
Fluvisols	20-60	20.1	32.9	5.5	0.3	0.03	11.1	0.121	0.226	1.47
	60-120	17.8	35.1	5.0	0.1	0.01	9.4	0.106	0.209	1.48

(OM: Total organic matter; CEC: Cation exchange capacity).

Tab. 2. Calibration results of the DSSAT model forthespring maize season.

Genotype / Crop indices	SX2010		SX5012		LVN47	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
Planting date (DOY)	Spring	53	Spring	53	Spring	53
Silking(Beginning Peg stage) (*)	77	70	75	62	77	70
Physiological maturity (Harvest) (*)	117	105	121	99	125	105
Leaf index, at harvest	3.6	5.72	3.9	5.59	4.0	5.98
Number of leaves per stem	20.2	15.62	20.2	14.18	20.1	15.29
Yield (kg/ha)	5720	5993	6350	6144	5990	6202

(*) (days after planting).

Climate change scenarios

Two climate scenarios from the Representative Concentration Pathways (RCP), RCP 4.5 and RCP 8.5 were used in this study. They are stabilized to limit radiative forcing at 4.5 and 8.5 W m^{-2}, respectively. Both of them were created by Danish Meteorology Institute and derived from CORDEX (coordinated Regional Climate Downscaling Experiment https://esg-dn1.nsc.liu.se/search/cordex/). The scenarios were based on the driving GCM (global circulation model), namely ICHEC-EC-EARTH and the RCM (regional climate model) DMI-HIRHAM5.

Methods

Crop simulation

In this study, spring (from February to early May) and winter (from October to early January) maize yields were simulated by the crop model CERES-Maize.

The simulation was implemented by setting the different sowing time of winter and spring maize and the share of three soil types within the case study region (Tab.1). The crop management was the same in all simulations, except for irrigation. Irrigation in the simulation was applied only for model calibration and validation, to reflect support irrigation practice. Every single estimated annual maize yield is calculated as an average of two simulated seasonal maize yields in the year. Annual yields were calculated in order to validate the model performance between simulated and reported annual maize yield. The maize yields were available only at annual basis for Thai Nguyen province for 15 years (TNDNRE, 2015).

Crop model calibration and validation

To ensure and enhance the accuracy of simulation results, model parameter estimation is a critical aspect of crop modeling because simulation results heavily dependent on parameter values, particularly crop (growth) parameters. The calibration of this study was based on the above described maize experiment in winter and spring 2008.

Based on the cultivars related calibration settings, validation of simulated grain maize yields was carried out using regional yield statistic reports of Thai Nguyen province of annual maize yield during the period of 15 years from 2000-2014 (TNDNRE, 2015). The three main regional soils (Tab.1), historical weather data and common crop management practice was used as input data to simulate the seasonal grain maize yields.

Finally, model performance analysis was carried out by two statistical methods as follows:

The Normalized Rood Square Error (NRMSE) was used to evaluate the performance of CERES Maize model using the simulated and observed maize yield as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(o_i\text{-}s_i)^2} \qquad (1)$$

$$NRMSE = \frac{RMSE}{\overline{O}}\times100 \qquad (2)$$

where RMSE: root mean square error, NRMSE: normalized root mean square error, n: number of simulated years, s_i: simulated maize yield in year I, o_i: observed maize yield in year I, : the mean of observed maize yield

NRMSE gives a relative measure (%) of the difference between simulated and observed data. The smaller the value of RMSE, the better the model performance,

while a minimum of zero implies the perfect model fit. The simulation is considered excellent with a NRMSE less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if the NRMSE is greater than 20% and less than 30%, poor if the NRMSE is greater than 30% (Bannayan and Hoogenboom, 2009).

The second indicator used for estimating model performance was the Index of Agreement (d):

$$d=1-\frac{\sum_i^n (O_i-S_i)^2}{\sum_i^n (|S_i-\overline{O}|+|O_i-\overline{O}|)^2} \qquad (3)$$

Where d: index of agreement, O_i: Observed yield in year i, S_i: Simulated yield in year I, : the mean of observed maize yield.The Index of Agreement (d) developed by Willmott (1981) is a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all (Willmott, 1981). Besides, the index of agreement can detect additive and proportional differences in the observed and simulated means and variances; however, it is overly sensitive to extreme values due to the squared differences (Legates and McCabe, 1999).

De-trending observed yields

Technological improvements that lead to more effective crop production techniques over time, e.g. during the validation period (2000-2014) add a yield impacting factor. These trends are normally not simulated in multi-year crop model application such as in our study. Therefore, to obtain a reliable comparison (for model validation) between multi-year regional yield reports and simulated yields, the observed yield trends caused by improved production technology were removed by de-trending the yield time series. The year to year residuals from the smoothed time series of observed maize yields were calculated by a 6-year running mean, as shown in equation (4):

$$y=\frac{x-\overline{x}}{\overline{x}}\times100(\%) \qquad (4)$$

Where y is the residuals, x is the actual value, and represents the smoothed 6- year running means.

RESULTS

Climate change in Thai Nguyen province

Local weather in Thai Nguyen province, Vietnam, revealed an increase in temperature and a reduction in precipitation (Fig. 1) within the observed period (1990-2015).

Similarly, an increasing trend of temperature and a decreasing trend of precipitation conditions in the local area was figured out by the data from projected period (2001-2100) under two climate change scenarios (i.e. RCP 4.5 and RCP 8.5. The average annual temperature increases from 24.4 °C (1990-2015) to 25.9 °C (2001-2100) under RCP 4.5 and 26.5 °C (2001-2100) under RCP 8.5. In contrast, a substantial reduction in precipitation by approximately 67.4% and 47.7% under RCP 4.5 and RCP 8.5 was determined in comparison with the average precipitation during the observed period from 1990-2015. Further, the decreasing trend of precipitation seems logical by the increase in annual and monthly percentage of dry days (Fig. 2). The total number of dry days was projected to increase, especially under RCP 4.5 by 72.3%, followed by RCP 8.5 with the value of number dry days is 71.2%.

The performance of CERES-Maize model

The result of the calibrated CERES-Maize model with three regional representative cultivars was very good for simulating the grain yields in the spring season, 2008. The percentage similarity between the observed grain yield and simulated grain yield was approximately 98% for all three maize varieties. Crop development was simulated acceptable, where e.g. for silking the deviation was 7 days (2 cultivars) and 13 days for the third cultivar (SX5012). A restriction for that comparison was that the sowing date from the experiment was not reported and, therefore, was set according to expert assessment. However, the observed leaf area indices were lower than the simulated ones, whereas the observed numbers of leaves per stem were higher than the simulated ones (Tab.2). These results show that there was still a misbalance between observed and simulated leaf areas (overestimation by the model) and the number of leaves (underestimation by the model) probably due to a deviation of mean leaf size and specific leaf weight to reality. Unfortunately, there were no further experimental data available for clarification.

Similar to the results for spring maize, for winter maize the CERES-Maize model showed a good agreement between observed and simulated grain yields. The percentage of similarity, however, ranged only from 78 to 88% for the three varieties. Crop development was slightly better simulated than for spring maize, where e.g. for silking the deviation was 5-6 days (2 cultivars) and again 13 days for the third cultivar (SX5012). Nevertheless, the accuracy of the crop model was again low
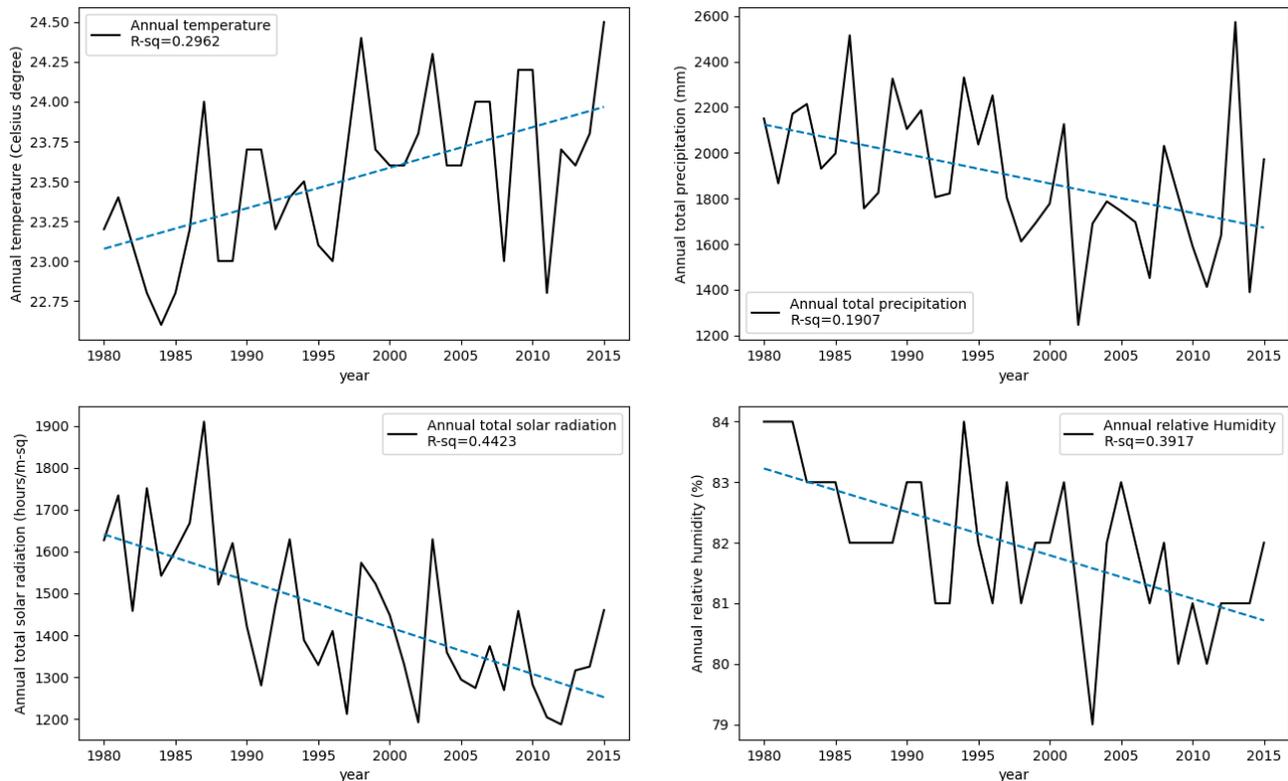
Fig. 1. Annual temperature and precipitation data from 1980-2014 in Thai Nguyen, Vietnam (R-sq termed R square).

in terms of leaf indices, in specific by a significant over-estimation of the leaf area index (Tab.3).

Based on these calibration results, we conclude that the CERES-Maize model was moderately good calibrated and acceptable for simulating maize grain yields in the region of interest with three representative cultivars. The genetic parameters for these maize cultivars are presented in Table 4.

CERES-Maize model validation under fixed irrigation

Due to a lack of suitable field experimental data, model validation was carried out on regional statistical grain maize yield reports (e.g. Grassini et al., 2015) of annual production, where no deviation between spring and winter maize is available. As in agricultural practice, maize is normally irrigated on demand, we validated CERES-Maize for irrigated simulation.

In general, moderately good performance of the CERES-Maize model was achieved with a NRMSE value for the annual maize yields of 10.3%. As the simulated yield level between spring and winter maize differs in most of the years, the comparison between the mean

simulated seasonal and mean annual reported yields shows a larger NRMSE value of 18.9% (spring maize) and 19.4% (winter maize) (Fig. 3).

Analysis of the performance of CERES-Maize by Index of Agreement (d) showed a moderate match between observed (statistical) annual maize yields and simulated annual maize yields with the (d) value of 0.77 (Fig.3).
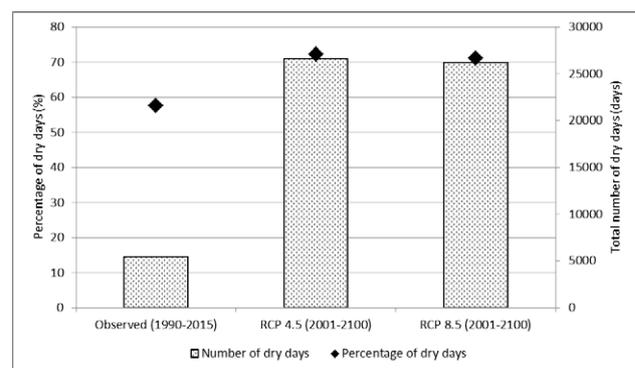

Fig. 2. Number of dry days from observed period (1990-2015) and projected period from 2001-2100 under RCP 4.5 and RCP 8.5.

Tab. 3. Calibration results of the DSSAT model for thewinter maize season.

Genotype / Crop indices	SX2010		SX5012		LVN47	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
Planting date (DOY)	Winter	265	Winter	265	Winter	265
Silking(Beginning Peg stage) (*)	66	60	67	54	68	63
Physiological maturity (Harvest) (*)	120	133	123	122	123	136
Leaf index	2.9	5.66	2.4	5.68	2.9	5.76
Number of leaves per stem	19.6	15.49	19.9	16.22	19.5	16.07
Yield (kg/ha)	6440	7816	7370	8271	5660	8072

(*) (days after Planting date).

Concerning the technical improvement, the results reveal that the performance of CERES-Maize grain yield simulation between de-trended observed yields and simulated yields is better than the performance of the model between the real observed yields and simulated yields, shown by an increase of d-index from 0.77 to 0.86 and a decrease of the value of NRMSE from 10.3% to 7.3%. It was assumed that the detrended results are removed from climate-related influences such as new technologies in crop management or better cultivars.

Rainfed winter and spring maize yields under the selected climate scenarios

The simulated annual rainfed maize yields were mostly highest in the second 30-year period from 2035-2065, followed by the first 30-year period from 2001-2030. The lowest maize yields were received in the period 2070 – 2100. Besides, the average maize yields under both RCPs are quite similar. Under the RCP 4.5 scenario, the mean annual maize yield, the mean spring maize yield, and the mean winter maize yield are about 3957 kg/ha, 2483 kg/ha, and 5411 kg/ha, respectively, where under RCP 8.5 they are about 3854 kg/ha, 2353 kg/ha, and 5355 kg/ha, respectively (v. 4a-d).

In comparison with observed annual maize yields in the historical period (2000-2014), under the RCP 4.5 scenario, the mean annual rainfed maize yields over the 100 year period 2001-2100 increase by +3.6%, contributed by the increase in winter maize yields by +33.3% and a reduction of spring maize yields by 30.3%.

Under the RCP 8.5 scenario, the simulated spring maize also decreased in comparison with observed spring maize yield, and especially dramatic from 2070-2100 with a decline of 50.1% (w. 5). The simulated win-

Tab. 4. Calibrated crop coefficients for Thai Nguyen, Vietnam.

| COEFF	Definitions	SX2010	SX5012	LVN47
P1	- Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not response to change in photoperiod.	140.4	121.0	125.0
P2	– Extent to which development (express as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h).	0.3	0.0	0.0
P5	- Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C).	685.0	685.0	685.0
G2	- Maximum possible number of kernels per plant.	907.9	907.9	907.9
G3	- Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).	6.6	10.0	10.00
PHINT	– Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	44.92	38.9	38.9
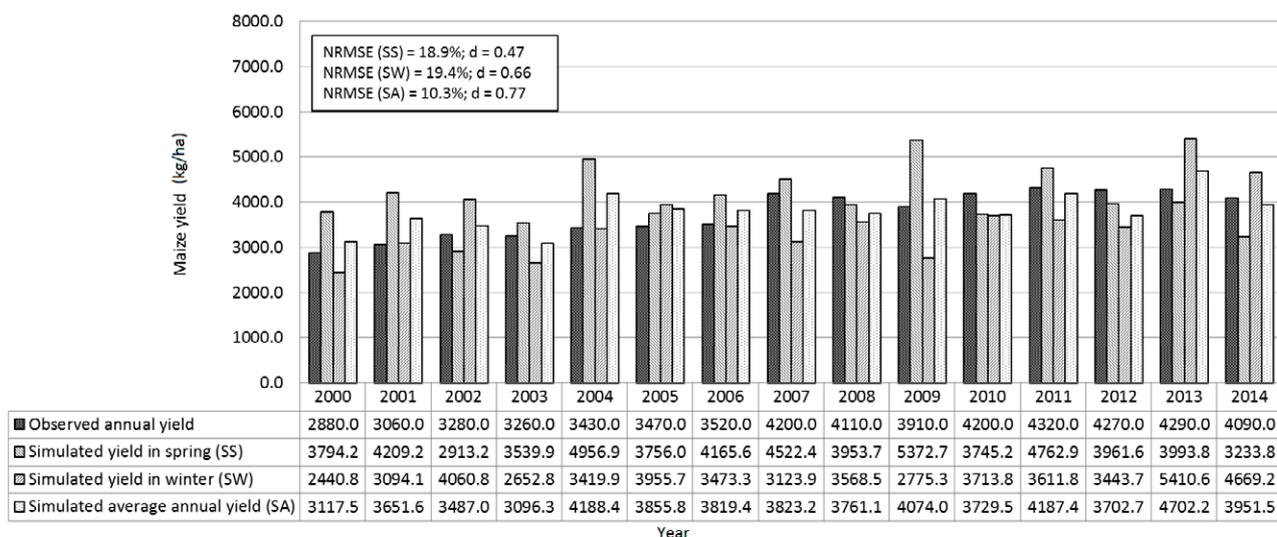
Fig. 3. Yield validation of spring and winter season maize 2000-2014 against statistically reported maize yields.

ter maize yield increased only by +18.2%, leading to a lower increase in annual maize yield compared to RCP 4.5 during the period 2001-2100 by +1.1% compared the observed yields 2000-2014.

DISCUSSION

To identify the impacts of climate parameters for maize yield potentials and trends in Vietnam under climate scenarios we focused on the simulation of rainfed maize only, although this does not fully represent current irrigation practice of occasional support irrigation.

The difference between spring and winter maize yields

On average, the simulated winter maize yields are significantly higher than spring yields. In reality, winter maize in northern Vietnam is sown after the end of the rainy season, where soils have still high water content. During winter maize growing season, precipitation is continuously decreasing, and effective solar radiation (data not shown) increases, forming ideal conditions for yield formation. The spring maize, sown in February, with low soil water contents often suffers drought stress during vegetative period, limiting its yield potential, so the spring maize yield stays lower on average than the yield of spring maize under current climate.

Climate change impacts on maize production in Vietnam and adaptation recommendations

Overall, under the two climate change scenarios in this study, RCP 4.5 and RCP 8.5, climate conditions are projected to be more extreme than in the past with higher temperature and lower seasonal precipitation. Both is expected to negatively impact maize production by a) shorter growing periods for annual crops due to higher temperatures and b) more drought stress conditions due to a higher number of dry days and higher evapotranspiration rates (forced again by higher temperatures).

Related to Thai Nguyen province, especially the spring maize season will suffer by increasing drought under future climate scenarios, while the winter growing season, despite increasing number of dry days, still remains with higher soil water content combined with increasing effective solar radiation. The study showed that annual rainfed maize yields in the 21st century will be slightly higher under two climate scenarios (RCP 4.5 and RCP 8.5) as in the reference period of 2000-2014, and only in the far future (period 2071-2100) would be generally lower than in the past, especially for spring season maize from 2070 to 2100 and under unchanged production technology. Although winter maize yield increase strongly, it could just outbalance the strong decreases in spring maize yields concerning annual yields under both applied climate scenarios. Other impacts on maize production, not considered in our simulation study, additionally can occur (e.g. reduced fertility, increased pest and disease challenges etc.). The influence of high temperature will become even more
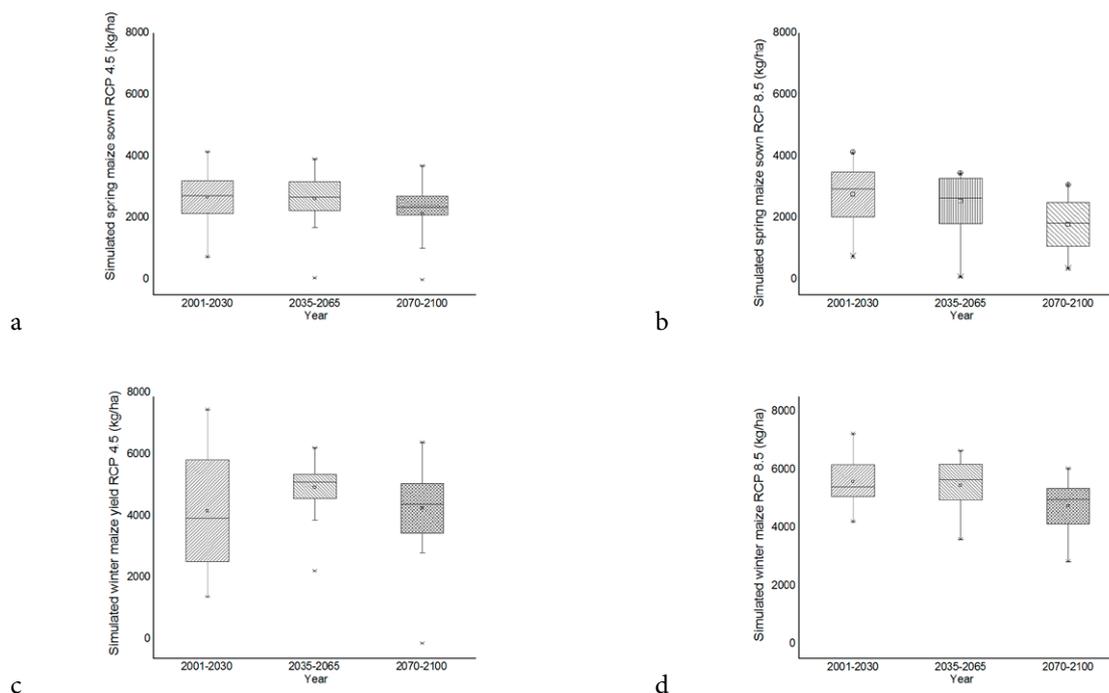
Fig. 4a-d. Simulated rainfed spring and winter season maize yields under the two different scenarios RCP 4.5 and RCP 8.5 for Thai Nguyen province, Vietnam. Boxes present 50% of all cases, including a horizontal line at the median and a dot at the mean.

extreme when it accompanies with water deficiency and drought stress. For example, in central Vietnam, maize yield decreased in dry seasons, driving farmers to change land use systems into other crops such as peanut, cassava or green bean (Uy et al., 2015).

Irrigation is considered globally as a crucial factor to mitigate the influence of drought stress on maize growth (van der Velde et al., 2010). Irrigation will become more important under the climate change perspective, especially in South Asia (Döll, 2002). Due to the typical characteristics of topography and hydrologic conditions of our study region Thai Nguyen, Vietnam, the irrigation system may expose to some difficulties in terms of water delivery in the dry season. Therefore, simultaneously building up an irrigation system, a system of dam or water storage in the local area might be a solution to store water in the rainy season and deliver water in the dry season.

In conjunction with irrigation, a shift in planting date also has positive influence in reducing drought stress impacts on maize production. Abraha & Gårn (2016) reported that flexible planting and rainwater harvesting have a substantial potential for reducing the negative impacts of climate change, and possibly even increasing outputs. In Southern Mali, earlier planting

date of maize in combination with recommended fertilizer rates and late-maturing varieties for medium farms were projected to decrease the impact of warming by 2.9 to 3.3 °C. Under controlled conditions, simulated maize grain yield even increased by 51-57% under current farmer fertilizer practices (Akinseye et al., 2017). Based on the local climate conditions (dry in early spring and late winter season), the planting date, therefore, may shift to be later in the spring season and sooner in the winter season to avoid the most extreme dry periods in early spring and late winter.

Limitations of the study

The uncertainties of our study can firstly be related to the availability of empirical data for crop model calibration and validation, however, fulfilling basic recommendations for crop model applications in data-poor countries (e.g. Grassini et al., 2015). Model validation was hampered by missing recorded seasonal maize yields that were not available in the local reports. Moreover, the recorded yields could have some mistakes that caused by the reporting local farmers and the local agriculture department. Another reason for deviations could be a difference in crop management between reality and
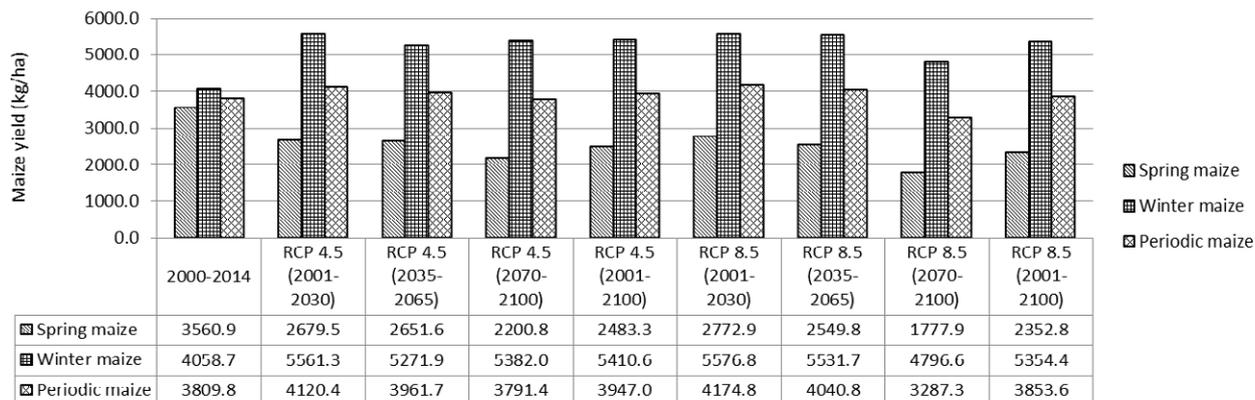
	2000-2014	RCP 4.5 (2001-2030)	RCP 4.5 (2035-2065)	RCP 4.5 (2070-2100)	RCP 4.5 (2001-2100)	RCP 8.5 (2001-2030)	RCP 8.5 (2035-2065)	RCP 8.5 (2070-2100)	RCP 8.5 (2001-2100)
Spring maize	3560.9	2679.5	2651.6	2200.8	2483.3	2772.9	2549.8	1777.9	2352.8
Winter maize	4058.7	5561.3	5271.9	5382.0	5410.6	5576.8	5531.7	4796.6	5354.4
Periodic maize	3809.8	4120.4	3961.7	3791.4	3947.0	4174.8	4040.8	3287.3	3853.6

Fig. 5. Comparison of historical maize and simulated climate scenario periods rainfed maize yields.

simulation, for example, a different irrigation scheme between the simulation and reality in winter and spring seasons. In addition, the applied crop model may not be robust in simulating grain yield under extreme weather conditions, such as soil erosion occurring in the midland of the mountainous area or flooding which occurs in the fields located near the rivers. Further, the fact that we did not account for the potential CO_2-fertilizing effect (although limited for maize, but with complex and still uncertain environmental vs cultivar interactions (Adishesa et al., 2017) as well as crop rotation effects in the simulation (Ngwira et al., 2014), contribute to uncertainties in the results. In the study region, maize is usually cultivated with other crops in a flexible rotation to obtain the highest productivity. Additionally, the real maize yields and long term yield trends are also influenced by various elements that were not considered in the CERES-Maize model runs, such as occasional support irrigation, impacts of diseases and pests, future changes in production methods and technologies (fertilization, irrigation or new hybrid varieties or cultivars better adapted to drought conditions). All these effects are, however, ongoing in our case study region, which is still strongly developing towards more effective production.

CONCLUSIONS

Being the first crop simulation study on the impact of climate change on maize production in the central north of Vietnam, our study revealed important ongoing and potential future climatic changes of the two regional applied maize growing seasons, the spring and winter growing seasons. Main conclusions include especially an increasing rainfed yield difference between the two growing seasons with important implications for increasing irrigation demand, especially for the spring season.

Although the CERES-Maize model applied in our study, showed good performance in estimating maize production under current conditions, several uncertainties remain, calling also for further research and data needs. First of all, there is still a gap on suitable, qualitative regional data bases for climate change impact studies, especially on experimental crop related data sets for model calibration and validation. This includes cultivar specific responses to various stresses such as drought, heat and nutrient based stresses and its combinations. Although the assimilation response to further increasing atmospheric CO_2-concentrations are considered as limited for C4 crops such as maize, uncertainties remain in relation to cultivar vs. environmental effects. More studies with complementary model approaches and ensemble simulations, based on improved and extended regional data bases of agricultural systems and ecosystems are needed to reduce potential uncertainties in future assessments.

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Evaluation of some evapotranspiration estimation models under CO_2 increasing concentrations: A review

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Abstract. The total volume of CO_2 emissions is building up dramatically, and because of the effect of this gas on the growth, physiology, and biochemistry of plants, it is becoming increasingly necessary to look into the impact of the relentless rise of carbon dioxide. Although there are several developed approaches that tried to model the canopy resistance, many of these methodologies ignored the effect of CO_2 or were not incorporated with the existing evapotranspiration calculation methodologies, mainly due to the complexity of the modeling procedure and the short time framework of the conducted studies. This review explores the few models estimating crop water requirements that account for this effect and examines their assumptions and theories. The inclusion of canopy resistance models in evapotranspiration calculation may be of questionable utility without improvements in some modeling aspects, such as the relationship between the stomatal conductance and CO_2 and the climatic variables taken in consideration in the modeling process.

Keywords. Penman Monteith, ETo, carbon dioxide, canopy resistance, surface resistance, climate change.

INTRODUCTION

According to UNDESA (2017), the world population is foreseen to grow between 20-30% by 2050, going from 7.7 billion people in 2017 to between 9.2 and 10,2 billion. Naturally, the global demand for food production is also expected to increase by almost 60% by 2025 (Alexandratos and Bruinsma, 2012; OECD, 2012). On the other side, global water consumption has already known a leap of 600% over the last century (Wada et al., 2016), and it keeps increasing by 1% yearly (AQUASTAT n.d.). Water demand is currently evaluated at 4.600 km^3 and could reach almost 6000 km^3 by 2050 (Burek et al., 2016). All this will put more pressure on the agricultural sector, which is the actual largest world consumer of freshwater, mostly for irrigation, accounting for 70% of freshwater withdrawals, up to 90% by 2050 (WWAP, 2012). Agriculture is also expected to face a fierce competition for water resources from other sectors, resulting in a decrease in its share of total water use in developing countries from 86% in 1995 to 76% in 2025 (Rosegrant et al., 2002). In addition, global warming is meanwhile affecting the water cycle and shifting weather patterns (IPCC, 2014a). Therefore, the agricultural sector is in great need of creating strategies to improve water management and, consequently, attain greater levels of water savings in order to face these aforementioned challenges (de Fraiture and Wichelns, 2010).

One of the key components to improving the management of water resources is accurately determining the water requirements of irrigated crops. These needs depend on the management strategy chosen, and are based on the demand for atmospheric water, known as evapotranspiration. Evapotranspiration (ET) is a major component of the hydrological cycle and has an important effect on the quality of water, since in the evaporation process the water is purified. This clean H_2O restores about 60% of global land surface water. For vegetated ecosystems, it is also the main component of energy balance, employing more than 50% of absorbed solar radiation (Trenberth et al., 2009). In fact, evapotranspiration is a component of the energy budget involving incoming energy and outgoing water, occurring at the crop surface. The other components of the budget are net radiation, sensible heat flux, soil heat flux, and solar radiation stored as photochemical energy. This exchange process creates an atmospheric demand that is satisfied by transferring water out of the plant system through evapotranspiration. Such phenomenon is regulated by the principle of energy conservation or energy balance: energy arriving at the vegetation surface equal energy leaving the same surface for the same time period. The energy balance equation for an evaporating surface can be written as:

$$R_n\text{-}G\text{-}\lambda ET\text{-}H=0 \qquad (1)$$

where R_n is net radiation, H sensible heat, G soil heat flux and λET is the latent heat flux. Terms can be either positive or negative: positive R_n supplies energy to the vegetation surface and positive G, λET and H remove energy from the vegetation surface. The latent heat flux (λET) is the evapotranspiration fraction and can be derived from the energy balance equation, if all other components are known. ET is an important hydrological variable for irrigation water management, hydrological modeling and water balance calculations. Penman (1963) defines ET as the combination of two separate processes occurring simultaneously, evaporation from the soil surface and transpiration from the crop. Since the evapotranspiration is strongly affected by crop type, crop development and management practices, there was a need to find a concept to express the evaporative demand of the atmosphere independently of those factors. Hence, reference evapotranspiration (ETo) was introduced for this purpose. ETo is defined as the evapotranspiration rate from a well irrigated hypothetical grass reference crop with specific characteristics. It expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider crop characteristics and soil factors. Instead, it is driven by weather parameters, which are solar radiation, air temperature humidity and wind speed. A thorough understanding of ETo is the first step to achieving efficient and effective water management and irrigation scheduling. The United Nations Food and Agriculture Organization (FAO) has adopted an updated Penman–Monteith equation (FAO-PM) as a global standard for estimating grass reference evapotranspiration (Allen et al., 1998). This equation was chosen as it provides a better prediction compared to other methods in a wide variety of geographic locations and climatic conditions (Kashyap and Panda, 2001; Yoder et al., 2005; López-Urrea et al., 2006; Suleiman and Hoogenboom, 2007; Adeboye et al., 2009; Rasul and Mahmood, 2009; Rácz et al., 2013). It includes all the different atmospheric variables that influence ET, which makes it suitable for climate change impact studies (Kingston et al., 2009; Islam et al., 2012; Priya et al., 2014). However, despite the completeness of this equation, it simulates poorly the effect of CO_2, that is represented by the "canopy resistance" or "surface resistance" term, r_c. In fact, daily r_c is fixed at 70 s m^{-1} and is considered constant regardless of climate type and change in climate patterns, thus contradicting published reports

(Long et al., 2004; Damour et al., 2010). Although Allen et al. (2006) considered that fluctuation in its value would have a negligible effect on the ETo calculation, many experimental studies disagree with their statement on hourly, daily and seasonal scales (Steduto et al., 2003; Katerji and Rana, 2006, 2011, 2014; Yan et al., 2017). This is particularly true when the crop is under well-watered conditions, i.e. when the physiological component of r_c is at its minimum. The alarming increase of CO_2 concentrations due to climate change, the physiological effects that it would have on crop plants (Tubiello et al., 2000; Long et al., 2004; Mall et al., 2017) and the uncertainties affecting the calculation of ETo using the FAO-PM equation, have prompted many researchers to develop other approaches and models to estimate reference evapotranspiration, taking into account the variability of the canopy resistance r_c. Following a short discussion on the effect of rising CO_2 on crops evapotranspiration, this paper provides an overview of these different methods, delineating their main theories and assumptions, and exploring their strengths and weaknesses.

EFFECT OF CO_2 ON CROPS EVAPOTRANSPIRATION

Our planet's atmosphere witnessed a gradual change throughout history, experiencing a wide range of CO_2 concentration. Studies suggest that this concentration may have been about 4000 to 5000 ppm some 500 million years ago (Ehleringer et al., 2005). Then, this concentration decreased to around 1000 ppm between 35 and 55 million years ago, falling abruptly to about 390 ppm during Oligocene by approximately 32-25 million years ago (Tipple and Pagani, 2007). This decline in CO_2 limited the efficiency of photosynthesis, triggering the evolution of C_4 plants from ancestral C_3 species as a clever solution to the problem of low atmospheric CO_2. Since the pre-industrial era, anthropogenic greenhouse gas (GHG) emissions have been causing new increases in the atmospheric concentrations of carbon dioxide, going from 270 ppm before 1700 to about 410 ppm in 2020, reaching unprecedented levels in at least 800,000 years. The concentration will keep increasing if no additional efforts are made to reduce emissions (IPCC, 2014a, 2014b). These increasing concentrations have important physiological effects on plants, e.g. faster rate of photosynthesis, greater leaf area, increase in biomass and yield and decrease in stomatal conductance and transpiration rate (Allen, 1990; Ainsworth and Long, 2004; van der Kooi et al., 2016). The latter effect has been confirmed by several experimental studies conducted in open-top and closed-top chambers or using the Free-Air Carbon dioxide Enrich-

ment (FACE) method (Wullschleger et al., 2002; Shams et al., 2012). On the other hand, more biomass means more evapotranspiration because of a higher leaf area index (LAI) (Wand et al., 1999; Piao et al., 2010), potentially offsetting the effect of the reduction in stomatal conductance (Bernacchi et al., 2007). However, even under experimental conditions, there is a large uncertainty in the CO_2 induced change in stomatal conductance, especially when scaling from the single leaf to a full canopy where other factors affect the whole process (Polley, 2002). For example, CO_2 effect is significantly different between C_3 and C_4 plants and between trees and smaller plants (Taiz and Zeiger, 1991), but also seems to depend on the scale of the experiment (Jarvis and McNaughton, 1986; Bunce, 2004). In fact, most of the existing knowledge on plants response to higher CO_2 concentrations is based on small scale research experiments conducted in open field with controlled environment. Even if there are techniques such as FACE that allow the exposure of plants to elevated CO_2 concentrations under natural and fully open-air conditions, they can be difficult and expensive to construct and operate, which limits the inference space of these experiments with regards to the range of global ecosystems (Norby et al., 2016). Moreover, there could be an overestimation of the CO_2 effect due to artificial ventilation and advection from outside the FACE area (Kruijt et al., 2008). Given the complexity of the effect of CO_2-sensitivity of evapotranspiration on future climate simulations and the large uncertainty in the CO_2 induced change in stomatal conductance under experimental conditions (Kruijt et al., 2008), understanding plant responses to CO_2 is becoming increasingly important.

This review paper summarizes some of the most documented r_c models, precisely those directly used or modified to account for the effect of CO_2 on the evapotranspiration. The models presented (Table 1) have their limitations that the authors tried to underline. However, because the literature is limited regarding this particular topic, the primary purpose of this review was to provide a brief reference document for researchers and the scientific community in general on the different models developed so far and their main findings and challenges.

DESCRIPTION AND DISCUSSION OF EVAPOTRANSPIRATION APPROACHES ACCOUNTING FOR CO_2 EFFECT

Penman-Monteith method adapted to an increase in CO_2 concentrations

The standardized Penman–Monteith equation (FAO-PM) (Allen et al., 1998) is based on the Penman–Montei-

th equation (Monteith, 1965). It is the most widely used method and has been proven to be a good ETo estimator when compared with other methods, especially for daily computations (Chiew et al., 1995; Liu et al., 1997; Ventura et al., 1999; Jacobs and Satti, 2001; Garcia et al., 2004; Temesgen et al., 2005). For a grass reference surface and for a daily time step, this equation is expressed as:

$$ETo=\frac{0.408\Delta(R_n\text{-}G)+\gamma\frac{900}{T_{2m}+273}.u_2(e_s\text{-}e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{2}$$

where ETo is the reference evapotranspiration (mm day^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^2 day^{-1}); T_{2m} is the mean daily air temperature at 2 m height (°C); u_2 is the wind speed at 2 m height (m s^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa); $(e_s - e_a)$ is the saturation vapour pressure deficit (kPa); Δ is the slope of the vapour–pressure curve (kPa °C^{-1}) and γ is the psychometric constant (kPa °C^{-1}).

The canopy resistance r_c describes the resistance of vapour flow through the transpiring crop and evaporating soil surface. It is represented in the equation above by the value 0.34 in the denominator:

$$0.34u_2=\frac{70}{208/u_2}=r_c/r_a \tag{3}$$

where r_a is the aerodynamic resistance (s m^{-1}), which describes the transfer of heat and water vapour from the evaporating surface into the air above the canopy. For a grass reference surface, assuming a constant crop height of 0.12 m and a standardized height for wind speed, temperature and humidity at 2 m, r_a becomes:

$$r_a=208/u_2 \tag{4}$$

Under the same reference conditions, and knowing that the stomatal resistance r_s of an actively transpiring C3 grass leaf surface has a value of about 100 s m^{-1}, r_c is represented as the following:

$$r_c=\frac{r_s}{0.5\ LAI}=\frac{100}{0.5\times2.88}=69\approx70\ s\ m^{-1} \tag{5}$$

where LAI is the leaf area index of the upper half of dense clipped grass, which is generally the only part actively contributing to the surface heat and vapour transfer (LAI = 24 × crop height (h) = 24 × 0.12 = 2.88)

Assuming that the $r_c \approx 70$ s·m^{-1} applies to a specific CO$_2$ concentration, estimating a new r_c value for higher CO$_2$ concentration provides a method to estimate possible impacts of higher CO$_2$ on ETo. Thus, the following form of FAO-PM equation should be adopted:

$$ETo=\frac{0.408\Delta(R_n\text{-}G)+\gamma\frac{900}{T_{2m}+273}.u_2(e_s\text{-}e_a)}{\Delta+\gamma(1+r_c/r_a)} \tag{6}$$

Lovelli et al. (2010) and Snyder et al. (2011) used this method in a Mediterranean climate, introducing in the equation published values regarding atmospheric CO$_2$ on stomatal conductance (Long et al., 2004; Ainsworth and Long, 2004), and considering the temperature increment effect on the reference evapotranspiration (ETo) variation. They concluded that the effect of increasing CO$_2$ concentration may be annulled by an increase in air temperature and subsequent increase in evapotranspiration rate. On the other hand, Moratiel et al. (2011) found out that the CO$_2$ increase from 372 ppm to 550 ppm would create a reduction of the ETo increment by half, from 11% to 5% in the next 50 years, as compared to the current situation in northern Spain. By recalibrating the canopy conductance for the widely acclaimed and recommended FAO-PM equation, this approach may be particularly effective in evaluating the effects of climate change on crop water use. However, The FAO-PM model is based on the "big leaf" approximation with constant

Tab. 1. Some of the models referenced in this work

Model	Reference	Simulation Period	CO2 concentration
Penman Monteith with a modified r_c	Lovelli et al. (2010)	2071 - 2100	550 ppm
	Moratiel et al. (2011)	2007 - 2050	372 and 550 ppm
	Snyder et al. (2011)	2050	550 ppm
CO$_2$-factor	Easterling et al. (1992)	Analog period: 1931 - 1940	330 and 660 ppm
	Ficklin et al., (2009)	NA	550 and 970 ppm
	Islam et al., (2012)	2010 - 2099	450 ppm to 900 ppm
	Wu et al., (2012)	2071 - 2100	330 and 660 ppm
	Fares et al., (2015)	NA	330, 550, 710 and 970 ppm
F factor	Olioso et al. (2010)	2020 – 2049 and 2070 - 2099	540, 703 et 836 ppm
	Salmon-Monviola et al. (2013)	1961–1990, 2010–2039, 2040–2069 and 2070–2099	330, 430, 545 and 640 ppm
Jarvis	Medlyn et al. (2001)	NA	350–700 ppm
Katerji and Perrier	Katerji et al. (2017)	1981 – 2006 and 2070 - 2100	600 and 850 ppm

canopy resistance, which is a simplistic assumption that could limit the accuracy of the predictions of the model. Considering the driving meteorological variables at a particular site, estimates made with the FAO-PM equation rely on the correct modeling of the effective values of both aerodynamic resistance r_a and canopy resistance r_c. Hence, the fixed value for r_c may be the cause of the tendency for the FAO-PM method to underestimate the higher values of measured ETo, and to overestimate the lower ETo values in semi-arid and windy areas with a high evaporative demand (Hussein, 1999; Ventura et al., 1999; Berengena and Gavilan, 2005). As r_a can be calculated from meteorological conditions, in order to provide more accurate estimations of evapotranspiration using the FAO-PM equation, it may be necessary to parameterise r_c as a primary factor in the evapotranspiration process (Monteith, 1965). Canopy resistance r_c is a physiological parameter with an aerodynamic component (Alves et al., 1998). It is difficult to estimate it for different climatic and crop water conditions, as it is influenced by solar radiation, temperature, vapor pressure deficit and soil water content (Lecina et al., 2003; Pereira et al., 1999). Nevertheless, a simple attempt to model this resistance may yield a better estimation when the FAO-PM equation is applied over both short and tall crops (Alves and Pereira, 2000; Pereira et al., 1999) and over other types of vegetation (Chávez and López-Urrea, 2019; Margonis et al., 2017). It could also be useful to incorporate the effects of the resistance due to vegetation into climatic and hydrological models (Yang et al., 2019; Bie et al., 2015).

In this context, some studies incorporated a "CO_2-factor" into the FAO-PM equation (Easterling et al., 1992; Ficklin et al., 2009; Parajuli, 2010; Islam et al., 2012; Wu et al., 2012; Priya et al., 2014; Fares et al., 2015). Then, equation (1) can be rewritten as:

$$\text{ETo} = \frac{0.408\Delta(R_n\text{-}G) + \gamma\frac{900}{T_{2m}+273}.u_2(e_s\text{-}e_a)}{\Delta + \gamma(1 + \frac{0.34u_2}{CO_2\text{-}factor})} \qquad (7)$$

where, in the denominator, a linear relationship for stomatal conductance as a function of CO_2 level is introduced. It was developed by Stockle et al. (1992), and based on 80 data sets comparing leaf conductance at 330 ppm and at 660 ppm of CO_2 concentration for a wide range of species including C_3 and C_4 crops:

$$g_{CO_2} = g\left[1.4\text{-}0.4\ {CO_2}/{330}\right] \qquad (8)$$

where g_{CO2} is the leaf conductance modified to reflect CO_2 effects (m s^{-1}); g is the conductance without the

effect of CO_2 (m s^{-1}); CO_2 is the actual atmospheric CO_2 concentration (ppm) and 330 represents the baseline atmospheric CO_2 concentration (ppm). The new r_c is as follows:

$$r_c = \frac{1}{g_{CO_2} \times 0.5\ LAI} \qquad (9)$$

The "CO_2-factor" is based on experimental observations of a 40% linear decrease in stomatal conductance between 330 and 660 ppm CO_2 concentrations (Morison and Gifford, 1983). Islam et al. (2012) incorporated this model in the FAO-PM equation to evaluate the effects of possible future anthropogenic climate change on ETo. Results of the different simulation studies showed an increase in ETo with changing climate, but the impact of increasing temperatures was almost offset by increasing CO_2 levels. In fact, sensitivity analysis showed that the effect of a 1°C rise in temperature was offset by an increase in CO_2 levels up to 450 ppm, whereas the effect of a 2°C temperature rise was offset by CO_2 concentrations of 660 ppm, thus in close agreement with results found by Priya et al. (2014) using the same model. Authors pointed out that, due to its linearity, this "CO_2-factor" is only valid in the range of 330 to 660 ppm. For CO_2 concentrations beyond 660 ppm, factors for specific crops reported by Allen (1990) were used. The same remark was made by Ficklin et al. (2009) when increasing CO_2 concentration to 970 ppm and temperature by 6.4 °C caused watershed-wide average evapotranspiration, averaged over 50 simulated years, to decrease by 37.5%, resulting in an increase of water yield by 36.5%. They explained that the linear assumption of eq. (8) means that it is suitable for all plant species, which may lead to an overestimation of the aforementioned reduction in ETo in the presence of multiple types of land cover. They concluded that because of this broad simplification of the effects of CO_2 on plant growth, their analysis was still too uncertain for water management purposes. The presumed overestimation of ETo is because this "CO_2-factor" is based on the assumption that a doubling of CO_2 concentration would lead to a general decrease of 40% in stomatal conductance (Morison, 1987) irrespective of the land cover type. This reduction of conductance is assumed to be linear over the entire range of CO_2 concentrations between 330 ppm and 660 ppm (Morison and Gifford 1983). To overcome this issue, Wu et al. (2012) proposed an optimised equation:

$$g_{CO_2} = g\left[(1+p)\text{-}p\ {CO_2}/{330}\right] \qquad (10)$$

where p is the percentage decrease in leaf conductance specific to vegetation types (Authors provided different values in their study). The modified equation inherently gave a better representation of this increasing CO_2 effects than the original equation by incorporating the CO_2 effects dynamically in more process-based details.

Olioso et al. (2010) suggested multiplying the FAO-PM ETo by another factor F to correct the daily values of reference evapotranspiration taking into account the effect of higher CO_2 concentrations. This factor was derived from evapotranspiration simulations of the ISBA-A-gs model (Calvet et al., 1998) at different CO_2 levels, and used in different studies (Martin et al., 2011; Lardy et al., 2012, 2014; Salmon-Monviola et al., 2013; Katerji et al., 2017):

$$F = 1.1403 - 3.8979 \times 10^{-4} \times [CO_2] \qquad (11)$$

The value of F is approximately 1 when the mean annual value of the air CO_2 concentration is equal to 370 ppm. F decreases or increases when the CO_2 concentration is higher or lower than this threshold. For example, the decrease in ETo is approximately 8 and 20 % when the CO_2 concentration reaches 550 and 900 ppm, respectively (Olioso et al., 2010). The factor is also based on a linear relationship between the decrease of ETo and the increase of the CO_2 concentration, which raises the same concerns previously discussed.

According to Katerji et al. (2017), the issue of the approaches mentioned above is that they are insufficient to adapt the FAO-PM equation to the increasing concentrations of CO_2. These solutions always consider the resistance r_c to be constant by neglecting its reliance on climatic variables, which means that r_c parameterisation is required to reduce the difference between the directly measured ETo values, and those estimated using the FAO-PM model.

PENMAN-MONTEITH METHOD WITH VARIABLE CANOPY RESISTANCE MODELS

Jarvis Model

Jarvis model is a phenomenological and multiplicative empirical model that interprets field measurements of stomatal conductance g_{CO2} in relation to environmental variables. It calculates g_{CO2} by multiplying the maximum conductance g_{max}, which is a value which represents the highest g recorded under optimal conditions (Korner et al., 1979), with a number of empirical response functions, including one for CO_2-sensitivity,

and it is assumed that each variable acts independently (Jarvis, 1976; Whitehead, 1998):

$$g_{CO_2} = \frac{1}{r_s} = g_{max} f(I) f(T_a) f(C_a) f(VPD) f(\Psi) \qquad (12)$$

where I is the absorbed photosynthetic photon flux density (µmol m^{-2} s^{-1}), T_a is the air temperature (°C), C_a is the CO_2 concentration (ppm), VPD is the Vapour Pressure Deficit (kPa) and Ψ is the soil water potential (Pa).

Same as the aforementioned models, Jarvis model is also based on a linear function between the stomatal conductance g_{CO2} and atmospheric CO_2. In fact, Jarvis (1976) concluded that g_{CO2} decreased linearly when the increase in CO_2 concentration is within the range of 100-1000 ppm, and that it stays constant when the CO_2 concentration is <100 ppm or >1000 ppm. Also, equation (12) may underestimate g_{CO2} when relative humidity (RH) is high because it correlates g_{CO2} linearly to RH (Wang et al., 2009). In this case, a nonlinear function of RH or VPD may reduce the bias (Leuning, 1995; Wang et al., 2009).

Nevertheless, Jarvis model has been used in different forms in many studies (Hanan and Prince, 1997; Gharsallah et al., 2013; Zhang et al., 2016; Zhou et al., 2019). In the east coast region of North America, elevated atmospheric CO_2 was found to reduce ET at a rate of 0.84 mm/year between 1901 and 2008 when calculating stomatal conducatance with a Jarvis-type equation in the Dynamic Land Ecosystem Model (DLEM) 2.0 (Yang et al., 2015). Using the same model in a global scale, Pan et al. (2015) concluded that increasing atmospheric CO_2 will lessen the positive effect of warming temperature and increasing precipitation on ET by the end of the 21st century. Medlyn et al. (2001) analysed data from 13 long-term (>1 year) field-based studies of the effects of elevated CO_2 concentration (350 ppm and 700 ppm) on European forest tree species by fitting data to two models namley Jarvis and Ball (Ball et al., 1987). Their meta-analysis indicated a significant decrease (21%) in stomatal conductance in response to growth in elevated CO_2 concentrations across all studies, resulting in a decrease of ET.

Some authors think that another limit of the Jarvis model is that each response function has to be adjusted to the data to be able to provide good predictions for any type of vegetation, since they are specific for only certain crops and climate conditions and they cannot be used for general purposes (Yu and Wang, 2010). Consequently, a site-specific calibration of the empirical response functions becomes necessary. Another criticism formulated against this approach is that the knowledge of stomatal resistance r_s alone may not be sufficient to

calculate ET because the FAO-PM equation requires r_c. Hence, the upscaling of r_s to the canopy level is required to calculate r_c, which could be quiet challenging (Irmak et al., 2008). Besides, Alves and Pereira (2000) questioned the validity of the multiplicative model because it only includes the physiological component of r_c but not the aerodynamic component r_a and because of the assumption of environmental variables acting independently.

Katerji and Perrier (KP) model

Based on the fact that r_c, for well-watered crops, varies during the day with different climatological variables, Katerji et al. (1983) suggested a new semi-empirical procedure to determine both resistances r_c and r_a by applying the Buckingham π-theorem (Kreith and Bohn, 2001). They established a linear relationship between the canopy resistance r_c and the climatic resistance r^* (Monteith, 1965):

$$r_c/r_a = a \, r^*/r_a + b \qquad (13)$$

where a and b are empirical calibration coefficients which vary with crop type but not with site (Rana et al., 1998). Parameter values for a few crops were provided by Katerji and Rana (2014). r^* (s m^{-1}) is represented by the following equation:

$$r^* = \frac{\Delta + \gamma}{\Delta \gamma} \frac{\rho C_p D}{R_n - G} \qquad (14)$$

where ρ is the air density (kg m^{-3}), C_p the specific heat of moist air (J kg^{-1} C^{-1}) and D is the vapor pressure deficit (VPD) (kPa).

However, this model still does not take into account the impact of the air CO_2 concentration value on the resistance r_c. After incorporating their model into the FAO-PM equation (PM-KP), Katerji et al. (2017) used a CO_2 correction factor (Olioso et al., 2010) with the PM-KP equation to compare it to the standard Penman-Monteith method (FAO-PM) with a fixed r_c value. PM-KP yielded better performances in forecasting the ETo directly measured by weighing lysimeters during the summer season for the measured period (1986–2006) in Apulia region in southern Italy (Katerji et al., 2017). The results demonstrated that the FAO-PM formula underestimated the measured ETo values by 20 %, whereas the underestimation is only 3 % for the PM-KP formula.

This semi-empirical KP approach has been widely used in the subsequent literature (Peterschmitt and Perrier, 1991; Alves and Pereira, 2000; Lecina et al., 2003; Steduto et al., 2003; Pauwels and Samson, 2006; Liu et

al., 2012b; Margonis et al., 2017). However, one of its main limitations is the need for a specific calibration, even if it can be unnecessary under certain circumstances (Rana et al., 1998, 2001; Katerji and Rana, 2008). Furthermore, Gharsallah et al. (2013) insisted that the model's performance would probably be improved calibrating the a and b parameters for the main phenological phases of crops, making the use of this model even more complicated. A second limitation is the fact that it depends on the temporary value of the Bowen ratio β, which is not readily available (Perez et al., 2006). Besides, the KP model seems to fail under irrigated conditions in semiarid to arid regions (Allen et al., 2006).

MODIFIED MAKKINK EQUATION

Makkink model (Makkink, 1957) is a simple empirical method for ETo estimation that uses only temperature and radiation parameters:

$$ET_o = \alpha \, \frac{S}{\lambda \, (S + \gamma)} \, K\downarrow \qquad (15)$$

where $K\downarrow$ is the incoming short-wave (global) radiation (W m^{-2}), λ is the latent heat of vaporization of water (J kg^{-1}), S is the temperature-dependent gradient of the saturated vapour pressure curve (Pa K^{-1}) and α is an empirical coefficient (= 0.65).

This formula does not take into consideration the effects of CO_2. To fix that, Kruijt et al. (2008) multiplied eq. (15) with a correction factor c:

$$c = S_g \times S_T \times F_T \times \Delta_{CO2} \qquad (16)$$

$$S_g = (dg/g)/dCO_2 \qquad (17)$$

$$S_T = (dT/T)/(dg/g) \qquad (18)$$

where g is the stomatal conductance (mol m^{-2} s^{-1}), S_g is the sensitivity of g to CO_2 (ppm^{-1}), S_T is the relative sensitivity of transpiration T to g (kg m^{-2} s^{-1}), F_T is the transpiration share of evapotranspiration and Δ_{CO2} is the change in atmospheric CO_2 concentration (ppm).

After parametrizing S_g, S_T and F_T based on the literature, Kruijt et al. (2008) provided correction factors applied to a projected additional increase of atmospheric CO_2 concentrations in 2050 and 2100 by 150 and 385 ppm respectively for various vegetation categories. Results of their study suggest that direct effects of CO_2 reducing evapotranspiration can be expected to be moderate, up to 5% in the coming 50 years and up to 15% by 2100. Applying their methodology in Central and

Eastern Europe resulted in a decrease in reference evapotranspiration rates compared with runs that did not consider increases in CO_2 levels (Eitzinger et al., 2013). Similarly, Huntington et al. (2016) concluded that crop evapotranspiration is projected to increase in all basins of Western United States, especially areas where perennial crops are grown, and with smaller increases in areas where annual crops are grown.

Based on the extensive number of manuscripts on the topic reviewed by the authors, there is an abundance of models with a modified canopy resistance r_c (e.g. Shuttleworth and Wallace, 1985; Massman, 1992; Stannard, 1993; Todorovic, 1999; Irmak and Mutiibwa, 2010). However, very few of them took in consideration the change in atmospheric CO_2, hence the small number of models discussed in this study. This is essentially because when the time span of the research is short, the change in atmospheric CO_2 concentration is very small and is generally ignored (Li et al., 2014; Zhang et al., 2008). Furthermore, some of these models were not even incorporated into the FAO-PM equation to estimate ET responses to increased CO_2 concentration (e.g. Ball et al., 1987; Wang and Wen, 2010). The main issue with the previously reviewed models is that the relationship between stomatal conductance and CO_2 concentration is assumed to be a simple linear one, which is an assumption only valid within the limited range of 330–660 ppm (Li et al., 2019). In fact, those models rarely went beyond that range where data are better fitted with a nonlinear curve. This observation is consistent with the findings of Health and Russell (1954), Morison and Gifford (1983) and Wang and Wen (2010). Thus, it is crucial and indispensable to validate the accuracy and reliability of these models when applying them into the FAO-PM equation especially when the CO_2 concentration is higher than 660 ppm, and to choose the appropriate one to improve the estimation of ET under elevated CO_2 concentration.

Although some studies applied modified simple empirical equations, such as Makkink (Kruijt et al., 2008) and Priestley-Taylor (Rosenzweig and Iglesias, 1998; Hatch et al., 1999; Strzepek et al., 1999) to account for the vegetation responses to an elevated atmospheric CO_2, the FAO-PM method has been always considered to be the most reliable one for various climatic conditions due to its physically based characteristic with incorporating both physiological and aerodynamic parameters (Xu et al., 2006). However, its use of a fixed canopy resistance of 70 s m^{-1} is perceived as weakness, as surface resistance may change with climate and weather parameters, variation in day length, or differences between daytime and nighttime wind (Pereira et al., 1999). In fact, this fixed r_c hypothesis has not been verified in experimental trials carried out on irrigated grass surfaces which underlined significant variations in the canopy resistance r_c on daily and seasonal scales (Rana et al., 1994; Steduto et al., 2003; Katerji and Rana, 2006; Lecina et al., 2003; Perez et al., 2006). The same criticism applies to the models discussed above since they are replacing the constant daily values of the grass r_c with different but always constant values, or using a simple correction factor with the FAO-PM formula, which could be because of the complexity of the canopy resistance modelling (Katerji and Rana, 2006).

CONCLUSION

This paper provides an overview of surface resistance models found in literature that included the effect of CO_2 on crop evapotranspiration. The paper reports a brief explanation of the main theories and assumptions involved in the models' development and underlines their main characteristics. Using these models would help improving the accuracy of ET estimations. Yet, modeling canopy resistance is a difficult task as its value depends on vegetation type, climate, plant architecture and, in water scarcity conditions, on plant and/or soil water status (Shuttleworth and Gurney, 1990). This complexity caused the dissimilarity in results when using some of the aforementioned models in this review, which is also due to the conflicting effect that increase in CO_2 concentration has with increase in temperature. Hence, there is still a need to enhance the robustness of the resistance modeling procedure in order to be applied to different crops under different climatic conditions and under diverse future climate change scenarios. Actually, the great bulk of studies carried out on canopy resistance modelling compared the performance of these models with that of the FAO-PM approach or with different models for estimating ETo, and very few researchers have actually attempted to estimate future changes in ETo based on projected climate change scenarios and estimates of increased CO_2 concentrations. Furthermore, many models were not even tested with the FAO-PM equation, justifying Yang et al. (2019) statement that many present climate models do not account for vegetation responses to an elevated atmospheric CO_2, thus seriously questioning the claim of 'warming leads to drying' in earlier studies.

We note in conclusion that there is a growing need for improved surface resistance models, that may simulate better the changes in stomata physiological responses, thus enhancing the accuracy, reliability and applicability of ET estimates.

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