FArming Tools for external nutrient Inputs and water MAnagement

D3.3.3 Prediction of SOM variability on mid-long term for the compared sustainable and current intensive managed soil-crop systems, including derived indicators

Rosario Napoli, Claudia Di Bene, Roberta Farina (CREA)

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Executive summary

In a processing tomato - durum wheat rotation, long-term sustainability of two alternative fertilization strategies, i.e. current, with synthetic fertilizers-SYN *vs* conservative, with organic sources of nitrogen (organic amendments plus green manure with a legume) -CONS, was assessed. To this end, the EPIC model was validated with field data and used to assess sustainability for 30 years, under three current and relative future climates. The indicators of sustainability considered were: yield, Soil Organic Carbon (SOC) stock change, Nitrogen Use Efficiency (NUE), Water Use Efficiency (WUE) and nitrate leaching. The climate elaborated by General Circulation Models (GCM), were obtained from AGRI4CAST and included the predictions of climate change. Under all the predicted future climate scenarios respect to current climate, in CONS tomato yield (8 Mg ha^{-1} DM as average of the three climates) increased in average by 9% and in SYN (7 Mg ha^{-1} DM as average of the three climates) remained almost stable. In wheat, under future climate, yield both in CONS and SYN increased, but the average yield of CONS in future climate was much lower than SYN (34% reduction). Nitrogen use efficiency and nitrate leaching followed the same trend of yield and both decreased in future climate in CONS. WUE was in average 9% higher in CONS compared to SYN under future climate, showing higher values in a range from -1% to 19%. With regard to SOC the effect of CONS was always positive. The overall evaluation of the N fertilization strategy proposed as alternative, taking into account profitability and environmental factors, suggests that it is a good performance and a good option for farmers and for environmental purposes.

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1 Introduction

1.1 Context

The Mediterranean basin is a recognized hot spot for climate change for the next decades (IPCC, 2013), with modifications of rainfall amount and pattern and temperature increase, and where extreme events are expected to severely affect agricultural sector and food security (Ventrella et al., 2012). As reported by Duveiller et al. (2017), in Southern Europe future impacts of climate change on agriculture can be generalized by a decline in both productivity and suitability. Moreover, in Mediterranean regions, characterized by high interannual and seasonal rainfall variability (wet and cool periods from autumn to spring, and long dry periods in summer) nowadays, one of the most important issue caused by intensive agricultural farming systems is the reduction of soil organic carbon (SOC), with a possible worsening in the perspective of climate change, with major side effects on soil functioning (Álvaro-Fuentes and Paustian, 2011; Di Bene et al., 2016). Zdruli et al. (2004) estimated that about 74% of the soils in Southern Europe contain less than 2% of organic matter in the topsoil.

For these reasons, sustainable agricultural practices such as crop rotation, cover crops, use of compost, and organic fertilizers, can reduce the external inputs (e.g., pesticides, fertilizers and herbicides) with the effect of increase of crop yield stability and biodiversity in the rhizosphere over time (Farina et al., 2017). To implement the best policies, appropriate prediction tools are required to characterize the vulnerability of agricultural systems in a future changing climate. To date, deterministic crop growth modelling is a major tool for analyzing the impacts of climate change on agricultural production.

1.2 Purpose and scope

The study aimed at evaluating the long-term agro-environmental sustainability (30-years) of a typical Mediterranean cropping system using a modelling approach under future climate change scenarios. Within the FATIMA project, measured data from the Italian field trail and EPIC model were used to assess the long-term agro-environmental impacts and sustainability of two different nitrogen fertilization treatments on crop yields, water use efficiency, nitrogen use efficiency, soil organic carbon stock change, soil bulk density change, and soil N cycle (nitrate leaching and N_2O emissions), under future climate change scenarios. The tested treatments, applied in a durum wheat – processing tomato rotation, were:

- Conservative N fertilization methods (CONS), based on the adoption of compost, leguminous cover crops (fava bean), and poultry manure
- Synthetic N fertilization method (SYN), based on mineral N fertilizer and used as control.

2 Methodological approach and scenario analysis framework

Figure 1 shows the flowchart overview of the integrated approach used to evaluate the long-term of agro-environmental sustainability of two different nitrogen fertilization treatments, applied in a durum wheat – processing tomato rotation, under future climate change scenarios with respect to the baseline.

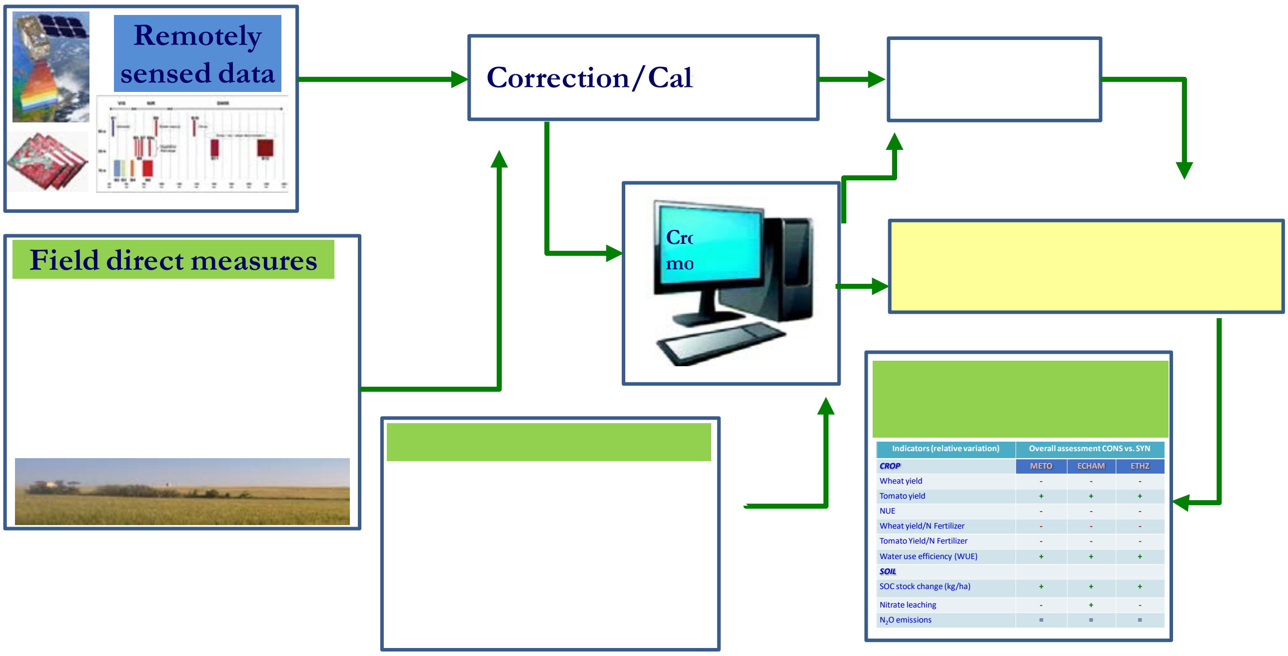

Figure 1 *Integrating Earth Observation (EO) data, direct field measures (soil-plant), crop growth modeling, and future climate change scenarios for assessing long-term (30-years) agro-environmental sustainability of a typical Mediterranean wheat-tomato cropping system.*

The overall assessment of agro-environmental sustainability was obtained in two steps. First of all, the thresholds of a set of agro-environmental indicators were defined in order to obtain three classes of sustainability, i.e. low, medium and high. The values used as threshold reported in table 2, were based on the 2-years FATIMA field experiment and are specific for the Italian pilot area in Tarquinia district. In the second step the predicted values of the agro-environmental indicators were assigned to the corresponding class and the long-term overall evaluation was assessed taking into account climate change scenarios.

3 Description of the model and calibration-validation procedures

3.1 Model description

The Environmental Policy Integrated Climate (EPIC) agroecosystem model is extensively applied at field-scale, tested in many pedo-climatic conditions (Farina et al., 2011), and simulates crop production as a function of weather, soil conditions, and management practices (Williams et al., 1984; Williams, 1995). EPIC model v.0810 (Gerik et al., 2014) was selected because it has been widely and successfully used for assessing the effects of management on crop productivity, soil water balance, and soil C and N dynamics in a range of environments and agricultural systems, including the United States (Causarano et al., 2007; 2008), Argentina (Apezteguia et al., 2009), and Europe (Billen et al., 2009; Farina et al., 2011; Rinaldi and De Luca, 2012). EPIC, developed and maintained by researchers at Blackland Research and Extension Center, Texas A&M Agrilife Research (USA), was designed originally to explore the impacts of soil erosion on crop productivity. Afterwards, it was refined including additional sub-models to predict water quality and the response of crops to atmospheric CO_2 (Gassman et al., 2005). As reported in Parton et al. (1994), EPIC has eight major components (i.e. modules on weather generation, crop growth, soil water dynamics, erosion, nutrient and carbon cycling, soil temperature, tillage, and soil-crop management), and operates on a continuous basis using a daily time step and performs short- and long-term predictions. Simulated processes include the effects of tillage, fertilizer and irrigation on crop yield and soil agro-environmental quality (surface residue, soil bulk density, and biogeochemical cycles) in the crop rotation and cropping system considered. Information about the cropping system management (such as tillage, irrigation volumes, amount of fertilizers distributed, and operation scheduling), soil and weather data, and crop growth data, such as plants density and crop growing period, is mandatory to run the model. As reported by Folberth et al. (2016), in addition to plant growth and yield formation, EPIC estimates a wide range of environmental externalities, such as wind and water erosion rates, turnover and partitioning of soil organic carbon, N and P, evapotranspiration (ET), fluxes of selected gases, and soil hydrologic processes.

Depending on N and lignin content, crop residues including roots are split in two litter compartments: metabolic and structural. From them, as a function of soil temperature and moisture, C is allocated in three compartments: microbial biomass, slow humus and passive humus, which are different in size, function and turnover times (Izaurralde et al., 2006). Furthermore, the model accounts for the effects of change in CO_2 concentration and vapor pressure deficit on radiation-use efficiency, leaf resistance, and transpiration of crops to estimate the increase of plant growth and water-use efficiency (Stockle et al., 1992).

Figure 2 shows the EPIC crop-growth sub-model block diagram. In details, EPIC estimates potential biomass increases on a daily time-step based on light interception and conversion of CO_2 to biomass. Solar radiation and temperature are the major climatic variables driving the model, while leaf area index (LAI) represents the main crop variable in the model. Plant growth and phenology are linked to the daily accumulation of heat units. Environmental stresses, such as water and nutrient (nitrogen and phosphorus) deficits, adverse temperature, and aeration, may affect plant growth through constraints on biomass, while harvest index is affected by water stress only. Root growth can be limited by soil strength, adverse soil temperature, and aluminium toxicity (Folberth et al., 2016). As reported by Steduto et al. (1995), EPIC model calculates LAI, dividing the crop cycle into two periods: one from emergence to the start of leaf area decline, and the other from the start of leaf area decline to physiological maturity (end of the growing season).

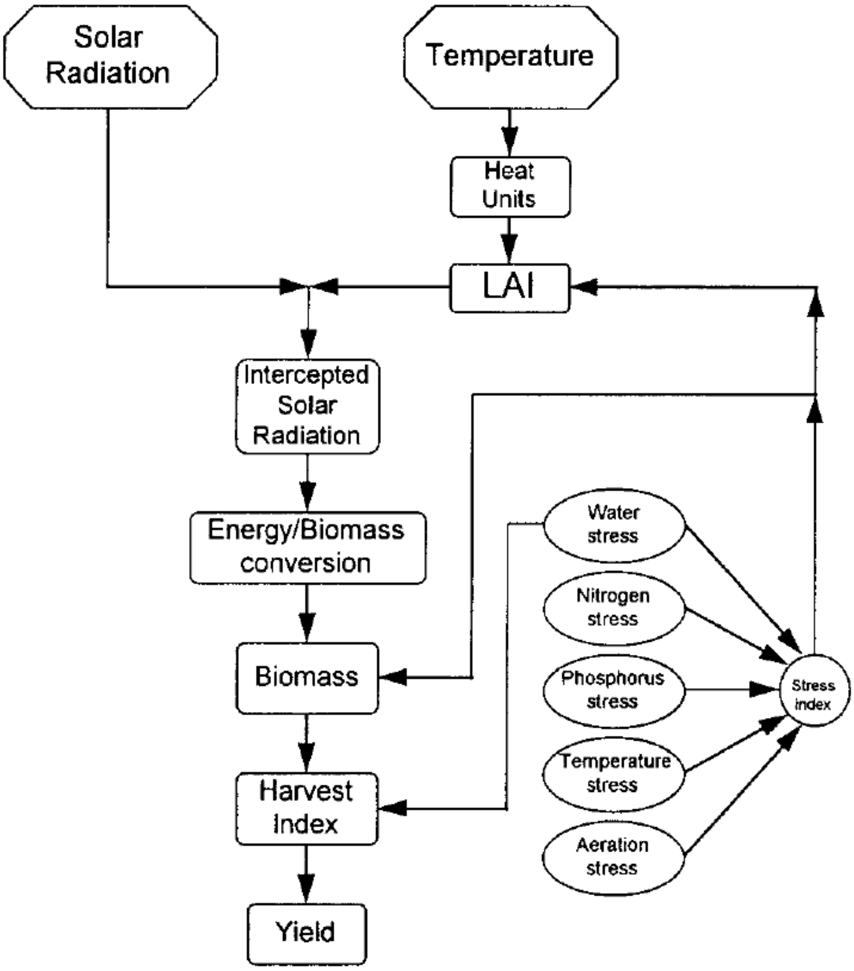

Figure 2 *Block diagram illustrates the functions of the crop-growth sub-model of EPIC (from Steduto et al., 1995).*

Water balance of EPIC model is composed by six main components, i.e. snowmelt, runoff, percolation, evapotranspiration, lateral subsurface flow and water table dynamics, as described by Williams (1995). Snowmelt is estimated as a simple function of snow pack and mean daily temperatures. Runoff volume is estimated by the curve number (CN) technique (USDA, 1972), from daily rainfall and a retention parameter based on the CN. Water that does not run-off can infiltrate into the soil, percolating by a storage routing technique through soil layers. Water flows downward from a soil layer when its water content exceeds field capacity. The saturated conductivity and storage volume control the flow rate. Water erosion can be estimated by one of eight methods, while water content at field capacity and wilting point can be estimated by 11 options (Gerik et al., 2014).

Evapotranspiration from soil and plants is calculated separately, based on potential evapotranspiration (PET). EPIC model offers several methods to calculate PET. The Penman–Monteith (PM) method is the most used. In the PM method PET = *f*(Tmax, Tmin, Rn, RH, WS, EL, CR), where Tmax and Tmin are the maximum and minimum daily temperatures, Rn is net radiation, RH is relative humidity, WS is wind speed, EL is station elevation, and CR is the canopy resistance, a function of leaf area and stomatal resistance, the latter being affected by vapor pressure deficit. In order to assess the effect of PET methods on EPIC performance, also the Hargreaves and the modified EPIC Hargreaves method was tested, which are the least demanding for weather data. A simplified diagram of soil water balance is reported in Figure 3.

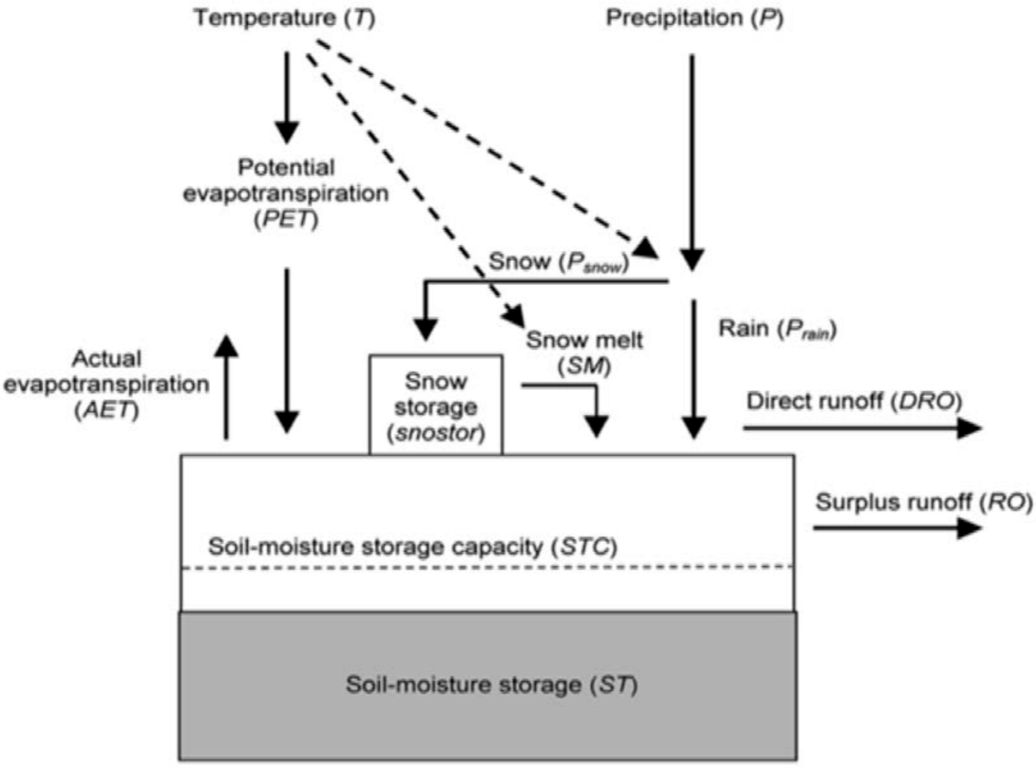

Figure 3.Simplified block diagram illustrates the soil water balance (from McCabe and Wolock, 2011).

3.2 Model calibration protocol (at parcel level)

Model calibration is the process of adjusting influential model parameters within their reasonable ranges to obtain model results realistic and consistent with the available observed data such as crop yields, soil nutrient content, soil carbon, soil water content, lysimeter data, and flow and water quality (Kersebaum et al., 2015). In the Italian pilot area, the durum wheat –tomato rotation, under SYN and CONS treatments, was simulated using EPIC model at parcels level. Information about the cropping system management (such as tillage, irrigation volumes, amount of fertilizers distributed, and operation scheduling), soil and weather data, and crop growth data, such as plants density and crop growing period, is mandatory to run the model. The process of EPIC simulations is controlled by three files of control: EPICFILE, EPICCONT and EPICRUN. Data elements developed by users include the following input files: Site, soil, field operation scheduled, weather, and crop data. Due to the limited availability of many important inputs (such as phenological and development parameters), model calibration becomes a critical modeling step for improving the accuracy of crop yield estimation at different scales (plot, field, and regional scales). During calibration step, a set of model parameters, such as phenological parameters and yield correction factors, is adjusted to maximize the agreement between model simulation and observations. Furthermore, these parameters should reflect the prevailing agricultural practices of the site, facilitating process-based explanations of the simulated outputs. Before starting calibration procedure, sensitive parameters at crop and soil level were selected. Validation is the examination and testing of the model performance in order to assess the capability of a calibrated model against an independent data set that has not been used for calibration. The calibration procedure was done only using the first year's data and included: root growth-soil strength (Parm 2), soil evaporation coefficient (Parm 12) and the Penaman-Monteith adjustment factor (Parm 74). The crop variables like potential heat unit, planting density, harvest index, and leaf area index (maximum leaf area index, fraction of growing season when leaf area index declines, and leaf area index decline rate) were input and validated step by step by maximizing fitting between simulated and observed yield at parcel level. For soil variables, the validation was done comparing the content of moisture in the root zone (RZSM), continuously measured through the Frequency Domain Reflectometry (FDR) at different soil depth, with the corresponding value obtained after the simulation as output. The initial values of the parameters to be calibrated were assigned, along with other parameters to the default values. Potential heat unit was calculated by summing mean daily temperature minus the base temperature of each crop during the growing season (planting and harvesting window). Planting density for each crop (400 plants m^{-2} for wheat and 2.9 plants ha^{-1} for tomato) was set according to the management, while harvest index was set according to the values measured in the field and in the district area (40%). Finally, the leaf area index (LAI) and LAI related inputs (maximum LAI, fraction growing season when LAI declines, and LAI decline rate) were adjusted, given their great influence on the rate of growth, stress during the growing season, and final crop yield in order to obtain the daily LAI output fitted to data monitored by Sentinel-2 images during the first crop growing season. The EPIC model offers several methods to calculate potential evapotranspiration (PET); in our local conditions the Penman–Monteith method showed to allow better performances in terms of yield and soil related variables. Neither the Hargreaves nor the modified EPIC Hargreaves methods were capable to reproduce the site conditions.

3.3 Model validation protocol (at point level)

Validation process refers to assess the accuracy of the model predictions by comparison to additional and independent observed data. For the validation process we used the second-year field measures, while the first-year data was used for calibration process. Coefficient of determination (R^2), slope and intercept of the linear regression, and correlation coefficient (r) between observed and simulated values were used to measure model performance. For better quantifying the effects of calibration on simulated crop yield and understanding the uncertainties associated with the calibration procedures, the differences between model outputs from simulations at different steps, by analysing the mean were examined. Data for calibration and validation procedure were reported in the deliverables 2.2.4.

3.4 Description of field trial and treatments

In a privately-owned farm in the Tarquinia Municipality coastal plain (Viterbo Province, western Central Italy; 7 km NW of Tarquinia, 2.7 km from seashore - 42° 69’ N and 11° 69’ E, at an average altitude of 25 m above sea level, with 3% mean slope), two different field plots (A and B) were set-up to improve the sustainability of the durum wheat (*Triticum durum* Desf. var. Iride) - processing tomato (*Solanum lycopersicum* L. var. Vulcano, indicated in the following as tomato) production system either in the short- and in the mid- long-term period. The field experiment aimed at testing the effects of conservative N fertilization methods (CONS) in comparison with synthetic N management (SYN) on crop yield and selected environmental quality indicators. To improve soil fertility and N use efficiency (NUE), and to reduce the potential nitrate (NO_3^-) leaching, the CONS method in tomato included the cultivation of field bean (*Vicia faba* L.), in the autumn-winter period as cover-crop, incorporated as green manure before the tomato transplanting together with an organic amendment, i.e. compost derived by vegetal local agro-forestry residues. For durum wheat, the CONS method included the application of poultry manure as organic N fertilizer. More details on pilot description, field operations and N fertilization practices are reported in deliverables D2.2.4, and D3.3.5.

4 Description of future climate scenarios and running EPIC model under climate scenarios

While current climate change is certain and measurable, thanks to the direct observations and the long-term past data series comparison, future climate projections include uncertainties (Brilli et al., 2014). Nevertheless, the majority of the studies over the Mediterranean basin indicated that the observed temperature and precipitation trends are expected to worsen in the next future (IPCC, 2007). Future climate will exhibit an increased frequency of extreme events with maximum temperature exceeding 40°C which will represent the normal conditions in the next future (Battisti and Naylor, 2009). In the present study, three different climate scenarios were used to run the model for long-term assessment. The climate scenarios were obtained from the MARS-AGRI4CAST website (http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d), where present and future climate scenarios (two-time projections, TPs) were generated by General Circulation Models (GCMs) from a consolidated daily weather dataset with a grid of 25x25 km. The GCM were: (1) METO-HC (METO); (2) DMI-HIRHAM5-ECHAM5 (ECHAM); and (3) ETHZ-CLM-HadCM3Q0 (ETHZ) and both present and the corresponding future climate for each of them were obtained. In terms of annual surface air temperature, the ECHAM future simulation is the coldest (15.7 °C), while METO and ETHZ future simulation are the warmest (16.2 °C). The temperature and rainfall in the GCMs for the two TPs and the ES, are reported in Table 1.

Table 1. Monthly pattern of baseline and future mean temperature (°C) and rainfall (mm).

Month	METO		ECHAM		ETHZ	
	Baseline	2030	Baseline	2030	Baseline	2030
			Temperature °C			
January	6.9	8.3	7.5	7.8	7.2	8.2
February	9.0	9.7	8.7	9.3	8.6	9.4
March	10.6	11.5	10.9	11.5	10.8	11.4
April	13.1	14.0	13.3	13.6	13.1	13.5
May	17.7	18.7	17.5	18.2	17.4	19.0
June	21.5	22.9	20.7	22.1	21.7	22.7
July	24.6	25.4	23.8	24.0	24.7	25.6
August	24.9	24.7	23.9	24.5	23.8	25.0
September	21.1	21.6	20.8	21.4	20.2	22.1
October	16.0	16.4	15.6	16.8	15.0	16.8
November	11.0	12.2	10.5	10.6	10.6	11.7
December	7.9	9.4	8.2	8.3	7.4	9.0
Year	**15.4**	**16.2**	**15.1**	**15.7**	**15.0**	**16.2**
			Rainfall mm			
January	37.4	30.5	37.7	34.1	41.2	27.3
February	56.2	78.5	29.6	35.6	25.6	35.4
March	10.3	15.0	25.7	30.6	16.1	24.3
April	29.0	33.0	26.8	15.7	21.9	30.3
May	16.1	9.4	21.9	14.2	20.0	7.9
June	9.1	8.9	13.6	6.4	15.5	14.6
July	2.1	2.0	6.8	5.9	4.5	3.9
August	7.2	13.0	9.0	17.5	13.1	8.1
September	30.9	30.9	39.4	61.1	35.2	48.4
October	30.6	34.1	46.7	37.4	42.9	54.0
November	38.3	64.0	51.6	47.1	56.8	58.8
December	32.9	33.0	44.1	45.2	46.7	40.9
Year	**300.1**	**352.3**	**352.8**	**350.8**	**339.5**	**353.9**

As regards annual rainfall, METO and ETHZ showed a similar precipitation patterns based on a precipitation increase in comparison with the baseline. Conversely ECHAM future climate scenario showed a reduction in precipitation regime with respect to the baseline, markedly different patterns than under the other two. An annual increase of mean temperature compared to the corresponding baseline by 0.8, 0.6, and 1.2°C was predicted with METO, ECHAM and ETHZ, respectively. A rainfall increase was observed with METO (52.2 mm, + 17.4%) and ETHZ (14.4 mm, + 4.2%), while a slight reduction in rainfall was predicted with ECHAM (-2.0 mm, 0.6%). Hence, each GCMs climate was run for two-time projections (TPs) (baseline and future climate), for 30 years. The TPs chosen were: (i) “2000” for the baseline, representing mean climate change for the period 1985–2015; and (ii) “2030” for climate change predictions, representing mean climate change for the period 2015-2044. Atmospheric CO_2 concentrations, for the considered periods, were 400 ppm for BL and 450 ppm for climate change. For all the baseline and climate change simulations, the predicted yield trend, and the SOC stocks, mineral N, and bulk density changes were considered. Within the same parcel, all simulations were done for each baseline and the corresponding future climate change scenario. In all simulations the same values of soil parameters were considered as data input in order to calculate the percentage of variation both for each baseline and future climate change scenario (i.e. soil parameter change = [(finale value – initial value)/initial value]). Similarly, to compare the effects of the three future climate changes considered (METO, ECHAM, ETHZ) the relative variation of soil parameters between each climate change scenario and the corresponding baseline used as control was computed.

5 Output analysis

5.1 Agronomic Indicators

5.1.1 Crop yield, Nutrient and Water Use Efficiency changes

Figure 4 shows the durum wheat and the tomato average yield changes for the SYN and CONS treatment, and the three GCMs in climate change scenario with respect to the corresponding baseline. Under the METO climate change scenario, the average yield of durum wheat and processing tomato increased for each treatment except for tomato SYN, where a slight decrease was observed (-2%). The highest value of increase was obtained for durum wheat SYN (14%), while the CONS treatment for both crops showed an increase of 8%. This behaviour is likely due to the positive effect of increased CO_2, combined with the increase of both rainfall and temperature observed under METO GCM. As regards ECHAM climate change, with no significant changes in rainfall, the average yield of both crops in rotation, increased under CONS treatment, while under SYN treatment increased only for tomato and reached a steady-state for durum-wheat. Finally, in ETHZ climate change scenario, the highest value of increase was obtained for tomato CONS (10%), followed by durum-wheat SYN (3%).

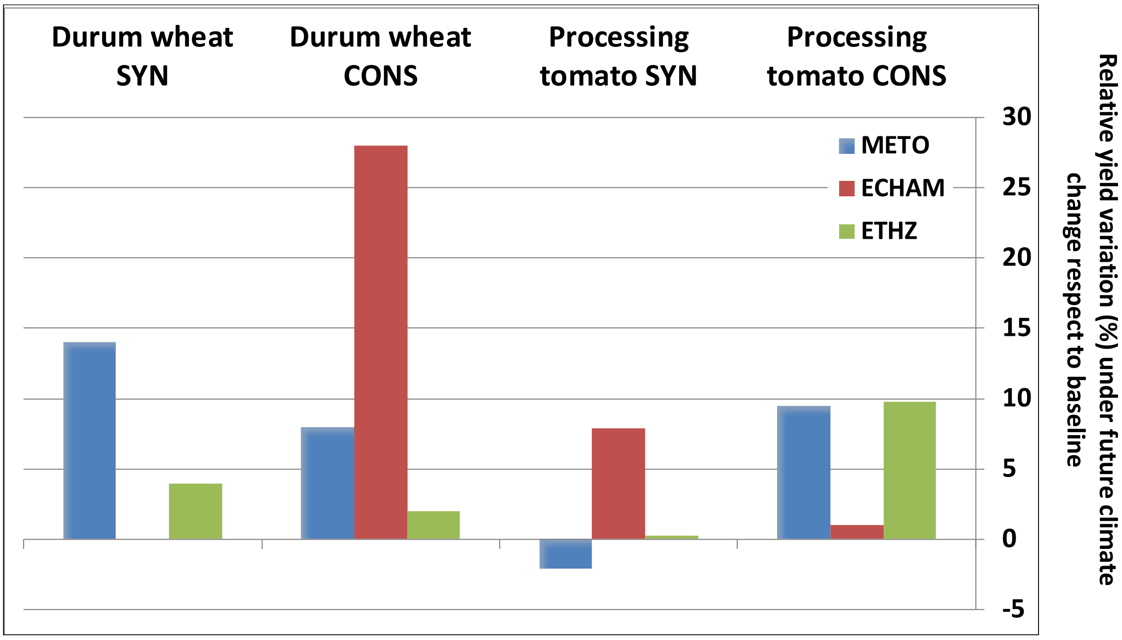

Figure 4.Durum wheat and processing tomato relative yield variation under future climate change respect to the baseline. METO = METO-HC; ECHAM = DMI-HIRHAM5-ECHAM5; ETHZ = ETHZ-CLM-HadCM3Q0. More information available at http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d

Nutrient use efficiency changes (NUE) in the 30-yrs period is reported in Figure 5. NUE of durum-wheat and tomato crops benefits of climate change under ETHZ both for SYN and CONS treatments. Nevertheless, the highest value of NUE was obtained for durum wheat CONS (23%) under ECHAM, while the lowest was observed in METO for durum wheat under CONS treatment and processing tomato under SYN treatment (-3%).

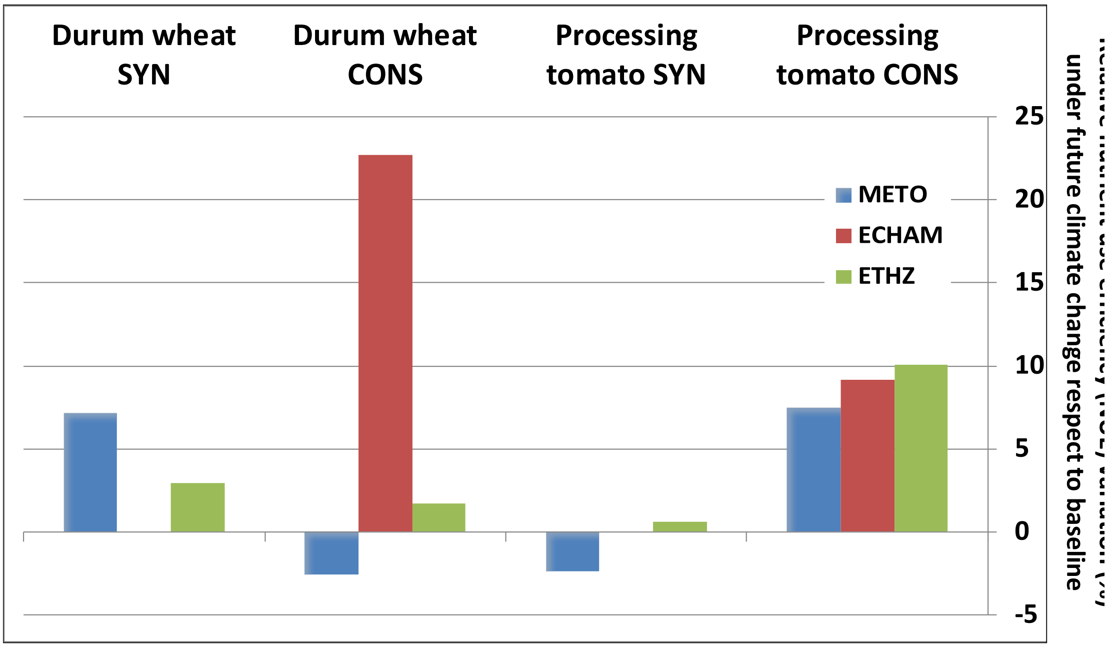

Figure 5. *Durum wheat and processing tomato nutrient use efficiency (NUE) relative variation under future climate change scenario respect to the baseline. METO = METO-HC; ECHAM = DMI-HIRHAM5-ECHAM5; ETHZ = ETHZ-CLM-HadCM3Q0. More information available at http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d*

Figure 6 shows the durum wheat and the tomato relative water use efficiency changes in the 30-yrs period for the SYN and CONS treatments, under the three GCMs in climate change scenarios with respect to the corresponding baseline. All climate change scenario showed higher performance than the relative baseline, except for ETHZ under tomato in SYN treatment.

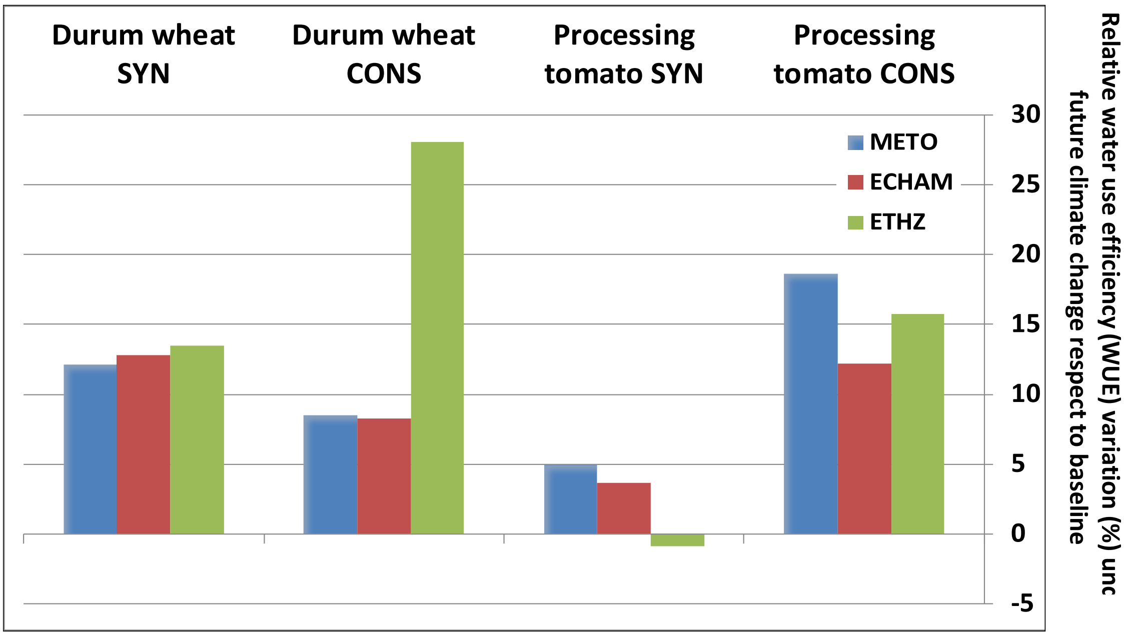

***Figure 6**. Durum wheat and processing tomato water use efficiency (WUE) variation under future climate change scenario respect to the baseline. METO = METO-HC; ECHAM = DMI-HIRHAM5-ECHAM5; ETHZ = ETHZ-CLM-HadCM3Q0. More information available at http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d*

In Figure 7 are reported the relative variations of crop yield and WUE for tomato SYN and CONS treatments under relative variations of temperature (Figure 7 left) and rainfall (Figure 7 right) in future climate change respect to the baseline. The effect of temperature increase under climate change on tomato yield is always positive (up to 10%) for CONS and is not significant for SYN (Figure 7 left). Rainfall change, both positive (as in ETHZ) or negative (as in METO) is associated with an increase of yield in CONS, particularly with the intermediate value of rain increase. SYN yield is slightly influenced by the change of rain, and the lower values of yield increase are associated with the higher rate of rainfall change. WUE is positively influenced by the most extreme change in temperature and rainfall in CONS, while WUE is less affected by climate change in SYN. As a general consideration, yield and WUE in SYN are less influenced by climate change and are more stable. Yield and WUE in CONS are positively influenced by climate change, with a magnitude that varies with the magnitude of rainfall and temperature change.

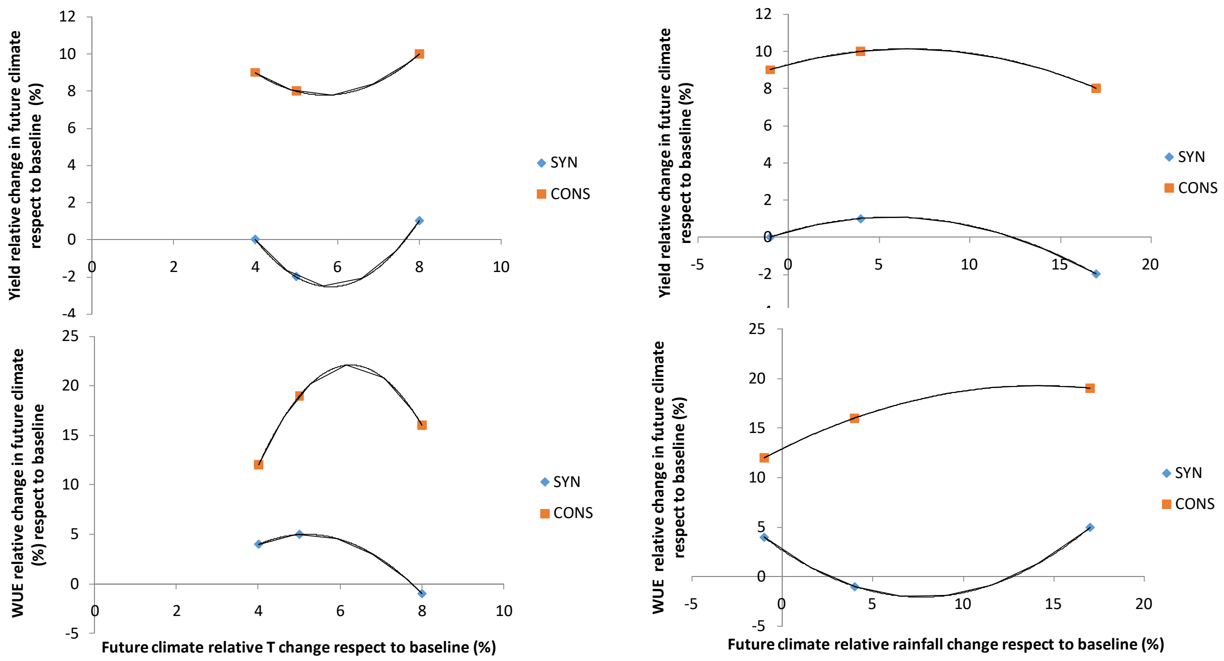

***Figure 7** Relative variations of crop yield and WUE for tomato in SYN and CONS treatments under changes of temperature (Figure 7 left) and rainfall (Figure 7 right) in the future climate change respect to the baseline.*

The higher stability of yield under climate change in SYN is confirmed also for durum wheat (Figure 8).

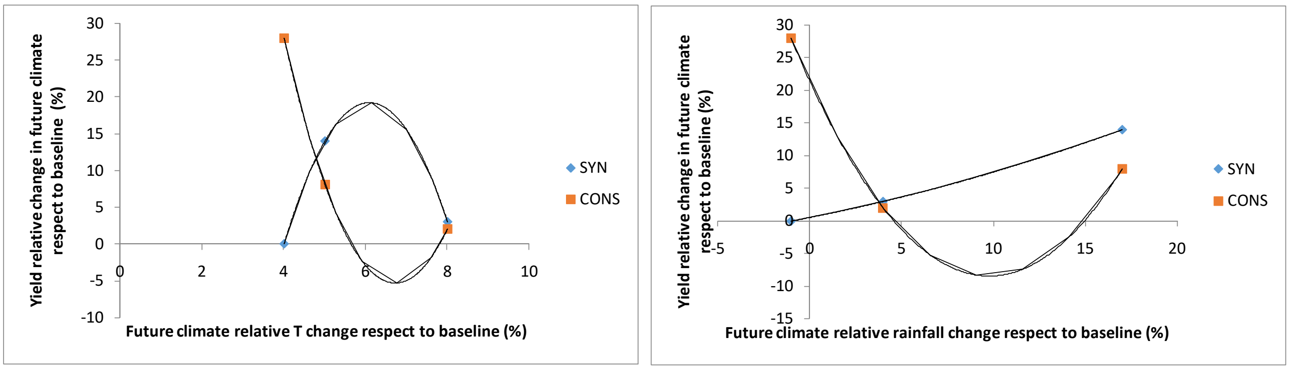

***Figure 8.** Relative variations of crop yield for durum wheat in SYN and CONS treatments under changes of temperature (Figure 8 left) and rainfall (Figure 8 right) in the future climate change respect to the baseline.*

5.2 Environmental Indicators

The effect on nitrate leaching of rainfall change in the tomato-wheat rotation is clearly different in SYN and CONS. In CONS both increase of temperature and decrease of rainfall reduced nitrate leaching, while the opposite can be observed for SYN (Figure 9).

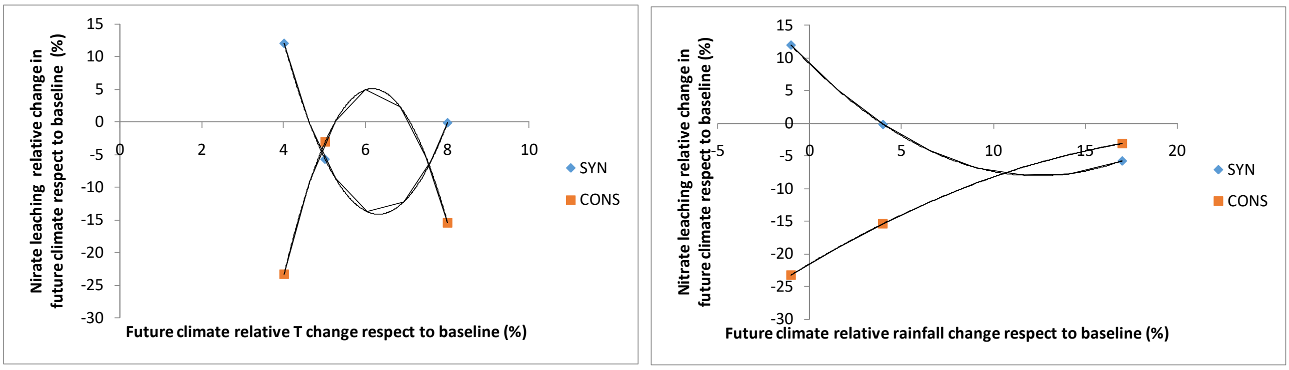

***Figure 9**. Relative variations of nitrate leaching in the tomato-durum wheat rotation in SYN and CONS treatments under changes of temperature (Figure 9 left) and rainfall (Figure 9 right) in the future climate change respect to the baseline.*

5.2.1 Main soil properties changes and Nitrate leaching

The bulk density change, under durum wheat –tomato cropping system, increased in the two simulated N management treatment (SYN and CONS), under current and future climate change scenarios, by about 0.02 g cm^{-3} on average, in the 30-yr period.

The SOC stock change, under durum wheat –tomato cropping system, decreased in the two simulated N management treatment (SYN and CONS), in current and future climate change scenarios, by about 0.62 Mg ha^{-1} yr^{-1}, on average.

Figure 10 shows the relative SOC stock changes for the SYN and CONS treatments, under the three GCMs in climate change scenarios with respect to the corresponding baseline. Under the METO and ETHZ climate change scenarios, the relative SOC stock changes were always negative both in SYN and in CONS treatments, ranging from -11% to -3%, on average. On the contrary, under ECHAM the relative SOC stock changes for the SYN and CONS treatments increased by 4%.

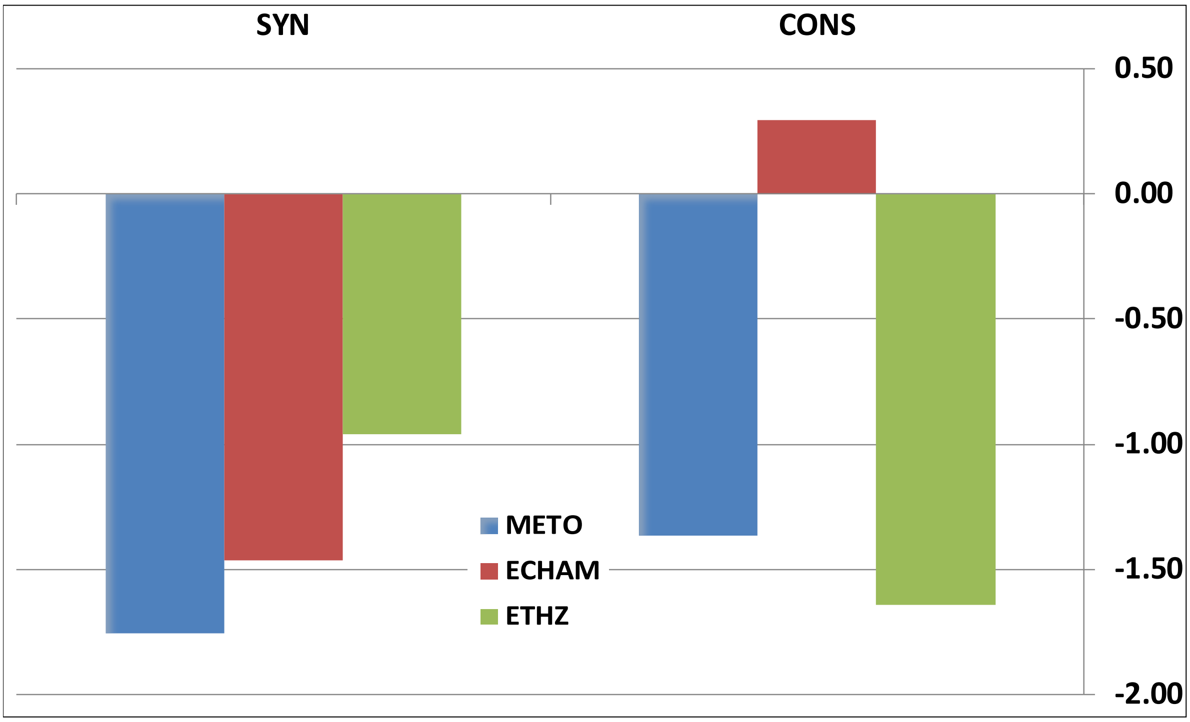

Figure 10. *Relative soil organic carbon stock variation in the 30-year period for each general circulation models (GCMs) under future climate change scenario respect to the baseline. METO = METO-HC; ECHAM = DMI-HIRHAM5-ECHAM5; ETHZ = ETHZ-CLM-HadCM3Q0. More information available at http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d*

Nitrate leaching in the 30-yrs period was reported in Figure 11. Nitrate leaching diminished under CONS treatment in the three-climate change scenario, while in the SYN treatment only METO scenario showed a decrease respect to the relative baseline.

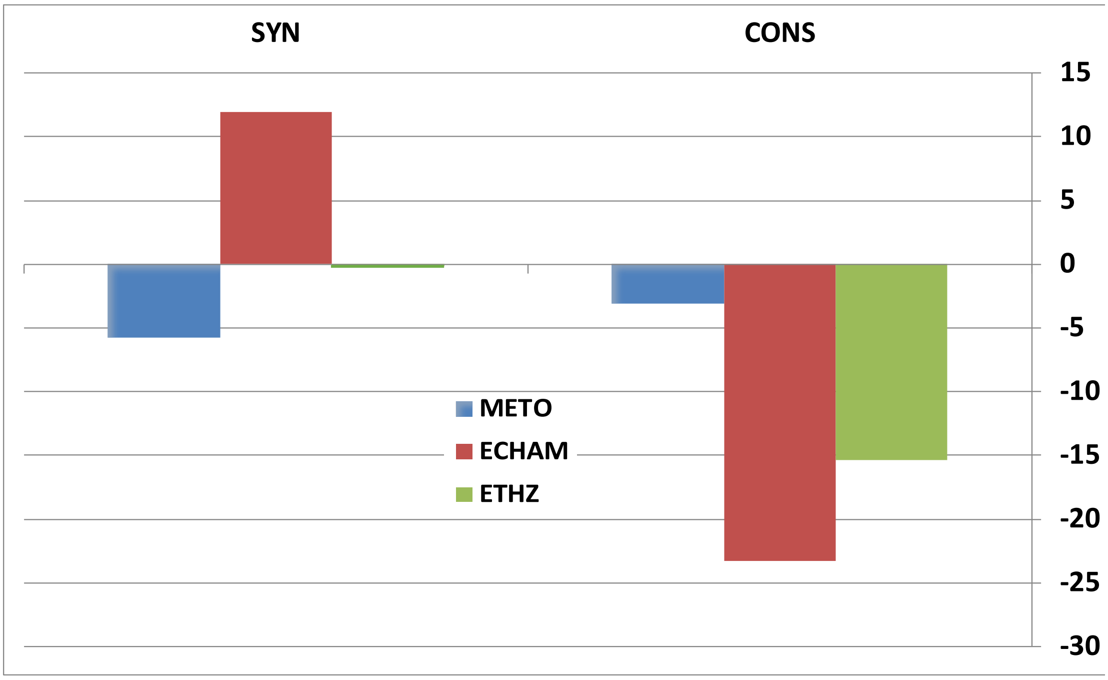

Figure 11. *Relative nitrate leaching variation in the 30-year period for each general circulation models (GCMs) under future climate change scenario respect to the baseline. METO = METO-HC; ECHAM = DMI-*

HIRHAM5-ECHAM5; ETHZ = ETHZ-CLM-HadCM3Q0. More information available at http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d

5.2.2 N_2O emission variation

The predicted cumulated N_2O emissions were mainly influenced by N management treatment (SYN or CONS). The cumulated N_2O emissions under SYN were zero and were slightly positive under CONS (0.07 kg ha^{-1} on average), ranging from 0.004 to 0.009 kg ha^{-1}. Future climate change scenarios only affected N_2O emissions under CONS treatment. The higher emissions were observed under ECHAM climate change scenario, while similar values were detected under METO and ETHZ. Finally, the predicted cumulated N_2O emissions were negligible or slight positive. These low emissions can be attributed to the reduced N fertilization rates applied for durum wheat - processing tomato cropping systems since the field is within a nitrate vulnerable zone (NVZ).

5.3 Overall evaluation of agro-environmental sustainability

To perform the overall long-term (30-years) agro-environmental evaluation of the impacts of the two N fertilization treatments tested in the Italian pilot area, under future climate change scenarios, we adopted the same indicators dataset as proposed in the deliverable 3.3.5., plus the Water Use Efficiency (WUE) because its recognized importance in assessing the crop type ability in using different water sources (rain or irrigation).

Table 2 shows the values used as threshold of the agro-environmental indicators and for the two considered crops, durum wheat and processing tomato. A threshold value, reported per each class of sustainability (i.e. low, medium and high), was based on the 2-years FATIMA field experiment, specific for the Tarquinia area.

Table 2. *Classes of agro-environmental indicators proposed for the long-term sustainability evaluation in the Italian pilot area.*

INDICATORS	Sustainability Evaluation Class		
	LOW	MEDIUM	HIGH
Yield Mg/ha (Wheat)	< 4	4-5	> 5
Yield Mg/ha (Tomato)	< 50	50-100	> 100
N Recovery Efficiency (%)	< 100	100-200	> 200
Water use efficiency (WUE) (kg/mm) (Wheat)	< 70	70-80	> 80
Water use efficiency (WUE) (kg/mm) (Tomato)	< 23	23-27	> 27
Nutrient use efficiency (NUE) (kg/kg)	> 100; < 50	50-80	80-100
Cumulative NO_3 loss by leaching (Kg/ha) relative variation (%) to N inputs	> 20%	20-10%	< 10%
SOC stock change (kg/ha)	Negative values (< -0.25)	Stable values (-0.25/+0.25)	Positive values (> 0.25)
Soil bulk density changes (g/cm3)	Positive values (> 0.1 g/cm3)	Stable values (-0.1/+0.1)	Negative values (< 0.1)

Where:

- Yield (Mg/ha): Grain for wheat (Mg/ha dry matter weight) and fruits for tomato (Mg/ha of fresh weight).
- Nitrogen Recovery Efficiency (%): expressed as the partial factor productivity is the ratio between crop yield and N applied with fertilizers (Dobermann, 2007).
- Nitrogen use efficiency (NUE) (kg/kg): expressed as the partial nutrient balance is the simplest form of nutrient recovery efficiency. It is calculated as the ratio between N content in grain or fruits and the N applied by fertilizers (Dobermann, 2007).
- Water Use Efficiency (WUE, Kg/mm): Ratio between crop yield and the evapotranspiration (ET) during the growing season.
- Cumulative Nitrate loss by leaching (Kg/ha) relative variation (%) to annual N input source.
- SOC stock change (kg/ha): Relative SOC variation between final and initial value.
- Soil bulk density changes (g/cm^3): Relative BD variation between final and initial value.

For yields, the values considered where based on the results of the FATIMA 2-years field experiment and on the historical experience and knowledge of the farmer involved in the experiment. For the N Recovery Efficiency (%) and Nutrient Use Efficiency (NUE) (kg/kg) the threshold values are based on the studies of Dobermann et al. (2007). Often the assumption is made that a PNB close to 1 suggests that soil fertility will be sustained at a steady state. Particularly, the NUE index value for the whole crop rotation indicates the percentage amount of N absorbed by crop yield. WUE is crucial for Mediterranean areas and represents an important indicator when evaluating long-term sustainability under climate change scenarios, particularly for the rainfed crops as durum wheat that depend entirely to rainfall. For tomato, the threshold of sustainability lay within very small range, due to irrigation and the possibility for the farmer to tune the doses very finely according to plant needs. Nitrate leaching represents the thresholds have not been defined as absolute value, but as relative variation (%) in comparison with N inputs as fertilizer both under SYN and under CONS treatments. In details, 138 kg/ha mean N value for SYN treatment, and 256 kg/ha mean N value for CONS treatment applied in the durum wheat – processing tomato rotation): amount of NO_3^- leaching below the roots depth. The N given to the soil as NH_4^+ can be quickly converted to NO_3^- by the nitrifier microorganisms. This anion is not absorbed by the soil, thus is easily released into the soil liquid phase, possibly moving to the leaching water flow. Sandy soils are particularly sensitive to leaching of nitrate to groundwater due to their higher permeability. SOC is considered one of the most important indicator of soil quality and is strictly linked to almost most of the ecosystem services provided by soil, such as nutrient and water cycles regulation, buffer capacity, biodiversity, GHG emission regulation and so on. Any reduction of SOC in Mediterranean conditions, must be considered negative and not desirable. Finally, bulk density change is an important soil quality indicator in terms of physical quality. Compaction of soil, due to a very intensive management, could result in a reduction of water infiltration, increase of energy required to plough the soil, crusting and erosion.

Table 3 is the final matching table results of the long-term simulations obtained by running EPIC model for 30 consecutive years under three different climate change scenarios (METO, ECHAM and ETHZ). The table summarizes the overall agro-environmental sustainability assessment of the nitrogen management strategies adopted in the Italian pilot area under FATIMA project for durum wheat and processing tomato rotation. SYN N treatment refers to "*Business as usual*" N fertilization management (synthetic N fertilizers) commonly adopted by most of the farmers in the Water User Association area of Tarquinia district. CONS N treatment refers to alternative N strategy based on the use of compost, cover crops (for irrigated tomato) and poultry manure (for rainfed wheat). The overall evaluation compares agronomic and environmental indicators under SYN and CONS treatments. The agronomic indicators were evaluated for each treatment and crop, while the environmental indicators were grouped by cropping systems and treatments. In the table were reported the indicator values averaged after the three climate change scenarios. For both agronomic and environmental indicators, a qualitative evaluation was performed according to three classes (negative, red face; equilibrium, yellow face; and positive, green face). The comparison between CONS vs. SYN was computed as relative variation. In the table the single value is reported in the corresponding colour of the evaluation class, thus it is possible to fit the single data inside the belonging qualitative class.

In the context of future climate change scenario, characterized by higher annual surface air temperature and precipitation differently distributed over year and concentrated few months, the trend of the agronomic and the environmental indicators reported in the table (i.e. reduction of some performances and improvement of some other aspects) as well as their performances must be must be read together and considered stable in the framework of the total agro-environmental sustainability assessment of cropping systems, in the mid- long-term (30-years on average).

Table 3. *Long-term sustainability assessment (30-years) of synthetic (SYN) and conservative (CONS) N fertilization management in tomato-durum wheat rotation under three future climate change scenarios: METO = METO-HC; ECHAM = DMI-HIRHAM5-ECHAM5; ETHZ = ETHZ-CLM-HadCM3Q0. More information available at http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d*

CROP MANAGEMENT (SIMULATION PERIOD)	SYN under future climate change scenario (30-YEARS)		CONS under future climate change scenario (30-YEARS)		Overall CONS *vs.* SYN evaluation as relative variation (%)	
CROPS	**WHEAT**	**TOMATO**	**WHEAT**	**TOMATO**	**WHEAT**	**TOMATO**
Agronomic indicators (average over 30-year)						
Yield (Mg/ha)	5	128	3	147	-34	15
N Recovery Efficiency (%)	38	49	25	21	-34	-57
Nutrient use efficiency (NUE, Kg/Kg)	137	112	96	48	-29	-57
Water Use Efficiency (WUE, Kg/mm)	70	22	83	29	17	28
Agronomic evaluation						
Environmental indicators (average over 30-year)						
CROPPING SYSTEM	**Wheat-tomato SYN**		**Wheat-tomato CONS**		**Wheat-tomato CONS vs. SYN**	
Cumulative NO_3 loss by leaching (Kg/ha) relative variation (%) to N inputs	26		16		-38	
SOC stock change (kg/ha)	- 1.3		-0.9		165	
Soil Bulk Density change (g/cm^3)	0.20		0.01		-94	
Environmental evaluation						

Over the long-term predictions, **crop yield** under future climate change showed a different trend for durum wheat and tomato in SYN and CONS treatments. As regards rainfed durum wheat, in SYN the yield was better stable and remained within the medium class range (Table 2), while a decrease in grain yield was observed in CONS treatment moving to low class (-34% in comparison with SYN). In order to increase durum wheat yield under future climate change scenario in CONS treatment, some variations in farm management practices such as supplemental irrigation and/or use of wheat varieties, more resistant to drough, can be feasible solutions to address the problem. Conversely, for irrigated tomato, both treatments maintained the yield in the best class range (15% higher in CONS than in SYN). As regards **Recovery Efficiency (RE)**, values observed for both crops and treatments are in the low range class (below 50%). This indicates the strictly relationship between crop yield and the capability of crops to use the nitrogen applied by fertilization. The lower RE values observed under CONS treatment respect to SYN (-47%) can be linked to the different pattern of N release in the two treatments (slow-release organic N under CONS, and faster release mineral N under SYN). In both cases, plant N uptake is linked to soil water content availability in the critical crop growth stages. As regards Nitrogen Use Efficiency (NUE), the higher value observed under SYN (greater than 100) means that more N is removed with the harvested crop than applied by fertilizer. This situation is equivalent to "soil mining" of N because soil N reservoir is used. On the other hand, the lower NUE value observed under CONS is positive, and demonstrates a greater crop efficiency in N uptake. In this case, organic N fertilizers become a positive factor because they release N for crop slowly and contribute to increase soil organic matter in soil. **Water Use Efficiency (WUE)** of durum wheat (rainfed) and tomato (irrigated) crops was higher under CONS (higher class range, green color) than under SYN treatment (low class range, red color). Therefore, the incorporation of compost and cover crop as green manure for tomato and the use of poultry manure for durum wheat showed a very positive effect in increasing the soil moisture retention over time. As regards the long-term evaluation of environmental sustainability under future climate change scenario, the value of **cumulative NO_3^- loss by leaching** durum wheat – tomato cropping system is in the low-class range (red color) in SYN and in medium-class range (brown color) under CONS, showing a NO_3^- percolation reduction of 38% in CONS in comparison with SYN. Since the nitrate permanently accumulates in the groundwater, these findings are particularly significant especially if we consider the Nitrate leaching at a wider geographic scale. The **SOC stock change** showed a higher decrease under SYN than under CONS. This trend is consistent with the **soil bulk density**, where a lower value (better in terms of soil quality) was observed under CONS in comparison with SYN. For increase the long-term environmental sustainability a higher SOC stock change and a lower bulk density value are desirable. To fulfil this aim, more conservative management strategies such as compost (different type and rate), minimum or no-tillage, agroecological service crops might be suggested.

6 Conclusions

The overall evaluation of the alternative fertilization strategy proposed is strongly dependent from either the environmental or productive aspect considered and should take into account the local applicability and the profitability for the farmer. In terms of productivity, i.e. relative yield change in CONS respect to SYN, the effect is positive for tomato and negative for wheat in all the climate scenarios. Given the highest profitability of tomato compared to wheat, the change proposed is considered a feasible strategy. If we consider the environmental variables, SOC stock change and nitrate leaching, the effect of CONS in the predicted climate change is strongly positive. Hence, despite some weakness of the strategy, i.e. type and rate of organic fertilisers and selection of cover-crop, the innovative management represent a good option for the farmer and for the environment.

7 Literature

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