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Article

Modelling Soil Health Indicators to Assess the Effectiveness of Sustainable Soil Management in a Mediterranean Arable Land

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Abstract: Considering future tasks in soil health, resources management and environmental protection, farmers are challenged to develop sustainable strategies for managing soil and land resources. In this study, the long-term sustainability of two fertilization strategies, - current, with synthetic fertilizers (SYN) vs conservative, with organic sources of nitrogen (organic amendments plus green manure with a legume - CONS) - was assessed in a processing tomato/durum wheat rotation. The EPIC model was used, validated with field data then run to simulate the management for 30 years under 3 current and future climates. Yield, soil organic carbon (SOC) stock change, nitrogen use efficiency (NUE), water use efficiency (WUE) and nitrate leaching were considered as sustainability indicators. Under all the future climate scenarios, tomato yield increased in CONS, remaining almost stable in SYN. Wheat yield increased both in CONS and SYN, but the average yield in CONS was considerably lower than in SYN. NUE and nitrate leaching followed the same trend, both decreasing in CONS, while WUE was higher in CONS compared to SYN. The effect of CONS on SOC was always positive. Thus, the alternative N fertilization strategy proposed can be a favorable option for maintaining soil health and a sustainable crop production.

Keywords: long-term sustainability; soil health indicators; fertilization strategies; EPIC model; Central Italy

1. Introduction

The Mediterranean basin is a recognized hot spot for climate change for the next decades [1,2], with modifications of rainfall amount and pattern and temperature increase, and where extreme events are expected to severely affect agricultural sector and food security [3]. As reported by Duveiller et al. [4], 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 issues 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 [5]. Several authors confirm that multiple forms of physical, chemical, and biological degradation affect the Mediterranean soils [6,7].

The EU Soil Strategy for 2030 provides the framework towards protecting and restoring soils, and ensuring that they are used sustainably, through a Proposal for a new Soil Health Law [8]. The proposal provides a harmonized definition of soil health, puts in place a comprehensive and coherent monitoring framework, and fosters sustainable soil management and remediation of contaminated sites. In this context, organic and conservation agriculture should be possible solutions to achieve a more sustainable agricultural production, which includes ensuring and maintaining productive capacity for today and the future, and increasing productivity without harming the environment and natural resources. 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 increasing crop yield stability and biodiversity in the rhizosphere over time [9,10]. Such management practices help in maintaining the soil functions - food, feed, fiber, and fuel production; water regulation, purification, storage, transformation; carbon sequestration and climate regulation; habitat for functional and intrinsic biodiversity; nutrient cycling and provision - and water quality and quantity [11]. All these functions should be maintained in an integrated, holistic way so that one function is not maximized at the cost of another [12,13].

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 [14]. Nevertheless, most of the studies over the Mediterranean basin indicated that the observed temperature and precipitation trends are expected to worsen in the next future [15]. 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 [16]. Indicators are useful tools for interpreting and summarizing the complexity of the impact of alternative scenarios of practices [17]. Thus, appropriate prediction tools are required to characterize the vulnerability of agricultural systems in a future changing climate, and to implement the best practices.

Deterministic crop growth modelling has proven to be a major tool for analyzing the impacts of climate change on agricultural production. The Environmental Policy Integrated Climate (EPIC) agroecosystem model is extensively applied at field-scale and tested in many pedo-climatic conditions [18]. It simulates crop production as a function of weather, soil conditions, and management practices [19,20]. EPIC model v.0810 [21] 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 [22,23], Argentina [24], and Europe [18,25,26]. The EPIC model was used also in a long-term organic vegetable field experiment, to evaluate the performance of agro-ecological practices as adaptation and mitigation measures to cope with climate change in Southern Italy [27].

The present study aimed to evaluate the long-term (30-years) agro-environmental sustainability of a typical Mediterranean cropping system using a modelling approach under future climate change scenarios. The agricultural management practices were assessed by means of several indicators. Within the H2020 FATIMA project, measured data from the Italian field trial and the 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 (WUE), Nitrogen Use Efficiency (NUE), SOC stock change, soil bulk density change, and soil N cycle (nitrate leaching and N₂O emissions), under future climate change scenarios. The tested treatments, applied in a processing tomato/durum wheat rotation, were: i) conservative N fertilization methods, based on the adoption of compost, leguminous cover crops (fava bean), and poultry manure; and ii) synthetic N fertilization method, based on mineral N fertilizer - used as control.

2. Materials and Methods

2.1. Study Area

The study area is located in the Tarquinia coastal plain (Viterbo Province, Latium, Central Italy), 7 km NW of Tarquinia city, 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 (Figure 1). The area is an intensive agricultural land, characterized by the cultivation of rainfed winter cereals, often in rotation with irrigated summer crops. The area lies within a Nitrate Vulnerable Zone (NVZ), where the excess in N input applied to the soil - coming from livestock and fertilizers - directly contributed to the groundwater pollution. The Nitrates Directive (Directive 91/676/EEC - Council of the European Communities Council, 1991) legally restricted annual N application to 170 kg ha⁻¹ as the maximum.

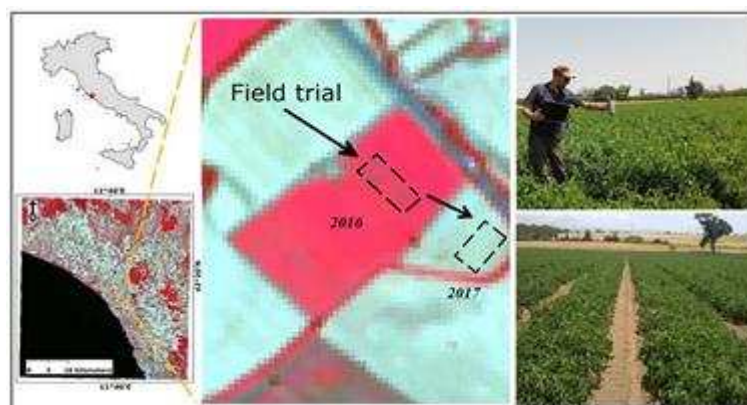


Figure 1. Location of the study area.

In autumn 2015, a field experiment was set-up within a 20 ha private farm, cultivated with a durum wheat (*Triticum durum* Desf. var. Iride)/processing tomato (*Solanum lycopersicum* L. var. Vulcano) rotation since 2005. The field experiment continued until June 2017. The soil of the experimental site, with a clay loam texture, was classified as Calcaric Cambic Phaeozems according to WRB [28]. The experiment aimed to evaluate the sustainability of the durum wheat/processing tomato production system in the long-term. Two different field plots (A and B) were set up to test the effects of conservative N fertilization methods (CONS) – based on the use of compost, cover crops (for irrigated tomato) and poultry manure (for rainfed wheat) - in comparison with synthetic N management (SYN) on crop yield and some selected environmental quality indicators. In plot A, the rotation started with processing tomato as main crop, while in plot B the rotation started with durum wheat. To improve soil fertility and NUE, and to reduce the potential nitrate (NO_3^-) leaching, the CONS method in tomato included the cultivation of fava 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. Tables 1 and 2 show an overview about nitrogen fertilization treatment for durum wheat and tomato, respectively.

Table 1. Nitrogen fertilization management in durum wheat [29].

Treatment	Time	Type	N % (w/w)	N (kg ha ⁻¹)
SYN	Sowing	NP	18	40
	Top dressing 1	$\text{NH}_4^+ \text{NO}_3^-$	26	52
	Top dressing 2	$\text{NH}_4^+ \text{NO}_3^-$	26	39
	Total			131
ORG	Sowing	Poultry manure	3	131

Table 2. Nitrogen fertilization management in processing tomato [29].

Treatment	Time	Type	N % (w/w)	Quantity (kg ha ⁻¹ dm)	N (kg ha ⁻¹)
SYN	Transplanting	Fertilizer	15	200	30
	Top dressing 1	Fertilizer	12	600	72
	Top dressing 2	Fertigation	-	-	30
	Total				132
ORG	Transplanting 1	Horse bean green manure	3.1	7260	226
	Transplanting 2	Green residues compost	1.6	6380	102
	Top 1	Fertilizer	12.0	600	72

Top 2	Fertigation	-	-	30
Total		3		430

2.2. Evaluation Procedure

The overall assessment of the long-term (30 years) agro-environmental sustainability and soil health of the two N fertilization treatments tested in the study area under future climate change scenarios was obtained in two steps. First, a set of agro-environmental indicators was considered, defining also some thresholds to obtain three classes of sustainability, low, medium and high (Table 3). 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, considering climate change scenarios.

Table 3. Classes of agro-environmental indicators proposed for the long-term sustainability evaluation in Tarquinia.

INDICATOR	SUSTAINABILITY EVALUATION CLASS		
	LOW	MEDIUM	HIGH
Yield Mg ha ⁻¹ (wheat)	< 4	4-5	> 5
Yield Mg ha ⁻¹ (tomato)	< 50	50-100	> 100
NRE Nitrogen Recovery efficiency %	< 100	100-200	> 200
WUE Water use efficiency kg mm ⁻¹ (wheat)	< 70	70-80	> 80
WUE Water use efficiency kg mm ⁻¹ (tomato)	< 23	23-27	> 27
NUE Nitrogen use efficiency kg kg ⁻¹	< 50; > 100	50-80	80-100
Cumulative NO ₃ ⁻ loss by leaching kg ha ⁻¹ – relative variation % to N input	> 20	20-10	< 10
SOC stock change kg ha ⁻¹	Negative values < -0.25	Stable values >-0.25 <0.25	Positive values > 0.25
Soil bulk density change g cm ³	Positive values > 0.1	Stable values >-0.1 <0.1	Negative values < -0.1

Where:

- Yield (Mg ha⁻¹): grain for wheat (Mg ha dry matter weight) and fruits for tomato (Mg ha of fresh weight).
- Nitrogen Recovery Efficiency (NRE) (%): expressed as the partial factor productivity, is the ratio between crop yield and N applied with fertilizers [30].
- WUE (Kg mm): ratio between the crop yield and the evapotranspiration (ET) during the growing season.
- NUE (kg kg⁻¹): expressed as the partial nutrient balance, is the simplest form of nutrient RE. It is calculated as the ratio between N content in grain or fruits and the N applied by fertilizers [30]. A value close to 1 suggests that soil fertility will be sustained at a steady state, while values well below 1 suggest avoidable nutrient losses [31].
- Cumulative nitrate loss by leaching (Kg ha): amount of NO₃⁻ lost from the soil (below the rooting depth) for the whole cropping season/year, expressed as the relative variation (%) to annual N input source.
- SOC stock change (kg ha): relative variation between final and initial values.
- Soil bulk density change (g cm³): relative variation between final and initial values.

The considered threshold values were based on the results of the FATIMA project – a 2-years field experiment - and on the historical experience and knowledge of the farmer involved in the experiment. For the NRE (%) and NUE (kg kg⁻¹) the threshold values were based on the study by Dobermann et al. [30].

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 rainfed crops -

such as durum wheat - depending entirely on rainfall. The sustainability threshold for tomato lays within a very small range, due to irrigation and to the possibility for the farmer to tune the doses very finely according to the plant needs. For nitrate leaching the thresholds were not defined as absolute values, but as relative variation (%) in comparison with N inputs as fertilizer, both under SYN and under CONS treatments. The N given to the soil as NH_4^+ can be quickly converted to NO_3^- by 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 nitrate leaching towards groundwater, due to their higher permeability. SOC is considered one of the most important indicators of soil quality and soil health, strictly linked to most of the ecosystem services provided by soil, such as nutrient and water cycles regulation, buffer capacity, biodiversity, and GHG emission regulation. Any reduction of SOC in Mediterranean conditions must be considered as negative and not desirable. Finally, bulk density change is an important soil quality indicator in terms of physical quality. Soil compaction due to a very intensive management could result in a reduction of water infiltration, an increase in the energy required to plough the soil, crusting and erosion.

2.3. EPIC Model

EPIC is a field-scale and a daily time step process-based model that has been developed to assess the impacts of soil management on biophysical and biogeochemical processes [32], such as plant growth and development, soil water balance, C and nutrient cycling, soil erosion, and GHG emissions. The model, 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 [19]. Afterwards, it was refined including additional sub-models to predict water quality and the response of crops to atmospheric CO_2 [33]. EPIC and the derived models have been applied extensively to a variety of soils and cropping systems worldwide [34]. As reported in Parton et al. [35], EPIC has eight major components - 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 performing 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 considered crop rotation and cropping system.

Information about the cropping system management (such as tillage, irrigation volumes, fertilizers supply, and scheduling of operations), 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. [36], 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, fluxes of selected gases, and soil hydrological 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 [32]. 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 WUE [37]. In this study, EPIC model v.0810 was used [21].

Model calibration is the process of adjusting influential model parameters within their reasonable ranges to obtain realistic model results, consistent with the available observed data such as crop yields, soil nutrient content, soil carbon, soil water content, water infiltration rate and flow and water quality [38]. In the study area the calibration procedure was performed using only the first year's data.

Validation process consists in the assessment of the accuracy of the model predictions, comparing the results to additional and independent observed data. For the validation process we used the second-year field measures. 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 the model performance. The differences between model outputs from simulations at different steps were examined by analyzing the mean values, for better quantifying the effects of calibration on simulated crop yield and for understanding the uncertainties associated with the calibration procedures.

2.4. Future Climate Scenarios

In the present study, three different climate scenarios were used to run the EPIC 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 are reported in Table 4.

Table 4. Monthly pattern of baseline and future mean temperature (°C) and rainfall (mm).

Month	METO		ECHAM		ETHZ	
	Baseline	2030	Baseline	2030	Baseline	2030
<i>Temperature °C</i>						
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
<i>Rainfall mm</i>						
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 pattern based on an increase in precipitation in comparison with the baseline. Conversely, the ECHAM future climate scenario showed a reduction in precipitation regime with respect to the baseline, and markedly

different patterns than under the others. 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. An increase in rainfall 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 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 CO₂ concentrations for the considered periods were 400 ppm for baseline 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 experimental plot, all simulations were performed for each baseline and the corresponding future climate change scenario. In all the 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 (soil parameter change = [(final value – initial value)/initial value]). Similarly, to compare the effects of the three future climate projections considered (METO, ECHAM, ETHZ), the relative variation of soil parameters between each climate change scenario and the corresponding baseline used as control was computed.

3. Results and Discussion

3.1. Agronomic Indicators

Figure 2 shows the changes in durum wheat and tomato average yields for the SYN and CONS treatment and the three GCMs in a 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 increase was obtained for durum wheat SYN (14%), while the CONS treatment for both crops showed an increase of 8%. This behavior is likely due to the positive effect of increased CO₂, combined with the increase of both rainfall and temperature observed under METO GCM. Under the ECHAM climate change scenario, which considers no significant changes in rainfall, the average yield of both crops increased under CONS treatment, while under SYN treatment only tomato yield increased, reaching a steady-state for durum-wheat. Finally, under the ETHZ climate change scenario, the highest increase was obtained for tomato CONS (+10%), followed by durum-wheat SYN (+3%).

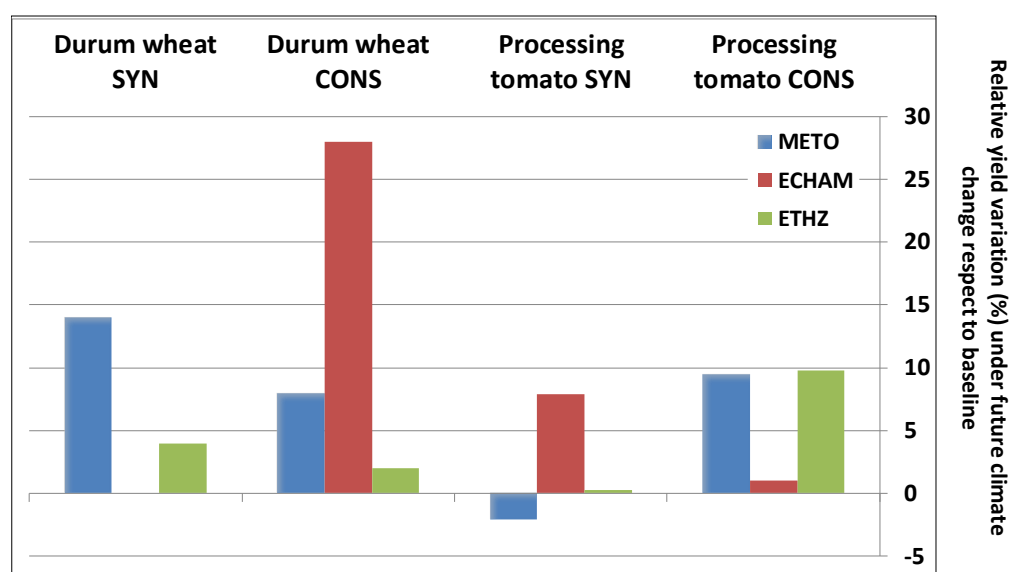


Figure 2. Durum wheat and processing tomato relative yield variation under future climate change with respect to the baseline.

Changes in NUE in the 30-yr period are reported in Figure 3. NUE of durum wheat and tomato crops benefit of climate change under ETHZ both for SYN and CONS treatments. Nevertheless, the highest NUE was obtained for durum wheat CONS (+23%) under ECHAM, while the lowest one was observed in METO for durum wheat under CONS treatment and processing tomato under SYN treatment (-3%).

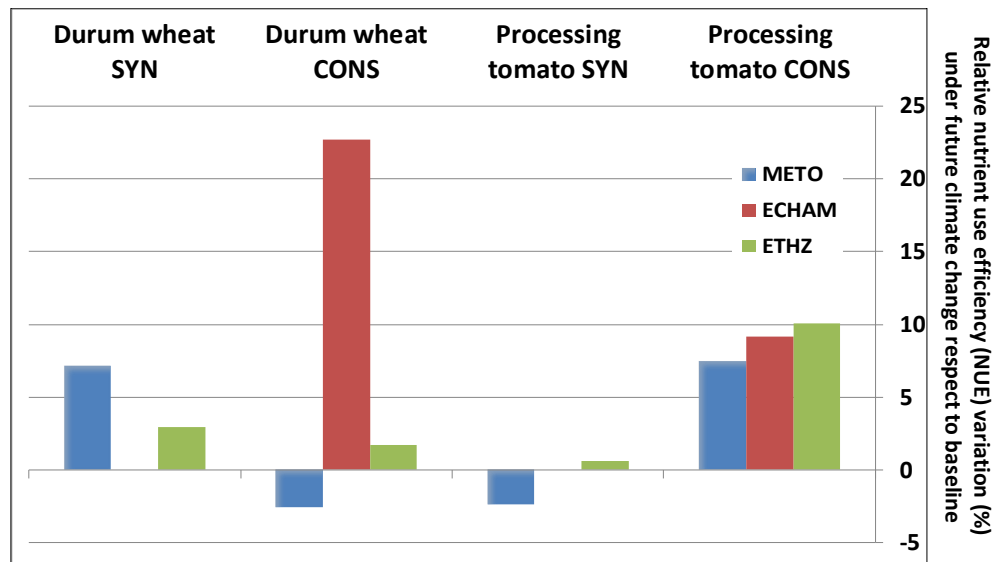


Figure 3. Durum wheat and processing tomato nitrogen use efficiency (NUE) relative variation under future climate change scenario with respect to the baseline.

Figure 4 shows the durum wheat and the tomato relative changes in WUE in the 30-yr period for the SYN and CONS treatments, under the three GCMs in climate change scenarios with respect to the corresponding baseline. All the climate change scenarios showed higher performance than the relative baseline, except for ETHZ under tomato in SYN treatment.

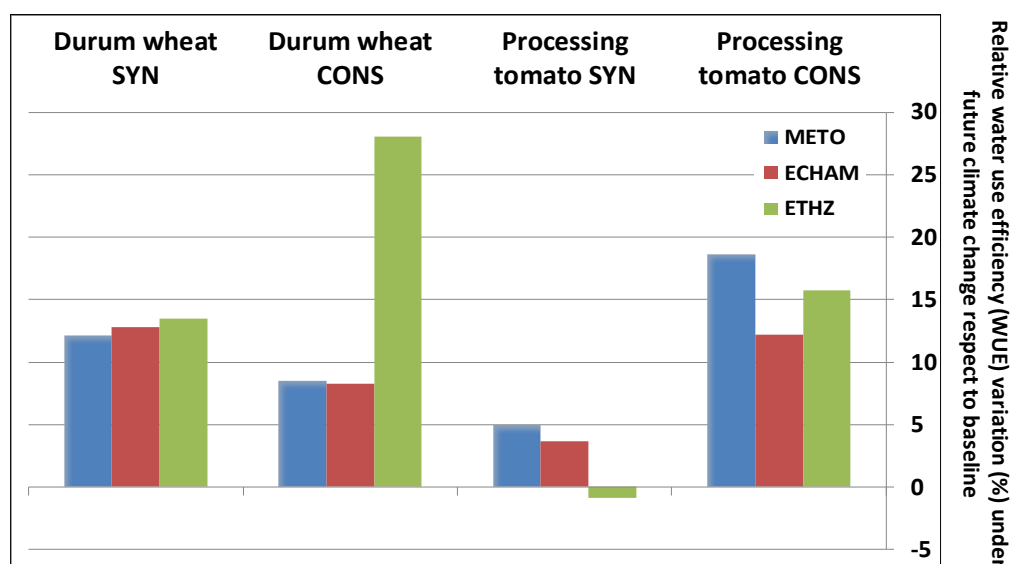


Figure 4. Durum wheat and processing tomato water use efficiency (WUE) variation under future climate change scenario with respect to the baseline.

In Figure 5 the relative variations of crop yield and WUE for tomato SYN and CONS treatments under relative variations of temperature (Figure 5a) and rainfall (Figure 5b) in future climate change with respect to the baseline are reported. The effect of the foreseen increase in temperature on tomato

yield is always positive (up to 10%) for CONS and is not significant for SYN (Figure 5a). The change in rainfall, both positive (as in ETHZ) and negative (as in METO), is associated with an increase in yield in CONS, particularly with the intermediate rain increase. In SYN the yield is slightly influenced by the change in rain, and the lower increases in yield are associated with the higher rate of rainfall change. WUE is positively influenced by the most pronounced 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, to a varying extent following the change in rainfall and temperature.

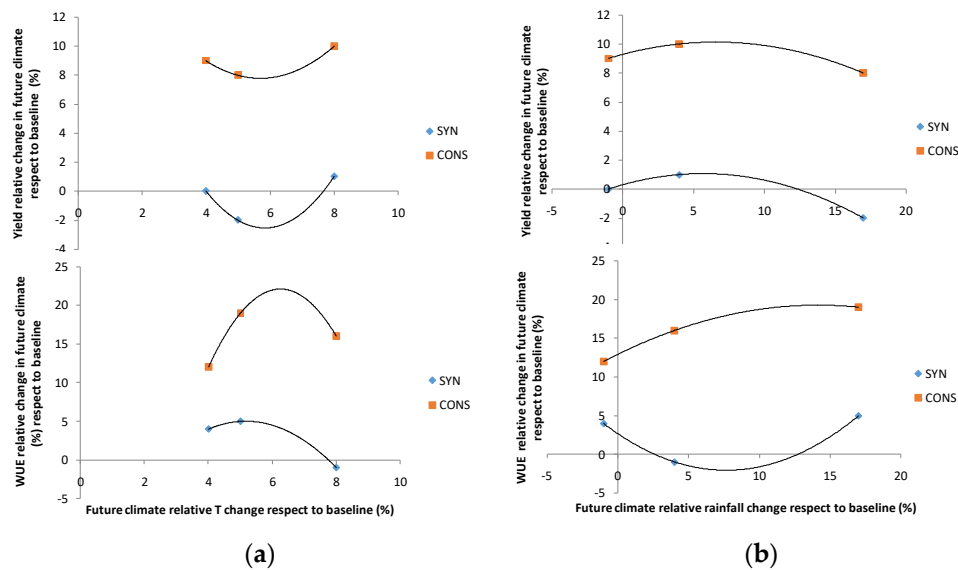


Figure 5. Relative variations of crop yield and WUE for tomato in SYN and CONS treatments under changes of temperature (a) and rainfall (b) in the future climate change with respect to the baseline.

The higher stability of yield under climate change in SYN is confirmed also for durum wheat (Figure 6).

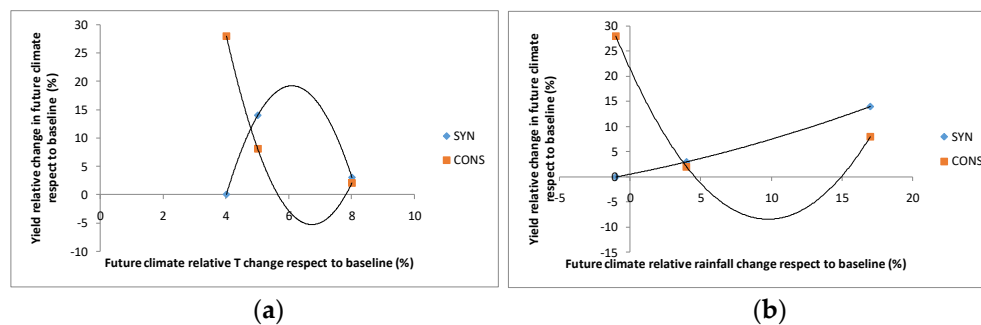


Figure 6. Relative variations of crop yield for durum wheat in SYN and CONS treatments under changes of temperature (a) and rainfall (b) in the future climate change with respect to the baseline.

3.2. Environmental Indicators

The effect of rainfall change on nitrate leaching in the tomato-wheat rotation is clearly different in SYN and CONS. In CONS both the increase in temperature and the decrease in rainfall reduced nitrate leaching, while the opposite can be observed for SYN (Figure 7).

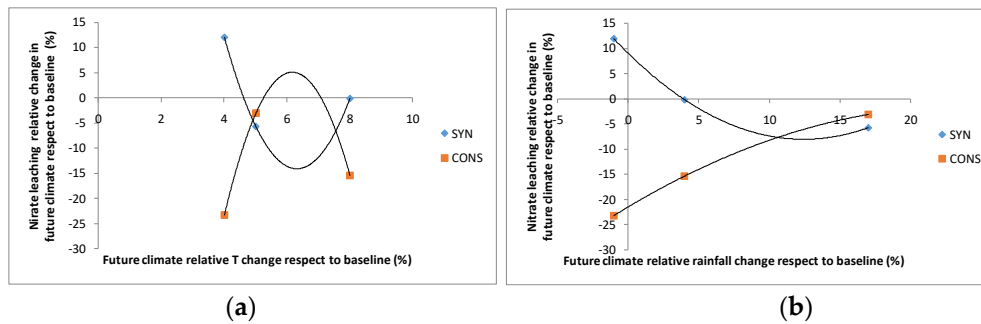


Figure 7. Relative variations of nitrate leaching in the tomato-durum wheat rotation in SYN and CONS treatments under changes of temperature (a) and rainfall (b) in the future climate change with respect to the baseline.

The bulk density in the 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.

Several studies have shown that SOC is affected by the management [39–42]. The SOC stock in the durum wheat/tomato cropping system decreased in the two simulated N management treatment (SYN and CONS) under current and future climate change scenarios, by about $0.62 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, on average, in the 30-yr period.

Figure 8 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 in both SYN and CONS treatments, ranging from -11% to -3%, on average. On the contrary, under ECHAM the SOC stock for the SYN and CONS treatments increased by 4%.

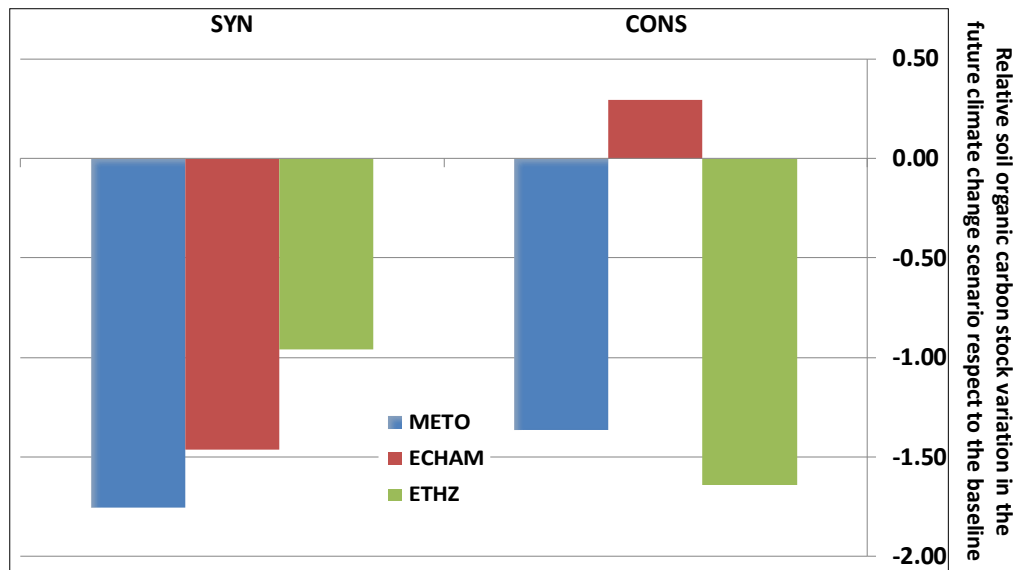


Figure 8. Relative soil organic carbon stock variation in the 30-year period for each general circulation models (GCMs) under future climate change scenario with respect to the baseline.

Changes in nitrate leaching in the 30-yr period was reported in Figure 9. Nitrate leaching decreased under CONS treatment in all the three-climate change scenario, while in the SYN treatment only in METO scenario a decrease with respect to the relative baseline is predicted.

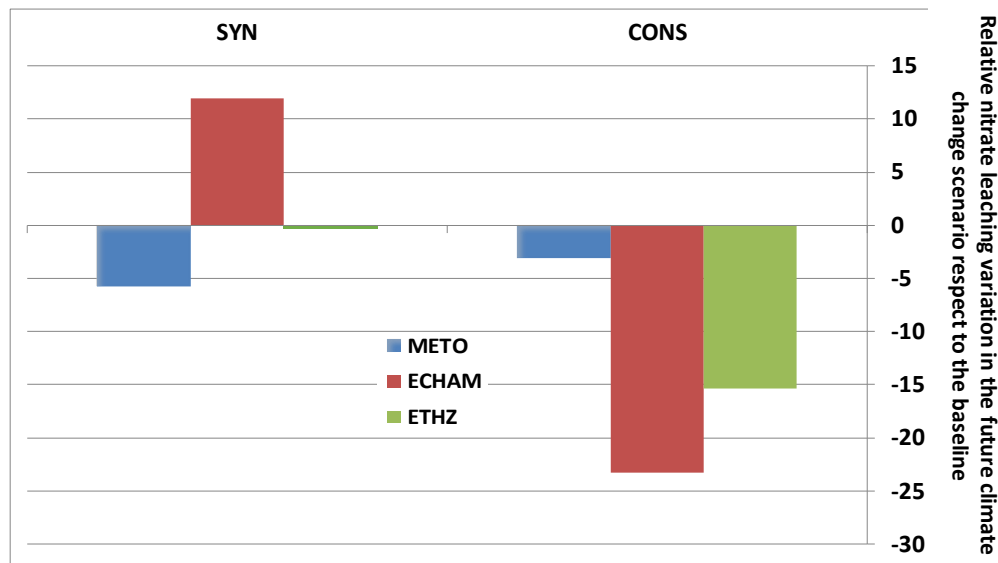


Figure 9. Relative nitrate leaching variation in the 30-years period for each general circulation models (GCMs) under future climate change scenario with respect to the baseline.

The predicted cumulated N_2O emissions were mainly influenced by N management treatment (SYN or CONS). The cumulated N_2O emissions were null under SYN 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 slightly positive. These low emissions can be attributed to the reduced N fertilization rates applied for durum wheat/processing tomato cropping systems, since the experimental field lies within a NVZ.

3.3. Overall Evaluation of Agro-Environmental Sustainability

In Table 5 the results of the long-term simulations obtained by running the EPIC model for 30 consecutive years under three different climate change scenarios (METO, ECHAM and ETHZ) are reported. The table summarizes the overall agro-environmental sustainability assessment of the nitrogen management strategies adopted in the study area of the FATIMA project for durum wheat/processing tomato rotation. 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, the values of the indicators averaged on the three climate change scenarios were reported. For both agronomic and environmental indicators, a qualitative evaluation was performed according to three classes, and the comparison between CONS and SYN was computed as a relative variation. Each value is represented with the corresponding color of the evaluation class, thus fitting the data in the qualitative class they belong to.

Table 5. 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.

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 (%)	
	WHEAT	TOMATO	WHEAT	TOMATO	WHEAT	TOMATO
Agronomic indicators (average over 30-years)						
Yield (Mg ha ⁻¹)	5	128	3	147	-34	15
N Recovery Efficiency (%)	38	49	25	21	-34	-57
Nitrogen use efficiency (NUE, Kg Kg ⁻¹)	137	112	96	48	-29	-57
Water use efficiency (WUE, Kg mm ⁻¹)	70	22	83	29	17	28
<i>Agronomic evaluation</i>	Neutral	Neutral	Neutral	Neutral	Neutral	Positive
Environmental indicators (average over 30-years)						
CROPPING SYSTEM	Wheat-tomato SYN		Wheat-tomato CONS		Wheat-tomato CONS vs. SYN	
Cumulative NO ₃ ⁻ loss by leaching (Kg ha ⁻¹) relative variation (%) to N inputs	26		16		-38	
SOC stock change (Kg ha ⁻¹)	-1.3		-0.9		165	
Soil bulk density change (g cm ³)	0.2		0.01		-94	
<i>Environmental evaluation</i>	Negative		Neutral		Positive	

In the context of future climate change scenario, characterized by higher annual surface air temperature and by differently distributed rainfall over the year -e.g. concentrated in few months, the trend of the agronomic and environmental indicators reported in the figure (i.e. reduction of some performances and improvement of some other aspects) as well as their performances 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).

In 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 stable and remained within the medium class range (Table 3), while a decrease in grain yield was observed in CONS treatment moving to low class (-34% in comparison with SYN). Aiming to increase durum wheat yield under future climate change scenarios in CONS treatment, some variations in farm management practices - such as supplemental irrigation and/or use of wheat varieties more resistant to drought - can be feasible solutions to address the problem. Conversely, in irrigated tomato both treatments maintained the yield in the best class range (+15% in CONS with respect to SYN). As regards RE, values observed for both crops and treatments are in the low-range class (below 50%). This indicates the strong relationship between crop yield and the capability of crops to use the N applied by fertilization. The lower NRE values observed under CONS treatment

with respect to SYN (-47%) can be linked to the different patterns 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 availability in the critical crop growth stages. Considering the NUE, the higher value observed under SYN (>100) means that more N is removed with the harvested crop than applied by fertilizer. This situation is equivalent to “soil mining” of N, since soil N stock is used. On the other hand, the lower NUE observed under CONS is favorable, demonstrating a better efficiency of the crops in N uptake. In this case, organic N fertilizers become a positive factor, because they slowly release N for crops, contributing to increase soil organic matter into the soil. WUE of durum wheat (rainfed) and tomato (irrigated) crops were higher under CONS (high class range) than under SYN treatment (low class range). Therefore, incorporating compost and cover crop as green manure for tomato and using poultry manure for durum wheat showed a very positive effect in increasing the water retention of soil over time. Looking at the other indicators, the value of cumulative NO_3^- loss by leaching in durum wheat/tomato cropping system is in the low class range in SYN and in the medium class range under CONS, showing a reduction of 38% in NO_3^- percolation in CONS in comparison with SYN. Since the nitrates tend to accumulate in groundwater, these findings are particularly significant, especially considering the nitrate leaching at a wider geographical scale. The SOC stock change showed a greater decrease under SYN than under CONS. This is consistent with the behavior of the soil bulk density, where a lower value - favorable in terms of soil quality - was observed under CONS in comparison with SYN.

Several authors found that conservative agriculture had a positive impact on soil characteristics [43–45]. Francaviglia et al. [46] showed that longer crop rotations (3–5 years) and the introduction of legumes resulted in higher increases in SOC contents (18%) in Mediterranean sites. Williams et al. [47] showed the impact of soil management on soil health. Organic matter inputs, such as on-farm compost, crop residue recycling, manure, or other organic fertilizers can improve soil fertility and SOC sequestration, under various climates and cropping systems [48,49]. In our case, since a greater SOC stock and a lower bulk density are desirable conditions for the objective of increasing the long-term environmental sustainability and the soil health, more conservative management strategies such as compost application (different types and rates), minimum or no-tillage, and agroecological service crops might be suggested. Anyway, it should be kept in mind that the conversion from one fertilization strategy to others considered more “environmental-friendly” - e.g., from the mineral fertilization to the organic one - not always is an assurance of higher sustainability [50].

4. Conclusions

In the study area - which represents a typical Mediterranean cropping system - the agro-environmental sustainability of two different fertilization strategies was evaluated in the long-term using a modelling approach under future climate change scenarios. Soil fertility and crop productivity were affected by the management, since CONS treatment shows higher SOC stock and WUE compared to SYN. The rainfall influenced crop yield. The overall evaluation of the alternative fertilization strategy proposed is strongly dependent from both the environmental and the productive aspects, and should take into account the local applicability of the option and its profitability for the farmer. In terms of productivity, i.e. relative yield change in CONS in comparison with 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 proposed change is considered a feasible strategy under climate change scenario, and could be sustainable in the long-term. Considering the environmental indicators, SOC stock change and nitrate leaching, the effect of CONS in the foreseen climate change is strongly positive. Hence, despite some weakness of the strategy, i.e. type and rate of organic fertilizers and selection of cover crop, the proposed management represents a good option for the farmer, for maintaining the soil health and for protecting the environment.

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