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# Modeling Soil Health Indicators to Assess the Effectiveness of Sustainable Soil Management on Mediterranean Arable Land

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**Abstract:** Considering future tasks in soil health, resource 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, and then run to simulate the management for 30 years under three current and future climates. Yield, soil organic carbon (SOC) stock change, nitrogen use efficiency (NUE), water use efficiency (WUE), and nitrate leaching were considered sustainability indicators. Under all of the future climate scenarios, tomato yield increased with CONS, remaining almost stable with SYN. Wheat yield increased both with CONS and SYN; however, the average yield with CONS was considerably lower than with SYN. NUE and nitrate leaching followed the same trend, both decreasing with CONS, while WUE was higher with 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 sustainable crop production.

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

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## 1. Introduction

The Mediterranean Basin is a recognized hot spot for climate change for the coming decades [1,2], with modifications to the rainfall amount and pattern and temperature increases, and where extreme events are expected to severely affect the 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 light 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 [6–8].

The EU Soil Strategy for 2030 provides the framework for protecting and restoring soils and ensuring that they are used sustainably through a proposal for a new Soil Health Law [9]. The proposal provides a harmonized definition of soil health, puts in place a comprehensive and coherent monitoring framework, and fosters sustainable soil management and the 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 a 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, and the 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 [10,11]. Such management practices help in maintaining the soil functions—food, feed, fiber, and fuel production; water regulation, purification, storage, and transformation; carbon sequestration and climate regulation; habitat for functional and intrinsic biodiversity; nutrient cycling and provision—and water quality and quantity [12]. All of these functions should be maintained in an integrated, holistic way so that one function is not maximized at the cost of another [13,14].

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 [15]. Nevertheless, most of the studies of the Mediterranean Basin have indicated that the observed temperature and precipitation trends are expected to worsen in the future [16]. The future climate will exhibit an increased frequency of extreme events with the maximum temperature exceeding 40 °C, which will represent the normal conditions in the future [17]. Indicators are useful tools for interpreting and summarizing the complexity of the impact of the alternative scenarios of practices [18]. Thus, appropriate prediction tools are required to characterize the vulnerability of agricultural systems in the future's changing climate and to implement the best practices.

Deterministic crop growth modeling has proven to be a major tool for analyzing the impacts of climate change on agricultural production. The Erosion/Productivity Impact Calculator (EPIC) agroecosystem model is extensively applied at field-scale and tested in many pedo-climatic conditions [19]. It simulates crop production as a function of weather, soil conditions, and management practices [20,21]. EPIC model v.0810 [22] 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 [23,24], Argentina [25], and Europe [19,26,27]. 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 [28].

The present study aimed to evaluate the long-term (30-year) agro-environmental sustainability of a typical Mediterranean cropping system using a modeling approach under future climate change scenarios. The agricultural management practices were assessed by means of several indicators. Water use efficiency (WUE), nutrient use efficiency (NUE), soil organic carbon (SOC), nitrogen (N) cycle, and bulk density are all critical factors that play key roles in the sustainability of arable land. They help ensure efficient resource utilization, environmental protection, and the long-term viability of agriculture in a climate-changing scenario with increasing pressure on resources. Within the H2020 FATIMA project, measured data from the Italian field trail and the EPIC model were used to assess the long-term agro-environmental impacts and sustainability of two different N fertilization treatments on crop yields 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. Our research hypothesis was that, in the long term, in the considered area, the application of organic fertilizers is feasible and if wisely applied together with the introduction of a cover crop, the environmental impact of the studied rotation can be reduced.

## 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 and 2.7 km from the 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 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 the annual N application to 170 kg ha$^{-1}$ as the maximum.

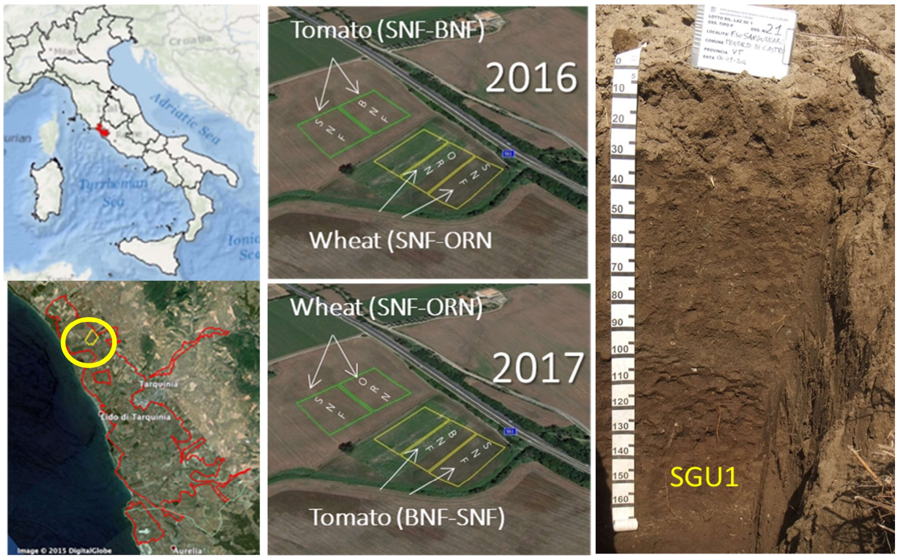



**Figure 1.** Location of the study area (red spot and yellow circle), field trials for the two-year span of 2016–2017 (green and yellow borders), and a soil reference pedon for the representative Soil Typology SGU1 (Calcaric Cambic Phaeozem).

In autumn 2015, a field experiment was set up within a 20 ha private farm that had been 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 a Calcaric Cambic Phaeozem, according to WRB [29]. 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 those of synthetic N management (SYN) on crop yield and some selected environmental quality indicators. In plot A, the rotation started with processing tomato as the 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 applied to tomatoes included the cultivation of fava beans (*Vicia faba* L.) in the autumn-winter period as a cover crop, which was 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 of N fertilization treatment for the durum wheat and tomato, respectively.

**Table 1.** Nitrogen fertilization management in durum wheat.

| Treatment | Time | Type | N % (*w*/*w*) | N (kg ha$^{-1}$) |
|---|---|---|---|---|
| SYN | Sowing | NP | 18 | 40 |
| | Top dressing 1 | $NH_4^+$ $NO_3^-$ | 26 | 52 |
| | Top dressing 2 | $NH_4^+$ $NO_3^-$ | 26 | 39 |
| | Total | | | 131 |
| ORG | Sowing | Poultry manure | 3 | 131 |

**Table 2.** Nitrogen fertilization management in processing tomato.

| 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 |

The doses of fertilizers, both mineral and organic, were studied to provide the same amount of N available for crops. Thus, with SYN, 132 kg ha$^{-1}$ of mineral N in the form of ammonia nitrogen ($NH_4^+$) is readily available for crops and represents the normal dose used by the farmers in the area. The N present in the poultry manure is in an organic form and is slowly released and made available to crops. On average, after 3 months, 30–40% of the applied N is mineralized [30], accounting for a release of 129–172 kg ha$^{-1}$. We have taken into account the more prudential value of 30%.

### 2.2. Evaluation Procedure

The overall assessment of the long-term (30-year) agro-environmental sustainability and the 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 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 |

**Table 3.** *Cont.*

| Indicator | Sustainability Evaluation Class | | |
|---|---|---|---|
| | **Low** | **Medium** | **High** |
| 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 (g $cm^3$) change % | Positive values >0.1 | Stable values >−0.1 < 0.1 | Negative values <−0.1 |

Where:

- Yield (Mg $ha^{-1}$): grain for wheat (Mg $ha^{-1}$ dry matter weight) and fruits for tomato (Mg $ha^{-1}$ of fresh weight);
- Nitrogen recovery efficiency (NRE) (%): expressed as the partial factor productivity and is the ratio between crop yield and N applied with fertilizers [31];
- WUE (Kg $mm^{-1}$): the ratio between the crop yield and the evapotranspiration (ET) during the growing season;
- NUE (kg $kg^{-1}$): expressed as the partial nutrient balance, it is the simplest form of nutrient RE. It is calculated as the ratio between the N content in grain or fruits and the N applied by fertilizers [31]. 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 [32];
- Cumulative nitrate loss by leaching (Kg $ha^{-1}$): the amount of $NO_3^-$ lost from the soil (below the rooting depth) for the whole cropping season/year, expressed as the relative variation (%) to the annual N input source;
- SOC stock change (kg $ha^{-1}$): the relative variation between the final and initial values.

The SOC stock was calculated by the following formula:

$$\text{SOC stock} = \sum_{1}^{n} \text{Organic Carbon } \% * \text{Bulk Density } (\text{g cm}^{-3}) * \text{Soil Depth}(\text{cm}) * \frac{100 - \text{skeleton } \%}{100}$$

- Soil bulk density change (g $cm^{-3}$): the relative variation in % between the final and initial values.

The considered threshold values were based on the results of the FATIMA project—a 2-year 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 a study by Dobermann et al. [31].

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 tomatoes lies within a very small range due to irrigation and the possibility for the farmer to tune the doses very finely according to the plants' 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 the 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 and, thus, is easily released into the soil liquid phase, possibly moving towards 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 cycle regulation, buffer capacity, biodiversity, and greenhouse gas (GHG) emission regulation. 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. Soil compaction due to very intensive management could result in a reduction of water infiltration, an increase in the energy required to plow the soil, crusting, and erosion.

### 2.3. The 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 [33], 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 the 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]. Afterward, it was refined, including creating additional sub-models to predict water quality and the response of crops to atmospheric $CO_2$ [34]. The EPIC and the derived models have been applied extensively to a variety of soils and cropping systems worldwide [35]. As reported by Parton et al. [36], the 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 plant density and crop growing period, is mandatory to run the model. As reported by Folberth et al. [37], in addition to plant growth and yield formation, the EPIC estimates a wide range of environmental externalities, such as the 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 the N and lignin content, crop residues including roots are split into two litter compartments: metabolic and structural. From there, as a function of soil temperature and moisture, C is allocated to three compartments (microbial biomass, slow humus, and passive humus), which are different in size, function, and turnover times [33]. Furthermore, the model accounts for the effects of changes in $CO_2$ concentration and vapor pressure deficit on radiation-use efficiency, leaf resistance, and the transpiration of crops to estimate the increase in plant growth and WUE [38]. 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 [39]. In the study area, the calibration procedure was performed using only the first year's data.

The validation process consists of 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. The coefficient of determination ($R^2$), slope and intercept of the linear regression, and correlation coefficient (r) between the observed and simulated values were used to measure the model's performance. The differences between model outputs from the simulations at different steps were examined by analyzing the mean values for better quantifying the effects of calibration on the 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 (URL http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d accessed on 28 October 2023), 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 25 × 25 km, specifically derived for crop modeling over Europe. The GCMs were (1) METO-HC (METO); (2) DMI-HIRHAM5-ECHAM5 (ECHAM); and (3) ETHZ-CLM-HadCM3Q0 (ETHZ) and both the 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 the METO and ETHZ future simulations 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 the 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 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 GCM 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 of 1985–2015, and (ii) "2030" for climate change predictions, representing mean climate change for the period of 2015–2044. The atmospheric $CO_2$ concentrations for the considered periods were 400 ppm for baseline and 450 ppm for climate change.

For all of 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 of the simulations were performed for each baseline and the corresponding future climate change scenario. In all of 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 the 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 the soil parameters between each climate change scenario and the corresponding baseline used as the control was computed.

## 3. Results and Discussion

### 3.1. Agronomic Indicators

Figure 2 shows the changes in the durum wheat and tomato average yields for the SYN and CONS treatments 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 the tomato with SYN, where a slight decrease was observed (−2%). The highest increase was obtained for durum wheat with SYN (14%) while the CONS treatment for both crops showed an increase of an average of 8%. This behavior is likely due to the positive effect of increased $CO_2$, 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 the CONS treatment; meanwhile, under the SYN treatment, only the tomato yield increased, reaching a steady state for durum wheat. Finally, under the ETHZ climate change scenario, the highest increase was obtained for tomatoes with CONS (+10%), followed by durum wheat with SYN (+3%).

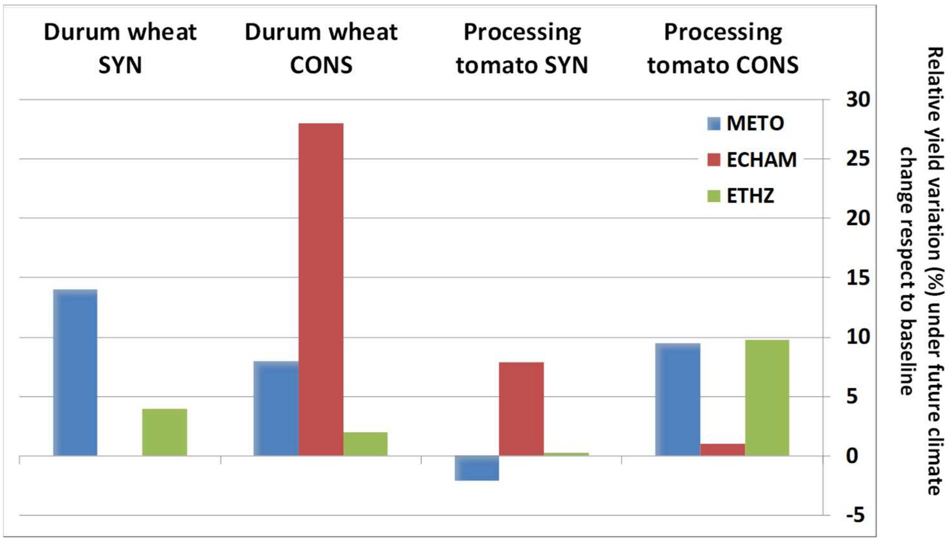



**Figure 2.** The durum wheat and processing tomato relative yield variation under future climate change with respect to the baseline.

Changes in NUE in the 30-year period are reported in Figure 3. The NUEs of durum wheat and tomato crops benefit from climate change under ETHZ both for the SYN and CONS treatments. Nevertheless, the highest NUE was obtained for the durum wheat with

CONS (+23%) under ECHAM while the lowest one was observed in METO for the durum wheat under the CONS treatment and processing tomato under the SYN treatment (−3%).

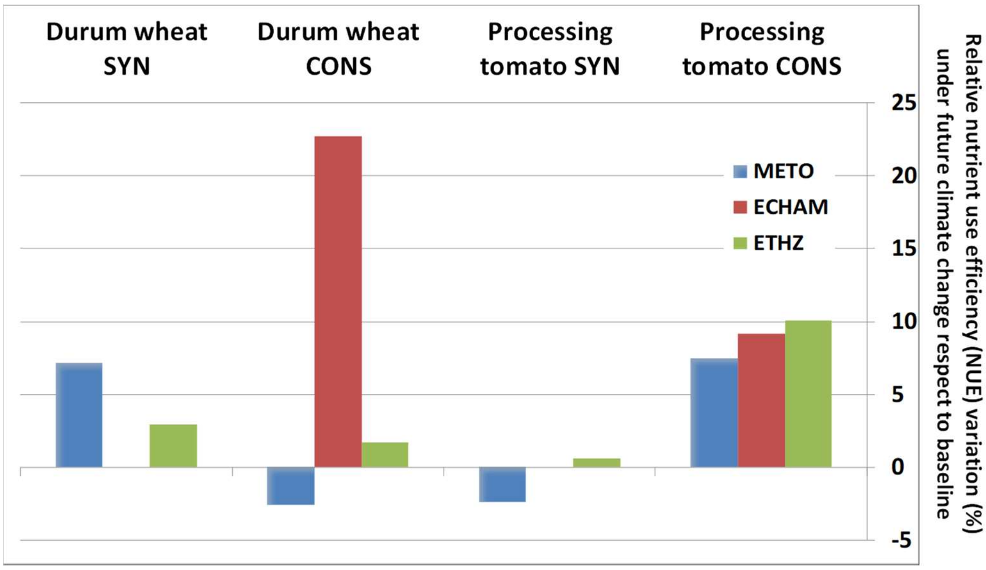



**Figure 3.** The durum wheat and processing tomato nitrogen use efficiency (NUE) relative variation under future climate change scenarios with respect to the baseline.

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

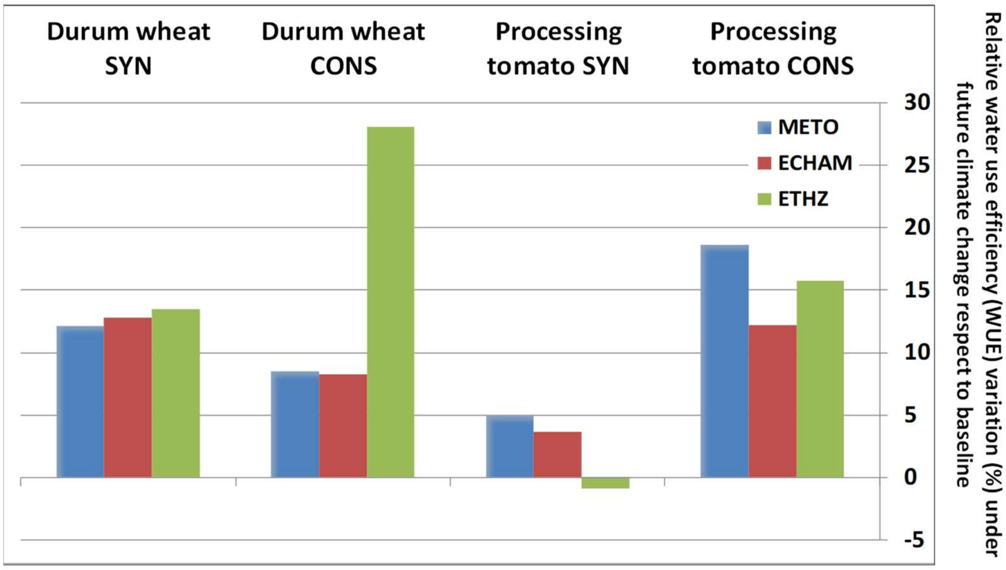
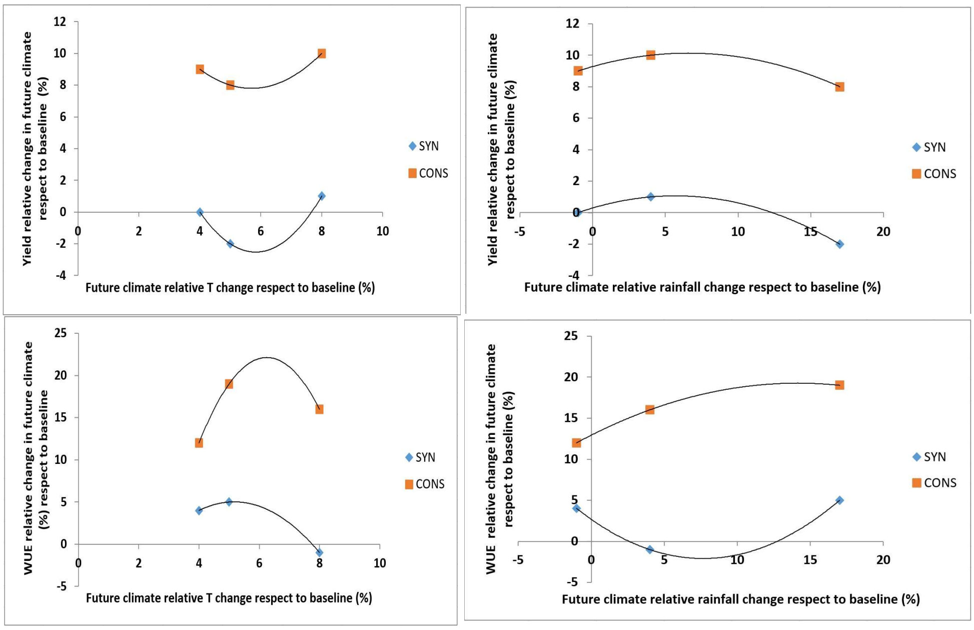



**Figure 4.** The durum wheat and processing tomato water use efficiency (WUE) variation under future climate change scenarios with respect to the baseline.

In Figure 5, the relative variations of crop yield and WUE for tomatoes under the SYN and CONS treatments under relative variations of temperature (Figure 5a) and rainfall (Figure 5b) in future climate change scenarios with respect to the baseline are reported. The foreseen climate change differently influences yield and WUE: the increase in temperature positively affects tomato yield (up to +10%) with CONS and insignificantly with SYN

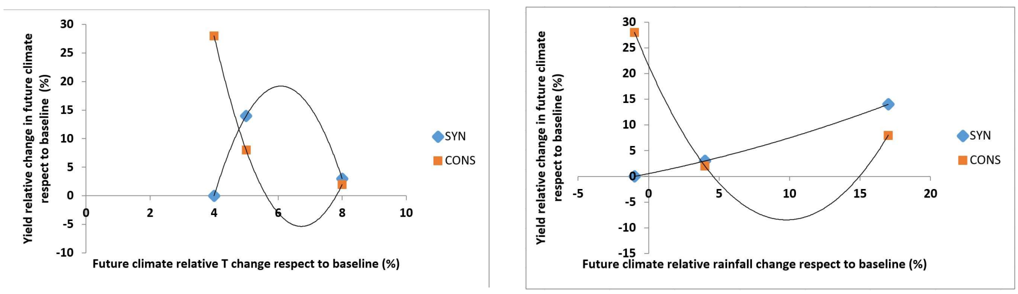
(Figure 5a). The change in rainfall, both positive (as in ETHZ) and negative (as in METO), is associated with an increase in yield with CONS, particularly with the intermediate rain increase. With SYN, the yield is slightly influenced by the change in rain and the lower increases in yield are associated with the higher rate of rainfall change. WUE is positively influenced by the most pronounced change in temperature and rainfall with CONS while WUE is less affected by climate change with SYN.




(**a**) (**b**)

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

In Figure 6, the relative variations in crop yield for durum wheat under the SYN and CONS treatments under relative variations in temperature (Figure 6a) and rainfall (Figure 6b) in future climate change scenarios with respect to the baseline are reported. The effect of climate change on the yield is clearly different with SYN and CONS.

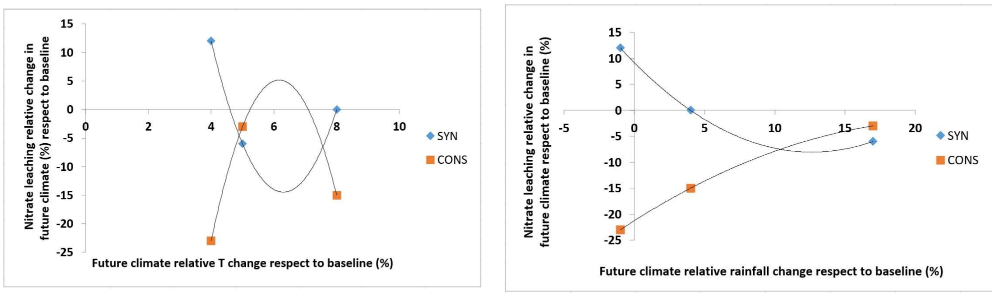



(**a**) (**b**)

**Figure 6.** Relative variations in crop yield for durum wheat under the SYN and CONS treatments under changes in temperature (**a**) and rainfall (**b**) in the future climate change scenarios 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 with SYN and CONS. With CONS, both the increase in temperature and the decrease in rainfall reduced nitrate leaching while the opposite can be observed for SYN (Figure 7).




(**a**) (**b**)

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

The bulk density in the durum wheat/tomato cropping system increased under the two simulated N management treatments (SYN and CONS) under current and future climate change scenarios, by about 0.02 g cm$^{-3}$ on average, in the 30-year period. The relative variation is different for the two treatments because the initial values were different.

Several studies have shown that SOC is affected by the management [40–43]. The SOC stock in the durum wheat/tomato cropping system decreased under the two simulated N management treatments (SYN and CONS) under current and future climate change scenarios, by about 0.26 Mg ha$^{-1}$ yr$^{-1}$ on average, in the 30-year period.

Figure 8 shows the relative SOC stock changes regarding 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 under both the SYN and CONS treatments, ranging from −17% to −9%, on average; meanwhile, under ECHAM, the relative SOC stock change under the CONS treatment increased by 3%.

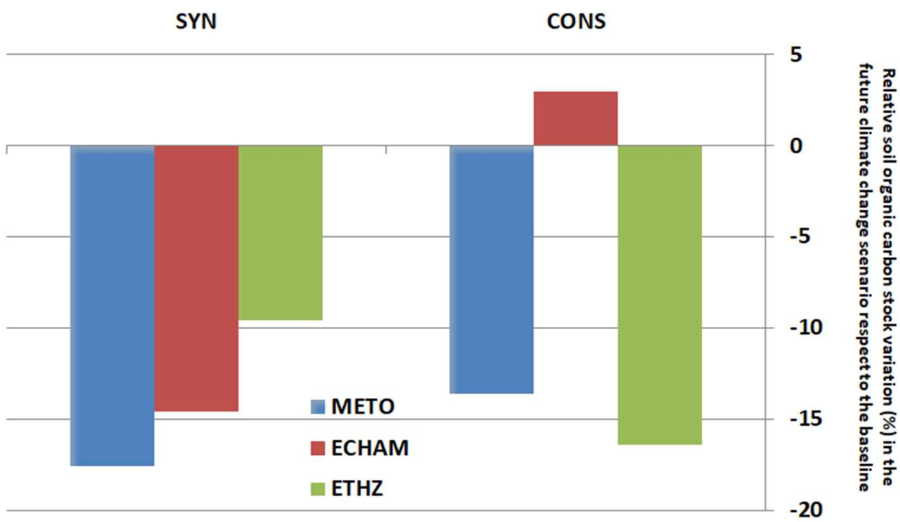



**Figure 8.** Relative soil organic carbon stock variation in the 30-year period for each general circulation model (GCM) under future climate change scenarios with respect to the baseline.

Changes in nitrate leaching in the 30-yrs period were 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.

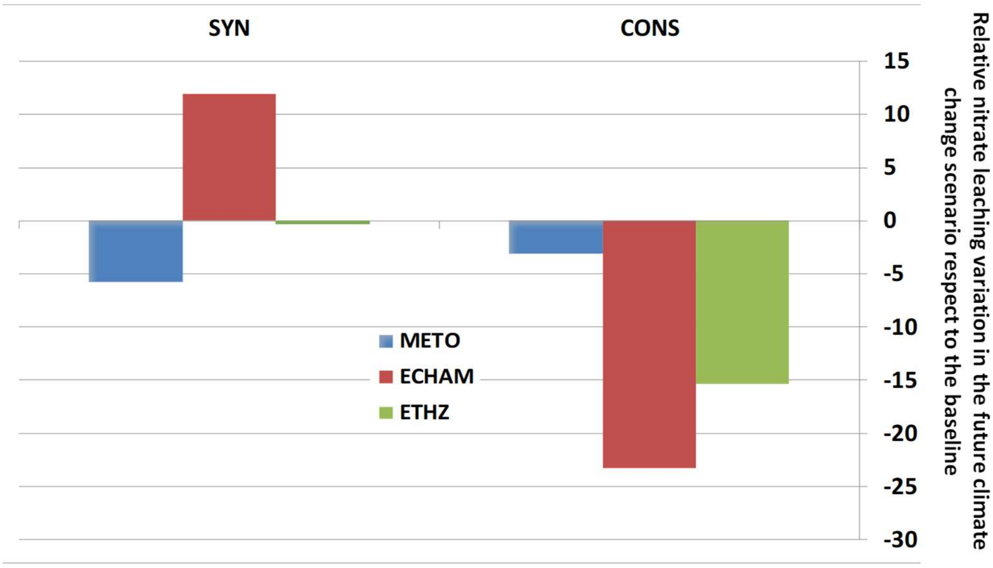



**Figure 9.** Relative nitrate leaching variation in the 30-year period for each general circulation model (GCM) under future climate change scenarios with respect to the baseline.

### *3.3. Overall Evaluation of Agro-Environmental Sustainability*

In Table 5, the average 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 N management strategies adopted in the study area of the FATIMA project for the durum wheat/processing tomato rotation. The overall evaluation compares agronomic and environmental indicators under the 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 regarding the three climate change scenarios were reported. For both agronomic and environmental indicators, a qualitative evaluation was performed according to three classes (negative, neutral, and positive), based on the prevalence of the evaluation classes in Table 3, and the comparison between the CONS and SYN treatments was computed as a relative variation.

**Table 5.** Long-term sustainability assessment (30 years) of synthetic (SYN) and conservative (CONS) N fertilization management in a tomato/durum wheat rotation under three future climate change scenarios (* = negative; ** = neutral; *** = positive).

| 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-years and for the 3 climate change scenarios) | | | | | | |
| Yield (Mg ha$^{-1}$) | 5 *** | 128 *** | 3 * | 147 *** | −40 * | 15 *** |
| N recovery efficiency (%) | 38 * | 49 * | 25 * | 21 * | −34 * | −57 * |
| Nitrogen use efficiency (NUE, Kg Kg$^{-1}$) | 137 * | 112 * | 96 *** | 48 * | −30 *** | −57 *** |
| Water use efficiency (WUE, Kg mm$^{-1}$) | 70 ** | 22 ** | 83 *** | 29 *** | 19 *** | 28 *** |
| Agronomic evaluation | Neutral | Neutral | Neutral | Neutral | Neutral | Positive |

**Table 5.** *Cont.*

| 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 (%) |
|---|---|---|---|
| Environmental indicators (average over 30 years and for the three climate change scenarios) | | | |
| 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 (Mg $ha^{-1}$) relative variation (%) to initial value | −1.3 * | −0.9 * | 31 *** |
| Soil bulk density change (g $cm^3$) relative variation (%) to initial value | 0.2 * | 0.01 ** | −95 *** |
| Environmental evaluation | Negative | Neutral | Positive |

In the context of future climate change scenarios, characterized by their higher annual surface air temperature and by differently distributed rainfall over the year—e.g., concentrated in a 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 different trends for durum wheat and tomato under the SYN and CONS treatments. As regards rainfed durum wheat, under the SYN treatment, the yield was stable and remained within the medium class range (Table 3) while a decrease in grain yield was observed under the CONS treatment, moving to low class (−40% in comparison with SYN). Aiming to increase durum wheat yield under future climate change scenarios under the CONS treatment, some variations in farm management practices—such as supplemental irrigation and/or the use of wheat varieties more resistant to drought—can be feasible solutions to addressing the problem. Conversely, in irrigated tomatoes, both treatments maintained the yield in the best class range (+15% with CONS with respect to SYN). As regards NRE, 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 the CONS treatment with respect to SYN (−57%) can be linked to the different patterns of N release in the two treatments (slow-release organic N with CONS and faster-release mineral N with 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 the SYN treatment (>100) means that more N is removed with the harvested crop than applied by fertilizer. This situation is equivalent to the "soil mining" of N since soil N stock is used. On the other hand, the lower NUE observed under the CONS treatment 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 increased soil organic matter entering into the soil. The WUEs of durum wheat (rainfed) and tomato (irrigated) crops were higher under the CONS treatment (high-class range) than under the SYN treatment (low-class range). Therefore, incorporating compost and cover crops as green manure for tomatoes 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 the durum wheat/tomato cropping system is in the low-class range under the SYN treatment and in the medium-class range under the CONS treatment, showing a reduction of 38% in $NO_3^-$ percolation under the CONS treatment in comparison with the SYN treatment. 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 the SYN treatment than under the CONS treatment. This is consistent with the behavior of the soil bulk density, where a lower value—favorable in terms of soil quality—was observed under the CONS treatment in comparison with the SYN treatment.

Several authors found that conservative agriculture had a positive impact on soil characteristics [44–47]. Francaviglia et al. [48] showed that longer crop rotations (3–5 years) and the introduction of legumes resulted in higher increases in SOC contents (18%) in Mediterranean sites. Nunes et al. [49] and Williams et al. [50] 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 [51,52]. In our case, since a greater SOC stock and a lower bulk density are desirable conditions for the objective of increasing long-term environmental sustainability and 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 a fertilization strategy to another considered more "environmental-friendly"—e.g., from the mineral fertilization to the organic one—is not always an assurance of higher sustainability [53].

## 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 modeling approach under future climate change scenarios. Soil fertility and crop productivity were affected by the management since the CONS treatment shows higher SOC stock and WUE compared to the SYN treatment. The rainfall influenced crop yield. The overall evaluation of the alternative fertilization strategy proposed is strongly dependent on 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 with CONS in comparison with the SYN treatment, the effect is positive for tomato and negative for wheat in all of the climate scenarios. Given the higher profitability of tomatoes compared to wheat, the proposed change is considered a feasible strategy under a 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 treatments in the foreseen climate change scenario is strongly positive. Hence, despite some weaknesses of the strategy, i.e., type and rate of organic fertilizers and selection of cover crops, the proposed management represents a good option for the farmer regarding maintaining the soil health and for protecting the environment.

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