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The TIMES Land-WEF model: An integrated analysis of the agricultural system of the Basilicata Region (Southern Italy)

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ABSTRACT

The unsustainable use of natural resources, in particular soil degradation and pollution, is one of the main factors contributing to the climate and biodiversity crisis. The European Union has outlined a new European Green Deal, whose objectives include increasing the overall quality of the agri-food chain in relation to environmental sustainability, focusing on reducing the use of pesticides and increasing the share of organic in overall production. A Nexus thinking perspective is applied to analyse this topic over a 50-year time horizon (2010–2060) for the agricultural system of the Basilicata Region (Southern Italy), represented by the TIMES Land-WEF, an optimizing, bottom-up energy-technology model, built to investigate the interactions and interrelations between water, energy food and land. The novelty of this modelling approach is the choice of land use as the guiding parameter of the optimization process. The main objectives of the Farm to Fork Strategy are modelled as system constraints and the scenario analysis allows to characterise their effects on the evolution of the agricultural system over the examined time. The results show that the pesticide reduction constraint leads to an increase in land use by organic crops from 24.6 % to 32.4 % in 2060. In particular, this is due to the increased contribution of cereal, forage, olive growing crops, permanent meadows and pastures, which lead to a 46 % reduction in irrigation water consumption. On the other hand, the reduction in inorganic fertilizers is not accompanied by a significant increase in organic crops, but resulted in the reduction of cereal crops.

1. Introduction

The AR6 Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC) [1] provides new estimates on the global warming trend for the coming decades. The study underlines the need to limit global average temperature increase to 1.5 °C and below 2 °C, according to the Paris Agreement [2], to avoid potential irreversible damages to the environment [3]. The Mediterranean region has been identified as a key region for the huge potential impact of climate change on environment [4] and, in particular, on agriculture in terms of water resources availability, irrigation needs [5], productivity, quality and distribution of crops [6], crop growth and livestock production conditions, spread of pests and agricultural diseases. In turn these features may affect the economy (product and food prices, business models, agricultural income and farmers' social conditions), widening the gap already existing between northern and southern Europe [7]. Moreover, around 10 % of the gross greenhouse gas emissions (GHG) in the European Union (EU) come from agriculture [8], due to agricultural practices, livestock and land use change [9]. On the other hand, agriculture being a carbon sink [10] may contribute significantly to climate change mitigation. Agriculture thus faces four main challenges: (i) to become more resilient and adapt to climate change [11], (ii) to reduce its impact in terms of greenhouse gas

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Abbreviations: BaU, Business-as-usual; CAP, Common Agricultural Policy; CH_4, Methane emissions; CO_2, Carbon emissions; GHGs, Greenhouse Gases emissions; ETSAP, Energy Technology Systems Analysis Program; K, Potash; N, Nitrogen; N_2O, Nitrous oxide emissions; P, Phosphates; REMS, Reference Energy and Material System; SDGs, Sustainable Development Goals; TIMES, The Integrated MARKAL-EFOM System model generator; WEF, Nexus Water-Energy-Food Nexus.

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emissions and land degradation [12], (iii) to increase its carbon sink potential [13], and (iv) to meet the growing demand of the population with safe and healthy food [14].

Therefore, there is a need to shift from current intensive production models to new models based on sustainable resource management [15]. In this regard, many international, national and local programs and policies promote more sustainable agricultural practices and organic farming. They aim to limit erosion, improve soil quality, increase soil nutrients [16] and reduce water and energy requirements.

Within this framework, an integrated approach is needed to model the complex interrelationships among the three key variables, namely water (W), energy (E) and food (F) to ensure their demand is met and agricultural production is sustainable [17].

The nexus approach, since its first appearance in 2011, has become increasingly important in modelling the interactions between the natural environment and anthropogenic activities [18]. In fact, it represents an attractive approach to overcome the limitations of separate modelling of different variables, highlighting their interactions and enabling their coordinated management [19]. The initial modelling approach was applied to the representation of the three key resources, i.e., water, energy and food, to optimize their supply under conditions of insecurity/scarcity [18]. Subsequently it has been extended to issues such as climate change, land management, ecosystem conservation, etc. In this way it became a tool for assessing the pursuit of the goals proposed in the Paris Agreement under the United Nations Framework Convention on Climate Change and the United Nations Sustainable Development Goals (SDGs) [20]. The WEF nexus also drew the attention of the Food and Agriculture Organizations' (FAO) to "explore how it can support food security and sustainable agriculture worldwide" [21] in pursuit of its vision of "sustainable food and agriculture to achieve its mandate of eradicating hunger, reducing poverty, and sustainably managing and using natural resources and ecosystems" [22]. The WEF nexus can be assessed through a variety of methods depending on the purpose and scale of the analysis (e.g. Life Cycle Assessment [23], economic and econometric modelling [24], sustainability indicators [25], spatial integrated indexes [26], ecological network analysis [27], system dynamics model [28] agent-based modelling [29]). Regardless of the method chosen, a crucial aspect of its application to policy design and implementation, concerns a clear description of the interconnections between the variables and their potential impacts on current and future socio-economic systems [30]. In developing a methodological approach based on the WEF nexus, it is important to clearly identify the objectives of the study, the goals to be achieved, and to describe in detail the relationships among competing resources.

Based on the above, this work has a twofold objective:

- to integrate the WEF nexus into the ETSAP-TIMES approach to develop a novel land-use-driven model for the analysis of the agricultural sector (the TIMES Land-WEF).
- to apply the TIMES Land-WEF model to the characterization of the agricultural system of the Basilicata Region and analyze the effects of the Farm to Fork strategy [31] on resource and land use through a scenario analysis.

The structure of the paper is as follows: Section 2 provides a review of the main methods and tools for nexus analysis; Section 3 describes the Land-WEF nexus (Section 3.1), the TIMES Land-WEF model (Section 3.2) and the principles of scenario analysis (Section 3.3); Section 4 provides the results and discussion of the scenario analysis, and Section 5 provides conclusions and suggestions for future study.

2. Review of methods and tools

Several methodologies and tools based on the nexus approach have been implemented to systematically represent the interconnections between water, energy and food [32], trying to overcome methodological gaps and lack of quantitative data. In such studies, qualitative or semi-quantitative analyses are mainly used, while in some studies the correlation between multiple systems is modeled, making explicit the complex mechanisms governing interactions in the WEF nexus [33]. Some examples of approaches and tools used to analyse these interconnections include: the Water Evaluation and Planning Model (WEAP) [34], later expanded to include biomass, energy and climate; the Climate, Land, Energy and Water Strategies (CLEWS), an interdisciplinary tool to quantify the use of resources, GHG emissions and the costs associated with achieving energy, water and food security objectives [35]; the Diagnostic Tools for Investments in Water for Agriculture and Energy (DTI) developed by FAO [36], "an integrated platform to systematically assess, at country level, trends in use of water resources, the policy and institutional frameworks and the investment needs and potential to boost the sustainable use of water"; the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), based on a resource accounting method [37]; the WEF Nexus Tool 2.0, an integrated modelling tool based on a input-output model for identifying sustainable resource management strategies [38]. In literature there are many review studies that analyze the main advantages or critical issues of the models relating to a specific variable (water [39] or energy [40] or food [41]) and analyze the interactions with the other variables. Existing models investigate the technical implications, taking into account also external factors such as climate change and population growth. Modeling advancements are necessary to emphasize and maximize all the synergistic effects between the components of the Nexus [35]. To this end, several energy systems modelling tools have been and/or could be used to address the nexus approach. Semertedizis [42] analyzed the potential of bottom-up and top-down models and highlighted the need for changes to incorporate the nexus concept, which many existing tools do not take into account. Morales-Garcia et al. [43] pointed out that the most appropriate methodology for analysing the nexus framework depends not only on the objectives of the research and the type of data available, but also on the scale at which the study is carried out. Bardazzi et al. [44] critically analysed the possibility of using Computable General Equilibrium (CGE) models to investigate the relationships among water, energy and food. They conclude their study by pointing out that there are no CGE models that can address the nexus in its entirety, although by their nature they might seem to be appropriate tools that cover multiple sectors and flows. One of the main obstacles in the nexus framework concerns the explicit modelling of the water input and its competing uses across sectors and agents. The main reasons are due to the difficulty of representing economically a zero-price resource, and by reliable data on water uses. Studies exist in the literature that use input-output models to analyze the WEF nexus. For example, the impact of the water-energy-food nexus on the economy was studied by Zhang et al. [45] in the case of thirty Chinese provinces, using the Data Envelopment Analysis (DEA) method to calculate the value of efficiency. The most versatile are partial equilibrium models, which are usually used to support decision making. These models are demand-driven and technology-oriented. Energy technology roadmaps related to different development hypotheses are defined by a minimum cost approach in accordance with exogenous constraints. They characterize system limits and scenarios, enabling the simultaneous achievement of multiple objectives. This category includes the ETSAP TIMES energy system model generator [46]. It provides a detailed representation energy flows within the network of technologies, with comprehensive energy, economic and environmental characterization of the technologies [47].

The ETSAP-TIMES model generator has also been used (in some cases in combination with other modelling tools) to represent the relationships between water, energy and food with reference to agriculture and renewable energy production and to determine CO_2 emission reduction strategies accordingly.

Many notable examples of application of the ETSAP-TIMES framework to model water, energy and agricultural resources can be found in literature. Sehn et al. [48] integrated the water system module into the TIMES PanEU energy system model. They estimated water demand for cooling and irrigation technologies for energy crops, taking into account total water demand and renewable water supply. In their study a land use optimization model, the MAGPIE (Model of Agricultural Production and its Impact on the Environment) [49] was used to derive the yield increase of biomass when irrigation is applied, while the TIMES PanEU model outputs were used to investigate the water and carbon footprint associated with the increase of bioenergy in the European energy system. In particular, the environmental footprint of different biomass mixes for the period 2015–2050 were compared with the short-term climate change projections [50] in terms of emissions related to land-use-change and water consumption. Life Cycle Assessment (LCA) methodology was integrated in the TIMES Spain energy model by Lechon et al. [51]. They estimated the environmental impacts (such as eutrophication, acidification and toxicity impacts as well as resource depletion, water consumption and climate change impacts) of various current and future electricity generation technologies. In this way they evaluated the evolution of the electricity technologies portfolio up to the year 2030 based on a number of restrictions imposed by current energy policy commitments. The integration of the two methodological approaches showed that decarbonization scenarios tend to reduce all impacts on the WEF nexus except aquatic ecotoxicity and resources depletion. This reduction is generally more pronounced in scenarios with higher CO_2 reduction rates. Agricultural and energy systems were also integrated by Chiodi et al. [52], who built Agri-TIMES, a representation of the agricultural system based on the ETSAP-TIMES modelling framework. They studied the impact of livestock emissions and identify suitable emissions reduction options. Land-use changes associated with bioenergy and biofuels were analyzed by the Irish TIMES model. It represents the first tool used to assess their possible impacts in the implementation of climate mitigation policies [53]. Al-Riffai et al. [54] proposed an integration of a CGE model for the whole economy and component models for energy (MARKAL/TIMES) and water and food (IMPACT) to analyze WEF issues. They applied this integrated approach to the Nile Basin, in a three-country study designed to investigate the impact of climate change on water, energy, and food resources. The policy interventions taken into consideration were changes in the cultivated area, changes in the energy mix by increasing the generation of electricity from renewable sources, increasing desalination, and investing in more efficient irrigation systems.

Although this study was conducted in a Mediterranean area that is climatically different from the study area, covering a very different type of crops and soil, the proposed approach emphasises the advantages of integrating different methodological approaches to deal with the complexity of modelling the water-energy-food nexus, overcoming the limitations of individual models and making the implications of the nexus explicit.

The strength provided by TIMES models based on a bottom-up approach is the in-depth analysis of the water, energy and food nexus through a detailed representation of commodities, technologies and commodity flows. However, they alone are unlikely to fully capture the interconnections between water, food and energy, but need to be complemented by other models especially to investigate and quantify the effects caused by climate change. The need to use one or more soft linkages with other types of models also depends on the specific objective that the modeler proposes to investigate. In this paper, the TIMES model is developed and used to assess the effects of European policies on the agricultural system in Basilicata.

3. Methods

3.1. The Land-WEF nexus

Each variable key of the WEF nexus is considered as a sub-system, whose components have interrelations with each other [55]. Food-Land is the most complex subsystem with the highest representation detail, containing the conventional and organic crop productions linked to the land use through the yield of each product. The water subsystem includes the irrigation system and precipitation water needed to meet crop needs. In the energy sub-system the main energy sources of the agriculture sector are considered as external inputs derived from the TIMES-Basilicata model [47]. In the TIMES Land-WEF model some of the interactions between water, energy and food are considered as shown in Fig. 1, where the uncoloured arrows represent interactions not considered in this model. In fact energy is used to allow the operation of irrigation systems essential for some crops and to operate machinery and equipment used for crop production. Instead water consumption is linked directly to crops productions. There is no information on the chemical characteristics of groundwater, which would be useful information for managing water resources and determining its suitability for agricultural uses [56]

The Food-Land subsystem provides also the information related to the production of biomass that can be used in the energy supply sector. Linking the TIMES Land-WEF model with the TIMES-Basilicata model will allow us to assess the contribution of biomass energy to meet demand in the end-use sectors of the TIMES-Basilicata model on the one hand, and the use of the water resource for energy production on the other. This model does not consider the actions of food-land on water, and in particular the effects of food taking into account use of fertilizers and pesticides on water quality [57].

The main interactions between the variable keys are schematized in Fig. 2. They are represented by processes and commodities flowing into a single optimization process.

3.2. TIMES Land-WEF model

The TIMES Land-WEF model represents an integrated application of the WEF nexus approach within the ETSAP-TIMES modelling framework [36]. The model is driven by the land use demand by crop category and the number of livestock heads, which represent the “end-use demands”. The minimum feasible cost of the material reference system is determined with a linear optimization programming approach in compliance with exogenous constraints on resources. A land use-driven model allows evaluating the effects of energy-environmental policy scenarios in terms of resource use (energy, water, land use by crops) and agricultural productivity. The number of livestock heads allows evaluating the environmental impacts associated with farming, in particular the release of GHG emissions. Fig. 3 represents the flowchart of the agri-food system.

Land use demand, expressed in hectares, is characterised by the Used Agricultural Area and the Forestry Area. The Used Agricultural Area includes the hectares for the cultivation of cereals, other arable crops, forage, horticulture, viticulture, olive growing, orchards and citrus groves, permanent meadows and pastures. Field horticulture and greenhouse horticulture are distinguished and, for each type of agricultural product, both conventional and organic productions are considered. The forestry area represents the hectares of surface area covered by forests or the canopy of the forest or open wood. Eight different types of forests are modelled (Beech forests, Mesophilic oak forests, Chestnut forest, Mesophilic deciduous forests, Hygrophilous forests, Holm oak forests, Mountain and Mediterranean pine forests, Wood plantation and reforestation), while shrubs and scrubland areas are excluded. For livestock heads, cattle, sheep, goats and swine are considered due to their significant energy consumption and GHG emissions. Crop productions are modelled as a process whose input are: energy carriers, water (rainwater and irrigation), fertilizers (nitrogen, phosphate and potash), chemical or organic active substances for plant protection. The outputs are tons of agricultural products and waste. Similarly, livestock is modelled as processes whose input are energy carriers (diesel, natural gas and electricity) and water supply and whose outputs are the number of cattle and waste produced. Forests are

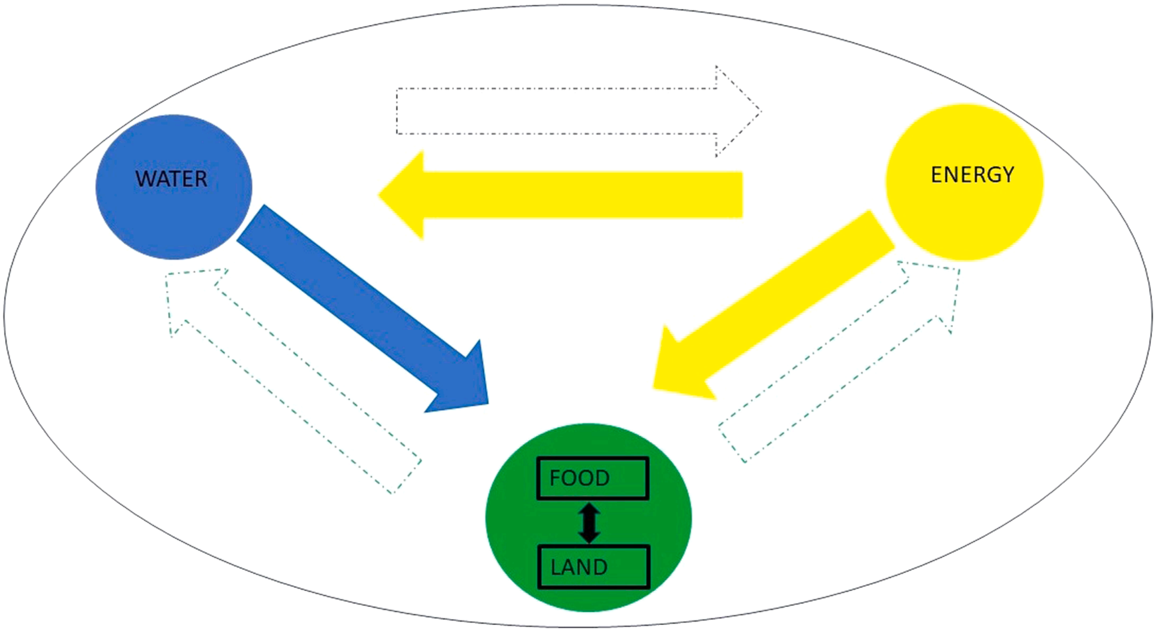

Fig. 1. Schematization of the WEF nexus.

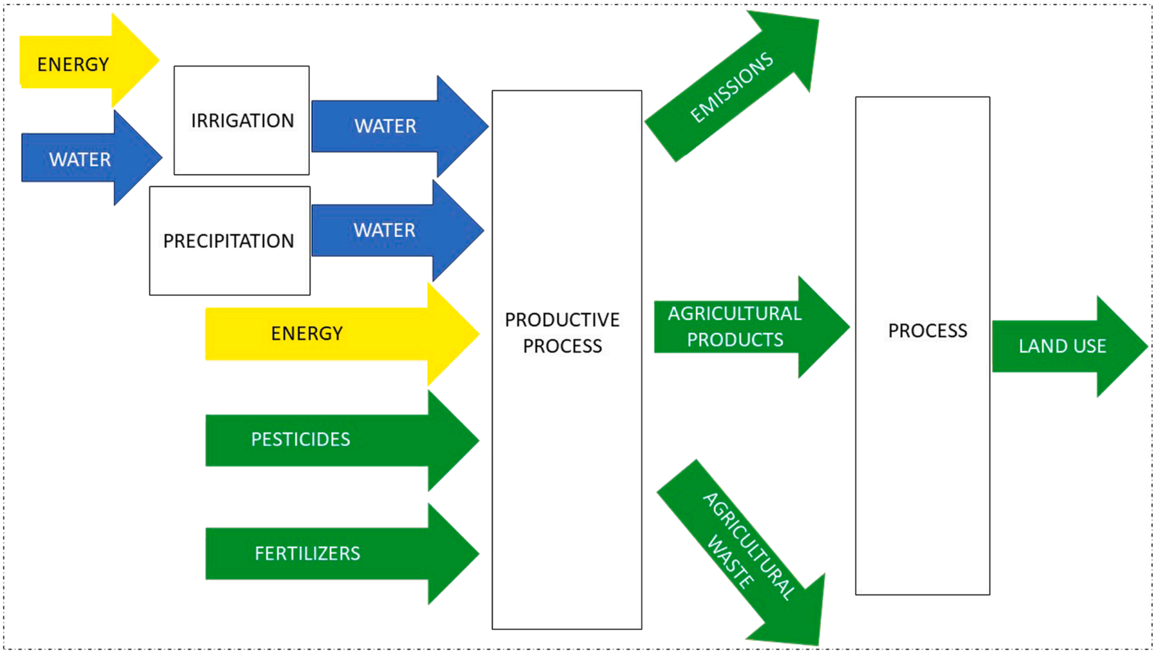

Fig. 2. Schematization of the WEF nexus interactions.

modelled through processes that have as input the CO_2 emissions absorbed and as output the hectares covered and the biomass produced. As concerns GHG emissions, CO_2 emissions are associated with fossil energy consumption and forest sink, while CH_4 and N_2O emissions are mainly produced by manure management and enteric fermentation. Moreover, N_2O emissions from nitrogen fertilizers were also considered.

The definition of Reference Energy and Material System (REMS) is the first step in the construction of any TIMES model and is critical to the implementation of the input database. The REMS of the TIMES Land-WEF (Fig. 4) is an oriented network diagram that schematizes the flows of commodities (crops, biomass, waste, and emissions, represented by vertical lines) between supply, transformation and final uses through real or dummy processes (represented by rectangles).

Fig. 4 reports as an example, the REMS of conventional and organic cereals production. The mining processes are characterized by the output commodities: diesel, fertilizers (Nitrogen (N), Potassium (P), Phosphate (K)), active ingredients for plant protection and rainwater. In turn, these commodities constitute the input of the two processes, which represent respectively the conventional and organic production of cereals. Their outputs are the quantities of conventional cereals and organic cereals produced, CO_2 and other GHG emissions, and biomass waste. Finally, two dummy processes are introduced to model crop yields (“Land use process for conventional cereal” and “Land use process for organic cereals”). Their inputs are conventional and organic cereals produced and outputs are land use (hectares) for conventional and organic cereal crops, respectively. In Forestry, CO_2 emissions are the

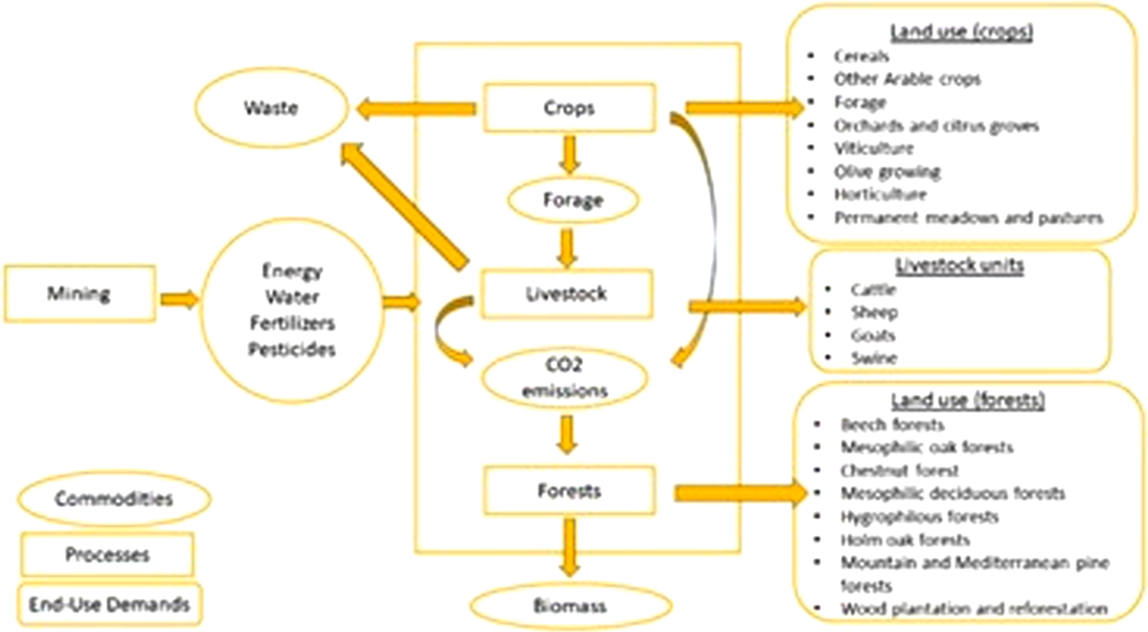

Fig. 3. TIMES Land-WEF model flowchart.

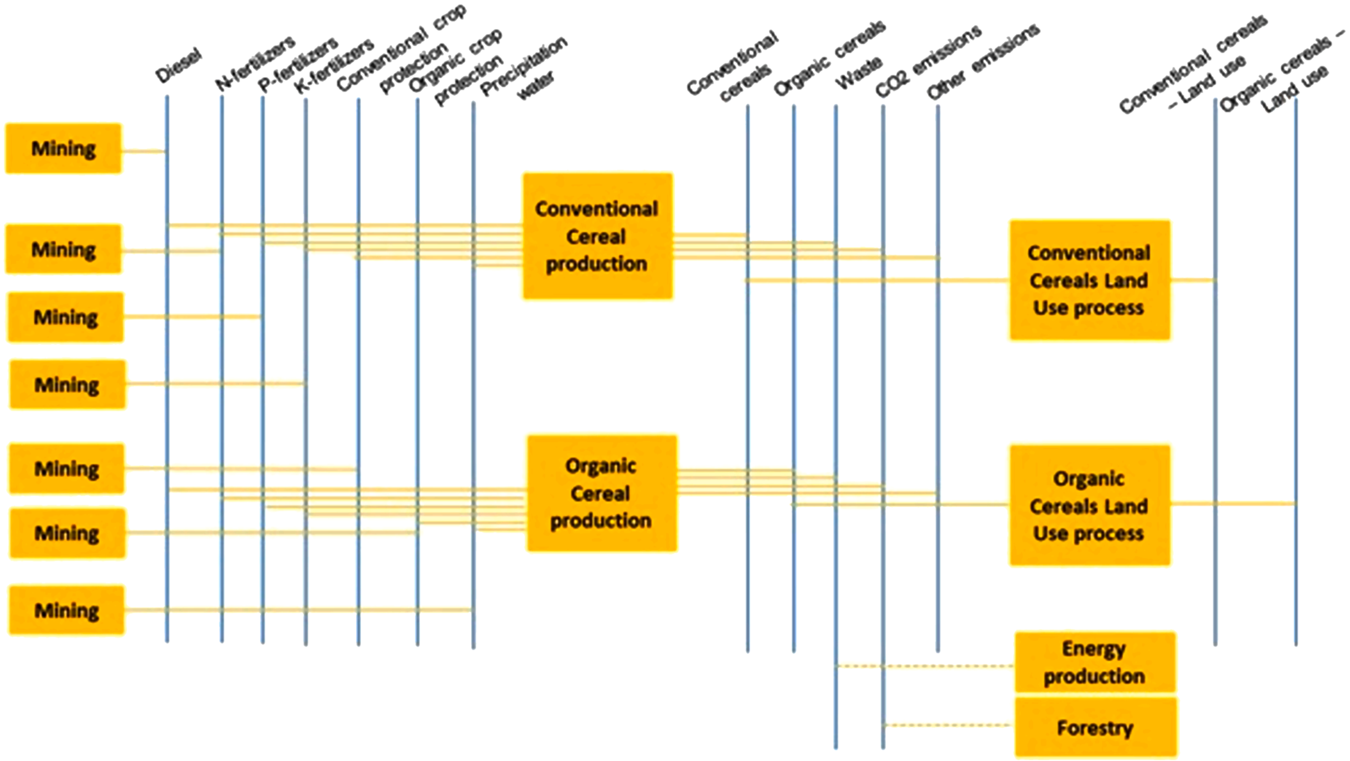

Fig. 4. REMS of conventional and organic cereals production considered in TIMES Land-WEF.

input commodity, while biomass waste is the input of the process for energy production.

TIMES-WEF model runs from 2010 to 2060 in five-year periods steps (except for the validation year 2011). Each year is divided into representative time slices that have been defined to take into account the seasonal and daily variability of commodities (e.g. electricity and water availability). The model is calibrated to 2010 statistical data (the model base year). A further validation to 2011, 2015 and 2020 according to the available information was also performed. The structure of the TIMES Land-WEF data input is made up of three main set of Excel spreadsheets (Fig. 5).

The four base year templates are primarily linked to statistical year data and contain technical and economic information on processes and commodities for forest, agricultural production, livestock, water (irrigation and livestock), energy, fertilizers and crop protection products supply. The “subres new-techs database” contains information on agricultural production technologies with distinct possibilities in terms of water consumption, fertilizers use, crop protection products inputs. The

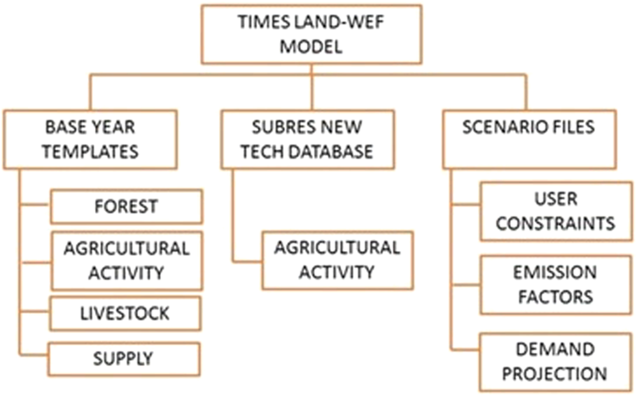

Fig. 5. Structure of the TIMES Land-WEF model data input.

scenario files contain the emission factors of the processes and all the information necessary to define the scenarios to be analysed, in particular the demand trajectories (Demand Projections) and exogenous constraints on resources (User Constraints).

A key step in the implementation of any TIMES-based model is its calibration against statistics and its validation in a status-quo development. An iterative process of comparing statistical data with model results is then conducted using VEDA, a powerful IEA-ETSAP set of tools [46] that allows browsing data and running the model, checking for discrepancies using specific functions. In order to obtain accurate and consistent results, subsequent revision of modelling assumptions can be introduced.

3.3. Scenarios

After calibration of the model, a scenario analysis is performed comparing the results of the BaU scenario, which represents the evolution of the system under the current policy, with counterfactual scenarios, which represent the effects of the policies to be evaluated.

In this analysis, the scenario analysis focused on the assessment of the new Common Agricultural Policy (CAP) for 2023–2027, which is a key pillar of the European Green Deal [58]. It is particularly ambitious in terms of commitments the European agricultural sector makes to contribute to the EU's climate change and environmental protection goals (Fig. 6).

The analysis covers the challenges announced under the Farm to Fork strategy on biodiversity and food chain circularity, namely, reducing pesticides and fertilisers and increasing the share of organic farmland by 2030.

Table 1 summarizes the scenario features modelled in TIMES Land-WEF to explore the effects of the Farm to Fork strategy.

In order to limit the consumption of pesticides and fertilizers, in the two alternative scenarios (PEST_50 and FERT_20) two external constraints are introduced respectively on the supply process of the two commodities are introduced respectively. All scenarios consider a constant change in total land use, corresponding to 391.5 thousand hectares.

4. Results and discussions

This section presents the results obtained from the modelling exercise and discusses them in relation to the factors underlying the cost-effectiveness criterion.

Table 1
TIMES Land-WEF Scenarios.

Scenario	End-use demand	CO_2 emissions	Use of pesticides and active substances for plant protection	Use of fertilisers (N, P, K)	Share of organic agricultural land
BaU	Constant over the entire time horizon	No restrictions	No restrictions	No restrictions	No restrictions
PEST_50	Constant over the entire time horizon	No restrictions	−50 % respect to 2020 by 2030	No restrictions	No restrictions
FERT_20	Constant over the entire time horizon	No restrictions	No restrictions	−20 % respect to 2020 by 2030	>= 25 % by 2030

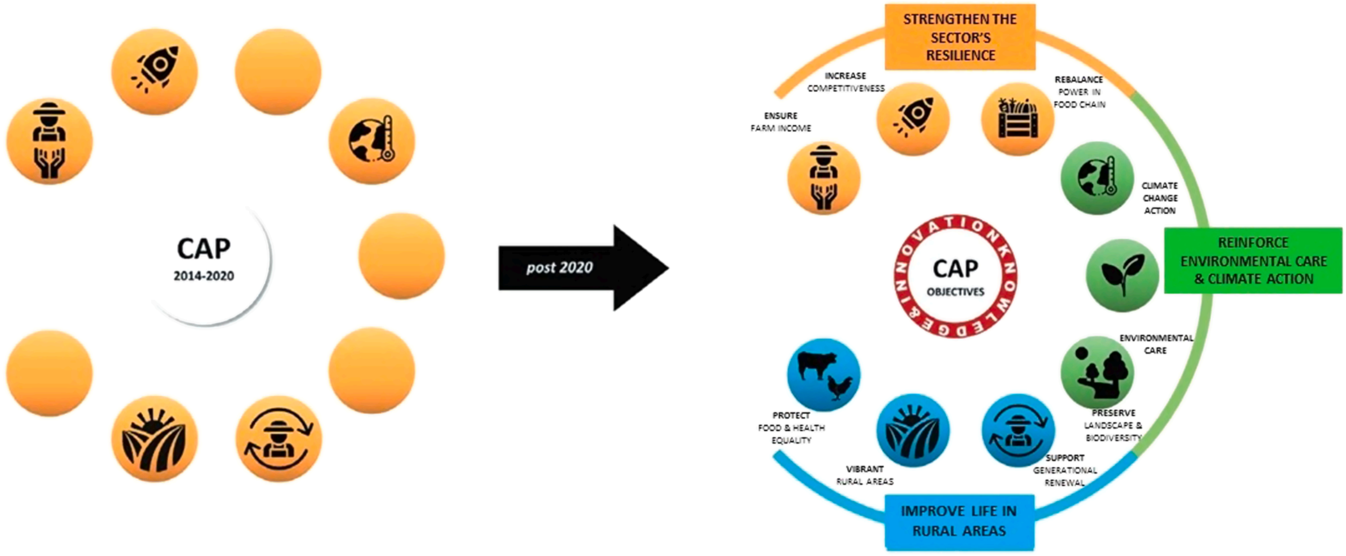

Fig. 6. Key policy objectives of the future CAP [58].

4.1. BaU scenario

The model-calculated BaU scenario optimization shows a change in land use among the various crop categories over the time horizon, with an increase in permanent meadows and pastures, and both conventional and organic cultivation olive growing. A 10 % increase in 2060 compared to 2020 is observed for conventional permanent meadows and pastures, organic permanent meadows and pastures, conventional and organic olive growing (Table 2). Land use for organic forage increases 5 % (from 26,297 ha in 2020 to 27,627 ha in 2060).

In contrast, other crops show a decline of about 10 % in land use in 2060 compared to 2020, with the exception of organic cereals, which decline by 3 %. The share of land use for conventional and organic farming does not show substantial variations (hectares devoted to organic production amount to about 25 % of the total land over the entire time horizon as also predicted by the Farm to Fork strategy).

These changes in land use are induced by the cost-optimization nature of the model, which favors crops that induce a reduction in system costs related to energy, water and fertilizers consumption.

In fact, in terms of fuel consumption, diesel decreases over the time horizon by up to 4 % in 2060 compared to 2020, with total consumption falling from 1.59 PJ in 2020 to 1.52 PJ in 2060. This decrease is mainly due to the model's preference for agricultural production characterized by lower diesel consumption per unit of output and the use of more efficient equipment. Energy consumption for irrigation decreases from 0.13 PJ in 2020 to 0.12 PJ in 2060, while energy demand for livestock remains constant over the time horizon.

In addition, fertilizer use decreases over the time horizon by 3 %: for nitrogen products and 6 % for phosphate and potash. The cost-effective solution leads to a reduction in the use of pesticides and other active substances for plant protection, which decreases by 6 % over time horizon (−38.7 tons) in conventional agricultural production and 9 % (−1 ton) in organic agricultural production.

A 10 % decrease in land use for orchards, citrus groves and horticulture results in a 10 % reduction in total irrigation water in 2060 compared to 2020 (corresponding to about 9.10 Mm^3) (Fig. 7). Orchards and citrus groves are mainly responsible for this reduction, with −58 % of water used (−5.23 Mm^3), followed by conventional horticulture in the field (−17 % i.e., −1.56 Mm^3), and organic orchards and citrus groves, (−13 % and −11 %, respectively).

Total CO_2 emissions decrease by 4 % in 2060 (about −4 tons compared to 2020) due to decreased diesel fuel consumption. Total N_2O emissions decrease negligibly, mainly due to very limited reduction in nitrogen fertilizers, while total CH_4 emissions from livestock are almost constant.

The total system cost estimated by the model (the optimal least-cost solution) is 2089 MEuro. The total annual cost decreases by 6 % in 2060 compared to 2020, corresponding to 16.13 MEuro. This cost decrease is mainly due to the decrease in water supply (−8.10 MEuro), and crop production (−5.46 MEuro). However, the reduction in crop protection (i.e., fertilizers and pesticides use), and energy consumption also contribute to the decrease in costs, although to a more modest extent, −1.28 MEuro and −1.18 MEuro, respectively.

4.2. Policy scenarios

The exogenous constraints of the PEST_50 and FERT_20 scenarios lead to significant changes in land use and resources consumed compared to theBaU scenario, as reported in this section.

Table 2 shows the observed changes for land-use.

Land use for conventional cereals shows the largest absolute decrease in both FERT_20 and PEST_50 scenarios compared to BAU, while a different trend is observed for organic cereal crops. Permanent meadows and pastures show the largest increase for both conventional and organic crops in both FERT_20 and PEST_50 scenarios as highlighted in Table 2.

Although for FERT_20 the share of organic versus conventional production follows the same pattern as BAU throughout the time horizon (i.e., 25 % organic compared to 75 % conventional), in the case of PEST_50 there is an increase of organic farming, bringing its land use to 32 % of the total area as early as 2030. This is the result of limiting the use of pesticides and other active substances for plant protection in this scenario, which being a common practice in conventional agriculture, limits its land use.

Diesel consumption decreases in both FERT_20 and PEST_50 compared to BAU in relation to the reduction in crop production. Thus, there is a decrease of 24 % in 2030 and 23 % in 2060 for FERT_20 and 16 % in 2030 and 15 % in 2060 for PEST_50. Changes in energy consumption for irrigation and livestock are negligible in the policy scenarios compared to BAU.

In both FERT_20 and PEST_50 scenarios, a high reduction in total irrigation water is observed (Table 3), with PEST_50 leading to a greater

Table 2
Land use in BAU and difference of land-use (thousands of hectares) in the Policy scenarios compared to BaU by crop.

	2020	2030			2060		
	BaU	BaU	Δ compared to BAU		BaU	Δ compared to BAU	
			PEST_50	FERT_20		PEST_50	FERT_20
C. Total	295.3	294.2	−29.8	−0.6	293.5	−29.0	0.1
O. Total	96.2	97.2	29.8	0.6	98.0	29.0	−0.1
C. other arable crops	1.8	1.7	−0.8	−1.6	1.7	−0.8	−1.5
O. other arable crops	0.2	0.2	−0.1	−0.2	0.2	−0.1	−0.2
C. cereals	121.8	114.9	−55.2	−106.4	109.7	−50.0	−101.1
O. cereals	37.1	36.5	16.2	−33.9	36.0	16.7	−33.4
C. forage	13.3	12.5	−6.0	−5.9	12.0	−5.5	−5.3
O. forage	26.3	27.1	6.0	9.7	27.6	5.5	9.1
C. orchards and citrus groves	11.9	11.2	−5.4	−10.4	10.7	−4.9	−9.9
O. orchards and citrus groves	3.1	2.9	−1.4	0.4	2.8	−1.3	0.6
C. field horticulture	5.6	5.3	−2.5	5.3	5.1	−2.3	5.6
C. greenhouse horticulture	0.7	0.7	−0.3	−0.6	0.6	−0.3	−0.6
O. field horticulture	3.8	3.6	−1.7	3.8	3.5	−1.6	4.0
C. olive growing	22.1	23.4	−11.4	18.8	24.4	−12.4	17.8
O. olive growing	5.5	5.8	2.5	4.8	6.0	2.2	4.5
C. permanent meadows and pastures	116.3	123.0	52.7	101.5	128.0	47.7	96.6
O. permanent meadows and pastures	19.3	20.4	8.7	16.8	21.2	7.9	16.0
C. viticulture	1.6	1.5	−0.7	−1.4	1.4	−0.7	−1.3
O. viticulture	0.9	0.9	−0.4	−0.8	0.8	−0.4	−0.8

Legend: C. – Conventional, O. – Organic.

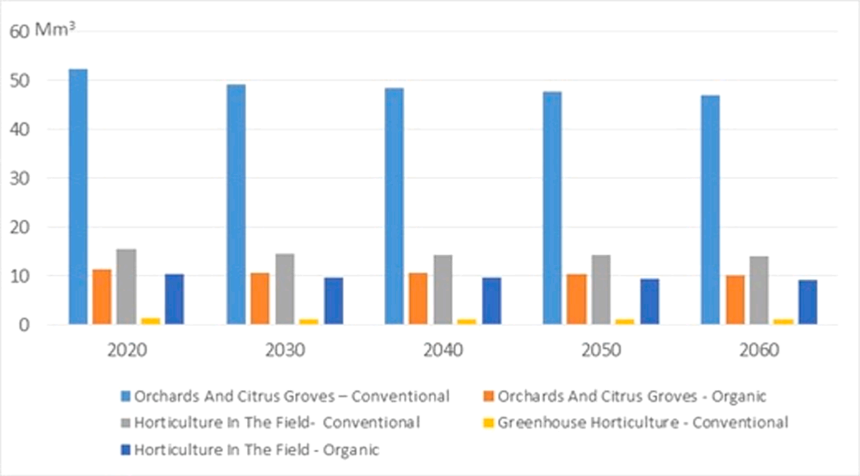

Fig. 7. Irrigation water by crop (Mm^3) – BaU scenario.

Table 3
Irrigation water in BAU and difference in irrigation water (Mm^3) in policy scenarios versus BaU by crop.

	2020	2030			2060		
Unit (Mm^3)	BaU	BaU	Δ compared to BAU		BaU	Δ compared to BAU	
			PEST_50	FERT_20		PEST_50	FERT_20
C. orchards and citrus groves	52.3	49.3	−23.7	−45.7	47.1	−21.5	−43.4
O. orchards and citrus groves	11.4	10.8	−5.2	1.6	10.3	−4.7	2.1
C. field horticulture	15.6	14.7	−7.0	14.7	14.0	−6.4	15.3
C. greenhouse horticulture	1.3	1.2	−0.6	−1.1	1.2	−0.5	−1.1
O. field horticulture	10.4	9.8	−4.7	10.2	9.3	−4.2	10.7
Total	91.0	85.8	−41.2	−20.3	81.9	−37.3	−16.4

Legend: C. – Conventional, O. – Organic.

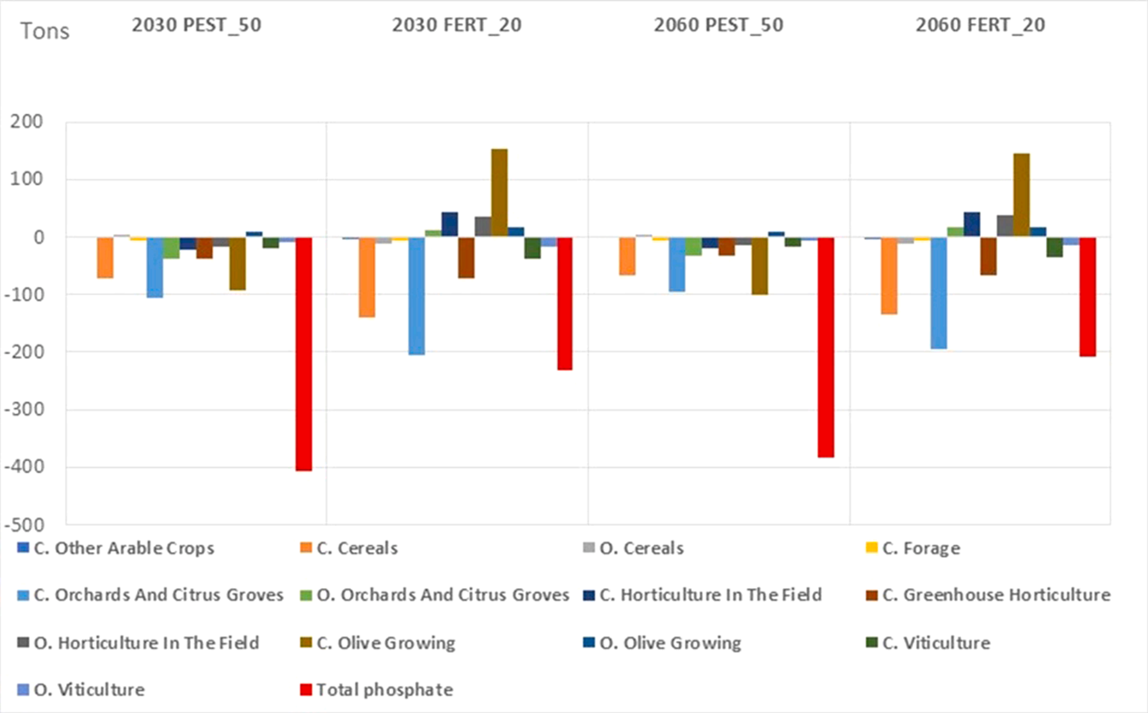

Fig. 8. Changes in nitrogen fertilizers (ton) compared to the BAU scenario. Legend: C. - Conventional; O. – Organic.

reduction in water use in the long run (−48 % and −24 % compared to BaU for PEST_50 and FERT_20, respectively). Comparing irrigation water use for different crops, there is a reduction in irrigation water use in PEST_50 for all crops, while in FERT_20 there is an increase in water use for organic crops and conventional field horticulture, justified by the smaller reduction in irrigated crops in FERT_20 compared to PEST_20.

Climate change is expected to have a significant impact on water availability in Mediterranean countries, intensifying drought conditions and water scarcity. At the same time rising temperatures will lead to an increased evapotranspiration, which may necessitate additional irrigation. Shifting to crops with a lower water footprint (e.g., permanent meadows and pastures, olive growing) as observed in both FERT_20 and PEST_50 may therefore be a key strategy for agriculture to adapt to climate change.

In the FERT_20 scenario, the 20 % exogenous reduction in nitrogen fertilizer use by 2030 to model the constraints of the Farm to Fork strategy corresponds to a total decrease of −4.4 ktons in 2030 and −4.2 ktons in 2060. In PEST_50 there is a cost-effective decrease in nitrogen fertilizers compared to BaU, although more gradual than in FERT_20 (−2128 tons in 2030 and −1930 tons in 2060). Fig. 8 shows the changes in nitrogen fertilizers per crop obtained in the two scenarios compared to BaU. It is evident that the greatest reduction in nitrogen fertilizer use compared to BaU concerns conventional cereal crops for both scenarios.

Total phosphate fertilizers use decreases by about −231 tons in 2030 and −209 tons in 2060 in the FERT_20, while in PEST_50, there is a greater reduction in phosphate fertilizers use under the scenario assumptions of −406 tons in 2030 and −384 tons in 2060. Their use decreases the most in conventional orchards and citrus groves and conventional olive growing, while it increases in organic olive growing in both FERT_20 and PEST_50. Organic orchards and citrus groves and conventional olive growing show the largest increase in phosphate fertilizers in FERT_20. In PEST 50, most crops show a decrease in phosphate fertilizer use (Fig. 9).

The overall reduction in phosphate fertilizers use compared to the BaU scenario is, −232 tons in 2030 and −206 tons in 2060 in FERT_20 and −405 tons in 2030 and −379 tons in 2060 in PEST_50. Conventional orchards and citrus groves show a significant reduction in both the policy scenarios. In PEST_50 phosphate fertilizers use increases for organic cereals and organic olive growing. The 20 % exogenous decrease in the use of fertilizers (FERT_20) leads to a reduction in the use of the active substances for plant protection in conventional crops by −48 % (−285 tons) in 2030 and −47 % (−268 tons) in 2060. In contrast, their use increases in organic crops by +31 % in 2030 and +34 % in 2060. In PEST_50, the reduction in organic crops is about 40 % in both 2030 and 2060.

The introduction of exogenous constraints on fertilisers and pesticides and the resulting land use distribution lead to a decrease in total CO_2 emissions as shown in Fig. 10. The FERT_20 scenario is the most favourable in terms of CO_2 emissions reduction, leading to a 24 % reduction by 2030 and 23 % in 2060 compared to BAU, while for PEST_50 the CO_2 reduction does not exceed 16 %. The decrease in CO_2 emissions is mainly due to the decrease in energy consumption for crop production and, to a lesser extent, for irrigation. On the other hand, in both scenarios there is no change in CO_2 emissions from livestock compared to BAU.

The slight decrease in CH_4 emissions due to lower energy consumption is negligible compared to CH_4 emissions from manure management and enteric fermentation, which remain unchanged because no remediation is planned. The decrease in N_2O emissions in the policy scenarios is mainly due to lower nitrogen fertilizers use and, to a lesser extent, to lower energy consumption. In the FERT_20, N_2O emissions decrease by –0.075 ktons in 2030 and −0.071 ktons in 2060, while in the PEST_50 scenario the decrease is almost half, −0.037 ktons in 2030 and −0.033 ktons in 2060.

The optimal solutions in accordance with the constraints on fertilizer and pesticide use of the FERT_20 and PEST_50 scenarios favour crops that require less energy and irrigation water, reducing the total system cost by about 10 % on average, with the lowest costs occurring for PEST_50 (Fig. 11).

Comparing the total costs of the FERT_20 and PEST_50 scenarios with those of BAU for the reference years, the reduction is −17 % in 2030 and −15 % in 2060, while for PEST_50 it is −23 % in 2030 and −24 % in 2060. The resulting total economic savings range from a maximum of 36 MEuro in 2025 to 15 MEuro in 2060 for FERT_20, and from 17

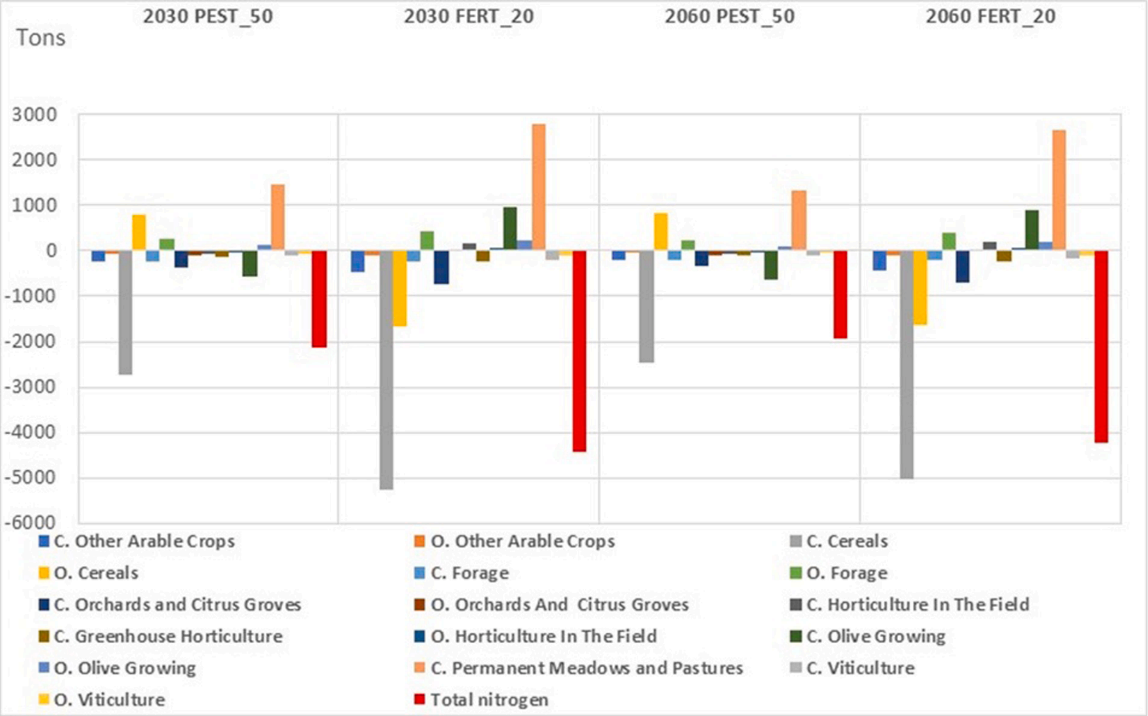

Fig. 9. Variations of phosphate fertilizers (tons) compared to the BaU scenario. Legend: C. – Conventional; O. - Organic.

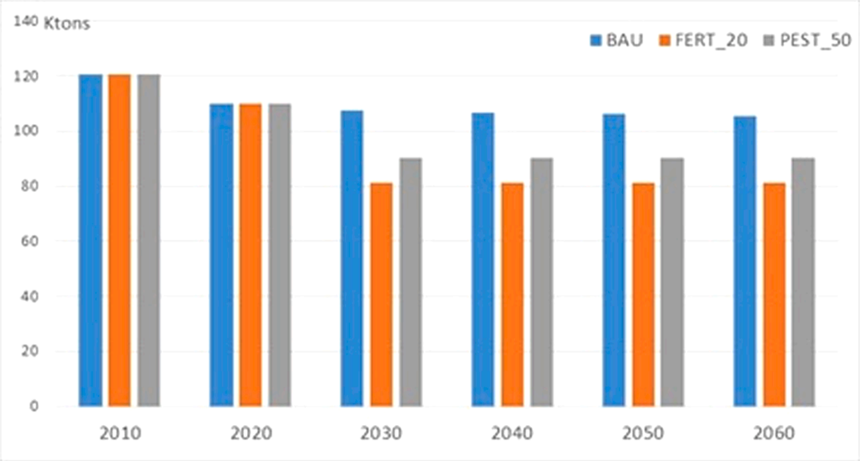

Fig. 10. Total CO_2 emissions by scenario.

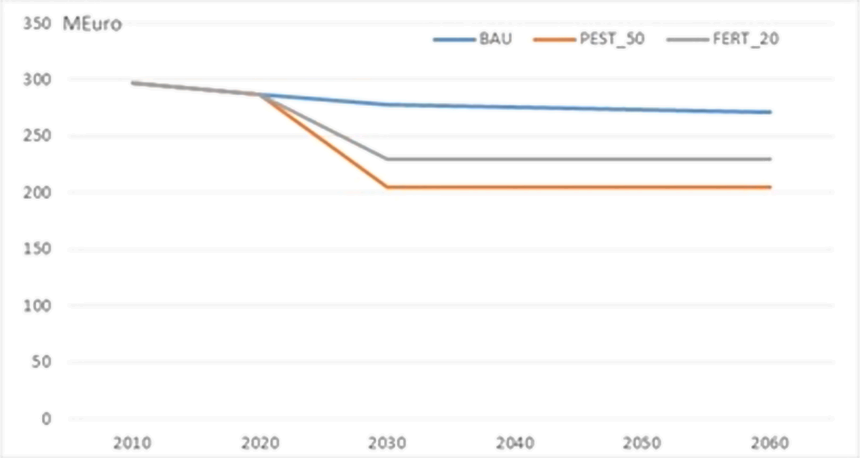

Fig. 11. Total costs by scenario.

MEuro in 2025 to 33 MEuro in 2060 for PEST_50. Variable crop production costs account for the largest share of the system cost reduction, decreasing by 23 MEuro in 2025, to 14 MEuro in 2060 in FERT_20 scenario and by 10 MEuro in 2025, 22 MEuro in 2030 and 20 MEuro in 2060 in the PEST_50 scenario.

5. Conclusions

This study focuses on the implementation of a comprehensive model based on the integration of the WEF and the ETSAP-TIMES modelling approaches to assess the effect of the implementation of European Farm to Fork policy objectives on the agricultural system of the Basilicata region (Southern Italy). To this end, a bottom-up model based on land use and livestock was designed to represent the region's agricultural system taking into account crop, livestock and forestry production over the time horizon of 2010 to 2060. Conventional and organic agricultural production were modelled as separate processes, including energy, water (irrigation water and rainwater), fertilizers and crop protection active substances as input commodities and greenhouse gas emissions as outputs.

The cost-optimal solution of the BAU scenario supports an increase in the amount of land devoted to permanent grassland and pasture and both conventional and organic olive growing over the entire time horizon. These crops are selected for their lower consumption of energy, fertilizers, active substances for crop protection and water. The reduction in total energy and water consumption for irrigation implies a consequent decrease in CO_2 emissions over the entire time horizon.

The exogenous constraints that model the Farm to Fork strategy induce significant changes in the land use patterns of the Basilicata Region's agricultural system. In fact, a 50 % reduction in chemical active substances for crop protection by 2030 (PEST_50 scenario) and the −20 % reduction in fertilizer use, in addition to achieving at least 25 % organic land (FERT_20 scenario), require the replacement of conventional cereals crops and conventional orchards and citrus groves with conventional and organic permanent meadows and pastures and organic olive growing.

In both policy scenarios, crops requiring more water irrigation are replaced with crops with lower water requirements, promoting a reduction in water consumption. This trend is more evident in the PEST_50 scenario (−46 % in 2060 compared to the BAU scenario), while in the FERT_20 scenario the increase in the land dedicated to organic horticulture in field partially offsets the reduction in total irrigation water (−20 % in 2060 compared to the BAU scenario).

The results obtained from the scenario analysis allow us to formulate some recommendations for local policy makers. A 50 % reduction in pesticide use must be accompanied by an increase in the use of land for organic cultivation. This must be higher than the 25 % target set by the EU strategy and must be at least 32 %. The resulting change in the distribution of land use leads to a saving of water for irrigation, a reduction in energy consumption and thus lower CO_2 emissions. The reduction in fertilizer use does not require an increased use of organic crops, but again requires a different distribution of land use, which at the same time favours crops with a lower demand for irrigation water and energy.

The results show that the identification of the 'ideal scenario' and, consequently, the definition of roadmaps are highly dependent on the policy objectives considered most relevant.

In our study, the FERT_20 scenario, which promotes a substantial reduction in CO2 emissions, has the greatest effect in terms of climate change mitigation, while PEST_50, which promotes a reduction in the demand for irrigation water and a decrease in total system costs, is the most suitable in the case of water and financial resources scarcity.

Overall, beyond the differences shown by the optimisation of the different scenarios, the achievement of the policy objectives has positive effects on the configuration of the system with respect to the BaU, providing relevant insights into the definition and implementation of agricultural policies.

Further modelling improvements will therefore focus on: (a) the identification of key indicators to assess the effects of climate change on the agricultural sector and to identify appropriate mitigation measures; (b) the integration of TIMES Land-WEF module with the TIMES-Basilicata energy model to analyse in detail the entire agro-food chain and to represent the interactions between Land-Food and Energy and between Water and Energy.

CRediT authorship contribution statement

Senatro Di Leo: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Maria Maddalena Tortorella:** Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Patricia Fortes:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Mauro Viccaro:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Mario Cozzi:** Writing – review & editing, Methodology, Conceptualization. **Severino Romano:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Carmelina Cosmi:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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