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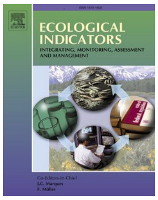

Environmental assessment of vegetable crops towards the water-energy-food nexus: A combination of precision agriculture and life cycle assessment

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ABSTRACT

The increase in world population and the resulting demand for food, water and energy are exerting increasing pressure on soil, water resources and ecosystems. Identification of tools to minimise the related environmental impacts within the food–energy–water nexus is, therefore, crucial. The purpose of the study is to carry out an analysis of the agri-food sector in order to improve the energy-environmental performance of four vegetable crops (beans, peas, sweet corn, tomato) through a combination of precision agriculture (PA) and life cycle assessment (LCA). Thus, PA strategies were identified and a full LCA was performed on actual and future scenarios for all crops in order to evaluate the benefits of a potential combination of these two tools. In the case study analysed, a life cycle approach was able to target water consumption as a key parameter for the reduced water availability of future climate scenarios and to set a multi-objective function combining also such environmental aspects to the original goal of yield maximisation. As a result, the combination of PA with the LCA perspective potentially allowed the path for an optimal trade-off of all the parameters involved and an overall reduction of the expected environmental impacts in future climate scenarios.

1. Introduction

The increase in world population, which is expected to be 9.2 billion people by the year 2050, and the resulting demand for food, water and energy are exerting increasing pressure on soil, water resources and ecosystems (Pastor et al., 2019). Agriculture is the largest consumer of the world's freshwater resources, and more than one-quarter of the energy used globally is expended on food production and supply (FAO, 2014). It contributes to climate change directly by emitting methane, nitrous oxide and carbon dioxide, and indirectly by affecting net carbon emissions through its impact on soil, forests and other land uses (FAO, 2018). On the other hand, climate change significantly impacts agriculture by increasing water demand, limiting crop productivity and reducing water availability in areas where irrigation is most needed (FAO, 2011). Thus, identification of approaches to reduce the related cross-sectoral environmental impacts for the water-energy-food (WEF) nexus is crucial. Nexus concept acknowledges planetary boundaries and calls for a more sustainable use of the Earth's resources. To that end, highlighting the water–energy–food nexus means directing attention to the interrelated pressures created in particular by agricultural production, water use, energy production and consumption practices (Del Borghi et al., 2020b; Ingrao et al., 2018). To deal with this threat, the Roadmap to a Resource Efficient Europe (European Commission, 2011) and the European Common Agricultural Policy (CAP) (European Commission, 2012) sets targets for agriculture in the next years according to three priority areas for intervention in the WEF context: the improvement of the sustainability in the agriculture, the reinforcement of the conservation of biodiversity and of ecological farming and forestry systems and the handling of the water management and use in accordance with the possible climate change scenarios that could occur in the near future. Then, the European Commission presented legislative proposals on the future of the common agricultural policy beyond 2020

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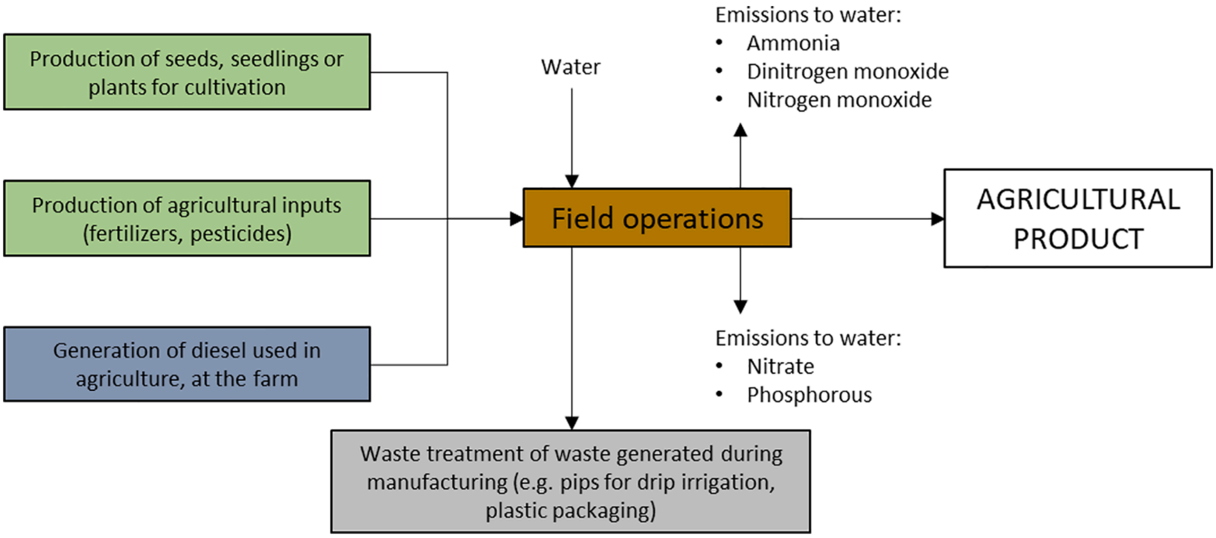

Fig. 1. System boundaries for crop cultivation.

(European Parliament and Council, 2018).

From a life cycle perspective, the phase with the highest environmental costs in the agri-food sector is the agricultural production. For this reason, the development of productively, economically, and socially sustainable agricultural methods is crucial as well as the identification of tools to assess and minimize such costs (Far & Rezaei-Moghaddam, 2018; Srinivasan, 2006). It is thus essential to evaluate the environmental impact and the utilization of resources in food production and distribution systems for sustainable consumption (Roy et al., 2009). In this context, Precision Agriculture (PA) - also known as site-specific crop management – can be considered an innovative and integrated farming management concept. PA is a management concept focusing on monitoring, measurement and responses to inter- and intra-variability in crops, fields and animals. PA has been made possible by the rapid development of sensing technologies, management information systems, advances in farm machinery and appropriate agronomic and economic models. PA provides a holistic system approach to managing the spatial and temporal crop and soil variability within a field in order to increase profitability, optimize yield and quality, reduce costs and environmental impact, prevent soil degradation in cultivable land, reduce of chemical use in crop production, promote an efficient use of water resources and improve sustainability (Failla et al., 2020; Mandal, 2013; Paustian & Theuvsen, 2017; Zingale et al., 2022). Another concept that has not yet been fully exploited is that of ideotype. Ideotype breeding aimed at modifying the plant architecture is a time-tested strategy to achieve increases in yield potential (Paleari et al., 2020; Ravasi et al., 2020).

Learned that the agricultural production is the most challenging and promising stage because of its potential in reducing its environmental impact and that PA may help to find farming managements alternatives, identifying which solution is the most beneficial for the environment is not straightforward. In this phase of uncertainty about how to choose the best agricultural system, life cycle assessment (LCA) can assist in performing an environmental sustainability analysis of products and technologies (Guinée et al., 2011), providing a systematic path to measure the enhancements in resource productivity as means for promoting eco-design and cleaner production (Strazza et al., 2011). At international level, it is well recognized that an integrated sustainability assessment must be based on a life cycle approach. This allows to deeply analyse the whole system or supply chain, in order to plan the appropriate strategies, aiming to the promotion of a shifting towards sustainable agriculture, farming and food production systems and leading towards more sustainable food consumption pattern (Andersson, 2000; Parent & Lavallée, 2011).

Despite there is a wide scientific literature on LCA applied to different crops and vegetable products to eco-design purposes (Del Borghi et al., 2018, 2020a; Parajuli et al., 2019) and on PA studies (Bhakta et al., 2019), there is a lack in scientific knowledge on the potential combination of both approaches. Life cycle approach, carbon and water footprint are emerging and promising issues for PA. The combination of PA and LCA could allow to consider all the environmental aspects related to the production chain, the specificity of the climate, its effects on agriculture and to evaluate the environmental benefits of agronomic choices with a life cycle approach. To test this approach and to quantify the potential reduction of the impact categories connected to the WEF nexus, a study was carried out in the vegetable sector. Four vegetables (beans, peas, sweet corn, tomato) cultivated in Italy were selected as case studies and data were collected from one of largest agri-food European companies. The study focused on the cultivation phase and on the management of water resources with the aim of mitigating the negative effects of expected climate variations by optimising management adaptation strategies, identifying different ideotypes and applying PA principles combined with a life cycle approach testing a possible combination of these tools.

2. Methods and data

2.1. Goal and scope definition

A “cradle to grave” perspective was applied in order to analyse the environmental loads of the investigated crops along their whole life cycles. With this goal, a LCA study was performed following a methodological pattern consistent with the requirements of the environmental labels (Del Borghi et al., 2018, 2020c; Schau & Fet, 2007). The studied products can be classified as processed food products and belong to the following Central Product Classification (CPC) classes: “Prepared and preserved vegetables, pulses and potatoes” (CPC 213) and “Prepared and preserved fruits and nuts” (CPC 214) (United Nations - Department of Economics and social affairs, 2015). Therefore, an ISO 14040 (ISO, 2021) compliant LCA was performed following the specific rules defined in the Product Category Rules (PCR 2019:10) document on “prepared and preserved vegetables” (International EPD System, 2019) published in the framework of the International Environmental Product Declaration (EPD) System (International EPD system, 2021; Strazza et al., 2016) and according to ISO 14025 (ISO, 2010) and PCR 2020:07 “Arable and vegetable crops” (International EPD System, 2020).

The declared unit is defined as 1 ton of agricultural product. The system boundaries of crop cultivation include the phases along the supply chain from cradle to farm gate, as reported in Fig. 1.

Table 1
Inventory data for actual scenario (referred to 1 ha of crop).

Inventory data for cultivation	Unit	Bean	Pea	Sweet corn	Tomato
Crop yield	t/ha	4.19	5.94	14.43	86.50
Seeds	kg/ha	169.5	139.01	7.51	–
Seedlings	number/ ha	–	–	–	32,400
Water	m^3/ha	1,264.12	211.36	1,313.95	2,807.41
Fertilisers (N)	kg N/ha	60.6	45.75	140.36	110.56
Fertilisers (P)	kg P/ha	–	–	8.63	64.06
Fertilisers (K)	kg K/ha	–	–	–	55.33
Pesticides	kg/ha	10.46	5.22	22.86	34.62
Diesel	MJ/ha	13,794	8,424	11,899	16,787.37
Packaging	kg/ha	3	2.5	2.5	77.64
Ammonia emitted to air	kg/ha	6.29	1.67	24.33	3.47
Dinitrogen monoxide emitted to air	kg/ha	1.33	1.01	3.16	2.43
Nitrogen monoxide emitted to air	kg/ha	2.61	2.84	3.47	5.94
Nitrate emitted to water	kg/ha	64.34	48.60	152.71	117.45
Phosphorous emitted to water	kg/ha	–	–	0.43	3.20

The foreground inventory data were directly collected from the involved farms. The background life cycle inventory data concerning the production of fertilisers, fuels and electricity, packaging materials were retrieved from Ecoinvent database v.3.5 (Wernet et al., 2016). No allocation procedures were applied as all crops are cultivated separately.

Emissions due to fertiliser application were calculated according to the rules defined by the Intergovernmental Panel on Climate Change (IPCC) and other sources (International EPD System, 2020). Emissions of nutrients were considered as nitrate, phosphate, and gaseous emissions such as nitrous oxide from nitrogen fertiliser application. Direct and indirect N_2O emissions were accounted: N_2O emissions from atmospheric deposition of N on soils and water surfaces and emissions from N leaching and runoff were included in the indirect emissions.

2.2. *Life cycle inventory*

The previously described methodologies were carried out in a sequential way. First, actual data on crop yield, seeds, water, fertilisers, pesticides and diesel consumption were collected for each crop: data were retrieved from the agricultural cooperatives involved in the cultivation phase. Then, a full LCA were performed according to the methodology described above. Subsequently, the study was modified taking into account the inputs deriving from all the scenarios identified by PA for the following parameters: yield, fertilisation, irrigation and number of irrigation interventions. The resulting changes in the selected impact categories in future scenarios were assessed for each crop and the advantages that can be obtained by using an ideotype or by different management of crops quantified.

Data and assumptions are described in the following paragraphs.

2.2.1. *Actual scenario*

Cultivation, harvesting and transformation processes are all implemented according to procedures belonging to the company's integrated Quality Assurance approach. According to the goal of the study, the following vegetables were investigated: beans, peas, sweet corn, tomato. Inventory data were directly collected from a sample of agricultural cooperatives involved in the cultivation of the studied vegetables in 2018. The sample covers each crop and is characterised by an adequate geographical representativeness and territorial coverage. In particular, about 10 farms, covering approximately 100 ha, were selected for each crop: 8 farms for borlotti beans, 10 for peas, 7 for sweet corn and 10 for industrial tomatoes. Beans, peas and corn are grown in Northern Italy, while tomatoes are cultivated also in Tuscany and Apulia. Table 1 reports the production-weighted average data collected during the reference year. Data are referred to 1 ha for crop. Crop yield, seeds, water, fertilisers, pesticides and diesel consumption were collected during the reference period, while direct and indirect N and P emissions were calculated starting from nitrogen and phosphate fertiliser application according to the rules described in paragraph 2.1. Crop yield can vary because of conditions such as weather, soil, location, input intensity, irrigation, and rotation. In particular, for tomatoes, considerably higher yields are observed for the companies located in Puglia, with values between 130 and 140 t/ha, due to more favourable climatic conditions. The amount of water, used for irrigation and pesticides dilution, varies with species, growth period, climatic and soil conditions, and with the type of irrigation. Due to the Italian climate conditions, pea plants grow with no supplemental irrigation and only three agricultural companies carry out 2–3 irrigation operations. Irrigation is performed through different irrigation systems: hose-reel (75% of efficiency), pivot (85% of efficiency) and hose (90% of efficiency and used only for tomato cultivation). Hose-reel irrigation machines are mainly used for borlotto bean and pea, and for corn. Urea (NPK 46–0-0) or ammonium nitrate (28–0-0) are applied as nitrogen fertilisers. In particular, an average amount of 30 kg N/ha of urea and 30.6 kg N/ha of ammonium nitrate is spread to beans, 45.75 kg N/ha of ammonium nitrate to peas, 140.36 kg N/ha of urea to sweet corn and 43.98 kg N/ha of ammonium nitrate to tomatoes. For sweet corn and tomato cultivation, nitrogen is spread also as ternary fertiliser (NPK) and organic fertiliser: 3.38 kg N/ha for sweet corn and 66.58 kg N/ha for tomatoes. Phosphoric anhydride (P_2O_5) and potassium oxide (K_2O) are used as phosphoric and potassium fertiliser respectively. Phosphoric anhydride is applied only to corn (8.63 kg P_2O_5/ha) and tomato (64.06 kg P_2O_5/ha) and potassium oxide is applied only to tomato for a quantity of 55.33 kg K_2O/ha. As far as chemical treatments are concerned, selected pesticides are used for pre and post emergence against weeds. The maximum number of their applications is set by the applicable Regional Integrated Production specifications. Direct energy use from agricultural inputs comes from on-farm diesel consumption for machinery operations and includes irrigation and fertirrigation. Packaging production, i.e. sacks of seeds, fertilisers and chemical treatments, are also included in the inventory.

2.2.2. *Future scenarios*

The studied fresh vegetables are of Italian origin: beans, peas, sweet corn and tomato are grown in Northern, Central and Southern Italy. Specific simulations models for the cultivation systems of interest are based on STICS models (Loague & Green, 1991). The choice of the model was conducted relying on three criteria: correspondence as direct as possible between the traits subject to breeding and the parameters of the model, possibility to perform simulations in series and ability to simulate crops with different growth habit (determined or undetermined); a fundamental requirement to be able to reproduce in-silico the dynamics of trophic competition between "*sink*" and "*source*" organs. In order to avoid equifinality phenomena (same model outputs for different combinations of parameters), several model output variables were used (e.g. phenology, leaf area index, total air biomass and biomass in different plant organs, yield).

The study areas were selected based on the distribution of field tests carried out during the project, as well as taking into consideration the areas occupied by individual crops on the regional territory (source ISTAT). Two sub-areas have been identified, one in the Piacenza area (45° N, 9.45° E) and one in the Ravenna area (44.25° N, 12° E) in Northern Italy, which were used as separate case studies. These standard management practices have been defined using the information contained in the field notebooks supplied by the farms where the experimental activity took place, and they were integrated with the consultation of the "Technical Cultivation Standards" present on the integrated production regulations of the Emilia Romagna region in order to obtain management techniques representative of the whole context

Table 2
Simulated data resulting from PA model (referred to 1 ha of crop).

No.	Culture	Province	Climate scenario	Genotype	Management	Yield [t/ha]	N supply used as a fertiliser [kgN/ha]	Total water supplies for irrigation [mm/ha]	No. of irrigations
1	Bean	Piacenza	Baseline	Current	No adaptation	5.128	50	172.1	6.1
2	Bean	Piacenza	RCP4.5_GISS	Current	No adaptation	4.88	50	184.3	6.5
3	Bean	Piacenza	RCP8.5_HAD	Current	No adaptation	3.966	50	162.5	5.9
4	Bean	Piacenza	RCP4.5_GISS	Ideotype	Current Sowing	5.252	49.2	166.3	5.9
5	Bean	Piacenza	RCP8.5_HAD	Ideotype	Current sowing	4.77	46.5	146.5	5.7
6	Bean	Piacenza	RCP8.5_HAD	Ideotype	Sow 15 days before	5.032	48.3	163.8	5.85
1	Pea	Piacenza	Baseline	Current	No adaptation	5.536	36	35.6	1.4
2	Pea	Piacenza	RCP4.5_GISS	Current	No adaptation	5.348	36	43.8	1.6
3	Pea	Piacenza	RCP8.5_HAD	Current	No adaptation	4.864	36	35.5	1.5
4	Pea	Piacenza	RCP4.5_GISS	Ideotype	Current Sowing	5.332	34.42	33.8	1.35
5	Pea	Piacenza	RCP8.5_HAD	Ideotype	Current sowing	5.012	35.05	29.5	1.35
6	Pea	Piacenza	RCP4.5_GISS	Ideotype	Sow 15 days before	5.468	34.83	35.8	1.4
7	Pea	Piacenza	RCP8.5_HAD	Ideotype	Sow 15 days before	5.224	34.71	26.3	1.2
8	Pea	Ravenna	Baseline	Current	No adaptation	5.28	36	31	1.35
9	Pea	Ravenna	RCP4.5_GISS	Current	No adaptation	4.864	36	41.3	1.6
10	Pea	Ravenna	RCP8.5_HAD	Current	No adaptation	4.62	36	33.8	1.4
11	Pea	Ravenna	RCP4.5_GISS	Ideotype	Current Sowing	5.116	34.63	31.3	1.35
12	Pea	Ravenna	RCP8.5_HAD	Ideotype	Current sowing	4.816	36.72	31.8	1.35
13	Pea	Ravenna	RCP4.5_GISS	Ideotype	Sow 15 days before	5.784	36.38	29.7	1.3
14	Pea	Ravenna	RCP8.5_HAD	Ideotype	Sow 15 days before	5.548	36.68	31	1.3
1	Early corn	Piacenza	Baseline	Current	No adaptation	16.235	200	207.3	5.75
2	Early corn	Piacenza	RCP4.5_GISS	Current	No adaptation	15.74	200	214.3	5.95
3	Early corn	Piacenza	RCP8.5_HAD	Current	No adaptation	14.529	200	191.8	5.35
4	Early corn	Piacenza	RCP4.5_GISS	Ideotype	Current Sowing	16.853	209.53	226.3	6.25
5	Early corn	Piacenza	RCP8.5_HAD	Ideotype	Current sowing	15.912	197.37	205.8	5.7
6	Early corn	Piacenza	RCP8.5_HAD	Ideotype	Early sowing	15.951	198.31	205.6	5.7
7	Late corn	Piacenza	Baseline	Current	No adaptation	15.382	170	184.7	5.15
8	Late corn	Piacenza	RCP4.5_GISS	Current	No adaptation	14.858	170	186.9	5.20
9	Late corn	Piacenza	RCP8.5_HAD	Current	No adaptation	13.539	170	185.1	5.15
10	Late corn	Piacenza	RCP4.5_GISS	Ideotype	Current Sowing	14.500	165.25	182.9	5.1
11	Late corn	Piacenza	RCP8.5_HAD	Ideotype	Current sowing	14.672	166.25	209.1	5.75
12	Late corn	Piacenza	RCP4.5_GISS	Ideotype	Early sowing	15.368	171.2	200.7	5.55
13	Late corn	Piacenza	RCP8.5_HAD	Ideotype	Early sowing	15.618	173.62	222.1	6.1
1	Early tomato	Piacenza	Baseline	Current	Current Sowing	86.62	140	175.8	4.95
2	Early tomato	Piacenza	RCP4.5_GISS	Current	Current sowing	84.07	140	186.2	5.20
3	Early tomato	Piacenza	RCP8.5_HAD	Current	Current Sowing	69.73	140	180.4	5.05
4	Early tomato	Piacenza	RCP4.5_GISS	Ideotype	Current sowing	87.01	131.79	190.4	5.30
5	Early tomato	Piacenza	RCP8.5_HAD	Ideotype	Current sowing	77.87	125.89	190.4	5.30
6	Early tomato	Ravenna	Baseline	Current	Current Sowing	82.87	140	173.8	4.85
7	Early tomato	Ravenna	RCP4.5_GISS	Current	Current sowing	78.79	140	188	5.25
8	Early tomato	Ravenna	RCP8.5_HAD	Current	Current Sowing	66.48	140	155.8	4.50
9	Early tomato	Ravenna	RCP4.5_GISS	Ideotype	Current sowing	85.19	137.08	198	5.50
10	Early tomato	Ravenna	RCP8.5_HAD	Ideotype	Current sowing	74.76	126.85	167.8	4.80
11	Late tomato	Piacenza	Baseline	Current	Current Sowing	88.88	117	169	4.80
12	Late tomato	Piacenza	RCP4.5_GISS	Current	Current sowing	81.60	117	168.1	4.75
13	Late tomato	Piacenza	RCP8.5_HAD	Current	Current Sowing	60.96	117	165.4	4.70
14	Late tomato	Piacenza	RCP4.5_GISS	Ideotype	Current sowing	92.83	114.27	175.1	4.90
15	Late tomato	Piacenza	RCP8.5_HAD	Ideotype	Current sowing	69.47	91.34	167.2	4.75
16	Late tomato	Piacenza	RCP8.5_HAD	Ideotype	Early sowing	74.51	99.41	187	5.20
17	Late tomato	Ravenna	Baseline	Current	Current Sowing	83.47	117	158.8	4.50
18		Ravenna	RCP4.5_GISS	Current	Current sowing	76.09	117	169	4.75

(*continued on next page*)

Table 2 (*continued*)

No.	Culture	Province	Climate scenario	Genotype	Management	Yield [t/ha]	N supply used as a fertiliser [kgN/ha]	Total water supplies for irrigation [mm/ha]	No. of irrigations
	Late tomato								
19	Late tomato	Ravenna	RCP8.5_HAD	Current	Current Sowing	56.11	117	167.1	4.70
20	Late tomato	Ravenna	RCP4.5_GISS	Ideotype	Current sowing	85.29	115.03	175	4.90
21	Late tomato	Ravenna	RCP8.5_HAD	Ideotype	Current sowing	60.72	85.88	159.1	4.50
22	Late tomato	Ravenna	RCP8.5_HAD	Ideotype	Early sowing	66.14	95.54	160	4.55

analysed.

Climate change scenarios were derived using the LARS-WG climate generator (Semenov & Barrow, 2002). The meteorological data of the historical reference series (baseline, 1986–2005) were provided by the European Centre for Medium-Range Weather Forecast (ECMWF) while the expected temperature and precipitation variations for different climate change scenarios were derived from the data provided by the IPCC (Data Distribution Centre, IPCC). To manage the uncertainty associated with the generation of medium-long term climate scenarios, the climate projections provided by two different global circulation models were used (GCM) - GISS GCM Model II (Rosenzweig & Abramopoulos, 1997) and HadGEM2 (Collins et al., 2011). These are respectively combined with two different CO_2 emission scenarios – Representative Concentration Pathways (RCPs) – from the IPCC's Fifth Assessment Report (AR5) (Stocker et al., 2014), one more optimistic (RCP4.5) and one more pessimistic (RCP8.5). Despite the new Shared Socio-economic Pathways (SSPs) present in the IPCC's Sixth Assessment Report (AR6) (Intergovernmental Panel on Climate Change, 2021), climate projections used in the simulation software are still based on RCPs provided in AR5.

To take into account the inter-annual climate variability, a time window of twenty years was used, both for future scenarios, centred on 2040 (2030–2049), and for the baseline. The analysis of the climatic projections obtained for the four combinations of RCP and GCM then allowed to identify the two scenarios RCP4.5- GISS GCM Model II and RCP8.5 HadGEM2, as representative of the variability obtained in the climate projections in the study areas. The task of defining the ideotypes for the different scenarios was performed using the EFAST sensitivity analysis method (Extended Fourier Sensitivity Test) (Saltelli et al., 1999; Tarantola & Becker, 2017), chosen as the best compromise between exploration effectiveness of hyperspace parameters and required computational time (Confalonieri et al., 2010). The potential ideotypes, obtained by exploring the hyperspace of the parameters through sensitivity analysis, were ordered according to their productive performance and evaluated considering both the yield and its stability. Furthermore, in order not to significantly increase the quantity of irrigation water in future scenarios, the ideotypes have also been chosen so as not to carry out more irrigation than the current scenario.

Data for future scenarios related to yield, fertilisation, irrigation and number of irrigation interventions were calculated applying the PA method described in paragraph 2.1 for all the combinations studied. Table 2 reports production-weighted average data for all the crops under study.

In order to use data resulting from the application of the PA method in the LCA model, the following assumptions were made. Urea was considered as N source, while the amount of pesticides was calculated on a yield basis. Similarly, packaging use was determined from the use of fertilisers and pesticides. Diesel consumption for irrigation was calculated starting from a specific consumption of 10 L/irrigation*ha. Diesel consumption for fertilisation and pesticides application were calculated proportionally to the applied quantities. Finally, a constant consumption of diesel was assumed for the remaining soil operations: 186.38 l/ha for borlotto bean, 185.5 l/ha for pea, 96.26 l/ha for sweet corn and 187.2 l/ha for tomatoes. Table 3 reports all the inventory data calculated for future scenarios based on the assumptions described above.

2.3. *Life cycle impact assessment*

Impact categories representative of WEF nexus were calculated: Global Warming Potential (GWP, 100 years, in kg CO_2 equivalents), Water Scarcity Indicator (WSI, AWARE, in m^3 equivalents), Ecological Footprint (EF, in m^2yr) and Cumulative Energy Demand (CED, in MJ). CML 2001, a methodology developed by the Center of Environmental Science (CML) of Leiden University in the Netherlands, is used as impact assessment baseline method (Guinée et al., 2001) for GWP. Greenhouse gas emissions from land use change can be considered negligible as, for lands that have been arable lands for more than 30 years, it is robust to assume that no land change occurs. AWARE is a regionalised, water use midpoint indicator representing the relative Available Water Remaining per area in a watershed after the demand of humans and aquatic ecosystems has been met. AWARE is the recommended method from WULCA (working group under the umbrella of UNEP-SETAC Life Cycle Initiative) to assess water consumption impact assessment in LCA (Boulay et al., 2018). The ecological footprint is defined as the biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption. The ecological footprint of a product is defined as the sum of time-integrated direct land occupation and indirect land occupation, related to nuclear energy use and to CO_2 emissions from fossil energy use and cement burning. In order to get a footprint, each impact category is given the weighting factor 1 (Frischknecht et al., 2007). Cumulative Energy Demand (version method V1.10) of a product represents the direct and indirect energy use throughout the life cycle, including energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. In particular, this method considers both the contribution of non-renewable energy (fossil, nuclear and biomass) and renewable (wind, solar, geothermal and water). In order to get a total ("cumulative") energy demand, each impact category is given the weighting factor 1 (Frischknecht et al., 2007).

3. Results and discussion

A full LCA was performed on actual and future scenarios for all crops in order to calculate the potential contributions to global warming, water scarcity, ecological footprint and cumulative energy demand.

3.1. *Actual scenario*

Figs. 2–5 show the results referred to 1 t of bean, pea, sweet corn and tomato.

As far as GWP is concerned (Fig. 2), it can be seen that bean is the crop with the higher environmental impact (476 kg CO_2 eq). This is mainly due to the low yield compared to the other crops analysed. For the same reason, tomato shows the lowest impact presenting a GWP

Table 3
Inventory data for future scenarios (referred to 1 ha of crop).

No.	Culture	Total water used for irrigation [m^3/ha]	Pesticides application [kg/ha]	Packaging [kg/ha]	Diesel consumption for irrigation [l/ha]	Diesel consumption for pesticides application [l/ha]	Diesel consumption for fertilisation [l/ha]	Total diesel consumption [l/ha]
1	Bean	1,720.50	12.80	2.65	61.00	15.15	2.48	265.00
2	Bean	1,843.00	12.18	2.63	65.00	14.41	2.48	268.26
3	Bean	1,624.50	9.90	2.53	59.00	11.71	2.48	259.56
4	Bean	1,663.00	13.11	2.63	59.00	15.51	2.43	263.32
5	Bean	1,564.50	11.91	2.47	57.00	14.09	2.30	259.77
6	Bean	1,638.00	12.56	2.57	58.50	14.86	2.39	262.13
1	Pea	355.50	4.86	2.00	14.00	9.51	2.52	211.52
2	Pea	438.00	4.70	2.00	16.00	9.18	2.52	213.20
3	Pea	354.50	4.27	1.98	15.00	8.35	2.52	211.37
4	Pea	338.00	4.69	1.92	13.50	9.16	2.41	210.56
5	Pea	294.50	4.40	1.94	13.50	8.61	2.45	210.06
6	Pea	357.50	4.81	1.94	14.00	9.39	2.44	211.33
7	Pea	263.00	4.59	1.93	12.00	8.97	2.43	208.90
8	Pea	310.00	4.64	1.99	13.50	9.07	2.52	210.58
9	Pea	412.50	4.27	1.98	16.00	8.35	2.52	212.37
10	Pea	337.50	4.06	1.96	14.00	7.93	2.52	209.95
11	Pea	312.50	4.50	1.92	13.50	8.79	2.42	210.21
12	Pea	317.50	4.23	2.01	13.50	8.27	2.57	209.84
13	Pea	296.50	5.08	2.03	13.00	9.93	2.54	210.98
14	Pea	309.50	4.88	2.04	13.00	9.53	2.57	210.59
1	Early corn	2,073.00	25.72	3.25	57.50	12.24	5.91	171.90
2	Early corn	2,142.50	24.94	3.24	59.50	11.86	5.91	173.52
3	Early corn	1,917.50	23.02	3.21	53.50	10.95	5.91	166.61
4	Early corn	2,262.50	26.70	3.40	62.50	12.70	6.19	177.64
5	Early corn	2,057.50	25.21	3.21	57.00	11.99	5.83	171.08
6	Early corn	2,055.50	25.27	3.22	57.00	12.02	5.86	171.13
7	Late corn	1,846.50	24.37	2.80	51.50	11.59	5.02	164.37
8	Late corn	1,869.00	23.54	2.79	52.00	11.20	5.02	164.47
9	Late corn	1,851.00	21.45	2.76	51.50	10.20	5.02	162.98
10	Late corn	1,829.00	22.97	2.71	51.00	10.93	4.88	163.06
11	Late corn	2,091.00	23.24	2.73	57.50	11.06	4.91	169.72
12	Late corn	2,007.00	24.35	2.82	55.50	11.58	5.06	168.39
13	Late corn	2,221.00	24.74	2.86	61.00	11.77	5.13	174.15
1	Early tomato	1,757.50	34.67	58.64	49.50	32.15	7.55	276.39
2	Early tomato	1,861.50	33.65	58.29	52.00	31.20	7.55	277.95
3	Early tomato	1,804.00	27.91	56.37	50.50	25.88	7.55	271.13
4	Early tomato	1,904.00	34.82	55.93	53.00	32.29	7.11	279.60
5	Early tomato	1,904.00	31.16	52.72	53.00	28.90	6.79	275.88
6	Early tomato	1,737.50	33.17	58.13	48.50	30.75	7.55	274.00
7	Early tomato	1,880.00	31.53	57.58	52.50	29.24	7.55	276.49
8	Early tomato	1,557.50	26.61	55.93	45.00	24.67	7.55	264.42
9	Early tomato	1,980.00	34.10	57.46	55.00	31.61	7.39	281.21
10	Early tomato	1,677.50	29.92	52.63	48.00	27.74	6.84	269.78
11	Late tomato	1,690.00	35.57	51.22	48.00	32.98	6.31	274.49
12	Late tomato	1,681.00	32.66	50.24	47.50	30.28	6.31	271.29
13	Late tomato	1,653.50	24.40	47.47	47.00	22.62	6.31	263.13

(*continued on next page*)

Table 3 (*continued*)

No.	Culture	Total water used for irrigation [m^3/ha]	Pesticides application [kg/ha]	Packaging [kg/ha]	Diesel consumption for irrigation [l/ha]	Diesel consumption for pesticides application [l/ha]	Diesel consumption for fertilisation [l/ha]	Total diesel consumption [l/ha]
14	Late tomato	1,751.00	37.15	50.83	49.00	34.45	6.16	276.81
15	Late tomato	1,671.50	27.80	40.00	47.50	25.78	4.93	265.40
16	Late tomato	1,869.50	29.82	43.38	52.00	27.65	5.36	272.21
17	Late tomato	1,588.00	33.41	50.49	45.00	30.97	6.31	269.48
18	Late tomato	1,689.50	30.45	49.50	47.50	28.24	6.31	269.25
19	Late tomato	1,671.00	22.46	46.82	47.00	20.82	6.31	261.33
20	Late tomato	1,749.50	34.14	50.07	49.00	31.65	6.20	274.05
21	Late tomato	1,591.00	24.30	36.99	45.00	22.53	4.63	259.37
22	Late tomato	1,599.50	26.47	40.96	45.50	24.55	5.15	262.40

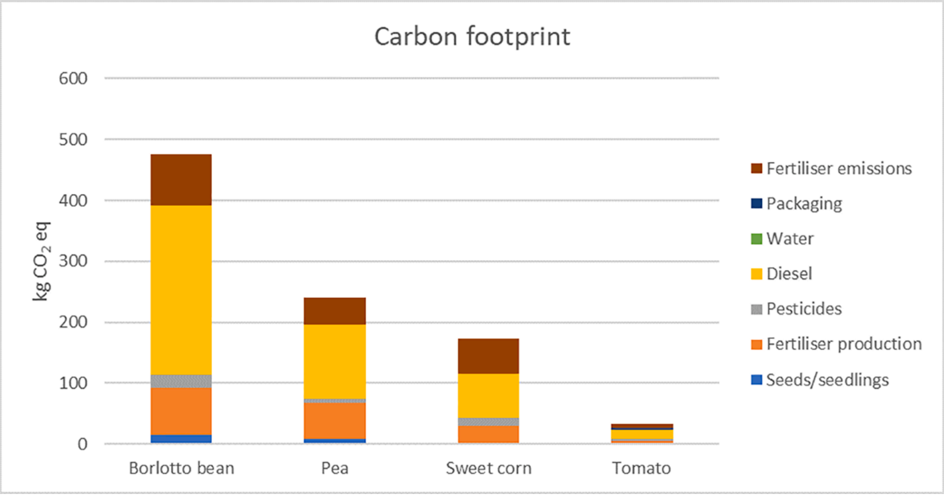

Fig. 2. GWP potential impacts referred to 1 t of crops.

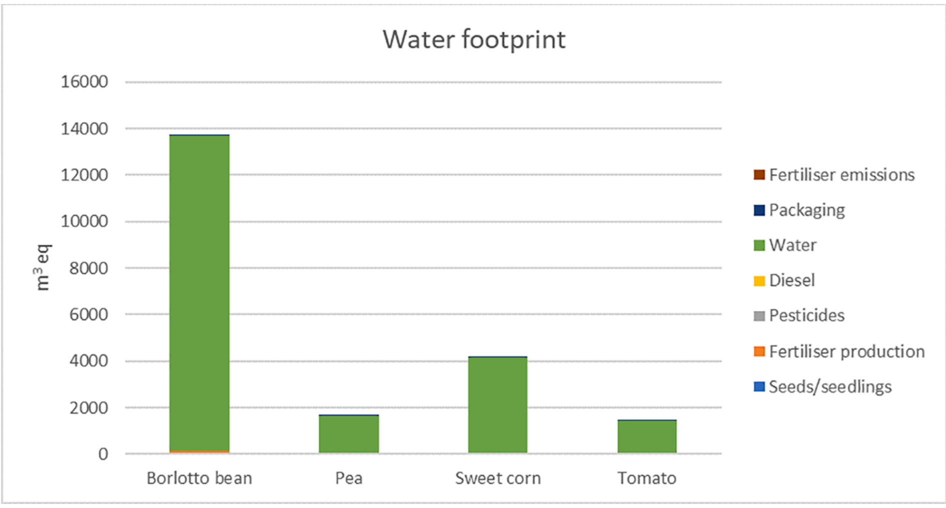

Fig. 3. WSI potential impacts referred to 1 t of crops.

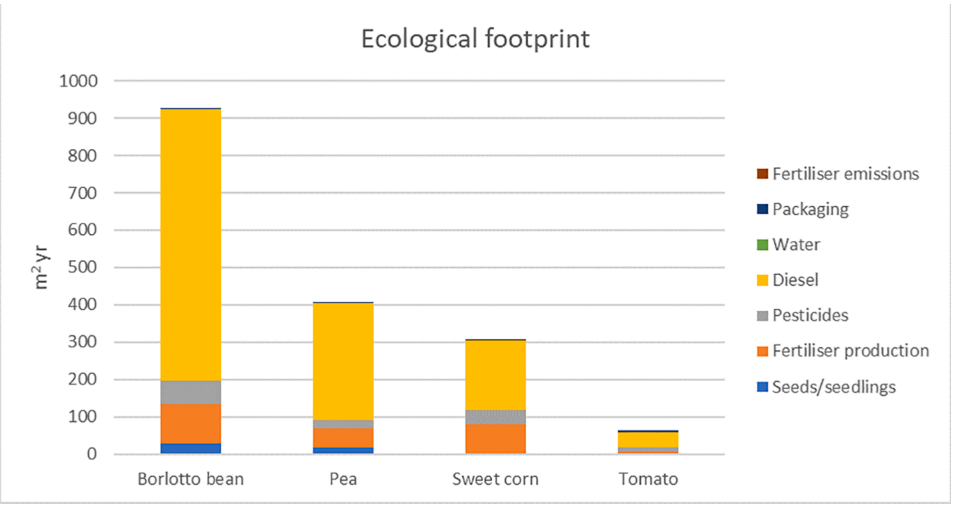

Fig. 4. EF potential impacts referred to 1 t of crops.

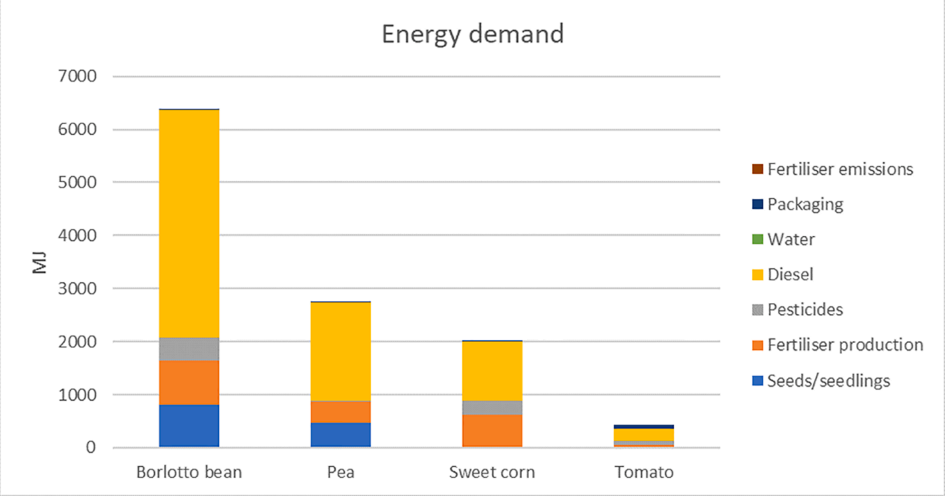

Fig. 5. CED potential impacts referred to 1 t of crops.

Table 4
Summary of climate and management scenarios for bean.

Scenario	Culture	Province	Climate scenario	Genotype	Management
2	Bean	Piacenza	RCP4.5_GISS	Current	No adaptation
3			RCP8.5_HAD	Current	No adaptation
4			RCP4.5_GISS	Ideotype	Current Sowing
5			RCP8.5_HAD	Ideotype	Current sowing
6			RCP8.5_HAD	Ideotype	Sow 15 days before

Table 5
Summary of climate and management scenarios for pea.

No.	Culture	Province	Climate scenario	Genotype	Management
2	Pea	Piacenza	RCP4.5_GISS	Current	No adaptation
3			RCP8.5_HAD	Current	No adaptation
4			RCP4.5_GISS	Ideotype	Current Sowing
5			RCP8.5_HAD	Ideotype	Current sowing
6			RCP4.5_GISS	Ideotype	Sow 15 days before
7			RCP8.5_HAD	Ideotype	Sow 15 days before
9		Ravenna	RCP4.5_GISS	Current	No adaptation
10			RCP8.5_HAD	Current	No adaptation
11			RCP4.5_GISS	Ideotype	Current Sowing
12			RCP8.5_HAD	Ideotype	Current sowing
13			RCP4.5_GISS	Ideotype	Sow 15 days before
14			RCP8.5_HAD	Ideotype	Sow 15 days before

equal to 33.51 kg CO_2 eq/t of tomato. Diesel consumption is the input responsible of the highest greenhouse emissions, contributing to more than 40% to GWP for all crops. The second contributor to global warming is fertilisers production, with an average 15% share at least. Emissions to air caused by fertilisers application contribute averagely to 20% to GWP for beans, peas and tomatoes, while the contribution raises to 33.5% for sweet corn due to the higher use of urea – having a higher generation of dinitrogen monoxide in field application rather than ammonium nitrate and other NPK – as N fertiliser and the lower use of diesel per unit mass of product with respect to pea and bean.

Pesticides application accounts less than 11% to GWP for all crops: tomato shows the highest contribution (10.4%) as the higher number of chemical treatments per hectare – if compared to other crops – is less compensated by the higher yield with respect to other inputs. Seed and packaging production show negligible impacts. Similar results are obtained for EF (Fig. 4) and CED (Fig. 5). With regard to WSI, on the contrary, almost all the impact associated with water scarcity is due to the water used for irrigation (Fig. 3). In particular, the cultivation of 1 ton of borlotto beans requires more than 3 times of water than other

Table 6
Summary of climate and management scenarios for corn.

No.	Culture	Province	Climate scenario	Genotype	Management
2	Early corn	Piacenza	RCP4.5_GISS	Current	No adaptation
3			RCP8.5_HAD	Current	No adaptation
4			RCP4.5_GISS	Ideotype	Current Sowing
5			RCP8.5_HAD	Ideotype	Current sowing
6			RCP8.5_HAD	Ideotype	Early sowing
8	Late corn		RCP4.5_GISS	Current	No adaptation
9			RCP8.5_HAD	Current	No adaptation
10			RCP4.5_GISS	Ideotype	Current Sowing
11			RCP8.5_HAD	Ideotype	Current sowing
12			RCP4.5_GISS	Ideotype	Early sowing
13			RCP8.5_HAD	Ideotype	Early sowing

crops.

3.2. *Future scenarios*

According to the purpose of the study, potential impacts affecting WEF nexus were calculated for each future scenario. Figs. 6–14 show, for each scenario, the percentage changes of impacts compared to the corresponding baseline climate scenario (current) with current genotype without adaptation. Looking at crop management without adaptation, as expected, current genotype in future climate scenarios has greater environmental loads if compared to the current baseline, with higher levels for the pessimistic RCP8.5 scenario compared to the optimistic RCP4.5 scenario. This occurs because the increase in temperatures – that characterises future climate projections – negatively affects yields, with different reductions depending on the climate scenario considered. Consequently, in order to maintain the yield of these crops comparable with the current one, in future scenarios a greater quantity of energy and water input will be required. Tables 4–7 briefly recap climate and management scenarios analysed for each crop.

3.2.1. *Bean*

In the case of bean (Fig. 6), the greatest yield drops are highlighted in the scenario characterised by the most pronounced thermal increases (RCP8.5), which determine a shortening of the vegetative cycle. This result demonstrates how climate changes negatively affects crop cultivation and how agriculture may in future lead to greater environmental costs with respect to those of today's production. Instead, for the RCP8.5 scenario, using an ideotype and maintaining the same crop management generate no reductions compared to the current baseline, with the exception of the WF (-2.2%). However, the definition of the ideotype offers considerable advantages for all four indicators (over 20% gaps) with respect to the current genotype. Moreover, modifying the management and therefore anticipating the sowing of 15 days allow the

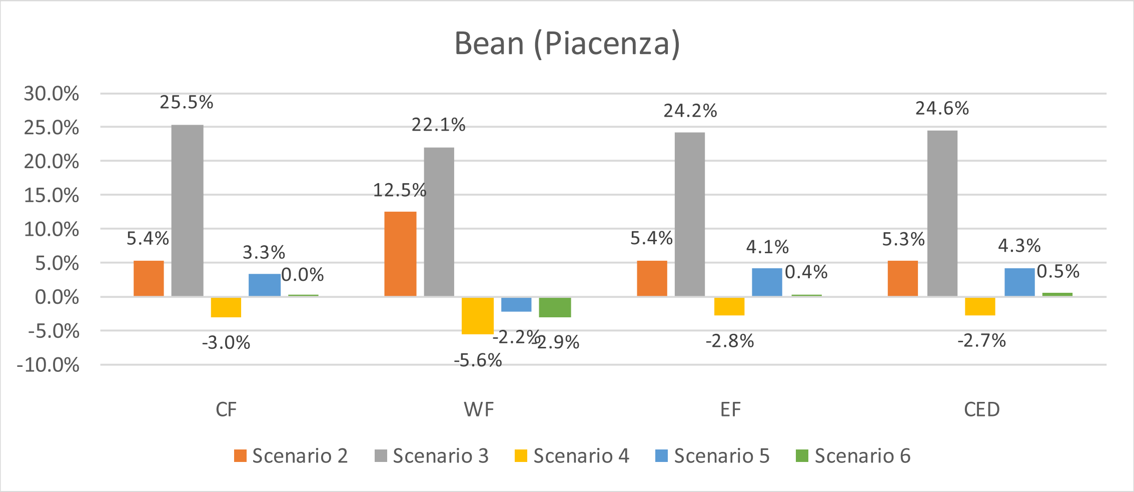

Fig. 6. LCA results compared to the baseline climate scenario for beans at Piacenza site.

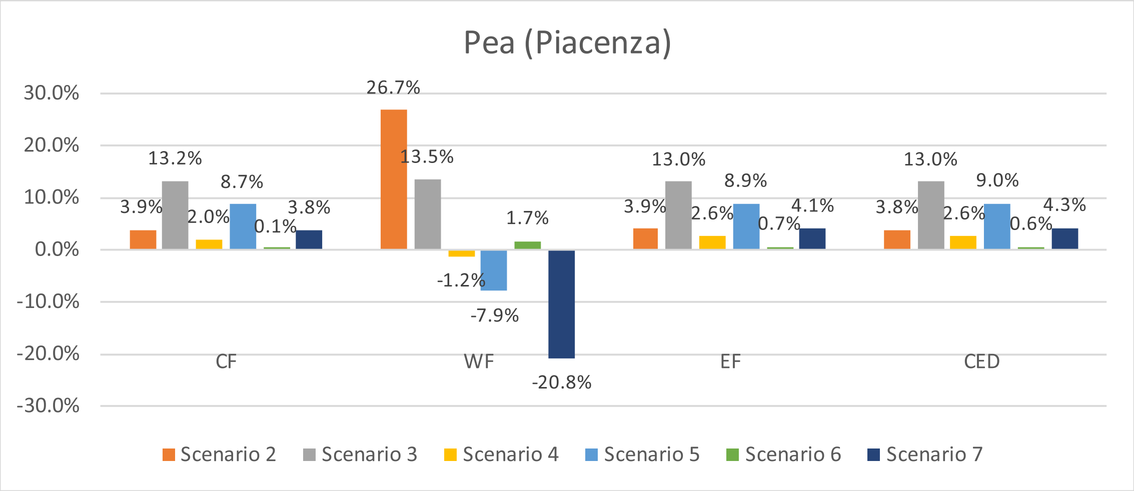

Fig. 7. LCA results compared to the baseline climate scenario for peas at Piacenza site.

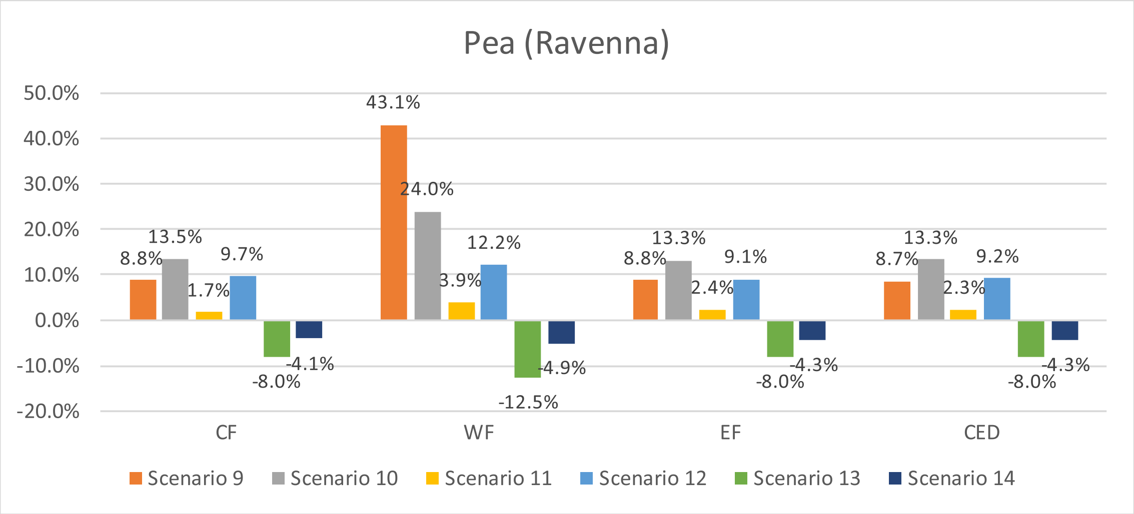

Fig. 8. LCA results compared to the baseline climate scenario for peas at Ravenna site.

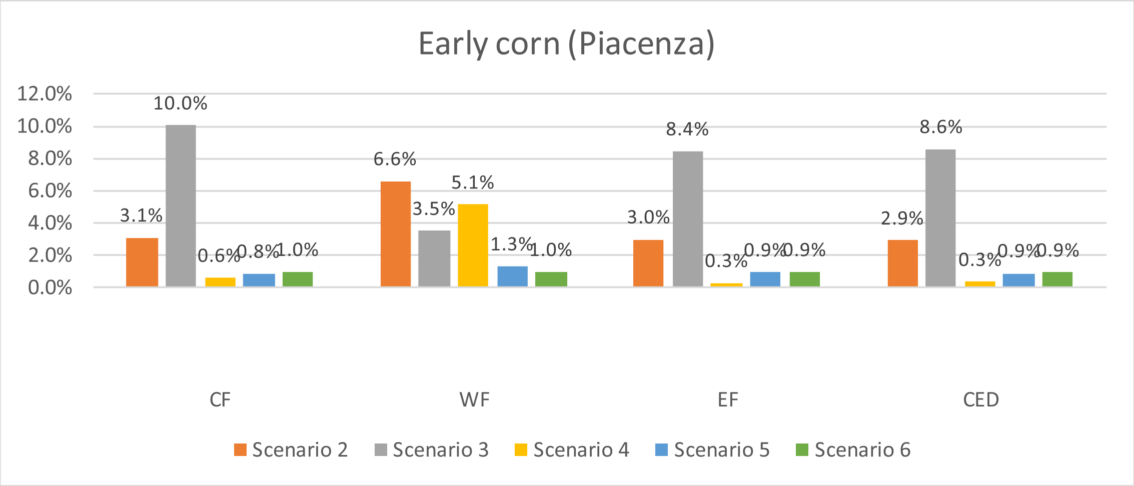

Fig. 9. LCA results compared to the baseline climate scenario for early corn at Piacenza site.

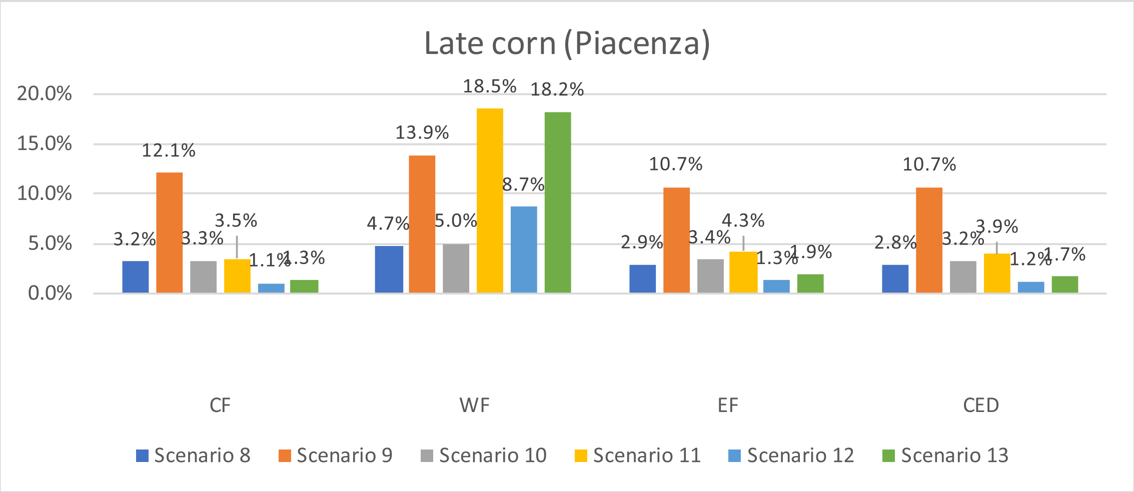

Fig. 10. LCA results compared to the baseline climate scenario for late corn at Piacenza site.

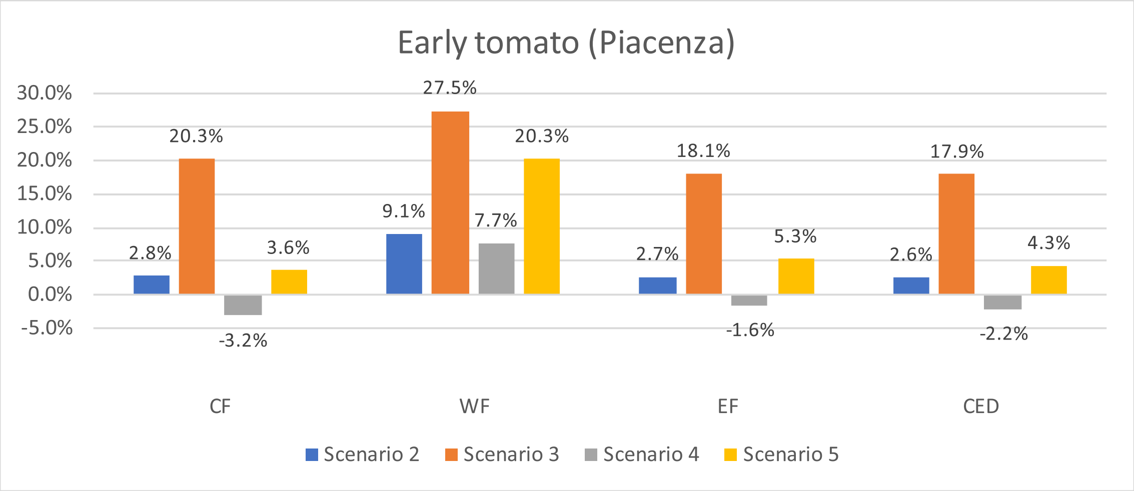

Fig. 11. LCA results compared to the baseline climate scenario for early tomato at Piacenza site.

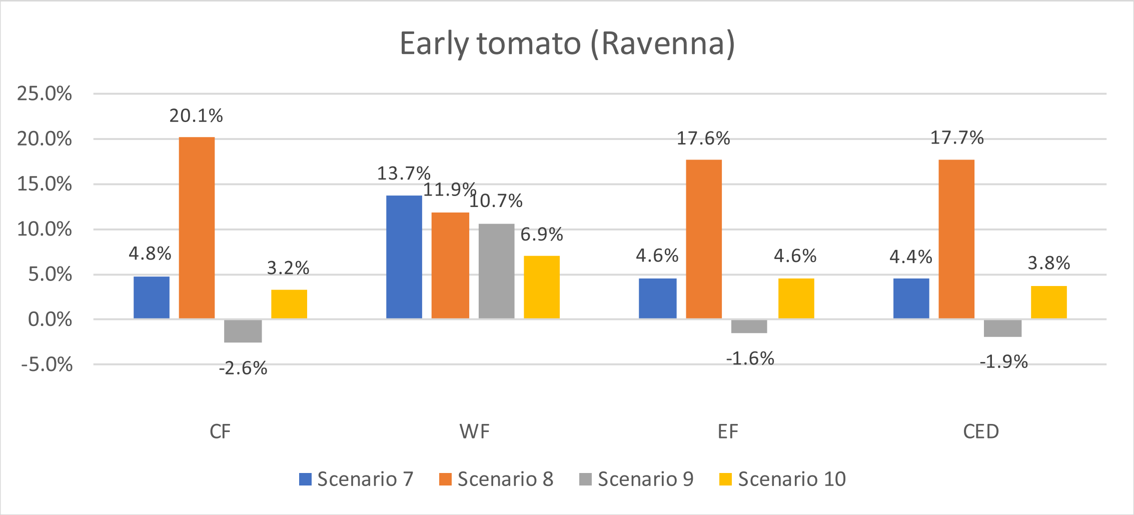

Fig. 12. LCA results compared to the baseline climate scenario for early tomato at Ravenna site.

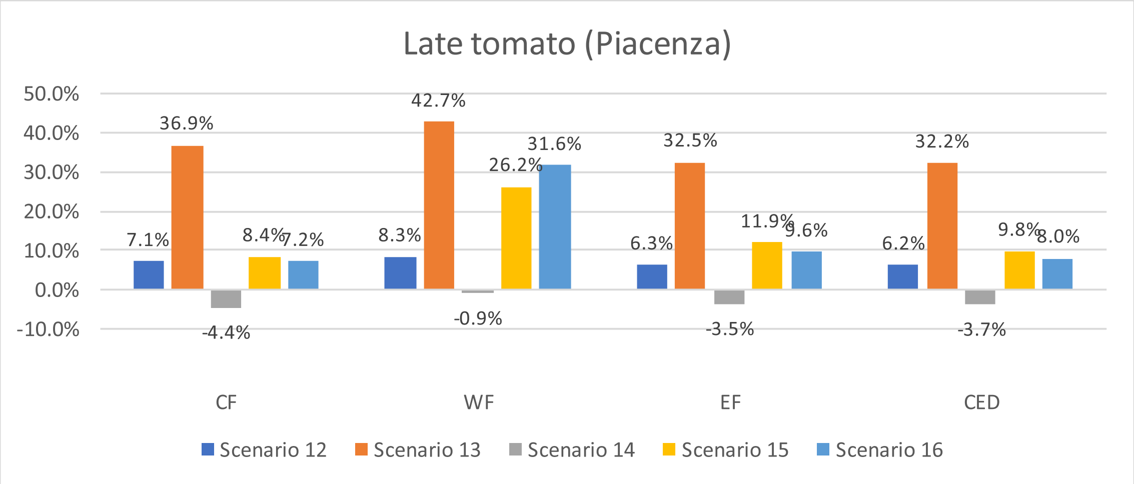

Fig. 13. LCA results compared to the baseline climate scenario for late tomato at Piacenza site.

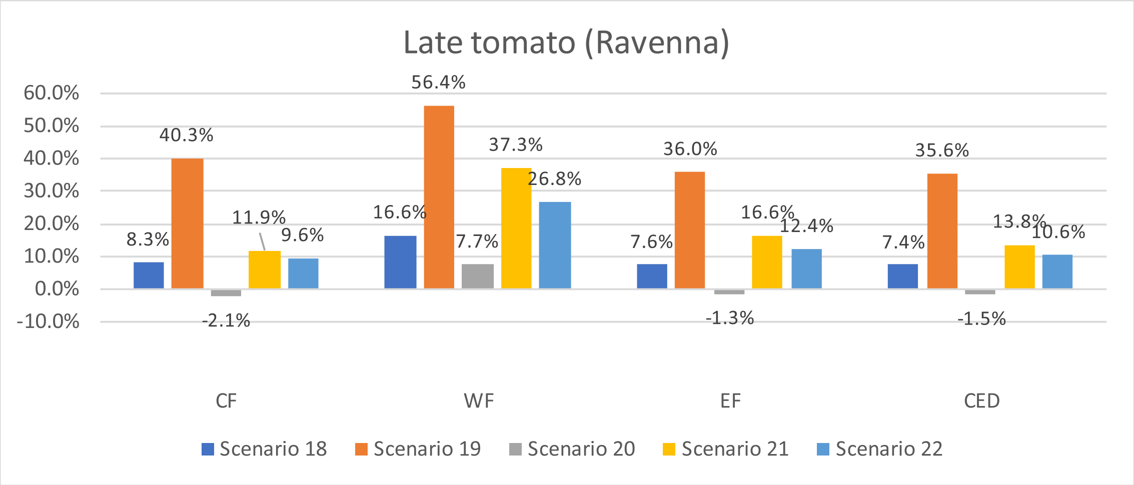

Fig. 14. LCA results compared to the baseline climate scenario for late tomato at Ravenna site.

Table 7
Summary of climate and management scenarios for corn.

No.	Culture	Province	Climate scenario	Genotype	Management
2	Early tomato	Piacenza	RCP4.5_GISS	Current	Current sowing
3			RCP8.5_HAD	Current	Current Sowing
4			RCP4.5_GISS	Ideotype	Current sowing
5			RCP8.5_HAD	Ideotype	Current sowing
7		Ravenna	RCP4.5_GISS	Current	Current sowing
8			RCP8.5_HAD	Current	Current Sowing
9			RCP4.5_GISS	Ideotype	Current sowing
10			RCP8.5_HAD	Ideotype	Current sowing
12	Late tomato	Piacenza	RCP4.5_GISS	Current	Current sowing
13			RCP8.5_HAD	Current	Current Sowing
14			RCP4.5_GISS	Ideotype	Current sowing
15			RCP8.5_HAD	Ideotype	Current sowing
16			RCP8.5_HAD	Ideotype	Early sowing
18		Ravenna	RCP4.5_GISS	Current	Current sowing
19			RCP8.5_HAD	Current	Current Sowing
20			RCP4.5_GISS	Ideotype	Current sowing
21			RCP8.5_HAD	Ideotype	Current sowing
22			RCP8.5_HAD	Ideotype	Early sowing

impacts to remain approximately equal to those of the current baseline (with increases <1%) for the CF, EF, CED and 2.9% lower for WF. The anticipation of sowing, combined with the use of an ideotype, makes it possible to further reduce the impacts with respect to the current genotype and crop management in the RCP8.5 scenario.

3.2.2. *Pea*

Also for the pea (Figs. 7 and 8), it can be observed how, with the current genotype without adaptation (for both provinces) in the two future scenarios there is an increase of all the indicators. In this case, unlike the bean, the WF value is higher for the RCP4.5 scenario compared to the RCP8.5 scenario, due to the greater quantity of water required for irrigation.

Using an ideotype but not adopting crop management adaptation strategies, an improvement can be observed comparing the same climatic scenarios. This improvement is more or less evident depending on the indicators and province considered. The most significant reduction can be seen for the WF indicator: in fact, for the RCP4.5 scenario for the province of Piacenza, it decreases from +26.7% to −1.2% compared to the current baseline, whereas for the province of Ravenna it decreases from a +43.1% to 3.9%. Also for the RCP8.5 scenario, considerable reductions are observed in both provinces for all indicators and, in particular, for Ravenna a WF reduction of 7.9% is obtained compared to the actual baseline. By anticipating the sowing of 15 days, a reduction in the impacts is also observed for the pea, with more marked differences for the province of Ravenna. In fact, for all the four indicators a reduction is obtained, both for the RCP4.5 and RCP8.5 scenario, not only with respect to the same scenarios with the use of the current genotype but also with respect to the actual current baseline.

3.2.3. *Sweet corn*

Even for sweet corn (Figs. 9 and 10), it can be observed a more limited worsening in the case of the two future scenarios compared to bean and pea. The increase in impacts is greater for late corn with values ranging from +2.9% for CED to +4.7% for WF in the RCP4.5 scenario and values from +10.7 % for CED to +13.9% for WF in the RCP8.5 scenario. Using the ideotype but not performing crop management adaptation strategies in future scenarios it is possible to obtain comparable CF, WF, EF and CED values with those of the current baseline, especially for early corn in which the increase in impacts is less than 1.5%, except for the WF in the RCP4.5 scenario (+5.1%). For late corn there are higher increases in all categories compared to the current baseline with values ranging from +3.3% for the CF in the RCP4.5 scenario to +18.5% for the WF in the RCP8.5 scenario. Unlike bean and pea, anticipating corn sowing generates no significant improvements if any. However, through the simulations no efficient solutions have been found such as to maintain the yield close to that of the current baseline and, therefore, this result is the best compromise.

3.2.4. *Tomato*

Also for the early and late tomato (for both provinces), it is clear how the current genotype in future climate scenarios will lead to greater environmental impacts, with higher levels for the pessimistic RCP8.5 scenario compared to the optimistic RCP4.5. The biggest differences between the optimistic RCP4.5 scenario and the pessimistic RCP8.5

Table 8
Major outcomes (best and worst scenarios) for future climate scenarios with respect to related baselines.

Crop	Province	Worst scenario	Best scenario	Notes
Bean	Piacenza	Variation between +22.1% (WF) to +25.5% (CF) for RCP8.5, current genotype and no management adaptation	Variation between −5.6% (WF) to −2.7% (CED) for RCP4.5, optimal ideotype and current sowing	Ideotype selection and early sowing are able to guarantee environmental impacts in line (or lower) with the current baseline for both RCP4.5 and RCP8.5
Pea	Piacenza	Variation between +13.0% (EF and CED) to +13.5% (WF) for RCP8.5, current genotype and no management adaptation	Variation between +0.1% (CF) to +1.7% (WF) for RCP4.5, optimal ideotype and early sowing	Ideotype selection and early sowing may guarantee environmental impacts in line (or lower) with the current baseline for both RCP4.5 and RCP8.5, but the assessment is not uniform (especially for water demand). Nevertheless, pea is not a relevant water-demanding crop so it should not represent a critical issue in future scenarios.
	Ravenna	Variation between +13.3% (EF and CED) to +24% (WF) for RCP8.5, current genotype and no management adaptation	Variation between −12.5% (WF) to −8.0% (CF, EF and CED) for RCP4.5, optimal ideotype and early sowing	
Early corn	Piacenza	Variation between +3.5% (WF) to +10.0% (CF) for RCP8.5, current genotype and no management adaptation	Variation between +0.9% (EF and CED) to +1.0% (CF and WF) for RCP8.5, optimal ideotype and early sowing	Ideotype selection and early sowing are only able to limit the increase in environmental impacts for both RCP4.5 and RCP8.5. Water demand represent a critical issue for late corn.
Late corn	Piacenza	Variation between +10.7% (EF and CED) to +13.9% (WF) for RCP8.5, current genotype and no management adaptation	Variation between +1.1% (CF) to +8.7% (WF) for RCP4.5, optimal ideotype and early sowing	
Early tomato	Piacenza	Variation between +17.9% (CED) to +27.5% (WF) for RCP8.5, current genotype and no management adaptation	Variation between −3.2% (CF) to +7.7% (WF) for RCP4.5, optimal ideotype and current sowing	Ideotype selection and early sowing are able to guarantee environmental impacts in line (or lower) with the current baseline only for both RCP4.5. RCP8.5 scenarios show increase (even relevant for late tomato) in environmental impacts despite the application of optimal genotype and early sowing.
	Ravenna	Variation between +11.9% (WF) to +20.1% (CF) for RCP8.5, current genotype and no management adaptation	Variation between −2.6% (CF) to +10.7% (WF) for RCP4.5, optimal ideotype and current sowing	
Late tomato	Piacenza	Variation between +32.2% (CED) to +42.7% (WF) for RCP8.5, current genotype and no management adaptation	Variation between −4.4% (CF) to −0.9% (WF) for RCP4.5, optimal ideotype and current sowing	
	Ravenna	Variation between +35.6% (CED) to +56.4% (WF) for RCP8.5, current genotype and no management adaptation	Variation between −2.1% (CF) to +7.7% (WF) for RCP4.5, optimal ideotype and current sowing	

scenario is found for the late tomato. For the early tomato in the province of Piacenza (Fig. 11) there are increases with the RCP4.5 scenario compared to the current baseline ranging from 2.8% for CED to 9.1% for WF while with the RCP8.5 scenario increases range from 17.9% for the CED to 27.5% for WF. In the province of Ravenna (Fig. 12), the RCP4.5 scenario shows increases compared to the current baseline from 4.8% for CED to 13.7% for WF, while for the RCP8.5 scenario it shows increases ranging from 11.9% for WF at to 20.1% for CF. For the late tomato the increase of the four indicators is on average higher and above 30% for the RCP8.5 scenario (+42.7% for WF in the Piacenza site and +56.4% for WF in the Ravenna site). The use of an ideotype for early tomatoes allows the reduction of impacts for both sites with respect to the same climate scenario. For the optimistic RCP4.5 scenario, in both sites the impacts are also slightly lower than the baseline climate scenario, with the exception of the WF whose values remain higher (+7.7% for Piacenza and +10.7% for Ravenna). For the RCP8.5 scenario reductions are observed with respect to the use of the current genotype in the same climate scenario (for example for the Piacenza site CF goes from a +20.3% to a +3.6% compared to the baseline), but compared to the baseline no reductions are observed in any site. Also for the late tomato (Figs. 13 and 14) the use of an ideotype in the RCP4.5 scenario allows to obtain a reduction in all the indicators. In this case, reductions are observed also with respect to the baseline with the exception of only the WF for the province of Ravenna, whose value remains +7.7%. In the RCP8.5 scenario, considerable reductions in the indicators are not feasible: this is due to the fact that it is a scenario with high temperature increases and low rainfall in conjunction with the crop cycle, and therefore it requires a greater input of resources to produce the same amount of product. A reduction in the indicators can be observed by anticipating the sowing as well as using an ideotype in the RCP8.5 scenario. For example, for the Piacenza site, there is a reduction in CF, WF and CED of about 3 percentage points, but an increase in WF (from +26.2% to +31.6%). For the Ravenna site reductions are observed in all the indicators and, in particular, for the WF that goes from +37.3% to +26.8%.

Major outcomes and relevant scenarios are summarized in Table 8.

4. Conclusions

The purpose of the study was to carry out an analysis of the agri-food sector in order to improve the water-energy-food nexus performance of four preserved vegetables products (beans, peas, sweet corn, tomato) through a combination of PA and LCA. Thus, PA strategies were identified and a full LCA was performed on actual and future scenarios for all crops in order to evaluate the benefits of a potential combination of these two tools. Firstly, the potential contributions to global warming, water scarcity, ecological footprint and cumulative energy demand were calculated to highlight the hotspots of the agricultural phase. Obtained results show a strong correlation with the crop yield and, despite not changing the percentage contribution of different inputs to the overall impacts, yield variations play a relevant role in the environmental performance of crops. Except for the water footprint, diesel consumption resulted the main contributor to the environmental impacts analysed. In future scenarios (both in the optimistic RCP4.5 and in the pessimistic RCP8.5 scenario), the main impact of energy consumption related to the use of diesel persists and it emerged that the cultivation phase of bean, pea, sweet corn and tomato will face an increase, even considerable, of the impacts assessed in the study. This occurs because the increase in temperatures that characterises future climate projections negatively affects yields, with different reductions depending on the climate scenario considered. Consequently, in order to maintain the yield of these crops comparable with the current one, in future scenarios a greater quantity of energy and water input would be required. Among the different crops, the greatest yield drops are highlighted in the scenario characterised by the most pronounced thermal increases (RCP8.5), which determine a shortening of the vegetative cycle. As PA strategies, such as the use of management adaptation (early seeding) as well as genetic selection (ideotype), can lead to a potential reduction of impacts, the identification and application of an ideotype in future climate scenarios are studied and compared to the use of the current genotype. Results show a strong reduction in all the impact categories with respect to the use of the current genotype depending on the indicator considered, the crop, the climatic scenario and the site. In particular, for beans, the ideotype identified for the RCP4.5 scenario allows the reduction of the indicators not only with respect to the use of the current genotype in future climate scenarios, but also with respect to the baseline, thus allowing a reduction in the environmental impacts of the cultivated product. For peas and tomatoes (both early and late), reduction potentials depend on the different yields deriving from different sites, soils and favourable climatic conditions. This difference affects future scenarios as, both using a selected ideotype and the current genotype, yield variation persists among the sites inevitably leading to different environmental loads and impact reductions. When identifying the genotype options, PA alone would have selected several ideotypes in order to maximise the yield with respect to the baseline scenario. It is clear that PA approach offers several instruments for resource management and energy efficiency but, used by itself, it may lead to simplistic results as setting the objective function just at maximising the yield inevitably asks for energy and water consumption increase and generates higher impacts, especially in terms of water footprint. On the other side, a life cycle approach alone is not able to return an optimised predictive model of the cultivation systems analysed but it can play the role of a decision supporting methodology. Unlike PA, LCA directly focuses on the environmental analysis and a life cycle perspective is able to guide and better address the efforts and the outcomes of a PA optimisation process towards an overall sustainable system. In the case study analysed, a life cycle approach was able to target water consumption as a key parameter for the reduced water availability of future climate scenarios and to set a multi-objective function combining also such environmental aspects to the original goal of yield maximisation. As a result, the combination of PA with the LCA perspective potentially allow the path for an optimal trade-off of all the parameters involved and an overall reduction of the expected environmental impacts in future climate scenarios.

CRediT authorship contribution statement

Adriana Del Borghi: Conceptualization, Methodology. **Valeria Tacchino:** Writing – original draft, Software. **Luca Moreschi:** Writing – review & editing, Software. **Agata Matarazzo:** Validation. **Michela Gallo:** Supervision. **Diego Arellano Vazquez:** Writing – review & editing, Data curation.

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.

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