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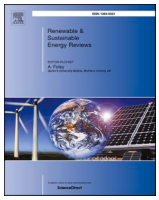

A novel modelling toolkit for unpacking the Water-Energy-Food-Environment (WEFE) nexus of agricultural development

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ABSTRACT

Increasing food demand has led to significant agricultural expansion globally with negative impacts on resources and the environment, a perfect manifestation of the Water-Energy-Food-Environment nexus. Whilst many tools have been developed to understand the complexity of the Water-Energy-Food-Environment nexus most have failed to explicitly consider biophysical and socio-economic aspects simultaneously. A novel Water-Energy-Food-Environment modelling toolkit is developed that integrates both these components by combining different modelling approaches including irrigation simulation, economic modelling and life cycle environmental assessment. The toolkit is demonstrated using two major agro-export crops (asparagus and table grapes) in the Ica Valley, Peru, a severely water-stressed region. The toolkit was able to provide novel insights into the implications of different farming practices on resource efficiency at the field level in relation to water and energy, under contrasting future scenarios reflecting socio-economic outcomes at the local to regional levels (e.g., food prices, employment, and income) as well as environmental impacts at local to global scales. This information enables different stakeholders to better understand the interlinkages and inter-dependences between the Water-Energy-Food-Environment nexus elements and the complex impacts of agricultural expansion beyond the immediate sector and its geographical extent, helping decision makers design more coordinated agricultural policies and support sustainable agricultural transformation.

1. Introduction

The rising global demand for food could provide opportunities to support economic growth in developing countries through exports of high-value agricultural commodities. However, much of the fruit and vegetables destined for European markets are grown in arid or semi-arid climates and water-stressed river basins where irrigation is used to increase yields and improve levels of crop quality for export markets. This has been linked to rapidly rising water abstraction, which has negatively impacted surface [1] and groundwater resources [2,3], contributed to reduced environmental flows, increased energy and carbon footprints [4,5] and land use change [6–8].

Over the last two decades, the Latin America and the Caribbean region (LAC) has provided a prime example of how agriculture has expanded to respond to increasing global food demand [9] and currently meets 11% of global food exports in value [10]. Although future global growth in trade of agricultural and fisheries products is expected to decline by 2.3% in comparison with the last decade, exports from LAC are projected to increase [11]. As a result, the irrigated area in LAC is expected to rise substantially. For example, in Argentina a threefold increase is expected between 2018 and 2030 [12], and in Ecuador an increase from 6154 km^2 [13] to 7390 km^2 is expected by 2035 [14]. There is also evidence that the expansion of high value crops in Ecuador [15] and Peru [16] are causing environmental and social conflicts over natural resources, most notably water. Changes in cropping patterns

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List of abbreviations including units and nomenclature

CO_2-eq/kg	Carbon dioxide equivalent per kilogram
A_h	Total hypothetical water availability in scenario h in units of cubic metre per year
A_T	Total observed water availability in units of cubic metre per year
c	cost function
gw	groundwater
GWh	Gigawatt hour
GWP	global warming potential
ha	hectare
H_i	Land allocation to product i in hectares
H_T	Total hectares of available farmland
kt CO_2-eq/kg	kiloton of carbon dioxide equivalent per kilogram
kWh/ha	kilowatt hour per hectare
kWh/m^3	kilowatt hour per cubic metre
LAC	Latin America and the Caribbean
LCA	Life Cycle Assessment
m^3/ha	cubic metre per hectare
m^3/kg	cubic metre per kilogram
Mm^3	million cubic metre
p_i	price of product i (in units of dollars or soles per unit of production)
π_i	Expected per-hectare net incomes for the crop i
S_i	Share of land allocated to product i
sw	surface water
TH	total pressure head
TID	Total irrigation demand
US$/kg	US dollars per kilogram
US$/$m^3$	US dollars per cubic metre
US$/kWh	US dollars per kilowatt hour
w_i	: price of input i (in units of dollars or soles per unit of production)
WEFE	Water-Energy-Food-Environment
X_{ic}	Exogenous factors of the crop i in district c
y_i	expected per-hectare production of the crop i (in the appropriate units, kilograms, tons)

have led to agronomic, environmental and socio-economic challenges that need to be effectively managed within policy for sustainable food provision [17]. Over the long term, this could lead to implications for water and energy security given expected increases in water scarcity, drought risks [18] and increased costs associated with higher water and energy prices [19,20]. In addition, electricity generation in most LAC countries rely on hydropower, which accounts for 45% of the total electricity supply in the region [21]. South America has a hydropower capacity of 176 GW and is one of the fastest growing areas with 5.2 GW new capacity added in 2019 [22]. However, climate change presents a risk to hydropower due to changes in precipitation patterns, melting glaciers, and an increase in the number of extreme weather events [21,23]. For these reasons, concerns have been voiced regarding the trade-offs that will be required between the environment and food and energy security objectives [24]. It has been estimated that agriculture and land use change in the region account on average for 17% of LAC greenhouse gas emissions [25], a proportion which is second globally after Asia [25]. Furthermore, agricultural expansion in LAC is causing inequalities in access to natural resources [26]. For instance, where the rural population density is low, there is an increasing use of agrochemicals and machinery to increase productivity, a direct response from large agricultural holdings to the international commodity markets. This has further decreased labour demand and caused rural population to migrate to large cities [27–29]. In areas where the rural population density is high, large land holders control most of the resources. In the Ica Valley in Peru for instance, nearly 70% of water allocations are held by large agricultural businesses to support irrigated production for export orientated crops [30].

Solving this challenge requires an integrated approach to identifying the impacts of agricultural expansion on water, energy and the environment in which synergies, conflicts and trade-offs between components systems are evaluated [31]. This is referred to as the Water-Energy-Food-Environment (WEFE) nexus. The application of the nexus approach is complex, requiring extensive input data [32] and tools that can capture the interactions and synergies between nexus components [33,34]. This necessitates the use of methods from different disciplines [33], selected in relation to the aim, scope, and scale of the analysis [35]. A multidisciplinary approach fosters an improved understanding of integrated systems [36,37], where the nexus perspective supports the evaluation of sector-specific development strategies and enhances decision-making and planning.

A diverse range of modelling tools have been developed to analyse various aspects of the WEFE nexus. Some tools such as OSeMOSYS [38], Water Evaluation and Planning software tool (WEAP [39]) and Long-range Energy Alternatives Planning System (LEAP [40]) follow a silo approach [33,41–43] that only considers one nexus element. There are also more integrative tools such as MuSIASEM [44], WEF nexus tool 2.0 [45] and Climate, Land, Energy and Water systems approach (CLEWs [46]) that incorporate three elements – water, energy, and food, with some including environment as a fourth element [47]. A systematic review [33] found that existing nexus tools often failed to use replicable methods and capture the interactions among nexus components and rarely use social science methods. Moreover, environmental and economic perspectives have not been explicitly considered in nexus research until recently [48], despite being essential nexus components [49,50].

In LAC countries, the WEFE nexus has been viewed as an approach that could help to identify and alleviate complex conflicts between growing and competing economic sectors. There has been a predominant focus in nexus analyses on water and its trade-offs across sectors including agricultural production, hydropower generation, and mining [51–53]. Some studies have highlighted the link between energy consumption and environmental damage [54–56], whilst others have focussed on the linkage between irrigation modernisation and over-exploitation of aquifers for agricultural development [57]. To our knowledge, there are no studies that uses a WEFE nexus approach to evaluating environmental and socioeconomic implications of agricultural transformation in the context of changing climatic conditions and global food demands.

This paper presents a novel modelling toolkit that combines irrigation and socio-economic modelling with life cycle assessment (LCA) to unpack the WEFE nexus of agricultural development in water-stressed regions engaged in export production to meet increasing global food demands. This toolkit provides an integrated nexus modelling approach based on well-established methods from different disciplines to identify socio-economic and environmental trade-offs across different crop production systems, thereby overcoming key limitations of existing tools such as reproducibility and failure to capture interactions among nexus components and environmental and economic perspectives. To illustrate the toolkit, this paper presents a case study application for two major agro-export crops (asparagus and table grapes) in the Ica Valley, Peru. The outputs provide valuable evidence for policy makers to help them develop informed and coordinated policies for sustainable agricultural development. The underlying methodology of the toolkit is transferable and applicable to other regions or countries facing similar challenges.

2. Method

2.1. Case study description

The Ica Valley is located in the region of Ica along the Pacific Ocean, about 300 km south of Lima, the capital of Peru (Fig. 1). The Valley is classified as a hyper-arid zone, with a mean annual precipitation of 100 mm [58]. This fertile valley has been an important agricultural area in Peru since pre-colonial times. During most of the 20th century, it was one of the leading exporters of cotton. However, by the late 1980s cotton started to be replaced by other emerging food crops with increasing demand in international markets.

Asparagus and grapes replaced cotton and the growing global popularity of these products has driven rapid expansion in large-scale farms over the last three decades [59]. By 2017, asparagus and grapes represented 52% of the cropped area and 68% of economic value of agricultural production in the Valley [60]. Both crops represent around a third of the country's exports of horticulture and fruit products [61]. Most production depends entirely on water abstraction from the largest aquifer in Peru - the Ica-Villacuri aquifer -that represents 40% of Peru's groundwater resources [62]. Both large and small-scale farmers grow asparagus and table grapes. Surface irrigation with surface water is the most widespread irrigation method for small-scale farms (up to 50 ha in the case of Peru), while large-scale farms (greater than 50 ha) use drip irrigation and mainly rely on groundwater. In the case of table grapes, different water sources and irrigation application methods are used, depending on farm type [63]. In addition, to identify variations in the use of resources and environmental impacts in the valley, it was divided into eight geographical zones. These zones were based on [63] by considering their location within the valley with respect to the Ica River's downstream flow and most common farm scale.

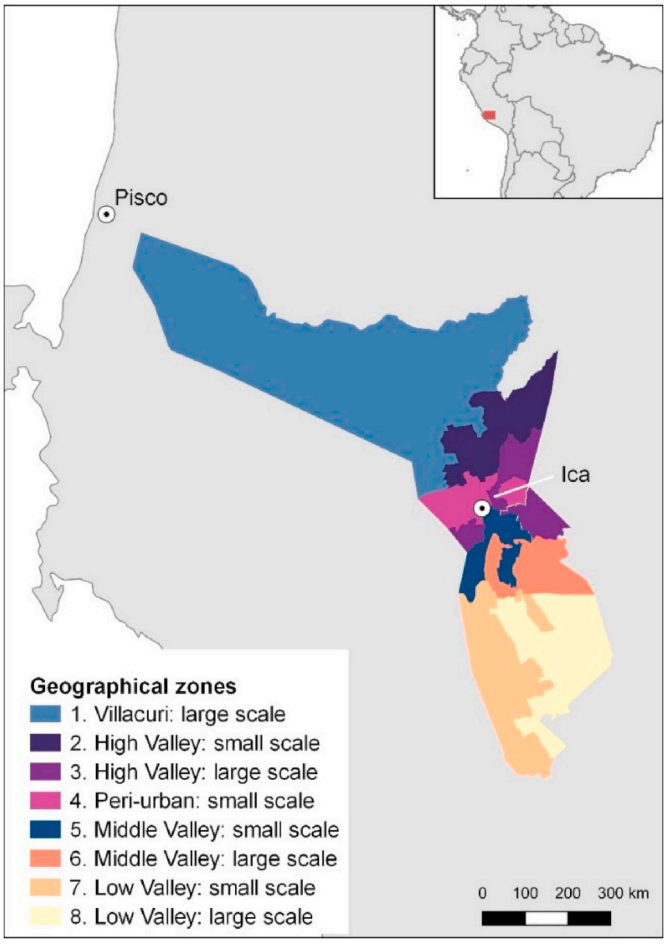

Fig. 1. Study area and geographical zones in the Ica Valley, Peru. Large and small scale designate the two farm-scale types identified in the area.

Expanded agricultural activity in the valley, coupled with a growing population, have dramatically increased water demand, especially from groundwater [64], while the natural variability in precipitation and a changing climate in the upper part of the Ica Basin have led to decreased water supplies [65].

2.2. Structure of the WEFE modelling toolkit

The integrated modelling toolkit (Fig. 2) was developed by linking three key components: (1) an irrigation simulation module that employs a soil water balance model [66] to estimate irrigation demands [67] and energy needs for water abstraction and application, (2) a socio-economic analysis module that uses a partial equilibrium model to simulate market dynamics and the behaviours of key actors, and (3) an environmental assessment module that employs LCA to evaluate key environmental impacts of agricultural production such as climate change, air pollution, water pollution, land use and resource depletion. The three modules are "soft-linked" so that they can operate individually but data and information output from one can be fed into the other two. There are also exogenous parameters that are inputs to one or more modules.

2.3. Irrigation simulation module

2.3.1. Irrigation demand

The WaSim model [66] was used to assess annual optimal irrigation needs (depths applied) for asparagus and table grapes. It requires information on soil textural characteristics, crop development parameters, daily rainfall and reference evapotranspiration as inputs to produce estimates of net irrigation and actual evapotranspiration. The WaSim model was parameterised using 2017 data and for the dominant soil textural class in the valley (Table S1). The total irrigation demand for each crop (*TID*) was calculated using Equation (1) based on the net irrigation demand from WaSim (*net irrigation*), the crop area (*area*) and the efficiency of the application method (*irrigation efficiency*):

$$TID_{(m^3)} = net\ irrigation_{(mm)} \times 10 \times area_{(ha)} \times \frac{100}{irrigation\ efficiency_{(\%)}} \quad [1]$$

Irrigation efficiency was assumed to be 90% for drip and 60% for surface irrigation application, respectively. The water efficiency of the WaSim irrigation schedule was based on the fact that for surface irrigation only a percentage of the water applied in the irrigation schedule in WaSim is consumed by the crop. Hence, the application efficiency was estimated by dividing the actual evapotranspiration by the net irrigation per crop. For surface irrigation, the application efficiency also considered the water losses in the irrigation schedule (i.e., 0.6/ratio water efficiency WaSim). The cropped areas for asparagus and table grapes were obtained from agricultural survey data for 2017 [60].

2.3.2. Irrigation energy demand

The energy demand for irrigation was calculated following [67]. The total pressure head (*TH*) was estimated using Equation (2), taking into account the elevation for water pumping, nominal operating pressure (H_{min}) of the application method (drip, surface) and friction losses (f_{losses}) associated with water distribution:

$$TH_{(m)} = Elevation_{(m)} + H_{\min(m)} + f_{losses(m)} \quad [2]$$

Depending on the source, pumps need to abstract the water from a certain depth. For cropped areas irrigated using wells, the maximum depth of groundwater abstraction was assumed to be 80 m [68]. For other cropped areas irrigated using rivers or other surface sources, it was assumed that the water was at ground level. Typical operating pressure

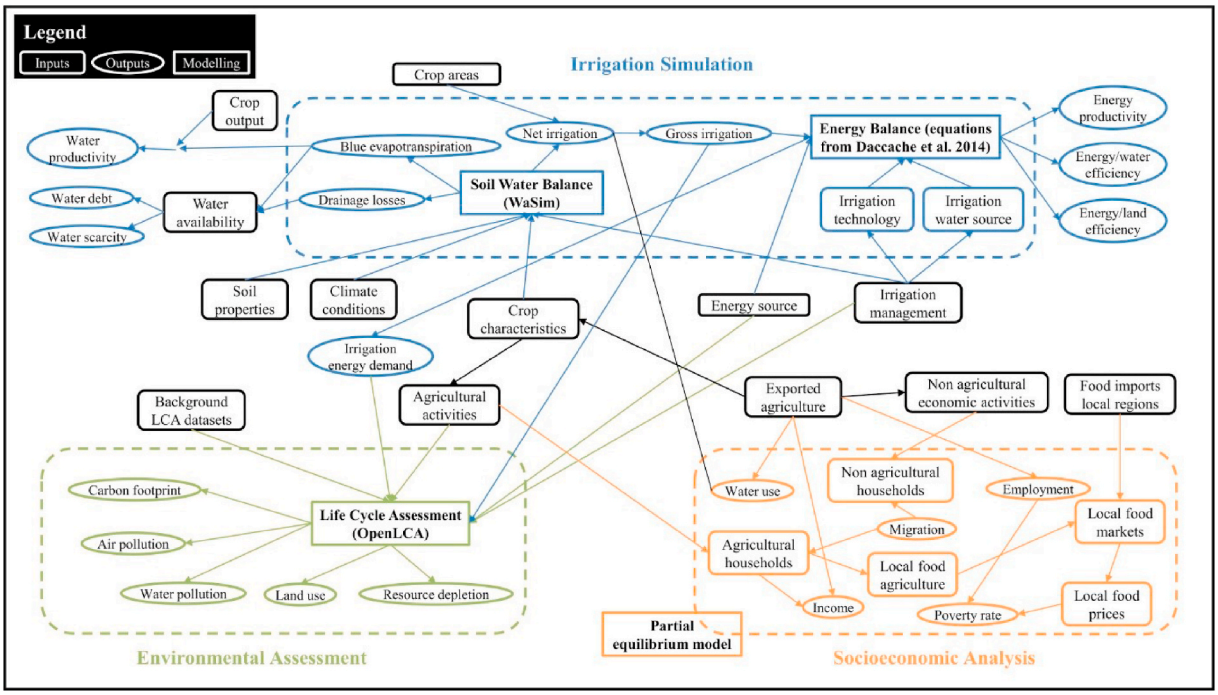

Fig. 2. Conceptual structure of the WEFE modelling toolkit to assess sustainability pathways in agricultural development.

(H_{min}) for drip irrigation systems were assumed to be 1 bar [69]. Surface irrigation methods rely on gravity. No data were available on the distance between the water sources and the fields irrigated. Therefore, all water sources were assumed to be on-farm with friction losses for distribution considered negligible.

The energy required (kWh) to pump the water needed at a desired total pressure head (*TH,* Equation (2)) was calculated using Equation (3):

$$Energy\ (kWh) = \frac{TID\ (m^3)\ \times\ TH\ (m)}{367\ \times\ pump\ efficiency\ \times\ motor\ efficiency} \quad [3]$$

The total irrigation demand (TID) was obtained from Equation (1). *Pump efficiency* was assumed to be 0.65, whereas the *motor efficiency* of electric and diesel pumps was 0.8 and 0.6, respectively [69]. Large farms were assumed to use electric pumps only, while 60% of small farms were assumed to use electric pumps and the reminder (40%) used diesel [70].

2.3.3. Indicators to assess water and energy demand in irrigation

Economic water and energy productivity indicators were derived to assess the efficiency of the irrigation demand between crops (grape and asparagus), farm types (large and small) and irrigation methods (surface and drip). Water (WP, US$/m^3) and energy (WE, US$/kWh) productivities were defined as the ratio between crop financial returns (US $) to total irrigation demand (m^3) and energy demand (kWh), respectively. Outcomes from energy and irrigation water demand per unit area were integrated with the socio-economic module results to estimate demands under future scenarios.

2.4. Socio-economic analysis module

A partial equilibrium model was developed to assess the socio-economic outcomes associated with two different scenarios of water availability and with a scenario with higher relative prices of export crops than the baseline [71,72]. Parameters of the model reflect the sensitivity of farmers' land-use decisions to changes in relative per hectare net incomes. The calibration of the model was accomplished by applying econometric estimation of these parameters using farm historical and cross sectional data of observed land use and per hectare profits. Additional control variables included in model estimation were water availability in the farmer's district, water source (surface or underground), farm scale, and district fixed effects. The assessment takes the form of comparing optimal allocations of land in one scenario in comparison with the baseline (i.e. comparative statics). The sensitivity of the variables of interest to changes in the parameters that characterize a scenario is determined by estimating a model of farmer decisions based on historical responses to observed changes in water availability and prices. The model of farmer behaviour was based on a simplified set of decision rules for allocating agricultural land to asparagus and table grapes and to a composite product of all other crops, with associated inputs (water, energy and labour employment). The estimated parameters that allow us to gage the sensitivity of farmer responses to changes in prices and water availability reflect underlying production systems and other constraints to producer decisions. The farmer decision model is based on profit maximization where farmers make land allocations based on relative profits of different activities. Farms receive a net income from sales, either to local or export markets, accounting for production costs. Product prices are, in this partial equilibrium approach, taken to be fixed, although the modelling effort can be extended to allow local product prices to be endogenously determined given a local net demand curve. Given the focus on export crops of asparagus and table grapes, the aggregate nature of "all other crops," and the openness and relatively small size of the local economy with respect to the rest of the country, the assumption of fixed product prices is considered to be reasonable. Similarly, input prices were taken to be exogenously determined, although in the short-run farm wages might be modelled in terms of the local demand and supply of labour. Input quantities were dependent on (constant) per-hectare use of inputs and the composition of hectares allocated to the three crop categories (asparagus, table grapes, 'other').

Inputs, land allocations and production outcomes were defined at the level of a geographically defined district. The decision rule for the allocation of land within the district was based on the relative per-hectare net incomes generated by the three crop categories. It was assumed that land resources were heterogeneous with respect to their productivities in the three crops; such that, given product and input prices, the most productive land for, say, asparagus, was planted to that

crop. As net income of asparagus increases relative to the other crops (e.g., in response to an increase in the price of asparagus as export demand rises), the proportion of all agricultural land devoted to asparagus also increases, marginally less productive land (for asparagus) shifting from the other crops to asparagus.

A general approach to approximating the outcomes of applying this decision rule was adopted. It was assumed that there was a fixed amount of agricultural land within the district and the shares of land allocated to the three crops summed to one. Let H_T represent the total hectares of available farmland available in the district; let H_i represent the land allocation to product i; and let S_i represent the share of land allocated to product i. Therefore, we have $S_i = H_i/H_T$, for any given district. Let the total water availability (in units of cubic metre per year) in a district, an exogenous variable, be represented by A_T. (Note that the movement of water between districts is prohibited by regulation.) The vector of prices of all products and inputs was represented by p and w (in units of dollars or soles per unit of production). The vector of expected per-hectare production of the crops is represented by y (in the appropriate units, kilograms, tons), which could be district-specific, also exogenous. Land was allocated to the three crops according to the relative per-hectare (expected) profitability of the crops, constrained by the availability of total agricultural land (fixed) and the total water (subject to change). Expected per-hectare net incomes for the three crops were constructed as the difference between the value of production and costs of inputs: $\pi_i = p_i y_i - c(y_i, w_i, X_{ic}), i = 1, 2, 3$. (All other exogenous factors that influence production costs, perhaps some product-specific, are represented by X_i.) The allocation of land for one crop depends on the net income of all competing crop activities. A simplified multinomial logistics model of the distribution of shares of land to the three products was used, given by the representation of the ratios of the land share of products #1 and #2 relative to the share of product #3, as presented in Equations (4) and (5):

$$\ln\left(\frac{S_1}{S_3}\right) = f_1\left(\frac{\pi_1}{\pi_3}, \frac{\pi_2}{\pi_3}, A_T\right) = \alpha_{10} + \alpha_{11}\ln\left(\frac{\pi_1}{\pi_3}\right) + \alpha_{12}\ln\left(\frac{\pi_2}{\pi_3}\right) + \alpha_{1A}A_T \quad [4]$$

$$\ln\left(\frac{S_2}{S_3}\right) = f_2\left(\frac{\pi_1}{\pi_3}, \frac{\pi_2}{\pi_3}, A_T\right) = \alpha_{20} + \alpha_{21}\ln\left(\frac{\pi_1}{\pi_3}\right) + \alpha_{22}\ln\left(\frac{\pi_2}{\pi_3}\right) + \alpha_{2A}A_T \quad [5]$$

The estimation of the parameters α_{ij} on the right-hand side of Equations (4) and (5) was based on panel-data regressions applied to data from 14 districts and 4 years (2015–2018). Relative shares of cropland (in logarithms) were regressed against relative crop profits levels (in logarithms) and total water availability. Crop profits levels were calculated from the difference between the sales and costs reported by the national agricultural survey. Total water availability was obtained from the irrigation module (see sections 2.3.1 and 3.1).

For each scenario simulation, a change in the cubic metres of water availability from the observed A_T to a hypothetical A_h was considered. The allocations under this hypothetical scenario were determined: S_{1h}, S_{2h} and S_{3h}. The allocation of hectares between products is given by Equations (6) and (7):

$$\ln\left(\frac{S_{1h}}{S_{3h}}\right) = f_1\left(\frac{\pi_1}{\pi_3}, \frac{\pi_2}{\pi_3}, A_h\right) = f_{1h} \quad [6]$$

$$\ln\left(\frac{S_{2h}}{S_{3h}}\right) = f_2\left(\frac{\pi_1}{\pi_3}, \frac{\pi_2}{\pi_3}, A_h\right) = f_{2h} \quad [7]$$

Note that $S_3 = \frac{1}{1+e^{f_1}+e^{f_2}}$, and therefore the projected share of land allocations is. $S_{ih} = \frac{e^{f_{ih}}}{1+e^{f_{1h}}+e^{f_{2h}}}$, for $i = 1, 2$.

For the total allocation in hectares, the total area available presented in Equations (8)–(10) was used:

$$H_{1h} = S_{1h} \cdot H_T \quad [8]$$

$$H_{2h} = S_{2h} \cdot H_T \quad [9]$$

$$H_{3h} = (1 - S_{1h} - S_{2h}) \cdot H_T \quad [10]$$

For the total cubic metres of water use by crop, the unit area water use multiplied by the total area was used: $A_{ih} = a_i \cdot S_{ih} \cdot H_T$, $i = 1, 2$ and $A_{3h} = a_3 \cdot (1 - S_{1h} - S_{2h}) \cdot H_T$. The unit area water uses, a_i, is a result of the irrigation simulation module; examples for asparagus and grapes are presented in Table 1, in the results section. Changes in the unit area use of labour and other inputs were derived similarly.

Data on energy use were also obtained from the results of the irrigation simulation module (Section 2.3). Agricultural production, farm characteristics, prices and labour use for asparagus and table grapes were gathered from the National Agricultural Survey [60]. The assumed land allocation in 2017 and net income serve as the baseline scenario from which one can compare the simulated results for each hypothetical scenario reflecting a change in water availability and profitability of export crops.

2.5. Environmental assessment module

The environmental assessment module is an LCA model built using the open-source software OpenLCA version 1.10.2 (www.openlca.org). Here, the details of the case study were described following the International Organization for Standardization guidelines [73,74]. Three of the four main stages in the LCA, i.e., goal and scope definition, compilation of the Life Cycle Inventory and Life Cycle Impact Assessment are presented here whilst the final stage (interpretation) is presented in the Results section.

2.5.1. Goal and scope definition

The goal of this LCA was to assess the environmental impacts incurred by the production of asparagus and table grapes in the Ica Valley. Given the emergency situation of water depletion in this hyper arid zone, it also aimed to explore potential trade-offs between greenhouse gas emissions and water use. The system boundary of the analysis was from the field to farm gate, covering all activities from field preparation to harvest without considering transport to consumers (Figure S1 supplementary materials). The two functional units used in this analysis were 1 kg and 1 US$ worth of produce at the farm gate in order to facilitate comparisons with other studies as well as between crops. The LCA results were then combined with the outputs from the socio-economic module to estimate total environmental impacts from asparagus and grapes under selected future scenarios.

2.5.2. Life Cycle Inventory

Farm scale, irrigation method, water source and energy source were key features defining crop production. Therefore, two farm scales (small and large) and 7 irrigation-energy combinations based on reported agricultural practices in Ica were considered. In total, there were 20 different farming systems, 9 for asparagus and 11 for grapes (Table S2). Data on farm scale, total production, yield, cropped areas, total value of produce and farm expenditures were obtained from agricultural survey [60]. Asparagus and grapes are perennial crops, and their environmental impacts change with the maturity of the cultivar [75]. Therefore, weighted averages over four years (2015–2018) for the variables

Table 1
Water (m^3/ha) and energy demand (kWh/ha) per unit area, and energy-water ratio (kWh/m^3), distinguishing irrigation method (surface, drip) and water source (sw: surface water, gw: groundwater).

		Water (m^3/ha)	Energy (kWh/ha)		kWh/m^3	
			sw	gw	sw	gw
asparagus	surface	23,972	0	7,293	0.00	0.30
	drip	16,444	943	6,722	0.06	0.41
grapes	surface	14,533	0	4,584	0.00	0.32
	drip	10,067	566	3,867	0.06	0.38

relevant to each farming system were used.

Foreground inventory data for each farming system were compiled using different methods and data sources depending on data availability while the background datasets were from the Ecoinvent v3.6 LCI database [76]. There is an existing Ecoinvent dataset for white asparagus production in Peru. Therefore, this dataset was modified to create the life cycle inventories for the nine asparagus farming systems. Inputs such as diesel consumption by agricultural machinery, fertiliser inputs and crop protection agents (including pesticides, insecticides, herbicides and fungicides) were differentiated between small and large farms. This was based on the ratios of expenditure on these inputs per unit of asparagus produced for each farm scale, assuming these ratios reflected physical quantities consumed. The amount of irrigation used was differentiated by farm scale and irrigation method (Section 2.3.1) while the type and amount of energy used was differentiated by application method, water source and pumping type (Section 2.3.2).

As there was no Ecoinvent dataset for table grapes production in Peru, the global generic dataset for grapes production available in Ecoinvent was modified to create life cycle inventories for the 11 farming systems. Inputs such as diesel consumption by agricultural machinery, fertilisers and protection agents for small farms were derived from Ref. [77]. Inputs for large farms were calculated based on the ratios of expenditure on these inputs per unit of grapes produced for small and large farms. Key inventory data for all 20 farming systems are summarised in the supplementary material (Tables S3a-c).

2.5.3. Life Cycle Impact Assessment

The widely applied ReCiPe 2016 midpoint v1.11 method [78] was used for the impact assessment. This is an updated version of ReCiPe 2008 [79], providing characterisation factors that are representative at a global scale. It also provides characterisation factors at a country level for several impact categories, including terrestrial acidification and freshwater eutrophication. Table S4 shows the environmental categories considered in this analysis. The LCA results, i.e., environmental impacts per unit of crop produced, were then combined with information from the socio-economic analysis (Section 2.4) for each farming system to estimate the total life cycle environmental impacts for each crop type under current and future scenarios.

2.6. Modelling scenarios

Three scenarios were simulated, (1) a 20% decrease in surface water availability, (2) a 20% decrease in groundwater availability, and (3) a 20% rise in profits associated with export crops, asparagus and table grapes. Scenarios 1 and 2 were considered in order to evaluate the effects of restrictions in water availability for irrigation due to projected hydrological changes [80]. The focuses were on the implication of these changes for the allocation of land to the three crops and if there is a differential effect according to water sources. Scenario 3 examines the effect of increasing the profitability of asparagus and table grapes relative to other crops, simulating an agro-export expansion and leading to a change in the proportion of agricultural land allocated to different crops. These three scenarios also have implications for overall farm profitability and agricultural labour demand.

3. Results

3.1. Baseline irrigation and energy demands

Irrigation water and energy demand are not evenly distributed in Ica due to different crop mixes on different types of farms. Asparagus and grapes accounted for an irrigation water demand of 205 and 124 Mm^3, respectively, with large farms representing 76% of the total (Fig. 3a) and groundwater representing 92% of the total (Fig. 4). In terms of spatial distribution, nearly half (47%) of the irrigation demand was in zone 8, followed by zone 1 (30%). Two thirds (66%) of asparagus irrigation

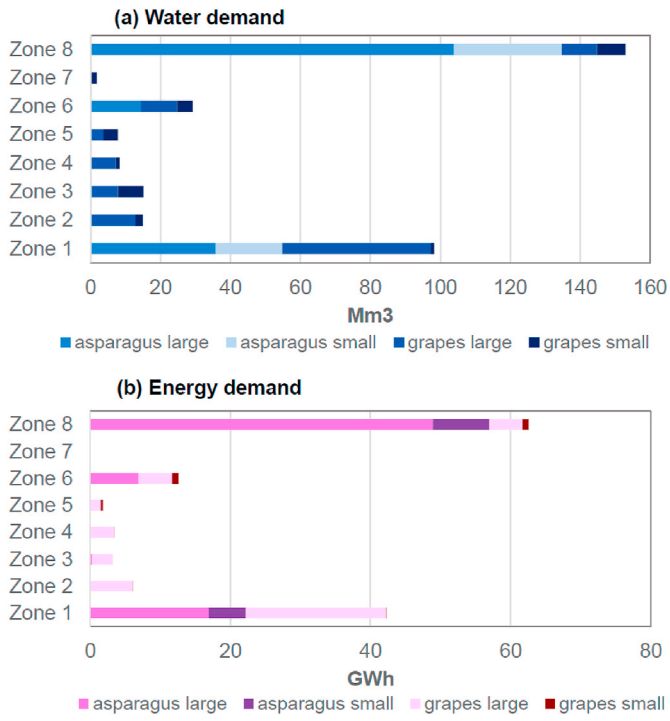

Fig. 3. Summary modelled outputs for each zone in Ica showing (a) total irrigation demand (Mm^3), and (b) irrigation energy demand (GWh) by zone, crop and farm scale.

demand was in zone 8, whereas grapes were mainly grown in zone 1 (35%). Energy demand for irrigation was 132 GWh (65% for asparagus), with a similar spatial distribution as water needs (47% and 32% of total energy demand in zones 8 and 1, respectively). Influence of farm scale was also evident. Small farms accounted for a smaller proportion of total energy demand per zone, particularly in the case of asparagus in zones 1 and 8, and there was no significant energy demand from small grapes farms in any of the zones (Fig. 3b).

The differences in the patterns of water and energy demand by farm scale can be explained by different crop technologies, irrigation methods and water sources (Table 1). Asparagus produced using surface irrigation had the largest water demand per unit area (~24,000 m^3/ha) and the greatest energy requirements when groundwater was used (~7300 kWh/ha). Drip irrigation from groundwater represented the largest energy need per unit of water applied (0.4 kWh/m^3). There was no energy consumption for surface irrigation using surface water, as these systems are gravtiy fed. The efficiency of the water and energy use can also be represented in economic terms using water and energy productivity ratios (Fig. 4).

In general, water and energy productivities were higher for drip irrigated crops compared to those using surface irrigation. This is expected given the much higher degree of irrigation control with drip which allows small and frequent watering, with much better targeting of irrigation to the crop, compared to surface irrigation where application depths are much greater and less frequent, often leading to deep percolation losses (drainage) or excess runoff. However, there were also differences between farm scales. Water productivity was highest for small farms using surface water to drip irrigate asparagus and large farms using groundwater to drip irrigate grapes. Possible reasons for this include greater reliability of groundwater supplies compared to surface water and/or improved irrigation management (scheduling) practices being used for grapes due to its much longer cultivation history in the region than asparagus. For energy productivity, similar differences were evident though grapes produced on large farms using surface water was more efficient due to the lower operation energy requirements.

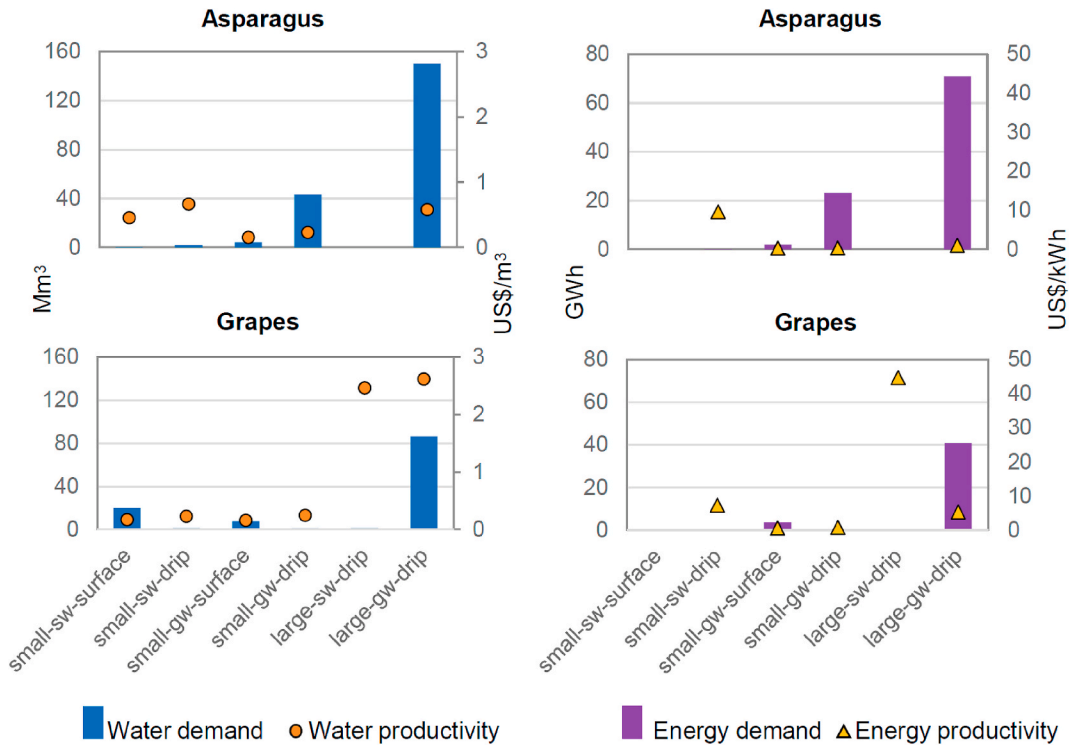

Fig. 4. Water (Mm^3) and energy (GWh) demands and related economic productivities ($US/$m^3$, $US/kWh) for asparagus and grapes differentiating farm scale (small, large), water source (sw: surface water, gw: groundwater) and irrigation method (surface, drip). Only the six farming systems shared between both crops are represented here to allow comparison between them.

3.2. Socio-economic baseline

Table 2 presents the information for the baseline scenario, to which simulated scenarios are compared. The total area cultivated was 43,652 ha, most of which was owned by large farmers who mostly used drip irrigation. The data also showed that small farmers use more surface irrigation than large farmers. Total agricultural labour occupied was 46,209 working-days, with the majority (40,690) on large farms.

3.3. Baseline environmental assessment

Here, the results for two key environmental impact categories – Global Warming Potential (GWP) and Water Consumption – per functional unit for each farming system (Figs. 5 and 6) under current conditions are presented. The detailed LCA results for the 20 farming systems (absolute values) are presented in Table S5 in the supplementary materials.

3.3.1. Global warming potential per functional unit

GWP per unit of product varied significantly across the farming systems and crops in Ica (Fig. 5a), ranging from 0.12 (asparagus produced by small farms using surface irrigation and surface water) to 1.42 kg CO_2-eq/kg of product (grapes produced by large farms using drip irrigation, groundwater and electric pumps). The variations for asparagus appeared to be primarily caused by differences in water source, with use of groundwater leading to significantly higher GWP compared with surface water. Farm scale also has a noticeable effect, with large farms having higher GWP than small farms when all other factors are identical. The variations for grapes appeared to be primarily caused by farm scale, with large farms having GWP 3–5 times bigger than that of small farms. Source of irrigation water contributed modestly to the variations, with groundwater having higher GWP than surface water. When all other factors are identical, GWP is higher when drip irrigation is used compared with surface irrigation and when diesel pumps are used compared with electric pumps.

In order to compare the two crops directly, GWP per US$ worth of product is shown in Fig. 5b. As asparagus had higher average prices (1.18 US$/kg for small farms and 1.38 US$/kg for large farms) than grapes (0.46 US$/kg for small farms and 1.25 US$/kg for large farms), GWP per US$ worth of product was higher for grapes than asparagus and large farms than small farms when all other factors were the same.

Contributions from different processes to the life cycle total impacts (Fig. 6) reveal the reasons for the differences in GWP results across the farming systems. For asparagus, the high GWP when groundwater was used for irrigation was primarily because of energy used for pumping (Fig. 6a). For grapes, the high GWP for large farms was primarily because of agricultural machinery use (Fig. 6b). The reason for drip irrigation having higher GWP than surface irrigation despite having less energy use appeared to be due to the manufacturing and waste treatment of the drip irrigation pipes.

Table 2
Cultivated land by crop (ha), distinguishing irrigation method (surface, drip) and farm scale (large, small), 2017 baseline.

		Hectares		
		large	small	Total
asparagus	surface	0	1,136	1,136
	drip	9,326	1,807	11,133
grapes	surface	16	2,104	2,120
	drip	9,126	32	9,158
other crops	surface	355	10,000	10,355
	drip	9,732	17	9,749
Total		28,555	15,096	43,651

3.3.2. Water consumption per functional unit

When all other factors were identical, water consumption per unit of product was consistently higher for asparagus than for grapes, higher for large farms than for small farms, higher for groundwater than for surface

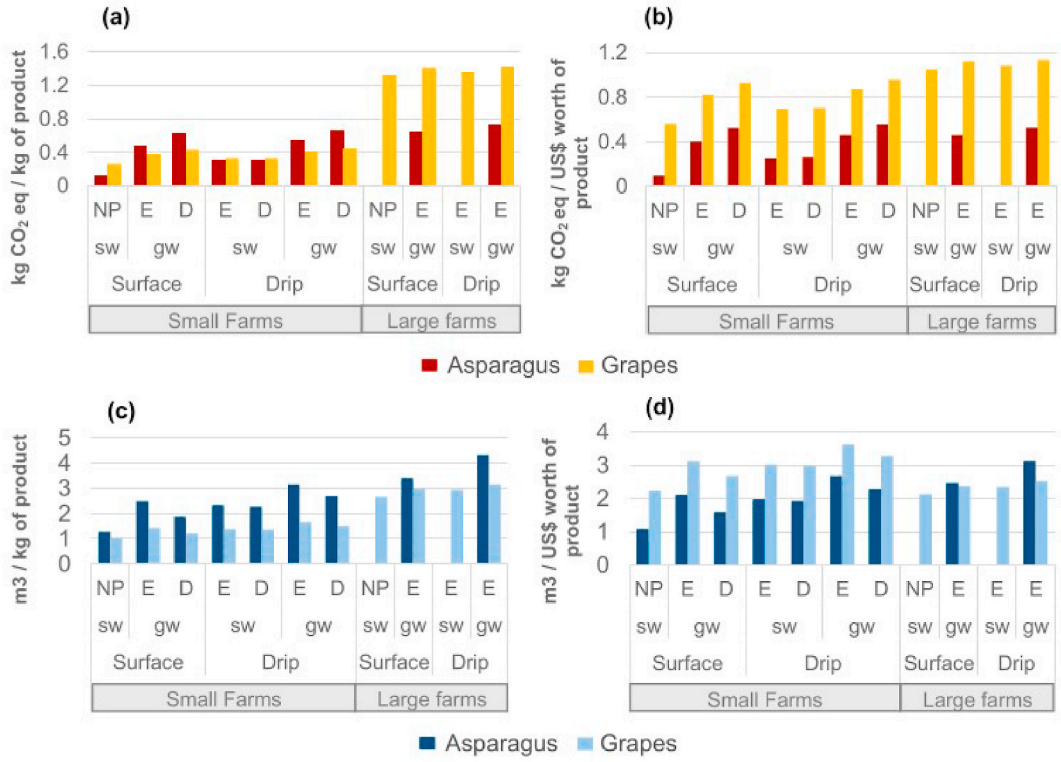

Fig. 5. Selected environmental impacts from asparagus and grapes production: (a) GWP per kg of product, (b) GWP per US$ worth of product, (c) water consumption potential per kg of product, and (d) water consumption potential per US$ worth of product. NP = no pump, D = diesel pump, E = electric pump, sw = surface water, gw = groundwater, Surface = surface irrigation, drip = drip irrigation.

water, and higher for electric pumps than for diesel pumps (Fig. 5c). Large farms growing asparagus using drip irrigation, groundwater, and electric pumps has the highest impact (4.32 m^3/kg) whilst small farms growing grapes using surface irrigation, groundwater, and diesel pumps had the lowest impact (1.22 m^3/kg). Measured per US$ worth of product, water consumption was higher for grapes than for asparagus when produced by small farms (Fig. 5d).

Water consumption for asparagus was dominated by irrigation water use, followed by water pumping and/or drip irrigation infrastructure when groundwater and/or drip irrigation are adopted (Fig. 6c). Irrigation water use and agrochemicals account for the majority of water consumption for grapes produced by small farms while agricultural machinery use is the most significant contributor to water consumption for grapes produced by large farms (Fig. 6d), which was mainly due to embodied water consumption in the manufacture of agricultural machinery such as trailer and tractor with the most significant upstream process being hydropower generation.

3.4. Future scenarios

3.4.1. Socio-economic analysis

This section presents the effects of water availability and profitability on land allocation (between asparagus, table grapes and other crops), income generation and labour demand, under the three different future scenarios. Water availability and profitability are key factors for producers' decisions, in particular for land allocation, and are also crucial to assess the potential impacts of economic growth and climate-related changes on household welfare in Ica.

3.4.1.1. Land allocation. Changes in land allocation under the three scenarios are not uniform across Ica, and variations are associated with farm scale, water source, and crop distribution. Under Scenario 1 (20% decrease in surface water availability), no significant changes were observed in for land allocated to asparagus whereas grape areas in zones 3 (High valley: large-scale) and 6 (Middle valley: large-scale) declined by 10.8% and 24.2%, respectively. This suggests that grapes were more sensitive to surface water shortages, probably because this was the main source of water for small farms in Ica. Under Scenario 2 (20% reduction in groundwater), there were imperceptible changes in asparagus areas whereas the grape areas in zones 3 and 6 decreased by 9.6% and 23.5%, respectively, similar to Scenario 1.

Finally, land allocated to both asparagus and grapes saw significant changes under Scenario 3 (20% increase in profitability of asparagus and grapes versus other crops). An unexpected result here was that producers expanded the area of asparagus but decreased the area of grapes. This can be explained by the relative economic advantage (and greater flexibility) of converting land for other crops or unused land to production of asparagus in comparison with grapes, particularly given asparagus requires lower upfront capital expenditure whereas grape plantations entail land preparation, trellising, delayed production and other capital expenditures that require at least 3 years to recover.

Also, a 20% increase in profitability does not necessarily translate into equal increases in absolute profitability. As profitability of both asparagus and grapes increases, there will be a tendency to scale up production of both crops even though they will compete with each other for land. The estimated parameters of the model are effectively showing that the returns to scale for asparagus decrease at a slower rate than those for grapes, either due to its adaptability to marginal lands, more extensive use of drip irrigation by small farmers (see Table 2), or other differences in the intensity of input use.

There were some spatial variations in these patterns. Simulations indicated that cropped areas increased by 64.7% for asparagus and 61.1% for grapes in zone 1 (Villacuri: large-scale), whereas in zones 3 and 8 (Low valley: large-scale) asparagus areas increased by 4.1% and 8.5% and grapes areas decreased by 38.3% and 26.6%, respectively. In zone 7 where there was no asparagus in the baseline scenario, grape

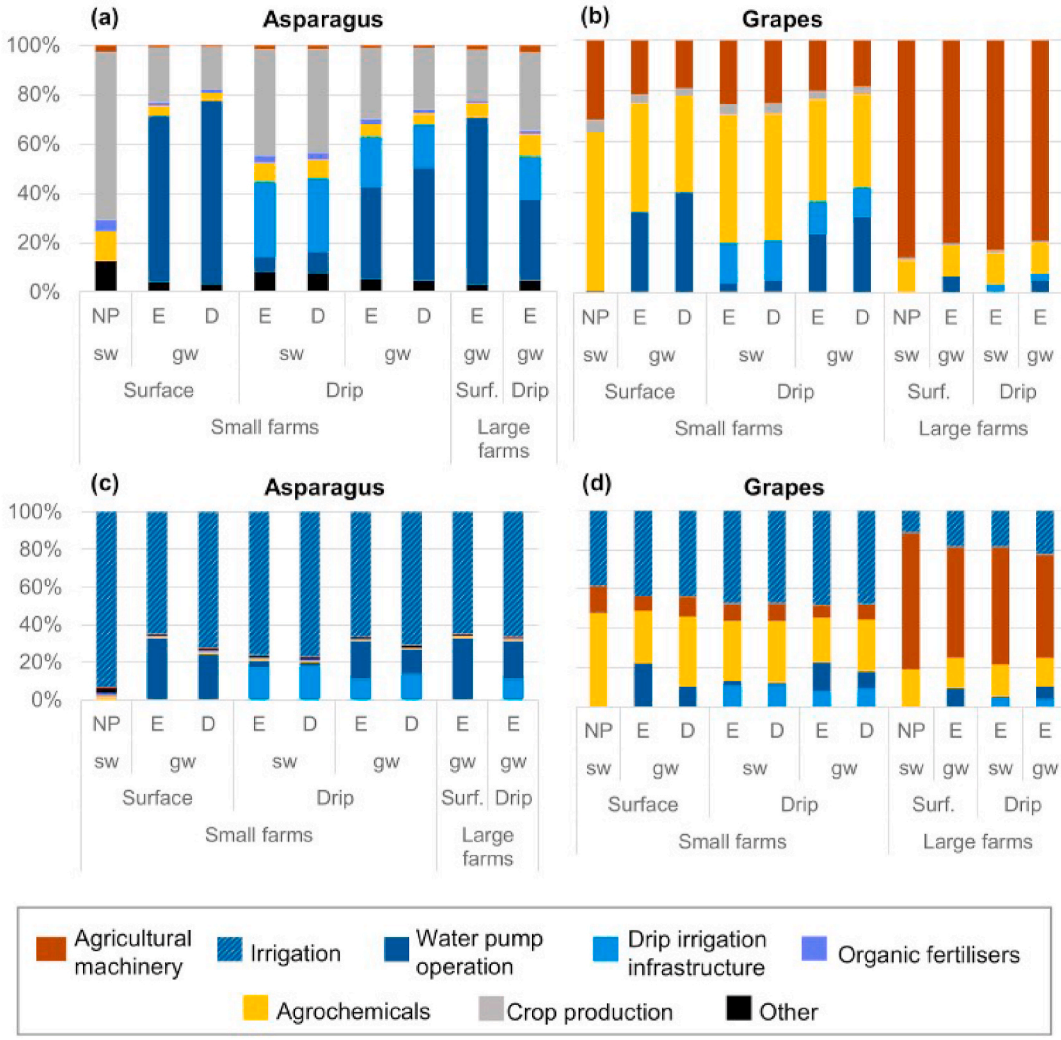

Fig. 6. Contributions from different processes to the life cycle total impacts for (a) GWP of asparagus; (b) GWP of grapes; (c) Water consumption of asparagus; and (d) Water consumption of grapes. NP = no pump, D = diesel pump, E = electric pump, sw = surface water, gw = groundwater, Surface/Surf. = surface irrigation, Drip = drip irrigation. "Crop production" include predominantly N_2O emissions. "Other" includes packaging for fertilisers and pesticides for all four figures, and seedlings, and horticultural fleece for asparagus.

areas decreased by 83.1% as producers switched to other crops (Fig. 7).

There was substitution between the three crops (grapes, asparagus and others) due to changes in the opportunity cost of water, i.e., as water availability changes, relative net benefits of allocating water to different uses also changes. As the opportunity cost of water from the two different sources changed, there were changes in the use of inputs and a transition to activities with a more efficient use of resources. These changes in land allocation would occur in the medium-to long-term as each crop would have different investment horizons from plantation to maturity of crop to harvest. For example, grapes require at least a few seasons to become fully productive, while horticultural crops start producing positive net incomes at a much earlier stage.

3.4.1.2. Crop profits. Fig. 8 presents the changes in total profits from all crops for the three scenarios over the baseline. The decrease in surface water (Scenario 1) resulted in low to medium decreases in total profits in all geographical zones. The results are similar when groundwater decreases (Scenario 2) except for the low Valley (zones 7 and 8) which showed slight increases (<1%) in profits as resources shift to other crops in this area in response to lower profits of grapes and asparagus elsewhere. Under Scenario 3, only the zone with the highest increase in asparagus and grapes cropped area (zone 1) showed a low increase in profits, due to substitution between crops.

3.4.1.3. Labour. Labour demand varied with changes in the crop mix and irrigation methods. Changes in labour demand were similar under Scenarios 1 and 2, where decreases in zones 1 to 6 and slight increases (<1%) in zones 7 and 8 were observed (Fig. 9). These increases are due to substitution between crops, but the magnitude is insignificant. Therefore, a key impact of reduced water availability was the loss of income and employment on farms and communities. Under Scenario 3, there was a small increase in labour demand in three zones that expanded asparagus and grape areas (1, 3 and 6), while the other zones experienced a slight decrease.

Changes in profits and labour for the entire Ica Valley by crop, farm scale and irrigation method are presented in Table 3. Due to shifts in land allocation between crops and between irrigation methods, total profits and labour use for grapes declined across the three scenarios, except under drip irrigation in Scenario 3 due to the higher profitability of exports.

3.4.2. Irrigation and energy demand

Changes in irrigation and energy demand under the different scenarios are due to variations in land allocation. There was no change in

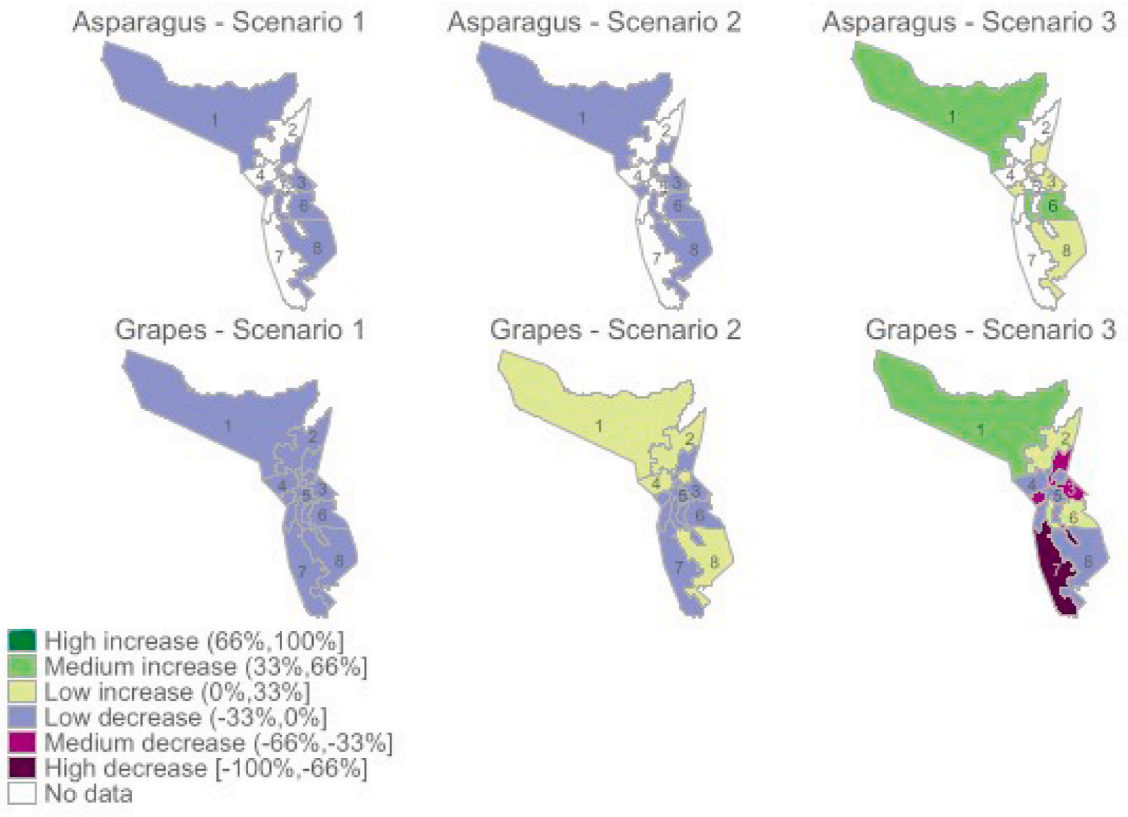

Fig. 7. Changes in cropped areas for asparagus and grapes by zones in Scenarios 1, 2 and 3 compared with the baseline (%).

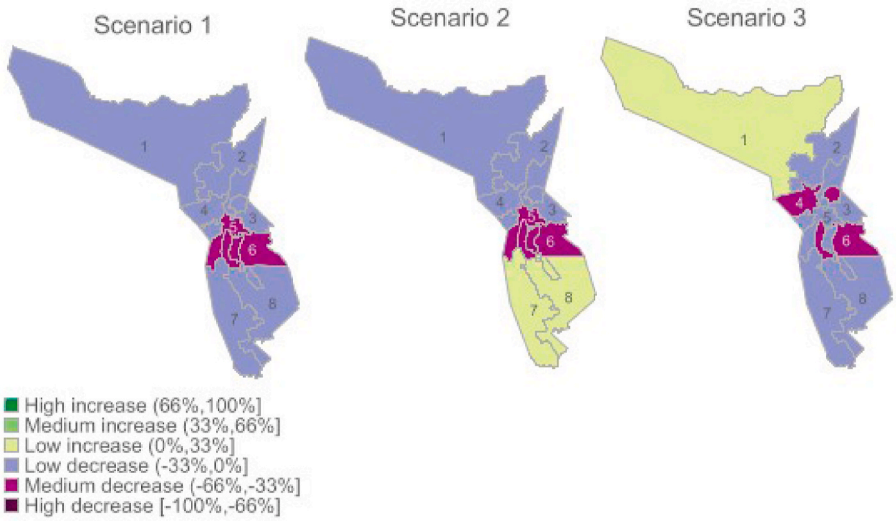

Fig. 8. Changes in profits under future scenarios (%).

asparagus irrigation demand from small farms under Scenarios 1 and 2, and only a slight decrease in demand from large farms (−1.7%) under Scenario 2. The main change in irrigation demand was caused by a decrease in grapes irrigation demand from small farms where a reduction of 16.4% and 15.1% occurred under Scenarios 1 and 2, respectively (Fig. 10a). Under Scenario 3, there was an increase in water demand for both asparagus and grapes by large farms and for asparagus by small farms, where a considerable decrease (81%) in grape production was also experienced. Grapes energy demand (Fig. 10b) showed a 41% decrease for small farms and a small decrease (~1%) for large farms under Scenarios 1 and 2. Under Scenario 3, energy demand for grapes by small farms dropped by 86% but increased by 40% for asparagus whereas demand by large farms increased for both crops. Figure S2 shows outcomes by zone, crop and farm scale.

3.4.3. *Total environmental impacts*

Total life cycle GWP and water consumption were higher for grapes than for asparagus under the three scenarios (Fig. 11). In the baseline scenario, GWP is 52.2 kt CO_2-eq for asparagus and 284.9 kt CO_2-eq for grapes while water consumption is 307.7 Mm^3 for asparagus and 652.5 Mm^3 for grapes, all dominated by large farms (87% for asparagus and 97% for grapes). Under Scenarios 1 and 2, reductions in GWP and water

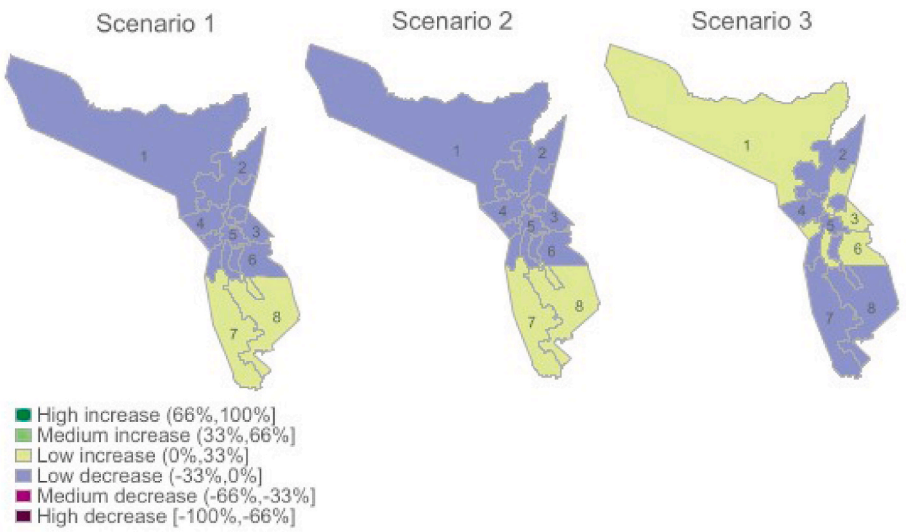

Fig. 9. Simulated changes in labour (%) for each future scenario.

Table 3
Changes in profits and labour relative to the baseline scenario by crop type, farm scale, and irrigation method (%).

Farm scale		Profits					
		Scenario 1		Scenario 2		Scenario 3	
		large	small	large	small	large	small
asparagus	surface		0%		−2%		12%
	drip	0%	0%	−1%	0%	29%	48%
grapes	surface	−51%	−21%	−49%	−21%	−90%	−82%
	drip	−9%	−20%	−9%	−19%	7%	28%
Farm scale		**Labour**					
		Scenario 1		Scenario 2		Scenario 3	
		large	small	large	small	large	small
asparagus	surface		0%		−2%		12%
	drip	0%	0%	−1%	0%	13%	46%
grapes	surface	−50%	−17%	−48%	−17%	−90%	−83%
	drip	0%	−14%	0%	−13%	13%	41%

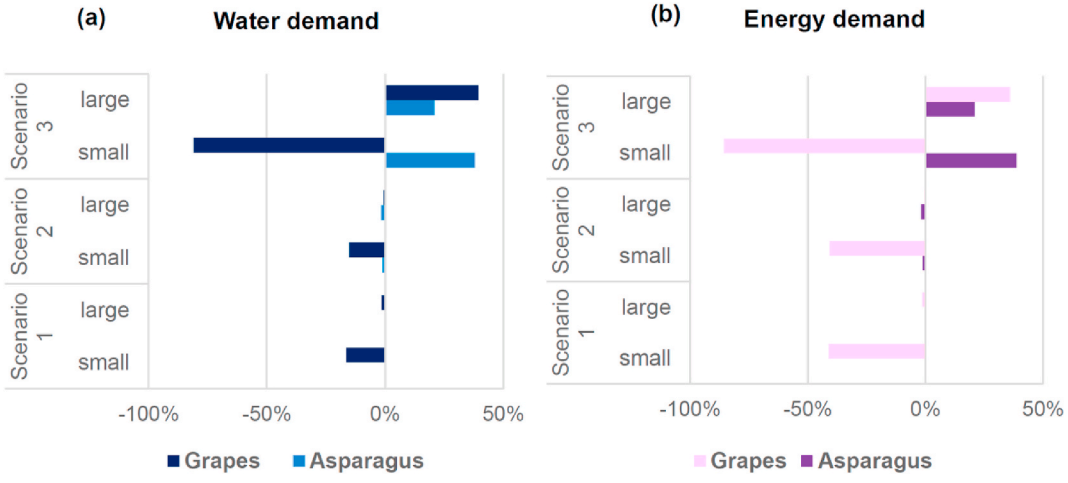

Fig. 10. Percentage change in (a) total irrigation demand and (b) total energy demand for each scenario. Outcomes are presented by farm scale and by crop type. Baseline scenario has been set to zero.

consumption relative to baseline are insignificant (<1%) for asparagus and small (1–4%) for grapes. Scenario 3 results in noticeable increases in GWP and water consumption relative to baseline for both asparagus (24%) and grapes (28–32%). Figures S3 and S4 show total and geographical distribution of GWP and water consumption per zone, crop and farm scale.

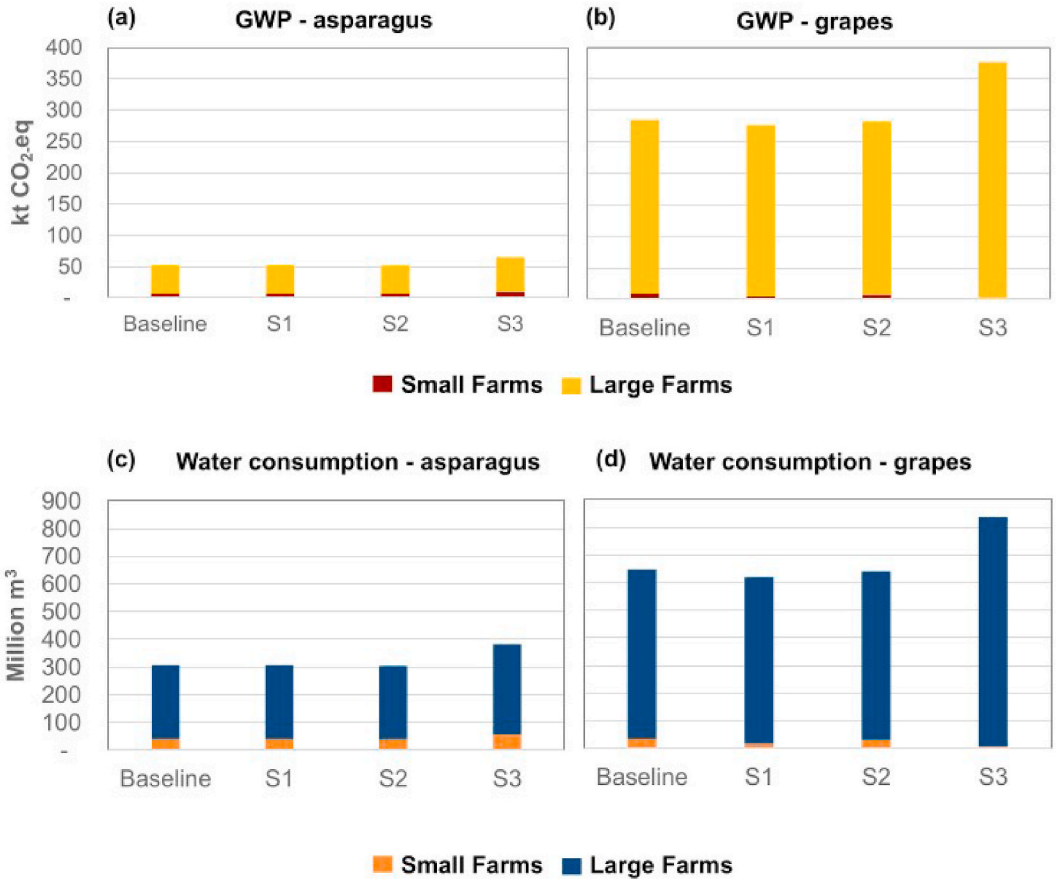

Fig. 11. Total global warming potential (a) and (b), and water consumption potential (c and d) for asparagus and grapes produced in Ica in the baseline and future scenarios (S1–S3).

4. Discussion

4.1. Insights from the integrated modelling

While potentially bringing socioeconomic benefits, agricultural exports are increasing pressure on existing environmental resources (water, land) and their current patterns of inter- and intra-sectoral distribution. Food production in arid and hyper-arid environments carries additional pressures, particularly but not limited to water resources, opening an opportunity for a nexus approach to aid decision making. The modelling toolkit developed here has proved effective in overcoming some key limitations in existing modelling tools by adopting a transdisciplinary and integrated approach to assessing water resource, social, economic and environmental outcomes of the nexus.

The Ica case study shows that current annual irrigation water demand from the production of two key crops asparagus and grapes amounts to 329 Mm^3, which is ~68% of total irrigation water demand in Ica (483 Mm^3 [63]). If groundwater and/or surface water resources in Ica decrease in the future (i.e., scenarios 1 & 2), there would be a reduction in grapes production (Fig. 7) and associated income and jobs, especially for small farmers (Table 3). This is also reflected in a reduction in irrigation water demand and associated energy demand by small grape farms (Fig. 10). This is not surprising given the low water productivities of small grape farms (Fig. 4). However, these reductions in grapes production by small farms would not bring noticeable reductions in life cycle GWP and water consumption, mainly because of the small farms' low contributions to the total impacts (Fig. 11) and lower impacts per unit of product compared with large farms (Fig. 5).

If prices of asparagus and grapes on the international market increase relative to other crops (i.e., scenario 3), there would be an increase in asparagus production and a decrease in grape production, reflecting a substitution effect between the two. These changes translate into an increase in profits and jobs for both small and large asparagus farmers and large grapes farmers but a significant reduction for small grapes farmers. Although the region as a whole benefit from the increased farm income and jobs, there would be significant increases in irrigation water demand and associated energy demand as well as life cycle GWP and water consumption. Groundwater currently accounts for 92% of the irrigation water use by asparagus and grapes (Fig. 4). An increase in the use of groundwater could lead to unfavourable hydrological conditions of the Ica aquifer (total storage capacity 1861 Mm^3 [63]) within several years. The increase in GWP is also in conflict with the global efforts to mitigate climate change. This presents a potentially difficult trade-off between the socioeconomic benefits and environmental costs.

Moreover, there are other WEFE trade-offs. For example, agriculture and fishing is currently the sector with the lowest energy consumption in Peru, accounting for 2.6 TWh or 1.1% of the total energy consumption in 2018 compared with 43.2%, 29% and 27% for transport, industrial and mining, and residential, respectively [81]. The model results suggest that total current energy demand from irrigation for asparagus and grapes in Ica is currently 132 GWh (or 5% of the total energy consumption in agriculture and fishing). However, there could be an estimated increase of 57% if a 20% rise in profitability associated with exports crops occur in the future (scenario 3), especially from large farms which depend on electricity for water extraction. This means that agriculture, especially irrigation, could noticeably increase energy demand and potentially compete with other sectors for energy. On the other hand, agriculture accounted for 52% of the total water consumption in Peru in 1992, followed by hydropower generation (37%). But in 2016 the National Water Authority reported that water used for

agriculture and energy increased by 28.4% and 62.7%, respectively during 1992 and 2016 [82,83]. A significant increase in irrigated agriculture could therefore not only directly increase water consumption through irrigation but also indirectly through the associated power consumption and embodied water in farming equipment.

The overall results from the Ica case study suggest that unless a paradigm shift happens, the long-term viability of agriculture in Ica is threatened. Apart from irrigation water use, energy demand and environmental impacts from agriculture should be accounted for to promote an integrated approach to decision-making. Trade-offs between different crops, type of farming, water sources and irrigation practices, all of which are key dimensions in the modelling, can help better inform the solutions to multiple challenges with a nexus approach.

4.2. Implications for decision-making

The toolkit can provide insights into biophysical, socioeconomic and environmental aspects of agricultural development and the impacts of future changes in agro-economic and socio-economic policy on agricultural transformation, which are useful for different stakeholders. It therefore offers significant potential for widespread application across a range of sectors and end-users including government agencies, farmers, agricultural development banks, NGOs, environmental organisations, and the research community. For instance, in Peru this type of multidisciplinary modelling is attractive for stakeholders both at local and national level. In Ica, local actors are showing increasing concerns about the sustainability of the so called "agro-export boom" in terms of water, social cohesion and the environment. Of particular interest are the trade-offs between accelerated export growth (based on exogenous international demand) and endogenous water depletion, increasing social inequalities and environmental degradation.

The integrated modelling in the Ica case study can help policy makers and local actors in Ica and Peru to unpack the complex interactions at regional and local scales between natural resources, economic systems, and the social consequences of WEFE policies and practices. The irrigation water and energy demand calculated by the irrigation simulation module can help farmers to estimate costs of production, and energy producers to assess demand and potential impacts on hydropower generation. The socio-economic results are useful for policy makers to estimate the effects of agricultural expansion of the main crops of the Ica Valley in terms of production mix, land use, profitability, rural employment and difference between small and large farmers considering the limited water resources available. The LCA results allow all stakeholders to understand the environmental implications of different farming systems as well as agricultural development in Ica under different water resources and economic scenarios.

Therefore, the toolkit can bring different stakeholders together to explore synergies and trade-offs among more local and short to medium term impacts such as socioeconomics and water availability and more global or regional and medium to long term impacts such as climate change in order to build consensus on future pathways. There is also scope for the toolkit to inform initiatives to implement integrated water resources management through multi-sector collaboration, particularly for sectors (including environment, urban development, agriculture, power generation) that may need to identify shared investment options for natural resources to build resilience to future climate and water-related risks.

4.3. Limitations and recommendations for future development

Access to data is a key limitation for our toolkit because the availability and quality of data will affect model outputs, especially at a local scale. For example, the estimation of irrigation water needs in our irrigation simulation module requires data on crop development parameters, soil textural characteristics, daily rainfall and reference evapotranspiration, some of which might not be available for other regions or crops in future studies. The economic modelling requires data on crop area, input use, production costs, yields, and product and input prices. To calibrate the partial equilibrium model parameters several years of spatially disaggregated data are needed. In terms of environmental impacts, our toolkit needs existing data in LCI databases on biophysical inputs and outputs for crop production, which may not always be available for some regions or crops. To overcome this limitation, a stronger collaboration between researchers and policy makers and other stakeholders should be developed, so that data sharing and analysis become a strength. Potential for employing other models and tools with less data requirements should also be explored. Another key limitation is the complexity of the results from our toolkit. Care should be taken to synthesize the results and to communicate the key findings to relevant stakeholders in accessible ways.

5. Conclusions

An integrated WEFE nexus modelling toolkit that covers the biophysical and socioeconomic aspects of agricultural expansion, combining different modelling approaches such as irrigation modelling (WaSim), economic modelling (partial equilibrium) and environmental assessment (LCA) was developed. The modules are soft-linked, therefore overcoming barriers to integration between nexus elements in other tools. In particular, its capability in analysing future scenarios under different socioeconomic drivers can better inform decision-making and policy development. An application on two major agro-export crops (asparagus and table grapes) in the Ica Valley, Peru showed that the toolkit was able to provide detailed insights into the implications of different farming systems on resource efficiency at the field level related to water (e.g., water productivity) and energy (e.g., energy productivity), and different future scenarios on socioeconomic outcomes at the local to regional level (e.g., food prices, employment, and income) and environmental impacts at the local (e.g., pollution of air and water) to global level (contribution to climate change). The overall results from the Ica case study suggest that unless a paradigm shift happens, the long-term viability of agriculture in Ica is threatened. This information will enable policy makers and different stakeholders better understand the interlinkages and inter-dependences between the WEFE nexus elements and the complex impacts of agricultural expansion beyond the immediate sector and geographic area of concern, helping them to design more coordinated agricultural policies and adopt more sustainable farming practices.

Credit author statement

Correa-Cano, M.E.: Methodology, Formal analysis, Investigation, Writing – original draft, Salmoral, G.: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, **Rey, D.:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition, **Knox, J.W.:** Resources, Writing – review & editing, **Graves, A.:** Resources, Writing – review & editing, **Melo, O.:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition, **Foster, W.**: Methodology, Formal analysis, Writing – review & editing, **Naranjo, L.:** Methodology, Formal analysis, Investigation, Writing – original draft, **Zegarra, E.:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition, **Johnson, C.:** Resources, Formal analysis, **Viteri-Salazar, O.:** Writing – review & editing, Funding acquisition, **Yan, X.:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Funding acquisition.

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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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.rser.2022.112182.

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A novel modelling toolkit for unpacking the Water-Energy-Food-Environment (WEFE) nexus of agricultural development

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