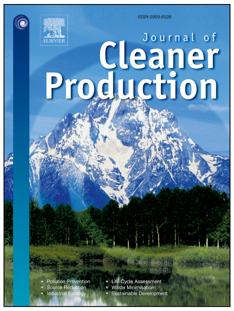

A scenario-specific nexus modelling toolkit to identify trade-offs in the promotion of sustainable irrigated agriculture in Ecuador, a Belt and Road country

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A scenario-specific nexus modelling toolkit to identify trade-offs in the promotion of sustainable irrigated agriculture in Ecuador, a Belt and Road country

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Abstract

Increased demand for food due to development and population growth has prompted irrigated agriculture expansion, posing enhanced global challenges to water, energy, and food security. To confront these challenges, an approach that considers the water-energy-food-environment nexus can address multidimensional trade-offs that complicate the efficient use of resources and the achievement of Sustainable Development Goals. In order to provide insights into solutions to these challenges for a specific case, this study develops a modelling toolkit that integrates biophysical and socioeconomic aspects of nexus components in the context of agro-export and irrigation expansion in Ecuador, a Belt and Road Country. The nexus toolkit is applied to agricultural-development scenarios defined in participatory workshops and incorporates a water resources model, a lifecycle environmental assessment, and a socioeconomic analysis. The modelling exercise is constructed around specific scenario-determined land use patterns in the Santa Elena peninsula of Ecuador. Agriculture in the peninsula is water-limited, relying on delivery infrastructure and transfers from a neighbouring catchment. Impacts on nexus components are analysed for ten crops under two potential land-use scenarios: a substantial increase in irrigated area due to investment in irrigation infrastructure; and a substantial shift in land use towards export crops. The two have distinct impact on water and energy use, global warming potential, freshwater eutrophication, terrestrial acidification, and fine particulate matter formation. The results provide insights into future water and energy resource challenges and environmental and socioeconomic trade-offs associated with likely changes in irrigation expansion. The results for scenarios show that, for example, banana production has the greatest environmental impacts (e.g. a 519% increase in global warming potential and 452% increase in fine particulate matter forma for scenario 2), primarily due to water and energy requirements, despite the crop being mainly produced organically. In addition, total net income and labour demand increase (net income increases by 43% and 217% under scenarios 1 and 2, respectively) due to a larger crop area and crop intensification. Scale effects on labour demand are mainly due to labour intensity of maize in Ecuador, which is disadvantaged in the crop export scenario (an unexpected result). However, expanding irrigated areas would also increase total water and energy demand for irrigation, global warming potential, and freshwater eutrophication. This type of information

enables stakeholders and decision-makers to design policies that achieve equitable and sustainable agricultural production, water use, and economic growth.

Highlights

- A nexus approach is needed to ensure the sustainability of irrigation expansion
- The toolkit addresses biophysical, environmental, and socioeconomic aspects
- A participatory approach can improve decision-making for sustainable agriculture
- The toolkit can help balance development priorities towards a low-carbon transition

Keywords

water-energy-food-environment nexus, export agriculture, Ecuador, sustainable agriculture

Word count

8327

1. Introduction

Recently, the Chinese government has promoted the Belt and Road Initiative (BRI) to improve international trade and to support infrastructure investments worldwide (State Council of the People's Republic of China, 2015). In 2018, Latin America and the Caribbean (LAC) countries joined the BRI (ECLAC, 2018). Ecuador became the first country in the region to be part of the Asian Infrastructure Investment Bank, to support and improve trade routes and to open new markets within the Asia-Pacific region (Cancillería del Ecuador, 2021). This was an important milestone, given that Ecuador and the LAC region face an infrastructure gap and would benefit from foreign investments (Jenkins, 2021). There are, however, challenges linked to the impacts of investments in natural resources, such as water and land, and on the provision of energy, especially in the context of poor regulation and enforcement (Gélvez & Gachúz, 2020). Potential effects could be further intensified when resources are interlinked, generating unintended consequences for different sectors (Liu et al., 2021). Analysing Chinese-funded BRI projects' economic, social, and environmental impacts is key to ensuring their long-term sustainability (Ascensão et al., 2018). Long-term sustainability is also related to climate change effects and its interaction with human activities and their relation to the water-food-ecology nexus (Qin et al., 2022; Zhou et al., 2022).

Most developing economies largely depend on natural resources (OECD, 2009). An example is export-oriented agriculture in LAC, which, although it can promote investment, employment, and incomes to boost local development, leads to trade-offs between environmental impacts, migration, and food insecurity (Mahlknechzt et al., 2020). Rapid growth could also translate into the expansion of the agricultural frontier, the intensification of food production, and an increase in the demand for inputs (e.g. irrigation systems and agrochemicals), having adverse effects on biodiversity, increasing pollution, and stressing water and energy supply (Embid & Martín, 2017). Moreover, small farmers' incomes and food security could be affected by the competition for production factors (e.g., land, water, energy, labour) in areas lacking adequate socioeconomic, political, and governance conditions (Gomez y Paloma, Riesgo, & Louhichi, 2020). Similarly, the rapid increase in farm labour demand could also increase migration and population density (Royuela & Ordóñez, 2018) and overwhelm public services in rural and least-developed areas (Zegarra, 2018).

To better understand the interlinkages and trade-offs, there is a growing interest in the study of the connection – or nexus – between water, energy, food, and environment (WEFE), because such integrated approaches can provide a multi-dimensional perspective to decision-makers for improved policy design and investments to promote sustainable growth (Simpson & Jewitt, 2019). Taking a WEFE nexus approach would be a holistic management measure to integrate data and hard evidence for decision-makers seeking to use national resources more efficiently to move toward Sustainable Development Goals (SDGs). To date, governments have made slow progress in achieving the SDGs, with a lack of adequate, comprehensible information likely playing an important role (Laspidou et al., 2020). Moreover, the SDGs might represent competing or even conflicting objectives, making a nexus approach all the more important to recognise and understand synergies and trade-offs (Machingura & Lally, 2017). The approach can be all the more effective if both multidisciplinary and transdisciplinary approaches are taken (Ghodsvali, Krishnamurthy, & de Vries, 2019).

There remain, however, critical knowledge gaps concerning what "nexus" entails (Torres et al., 2019), leading to a body of research with various objectives and consequently to a variety of methodologies and results (Albrecht, Crootof, & Scott, 2018). Existing research applies to different elements of the nexus, to different types of interrelationships, and at different geographic scales; and the applied cases are scattered and context-specific. For example, the scarce nexus-related research on the LAC region mainly focuses on institutional framework analyses and proposed mechanisms for nexus analysis.

WEFE modelling toolkits are nevertheless emerging as an effective strategy for understanding the interlinkages and complexities of nexus components. However, most of these WEFE modelling toolkits only consider biophysical aspects. The few existing toolkits that consider biophysical *and* socioeconomic aspects either model a limited number of crops or cannot capture rapid changes in food production. Some efforts have been made to develop toolkits and models to incorporate critical socioeconomic interlinkages into the WEFE nexus approach (e.g. Correa-Cano et al., 2022). Such models allow the incorporation of policy-relevant trade-offs between resource decisions at the micro level and environmental consequences, such as water stress, pollution, and impeding a transition to low-carbon production systems.

A missing element in many nexus studies is the engagement and collaboration with stakeholders, essential to addressing global sustainability challenges related to water, land and energy use (Salmoral et al., 2020). This present study enhances the nexus approach by incorporating information regarding the local circumstances and stakeholders to which it will apply. We include an additional dimension to the nexus-integrating framework by taking case-specific information (i.e., the local context) to calibrate analytical models and community-specific priorities to determine relevant scenarios for policy evaluation. A further specific contribution of this study is the toolkit's application to the Santa Elena Peninsula in Ecuador, an area of fast-growing export-oriented agriculture. This area is vital to rural development in the country and representative of other water-stressed regions worldwide, to which the nexus approach could apply. This present case study builds on Correa-Cano et al. (2022), which presented a modelling approach to assess WEFE nexus interlinkages in water-stressed regions. The principal objective of this current study, is to developed a participatory scenario-specific integrated toolkit to explore future challenges to nexus components in a changing agricultural system using a transdisciplinary approach that evaluates water, energy, environmental and socioeconomic dimensions. A more specific objective is to provide insights into challenges a BRI country faces while planning investments and other development policies for agricultural and territorial developments. Although agricultural expansion can generate benefits, such as employment growth, which reduces poverty and food insecurity, it can also produce essential trade-offs in nexus resource exploitation and environmental consequences beyond the farm sector. Even more specifically the objective of this Santa Elena case study is to illustrate how the Nexus approach can contribute to an overall understanding of resource use and trade-offs under two realistic policy scenarios, including the consequences for energy use and the prospects of a low-carbon, green transition in BRI countries. These two alternative policies are development strategies meant to stimulate the agricultural sector in the SEP and generate value added for both the area and Ecuador as a whole. The focus on trade-offs in the WEFE context is of central importance (Lee et al., 2020; 2023). The results in this present paper bring in to sharp relief the trade-offs between increasing local agricultural production and the impacts on water, energy, indicators of environmental health and socio-economic outcomes.

2. Materials and methods

This section first describes the national and local characteristics relevant to a nexus analysis. It then describes how the toolkit's modules were implemented and the participatory approach used.

2.1. Case study description

During the last ten years, the Ecuadorian government has elaborated several policies for the development and sustainable use of WEFE nexus resources (see Table A.1 Appendix). The National Development Plan is the main instrument on which public policies and programs focus (Asamblea Nacional de Ecuador, 2008). The decentralised autonomous governments (GADs) at different administrative levels must elaborate development and land use plans in an articulated manner with national, provincial, cantonal, and civil parish planning, incorporating territorial environmental criteria (Gobierno de Ecuador, 2017). Most GADs require capacity building to achieve an articulation between the planning instruments (SENPLADES, 2015).

The Santa Elena Peninsula (SEP) is part of the Guayas River basin in the coastal zone of Ecuador, with an approximate area of 6,400 km² and an estimated population of 300,000 inhabitants (CISPDR, 2016). Most of rural territory (80%) is formally declared as communal property, which translates into small portions of land assigned to farmers. According to Santa Elena's Province GAD (2015), 72% of the population of the SEP lives in rural areas, and 82% of these are considered poor. The SEP has a dry, arid climate, averaging 300mm yearly rainfall (January through March), which constrains economic development (GAD Provincial de Santa Elena, 2015). To address this constraint, a water transfer infrastructure was built (called the Hydraulic Plan of the Santa Elena Aqueduct or PHASE, its acronym in Spanish). This multipurpose project brings water to the area through transfers from the river Daule, providing access for both human consumption and irrigation (GAD Provincial de Santa Elena, 2015). This project began in the 1970s and intended to reach approximately 40,000 ha irrigated (Castillo & Beilock, 2004), something that has not yet materialised. However, the project's long-term sustainability is questionable, and conflicts are emerging caused by unequal access to land and resources (Velasco Andrade & Tamayo Ortiz, 2020). In addition, a substantial amount of energy is consumed to transport water to and within SEP, implying high irrigation costs and environmental impacts (e.g., carbon emissions).

The present research begins by selecting the ten main crops produced in the entire SEP, representing at least 85% of the peninsula's irrigated area (INEC, 2019). Proportions of that area for each crop were allocated to the PHASE project zone of interest to this study using a land cover map (MAGAP, 2015). In total, there are 13,582 hectares in the study area (**Error! Reference source not found.**Table 1 and Table A.1 Appendix). Maize in the SEP is produced mainly by small farmers and is oriented to the local market and self-consumption, while agro-export products – such as banana, cocoa, and mango – are produced by large farming systems (GAD Provincial de Santa Elena, 2015). The three predominant irrigation systems are sprinkler, drip, and surface irrigation (INEC, 2019) (Table 1).

Table 1 Area by crop and irrigation method **in the study zone in Santa Elena, Ecuador, 2019.**

Crops	Total area (ha)	Irrigation method (ha)		
		Surface	Sprinkler	Drip
Banana	3,106	0	3,106	0
Cocoa	1,125	128	823	175
Grapes	1,151	0	0	1,151
Lemon	56	0	15	42
Maize	2,748	173	1,126	1,448
Mango	2,109	975	1,135	0
Papaya	257	11	0	246
Plantain	175	14	9	153
Sugarcane	1,276	0	0	1,276
Cucumber	196	0	0	196
Other crops	1,382	64	518	800
Total	13,582	1,364	6,730	5,488

2.2. Structure of the WEFE modelling toolkit

The modelling toolkit used in the present study is based on Correa-Cano et al. (2022). This section describes how the irrigation, energy, and environmental assessment modules were implemented. Also, the socioeconomic analysis and data sources are presented. The toolkit presented in Correa-Cano et al. (2022) is based on three modules: irrigation simulation, economic modelling and life cycle environmental assessment, which are soft-linked, allowing independent runs but sharing results among them. That previous study presents the structure, theoretical foundations, and calibration procedures. The main difference in this present study is the use of participatory-defined scenarios, which explicitly state future crop area, and thus the socioeconomic module is simplified since no land-use model is needed (Figure 1). The latter is an example of the flexibility of this toolkit to be implemented under different informational contexts.

Figure 1 presents the conceptual framework and basic underlying assumptions of the WEFE modelling toolkit for the Santa Elena peninsula case study. Starting from the top of the chart, it begins with an assumed stylized fact that, in addition to land, any agricultural system is reliant on the use of basic resources in the form of two basic nexus components, water and energy. In our specific case study we will focus on the allocation of cropland within defined irrigation zones, which are the second two layers from the top in Figure 1. It is at the level of the cropland allocation that the two scenarios are implemented. Below the dash line is the scenario analysis, where the nexus model is implemented in terms of simulating water demand, crop production and energy demand, under a reference scenario and the agro-export development and the irrigated cropping expansion. It is at this level that we observe the agricultural and socio-economic impacts. We incorporate the premise that the changes of composition of agricultural production area lead to changes in water demand, crop production, energy demand and income generation. Any WEFE based simulation model assumes certain parameters do no change: relative input and out prices are constant, there are no radical shifts in weather patterns, and factors such as demography and political regime are stable. The interplay of cropping patterns and the socioeconomic implications finally lead to nexus relevant outcomes. The results from the irrigation simulation under the two scenarios allows the measurement of the variables relevant to the environmental assessment (land use, carbon foot print, Air and water pollution, and resource depletion) and the socio-economic analysis (labor demand, income).

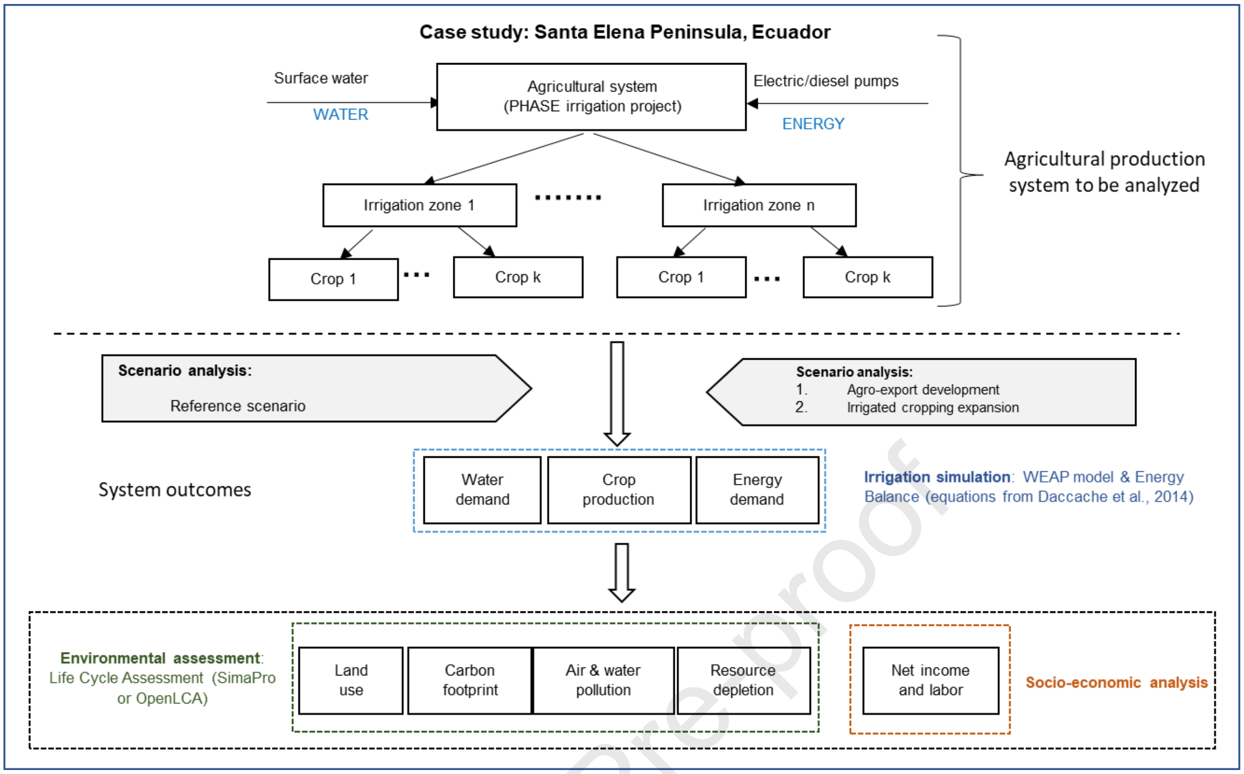

Figure 1 WEFE modelling toolkit conceptual framework.

2.2.1. Irrigation simulation module

The Water Evaluation and Planning System (WEAP) model was used to evaluate irrigation water demands, supplies, water transfers within the reservoir system, and annual crop production (Ougougdal et al., 2020). The model was parameterised using a combination of climate, soil, crop, and water consumption data (Table 2). Irrigation needs and annual crop production were estimated using the MABIA module in WEAP, which is a daily water balance method considering evapotranspiration, crop development, soil characteristics, and irrigation schedules (Sieber & Purkey, 2015). Seepage losses from canals were estimated to represent 7% of the flow, and reservoir losses were assumed to be 1 million m^3 per month (Cornejo, 2003). Irrigation zones 1 to 8 (Figure 2) were identified from the schematic (CEDEGE, 2001). Zones 9 and 10 were not in the initial plan for the irrigation project, which was later extended and hence identified from the land-use/land-cover data. About 51% of the total irrigated area uses sprinklers, 38% by drip, and 11 % by surface irrigation. Irrigation efficiencies of 70%, 90%, and 40% were assumed for sprinkler, drip, and surface irrigation, respectively. The goodness of fit of the WEAP model to predict irrigation need and annual crop production was evaluated by calibrating the model against daily observed reservoir storage volumes and observed crop production of each selected crop (Figures A.1 and A.2 Appendix).

Table 2 Data type and sources used for the study

Data	Source
Climate data (2014-2019)	Meteorological and Hydrological National Institute (INAMHI, 2019)
Irrigated crops (2019)	National Institute of Statistics and Censuses (INEC, 2019)
Land-use land-cover data (2015)	Ministry of Agriculture and Livestock (MAGAP, 2015b)
Irrigation application systems (2019)	National Institute of Statistics and Censuses (INEC, 2019)
Technical details on reservoirs, canals, and pumps	Public Water Company (EPA, 2019)
Crop characteristics such as the development calendar, crop coefficients, depletion factor, rooting depth, and plant height	Food and Agriculture Organisation (FAO, 2007)
Typical planting dates for each crop	Ministry of Agriculture and Livestock (MAGAP, 2018)
Soil data	Ecuadorian Space Institute (IEE, 2012)

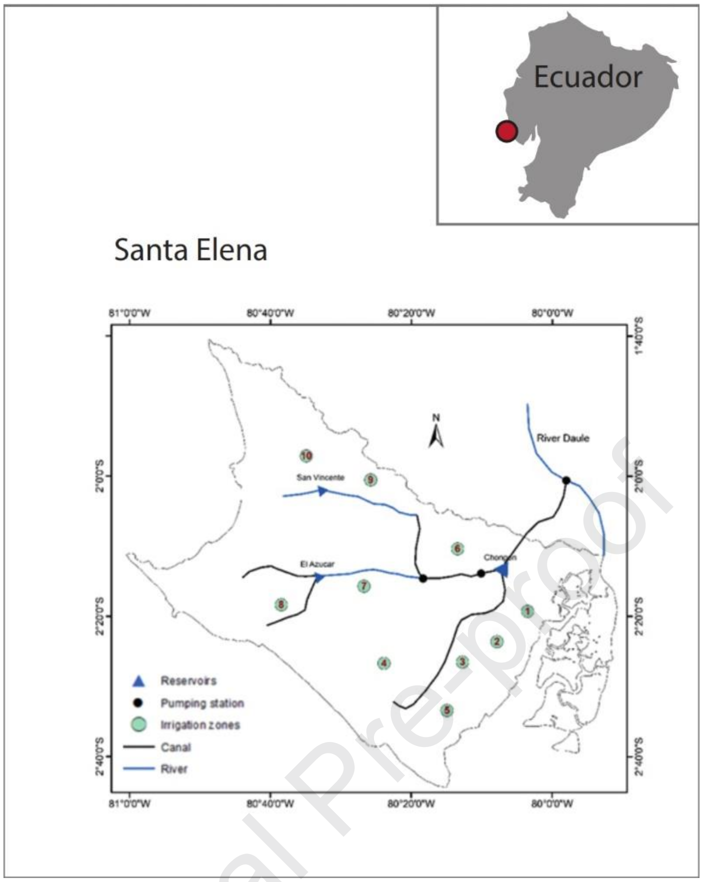

Figure 2 Schematic representation of the water infrastructure and irrigation zones in the SEP

Simulated monthly average flow and volumes from the WEAP-MABIA model were used as inputs for the energy model to simulate energy demands to operate the irrigation network. The energy required to pump irrigation water for each crop within each irrigation zone was calculated based on (FAO, 2007) as follows :

$$\boldsymbol{Energy}\ (\boldsymbol{kWh}) = \frac{\boldsymbol{V}\ (\boldsymbol{m^3})\ \times \boldsymbol{PH}\ (\boldsymbol{m})}{\mathbf{367} \times \boldsymbol{\eta_{motor}} \times \boldsymbol{\eta_{pump}}} \tag{1}$$

Where *V* is the WEAP simulated irrigation volumes; η_{motor} and η_{pump} represent efficiencies of the motor and pump, respectively. Pumping efficiency was assumed to be 80%; diesel and electric motors were assumed to have 40% and 90% efficiency, respectively (Daccache et al., 2014). Irrigation pumps are powered by electric pump sets in the lower sector (zone 1, to 5) and diesel pump sets in the upper sector (zone 6 to 10). (Daccache et al., 2014)(Daccache et al., 2014)The typical operating pressure for drip of 1 bar and sprinklers of 3 bar with friction losses (f_{Losses}) representing 20% of the nominal discharge were assumed (Daccache et al., 2014). As water is abstracted from surface sources, no pumping lift was assumed. Thus, the total pressure head (PH) was calculated as:

$$\boldsymbol{PH\ (m) = Operating\ pressure\ (m) + f_{Losses}\ (m)} \tag{2}$$

2.2.2. Environmental Assessment Module - Life Cycle Assessment (LCA)

The four stages of the LCA methodology, as established by the International Organization for Standardisation guidelines (ISO 14044, ISO 14040), are followed to model the extent of the environmental impacts of selected crops grown in this study case. This section presents the goal and scope definition and compilation of the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA). The modelling was built using openLCA 1.10.2.

The goals of this LCA are twofold: first, assess the environmental effects incurred by the production of ten commodity crops in SEP. Then, understand the variation in environmental impacts between farming systems. The system boundary of the analysis was from field to farm gate, covering all activities from field preparation to harvest (Figure A.3 Appendix). The functional unit of this case study is 1 kg of produce at the farm gate. The LCA results were then combined with the estimations from the irrigation and energy demand module (section 2.2.1) to evaluate environmental impacts under prioritised future scenarios (section 2.3).

Water and energy demand are essential to define the existing farming systems in Santa Elena. The amount of water used for irrigation is defined by the WEAP model and energy for irrigation was determined by irrigation method and pumping type. Foreground data regarding the amount of organic, major inorganic fertilisers (nitrogen, phosphorus, and potassium or NPK), yield, and total production were obtained from the Agricultural National Survey (INEC, 2019). The weighted average over five years (2014-2019) was considered for all crops when data was available. The amount of NPK as a compound reported by the Agricultural National Survey was adjusted based on the specific NPK ratios per crop used in the region (Table A.3 Appendix). Background datasets were modified from available regional or global LCIs from Ecoinvent v3.6, except for banana, which is the only existing specific dataset for Ecuador (Table A.4 Appendix).

To estimate the potential environmental impacts of the selected crops, the ReCiPe 2016 midpoint v1.11 method was used, applying the hierarchist perspective (Huijbregts et al., 2016). A moderate time horizon of 100 years was used to assess the global warming potential (GWP). Freshwater eutrophication (FE), terrestrial acidification (TA), and fine particulate matter formation (FPMF) were evaluated, for which the ReCiPe 2016 method offers characterisation factors at the country scale.

2.2.3. Socioeconomic analysis

The integration of the agricultural system with the socio-economic analysis module is straightforward. To analyse the socio-economic effects, the net income and employment generated by the agricultural production of the ten crops selected in this case study were evaluated. Net income per hectare of crops was constructed as the difference between the value of production, sold to either local or export markets, and input and labour costs. Sales data in US dollars (the official currency of exchange in the country) were taken from INEC (2019) which reports information on the cropped and harvested area for the country's main agricultural products. Subsequently, the weighted average of sales per hectare was calculated. Labour requirements and estimated costs presented here represent fixed coefficients per hectare derived from information provided by the Ministry of Agriculture and Livestock (MAG, 2021), the National Institute of Agricultural Research technical data sheets (INIAP, 2008), Suárez (2015), Cobeña (2013) and, Saltos (2015) (Table A.5 Appendix). The two scenarios do not involve changes in agricultural technology but merely changes in area under production, and therefore should not affect per hectare use of various inputs for each crop. Because there is no reason to think that per hectare input use will change appreciably we make use of fixed coefficients to translate the effects of the scenarios into the socio-economic outcomes of interest. Table 3 summarises the basic assumption regarding per hectare sales, costs, net income, and labour demand.

Table 3 Sales, costs, profits, and labour for ten selected crops in SEP

Crops	Sales (USD/ha)	Costs (USD/ha)	Net income (USD/ha)	Labour (workers/ha/year)
Banana	18,837	10,166	8,671	0.57
Cocoa	2,026	838	1,188	0.15
Grapes	22,641	12,517	10,124	0.44
Lemon	16,000	3,064	12,936	0.28
Maize	1,969	1,156	813	0.12
Mango	1,787	982	805	0.05
Papaya	5,293	2,464	2,829	0.22
Plantain	7,216	6,785	431	0.44
Sugarcane	4,598	2,922	1,676	0.05
Cucumber	11,280	5,883	5,397	0.36

Source: Ministry of Agriculture and Livestock (MAG, 2021), the National Institute of Agricultural Research technical data sheets (INIAP, 2008), Suárez (2015), Cobeña (2013) and, Saltos (2015)

The net income and labour per hectare of each crop in SEP were multiplied by the corresponding hectares in the study area (section 2.1) for the baseline scenario and the irrigated areas defined for the prioritised future scenarios (section 2.3).

2.3. Participatory modelling approach

As defined by (IPBES, 2016), scenarios are "plausible representations of possible futures for one or more components of a system, or an alternative policy or management options intended to alter the future state of these components." Several studies have demonstrated that the involvement of stakeholders in scenario development can ensure the relevance of scenarios for local decision-making (e.g., Walz et al., 2007). A participatory scenario development approach was applied to model plausible long-term (2050) future scenarios for SEP. This process involves multiple stakeholders with different interests and objectives to define future scenarios and build a shared understanding of complex problems. Members of the NEXT-AG Project Advisory Board, representing key stakeholders, were invited to join a workshop in May 2021 to help select and define the most relevant future scenarios that should be included in the analysis. A total of eight stakeholders attended the workshop, representing key sectors (academia, government, NGOs). Prior to the day of the workshop, a document containing a brief description of the modelling tool, the results for the baseline scenario, a brief explanation of the aim of the workshop, and a list of scenarios to discuss was shared with attendees.

The workshop consisted of three main parts:

1. Presentation of the modelling tool
2. Presentation of the baseline scenario
3. Scenario development

During part 3, seven pre-defined scenarios were presented (Table A.6 Appendix), and participants were asked to select two of them based on the relevance for the SEP. These seven scenarios were selected by the research team based on literature, and previous interviews with experts and policymakers. After the two scenarios were selected, participants were split into two groups and asked to define each scenario in more detail, focusing on: a) what key factors would make this scenario happen; b) what would be the associated impacts on water, the environment, agriculture and the economy; and c) what policies could be put in place to promote the positive impacts and reduce the negative impacts derived from the scenario. The scenarios prioritised by the Ecuador Advisory Board are described in Table 4. Also, an explanation of how they are represented in the modelling is presented.

Table 4 Future scenarios prioritised by key stakeholders in SEP

Scenario	Description
1. Agro-export development	This scenario represents a future in which policies aimed at strengthening the agro-export sector are applied, betting on export agriculture as an agricultural model in Santa Elena. The irrigated area of traditional crops with low economic profitability (i.e. maize), is replaced by crops demanded in the international market (i.e. bananas).
2. Irrigated crop area expansion as per the initial design of PHASE irrigation scheme	The development of irrigation in the area is promoted by promoting the transfer, reaching its maximum capacity, with a greater volume of water from the Daule River. The production area is increased.

Table presents the irrigated area per crop for each scenario. These scenarios represent land use changes from the baseline scenario for modelling purposes. For scenario 1, the irrigated area of agro-export crops (banana, cocoa, and mango) was doubled and for those oriented to the local market (grapes, lemon, maize, papaya, plantain, sugarcane, and cucumber) it was reduced by half. For scenario 2, the irrigated area of the peninsula was increased for all crops, reaching the maximum capacity of the PHASE project (40,000 ha) (GAD Provincial de Santa Elena, 2015). The "other crops" area remained constant in both future scenarios.

In summary, the two scenarios serve as the basis for the change of irrigated area of each crop relative to the baseline scenario. In the case of scenario 1, expert opinion anticipated that future government policy shifts and private investment incentives could, in the near term, expand total irrigated area to almost 17,000 ha compared to 13,583 of the baseline. This represents a significant expansion in land area, but considerably less than scenario 2. The change in the irrigated area for each crop in scenario 2 is a simple proportional increase relative to the baseline, such that the resulting sum of all crop area is 40,000 ha. The rationale for scenario 2 comes from another policy initiative, pushed by the local government to complete a proposed infrastructure irrigation plan (PHASE). The plan entails adding two additional pumps and delivery infrastructure that would allow a near quadrupling of the irrigated area in the region.

There are sufficient water resources available to meet the quantity requirements for an expansion to 40,000 ha. In fact, the total hectarage proposed by the PHASE project designers was a consequence of experts' estimation of the availability of the water resources, of land, and of the investment requirements to implement the project. The water resource is not a binding constraint. What is needed are additional investments to increase the pumping and delivery capacity, plus additional operational costs. Once the investments in water delivery capacity are in place, final water consumption depends principally on the assignment of land resources. Without any *a priori* reason to think that the present composition of production in terms of land shares will be altered, we simulate the impact of an expansion to 40,000 ha by scaling up the present land use for each crop.

In both scenarios, policy experts in Ecuador did not consider explicitly the possible effects of policy implementation on the environment, energy and social and economic benefits (beyond the immediate cost associated with infrastructure development). One contribution of the present paper is to remedy this absence of a consideration of nexus effects, on water, energy, the environment, and communities.

Table 5 Irrigation area in the baseline and future scenarios

Crops	Irrigated area (ha)		
	Baseline scenario	Scenario 1	Scenario 2
Banana	3,106	6,211	9,831
Cocoa	1,125	2,251	3,562
Grapes	1,151	576	3,644
Lemon	56	28	179
Maize	2,748	1,374	8,697
Mango	2,109	4,219	6,677
Papaya	257	129	814
Plantain	175	88	555

Sugarcane	1,276	638	4,038
Cucumber	196	98	621
Others crops	1,382	1,382	1,382
Total	13,582	16,992	40,000

3. Results

This section presents the results of the modelling toolkit for the study area within the SEP. First, the results for the baseline scenario are presented for the three dimensions considered, and then the results for the future scenarios are shown.

3.1. Baseline scenario assessment

This subsection presents the results of the water and energy demands, the LCA, and the socioeconomic analysis for the baseline. The central figures are included in the paper, and the more detailed figures are presented in the Appendix.

3.1.1. Water and energy demands

The SEP's total irrigation demand, including losses, was approximately 153 Mm^3; out of which 97 Mm^3 was for zone 8, a cropped area of 6,784 ha. The total water used by sprinkler irrigation was 85 Mm^3; drip and surface irrigation systems account for 51 Mm^3 and 17 Mm^3, respectively. The total energy demand for operating the irrigation system in the SEP was estimated to be 29 GWh, with 4 GWh and 25 GWh for the drip and sprinkler systems, respectively.

Banana and maize account for more than half of the annual water demand in the SEP, followed by cocoa and mango with 10% and 9,5%, respectively (Figure A.**Error! Reference source not found.**4a Appendix). These four crops also represent the largest share of the annual energy demand (Figure A.**Error! Reference source not found.**4b Appendix).

3.1.2. Life Cycle Assessment

This section presents, for each crop, the impact values per hectare and the total for the study area. GWP values range from 0.94 to 9 t CO2-eq/ha (Figure 3a). Most crops grown using drip irrigation have lower impacts when using electric pumps, except for maize (2.64 vs 2.4 t CO_2-eq/ha, using electric and diesel, respectively). However, crops grown using sprinkler irrigation and diesel pumps have higher GWP than those grown using drip irrigation and diesel or electric pumps (i.e., lemon, maize, mango, plantain, and cocoa). The average GWP for the peninsula shows that banana has the highest impact value (29.46 kt CO_2-eq) and lemon the lowest (0.04 kt CO_2-eq, Figure 3b). Regarding FE, per-hectare values range from 0.3 to 2.3 kg P-eq/ha. Crops grown using surface water and no pumps have the lowest impact values among irrigation systems (Figure 3c). Following banana, papaya has a high per hectare value when grown using drip irrigation and diesel pumps (1.9 kg P-eq/ha).

Banana and maize have the highest per-hectare values of TA (approximately 74 and 40 kg SO_2-eq/ha, respectively; Figure 4a), and highest total values of TA (244 and 52 t SO_2-eq, respectively; Figure 4b). Per hectare FPMF results range from 2.12 to 17.37 kg $PM_{2.5}$- eq/ha, for cocoa and banana, respectively (Figure 4c). The FPMF for the total cropped area in the peninsula shows banana with the highest impact value (56.82 t $PM_{2.5}$-eq, Figure 4d).

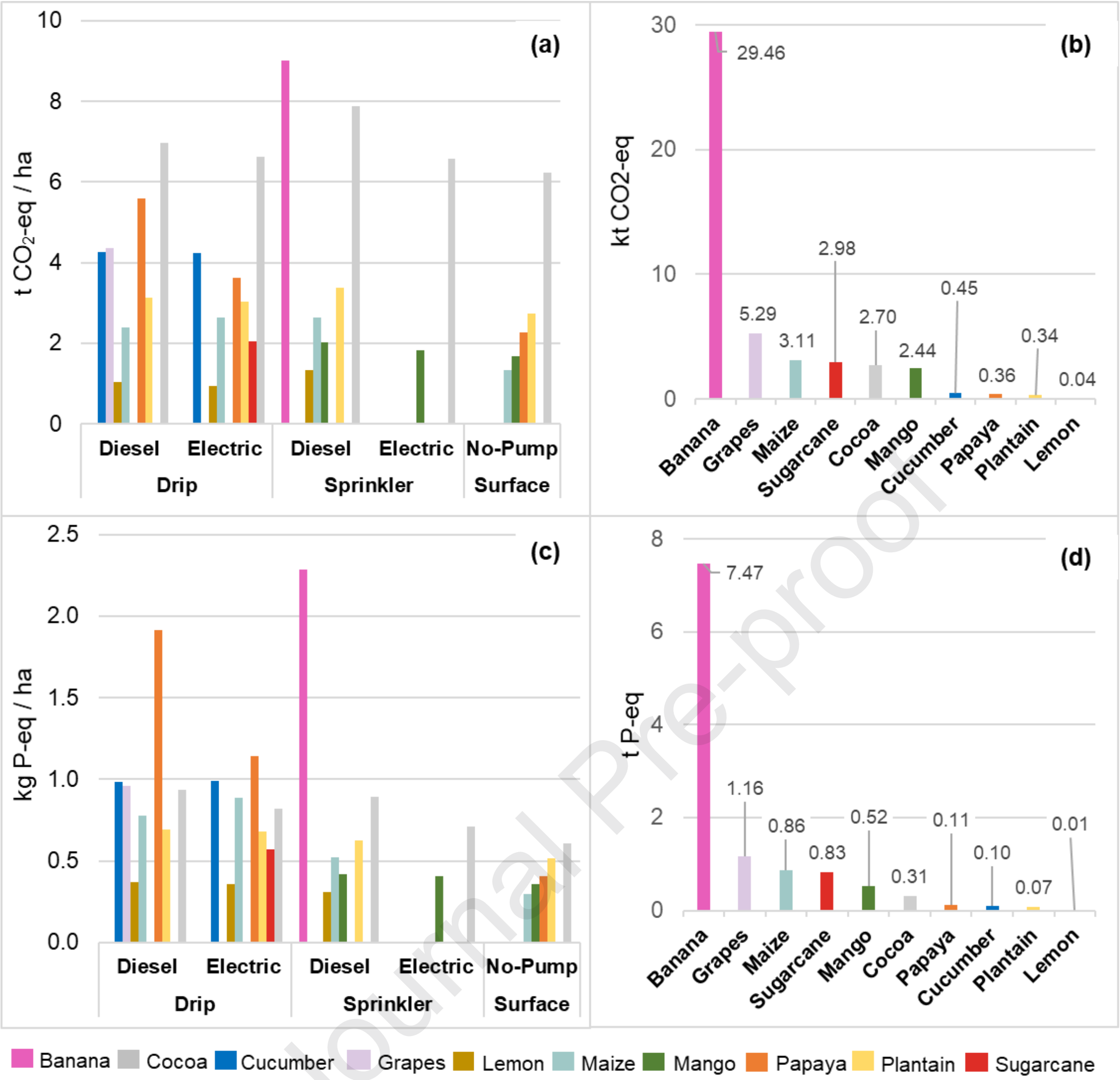

Figure 3 Environmental impacts for ten commodity crops in SEP. (a) GWP per hectare, (b) average GWP at a Peninsula scale, (c) FE per hectare, and (d) average FE at a Peninsula scale

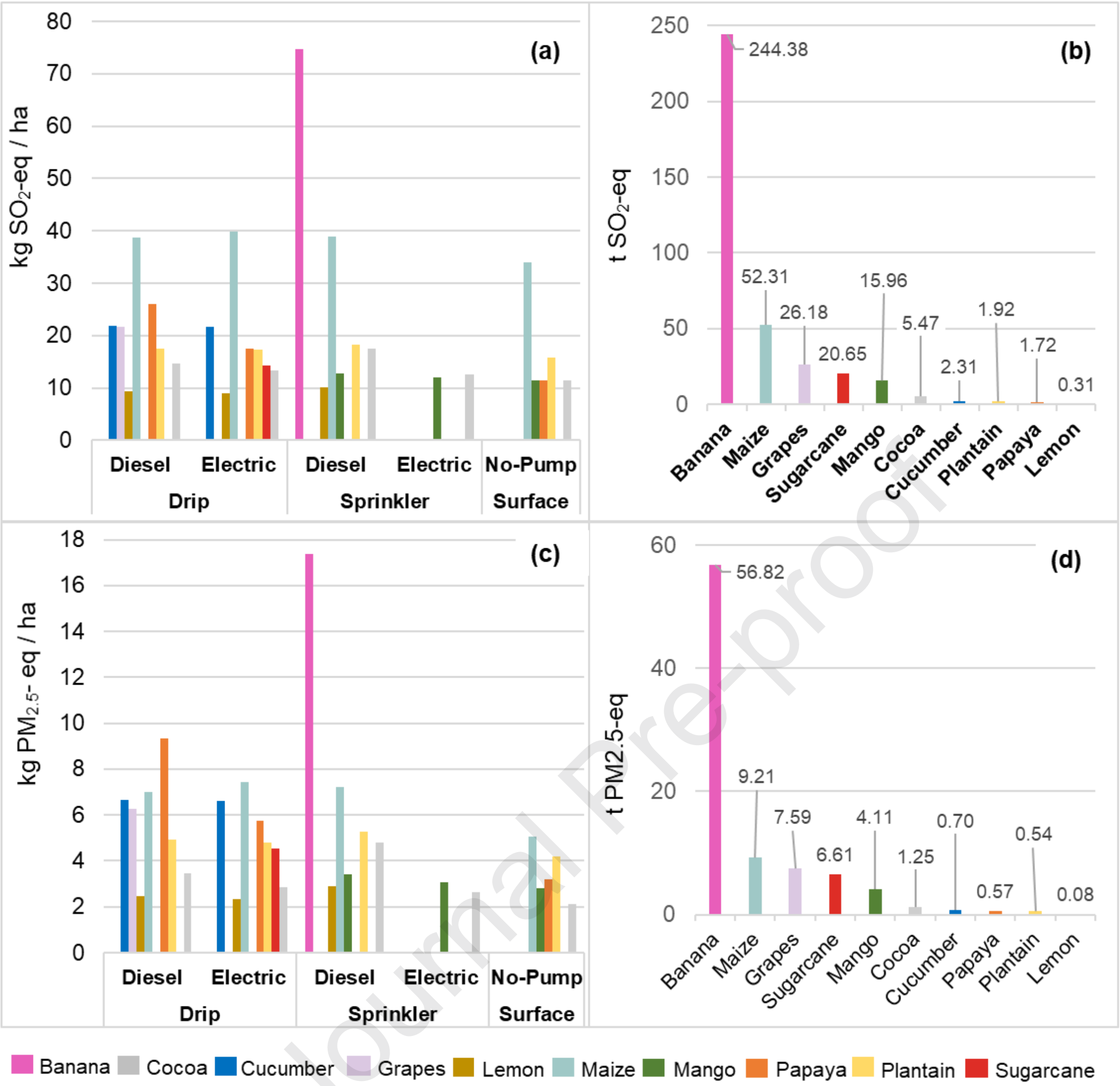

Figure 4 Environmental impacts for ten commodity crops in SEP. (a) TA per hectare, (b) average TA at a Peninsula scale, (c) FPMF per hectare, and (d) average FPMF at a Peninsula scale

The contribution of on-farm production processes to the impact categories varies substantially between crops, with irrigation, agrochemicals and direct emission playing the most significant role. **Error! Reference source not found.**5 in the Supplementary material presents the proportional contribution of each production process, by crop and irrigation system, to each impact category.

3.1.3. Socioeconomic analysis

Lemon, grapes, and bananas are the three most profitable crops per hectare, while maize, mango, and plantain are the less profitable (Table 6). However, the banana is the most relevant crop in SEP regarding total net income, representing USD 27 million and 55% of SEP's total net income, which is well-aligned with the irrigated area allocated to this crop (25%). With 9% of the total irrigated area, grapes account for 24% of the total net income in the peninsula (USD 11.7 million). In the case of maize, even though it has 23% of the total irrigated area, it only contributes 5% of the total net income of the SEP with USD 2 million. Mango and cocoa, both 27% of the total irrigation area, account for 6% of net income.

Bananas, grapes, and plantain are the most labour-intensive crops, while maize, mango, and sugarcane are the less so (Table 6). Banana uses 56% of the labour force in the SEP (1,761 workers/year). Grapes account for 16% of total labour (510 workers/year), followed by maize(10% of the labour force or 323 workers/year). Mango and cocoa account jointly for 9% of labour.

Table 6 Net income and labour for ten crops in the baseline scenario

Crops	Profit/ha (USD)	Total profit (USD)	Labour (workers/ha/year)	Total labour (workers/year)
Banana	8,671	26,929,422	0.57	1,761
Cacao	1,188	1,336,824	0.15	165
Grapes	10,124	11,654,290	0.44	510
Lemon	12,936	730,245	0.28	16
Maize	813	2,233,722	0.12	323
Mango	805	1,698,027	0.05	109
Papaya	2,829	727,568	0.22	56
Plantain	402	75,587	0.44	77
Sugarcane	1,676	2,138,281	0.05	67
Cucumber	5,397	1,058,933	0.36	71
Total		48,577,826		3,154

3.2. Future scenarios assessment

This subsection presents the results of the water and energy demands, the LCA, and the socioeconomic analysis for scenarios 1 and 2.

3.2.1. Water, energy demand, and crop production

Scenario 1 (agro-export development) leads to an increase in water demand relative to the baseline, with the conversion of traditional crops to export-oriented crops in most irrigation zones for different irrigation systems (**Error! Reference source not found.**Table A.7 Appendix). Under scenario 2 (increased irrigation capacity), the irrigated area is nearly tripled, and the corresponding increase in simulated water and energy demand is evident. The baseline water demand coverage (Figure 6) is 95 to 100% for all irrigation zones. With an increase in agro-export crop production (scenario 1), the coverage declined to 85% for all zones except for zone 10. For scenario 2 (increased capacity), the coverage increased slightly for irrigation zones 1-5, while a marked decline is visible for irrigation zones 6 to 10. Under scenario 1, the irrigated banana, cocoa, and mango area doubles; the area devoted to other crops falls by half (Figure 7). Annual crop production of banana increases by 99%, cocoa by 91%, mango by 56%, and traditional crops declines between 42 and 53%. Under scenario 2, due to a tripling of irrigated area, production of all crops increases (>70%) in all irrigation zones.

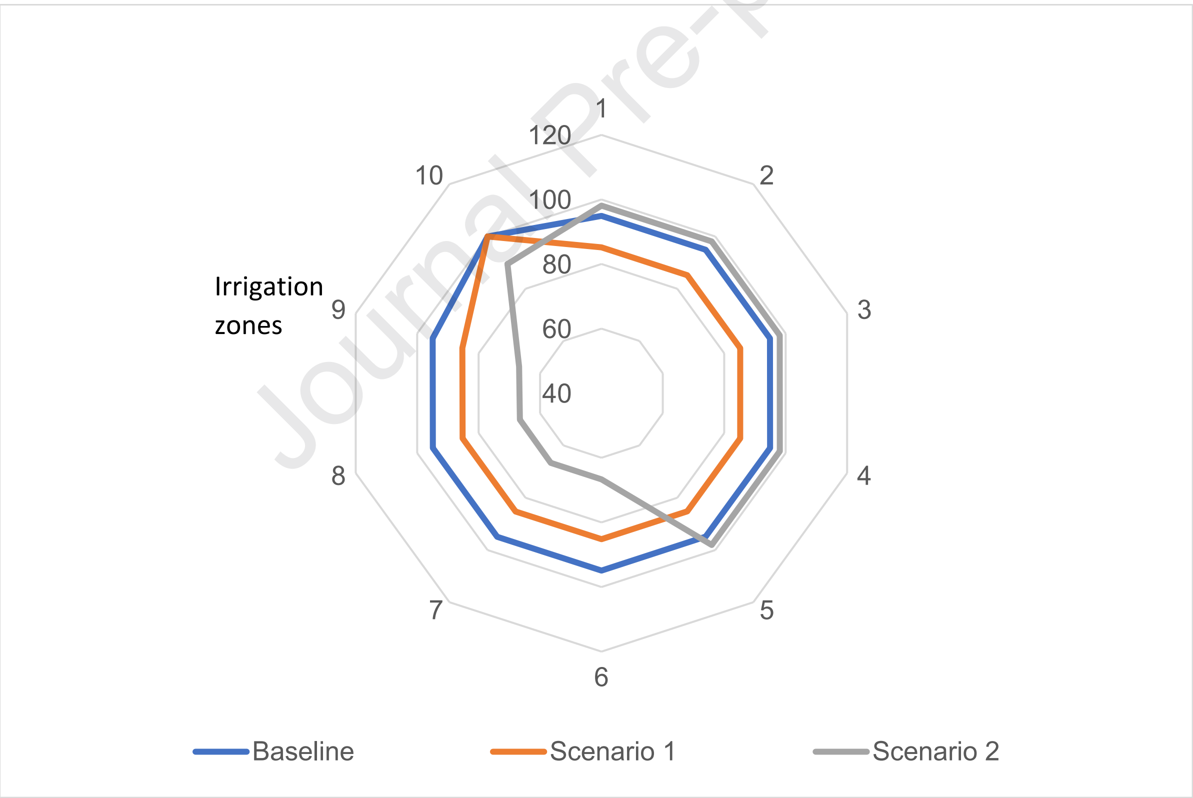

Figure 6 Simulated annual average water demand coverage for different scenarios for each irrigation zones

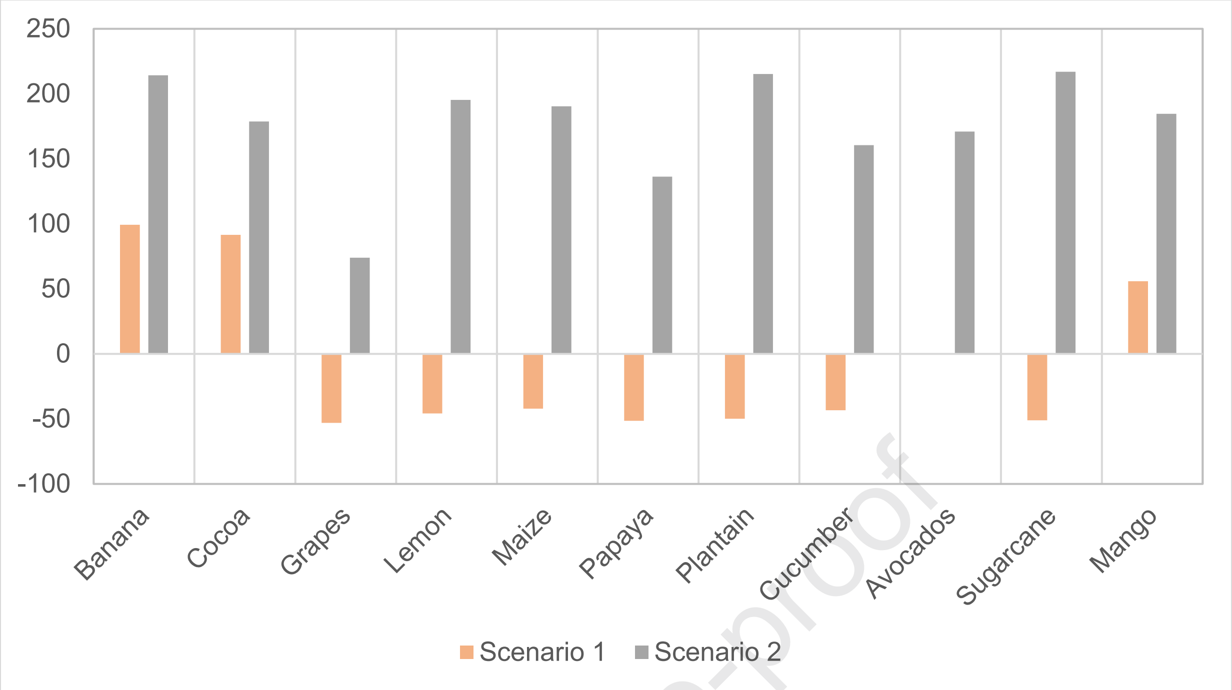

Figure 7 Percentage change in annual crop production for the selected scenarios

3.2.2. Life Cycle Assessment

There are significant changes from the baseline for the four environmental impacts considered. The most notable changes to the environmental metrics are in scenario 2 for all crops and all impact categories. As seen in Figure 8, the increase in the GWP metric is especially noteworthy (rising 200% or more). The banana GWP increases 519% from the baseline. Freshwater eutrophication increased significantly more for papaya (462%), mango (433%), and banana (385%) than for other crops. FPMF was significantly higher for banana (452%) and papaya (420%). Cocoa had the lowest increase across impact categories. By contrast, in scenario 1, the impact metrics for seven crops decrease compared to the baseline, with decreases of up to -50%. In scenario 1, the papaya metrics decrease the least, while sugarcane showed the greatest decreases in all impact categories (-50%). Unsurprisingly, the export crops, mango, cocoa and banana, show increases in the impact metrics by over 95%.

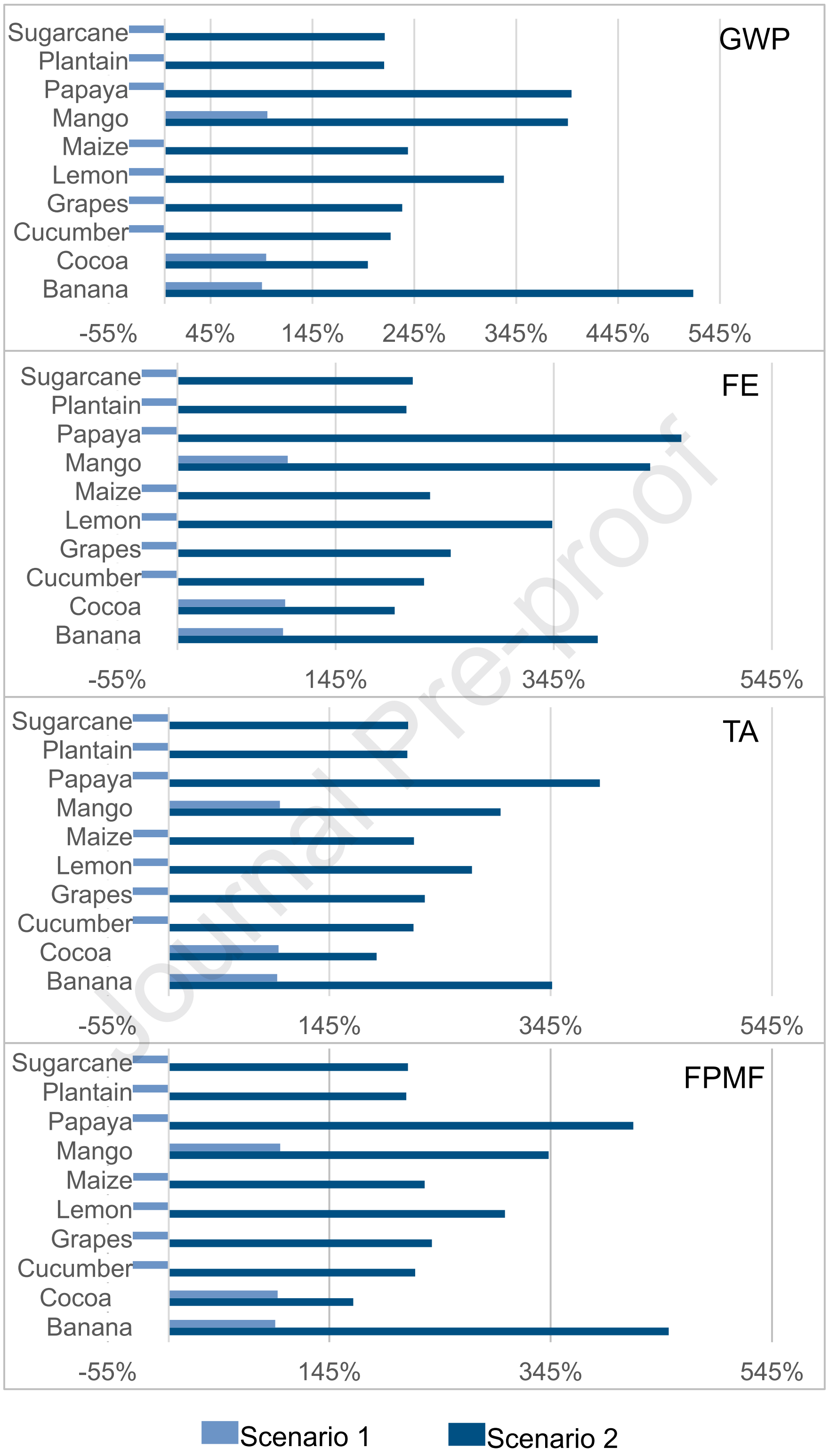
GWP
FE
TA
FPMF
Sugarcane
Plantain
Papaya
Mango
Maize
Lemon
Grapes
Cucumber
Cocoa
Banana
-55%
45%
145%
245%
345%
445%
545%
Scenario 1
Scenario 2

Figure 8 Percentage change for global warming potential (GWP), freshwater eutrophication (FE), terrestrial acidification (TA), and fine particulate matter formation (FPMF) evaluated under future scenarios

3.2.3. Socioeconomic analysis

Net income levels by crop under the baseline and the two scenarios are presented in Table 7. The variations of each crop's net income between scenarios (1 and 2) and the baseline are proportional to the land-use changes proposed in section 2.3. Under scenario 1, the total net income in the SEP increases by 43% (20.6 million USD). Under scenario 1, bananas represent 78% of total net income (54 million USD), followed by grapes (8%), mango (5%), and cocoa (4%). The net income of non-export crops decreases. Under scenario 2, total net income in the SEP grows by 217% increase. In scenario 2, the crop shares of total net income remain equal to the baseline.

Table 7 Net income results by scenarios

Crops	Net income (USD)		
	Baseline	Scenario 1	Scenario 2
Banana	26,929,422	53,858,844	85,242,332
Cacao	1,336,824	2,673,648	4,231,579
Grapes	11,654,290	5,827,145	36,890,463
Lemon	730,245	365,123	2,311,517
Maize	2,233,722	1,116,861	7,070,619
Mango	1,698,027	3,396,054	5,374,930
Papaya	727,568	363,784	2,303,043
Plantain	75,587	37,794	239,263
Sugarcane	2,138,281	1,069,140	6,768,510
Cucumber	1,058,933	529,466	3,351,943
Total	48,577,826	69,235,322	153,768,143

Table 8 presents the results of labour demand by crops under the proposed scenarios. Under scenario 1, the total labour demand in the SEP increases by 47%. Banana production demands the largest workforce, with 76% of total labour (3,521 workers/year), followed by cocoa (7%), grapes (6%), and mango (5%). On the other hand, maize decreases its proportion of labour demand to 3%, the same for the rest of the crops oriented to the local market. Under scenario 2, expanding the irrigated area in the SEP increases total labour demand by 217%. Likewise, the proportions of labour demanded by crop remain equal to the baseline.

Table 8 Labour results by scenarios

Crops	Labour (workers/year)		
	Baseline	Scenario 1	Scenario 2
Banana	1,761	3,521	5,573
Cacao	165	331	524
Grapes	510	255	1,613
Lemon	16	8	50
Maize	323	162	1,023
Mango	109	219	346
Papaya	56	28	176
Plantain	77	39	244
Sugarcane	67	33	211
Cucumber	71	35	223
Total	3,154	4,630	9,984

4. Discussion

Irrigated agriculture is the most intensive production system regarding labour and production per surface unit (Puy, Lo Piano, & Saltelli, 2020). It also effectively reduces climate impacts in many regions and has several livelihood benefits. It requires, however, appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of water sources (IPCC, 2022). Other effects of irrigated agriculture, such as land use conversion, water and energy consumption, and impacts on global warming, need to be understood to make more informed decisions, particularly in arid zones (Niu, Zheng, Han, & Qin, 2019). As presented here, using a WEFE nexus toolkit allows analysing the synergies and trade-offs of changes in irrigation expansion under different scenarios (Figure 9).

The scenarios translate into land use changes and accompanying changes in factor use (e.g., water, labour, energy). Future work could address in more detail the effects that resource constraints in factor use may imply for the rest of the economy. It should be noted that price effects will probably be small because the scale of production expansion in the SEP is not likely to affect international or national prices. Anyhow, this change in factor use in turn leads to impacts on the

WEFE metrics. In both scenarios, total net income and labour demand in the SEP increases because crop production increases for sale in national and international markets (Figure 9). However, expanding irrigated areas would also increase WEFE metrics, such as total water and energy demand for irrigation, FE, and GWP. As an example of a trade-off, note that despite scenario 1 increasing total net income and labour demanded, water coverage declined by about 85% with the conversion of traditional to export-oriented crops. Regarding energy use for irrigation, the results show that irrigation already used 29 GWh in the SEP. This energy use would increase considerably under both scenarios due to the increase in the irrigated area.

The crop with the highest average GWP is banana, and the lowest is lemon. Maize ranked third after grapes. Per kilogram of product, maize has the highest GWP when produced using diesel pumping for sprinkler irrigation. Contributions to carbon footprint from on-farm production vary considerably over crops. Agrochemicals constitute a significant source of GWP for banana, cucumbers, grapes, mango, papaya, plantain, and sugarcane, while irrigation contributes significantly for lemon, maize, and papaya. It is notable that for the three export crops, GWP increases significantly under scenario 2.

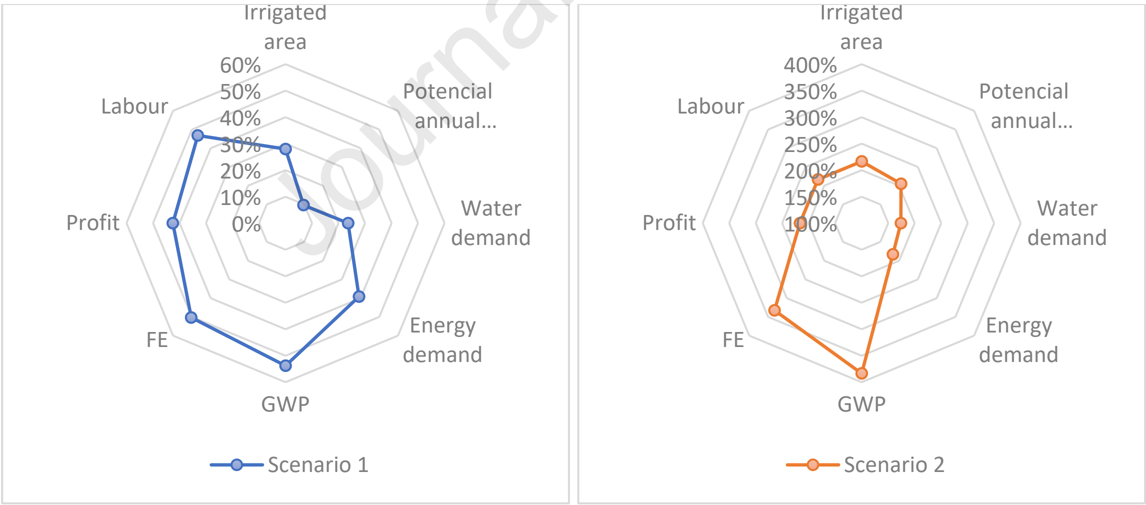

Figure 9 Synergies and trade-offs: variations between the prioritised scenarios and the baseline at the SEP scale

The results for both scenarios show that, despite the crop being mainly produced organically (El Universo, 2021), banana production has the greatest environmental impacts, primarily due to water and energy requirements. On the other hand, while local leadership in the SEP promotes export-oriented agriculture, Ecuador's central government is promoting more traditional crops, such as maize, to concerns about food sovereignty and small producers' livelihood. The Ministry of Agriculture usually subsidises maize production by delivering technology packages (irrigation systems, seeds, fertilisers and agrochemicals) (GAD Provincial de Santa Elena, 2017). The crop is typically consumed as animal feed, mainly for poultry. Remarkably, although maize is a low-profit crop, it consumes a quarter of the total water demand for irrigation in the peninsula.

This study has some limitations worth mentioning. The availability and quality of updated data are one of the study's main limitations. In the case of Ecuador, as is the case for several other BRI countries, there are usually several official sources that report different data at different scales and levels of detail. For example, the INEC reports annual data on the country's main crops based on ESPAC at the farm level. In contrast, the Ministry of Agriculture reports information based on field data collection carried out by its technicians. However, these data are not always published, have no specific periodicity, and are reported at the provincial level. For future studies of nexus in Ecuador, it is recommended to use the forthcoming Agricultural Census (El Universo, 2022).

For the socioeconomic component, it is suggested to use an econometric land allocation model if historical data is available (Melo & Foster, 2021). In this way, future scenarios and impacts on land use, net income, and labour could be more accurately simulated. However, information may not be available. Similarly, the irrigation module in WEAP requires data on irrigation systems, crop development parameters, soil textural characteristics, daily rainfall, and reference evapotranspiration, some of which might not be available (Correa et al., 2022). The environmental impact assessment relies on existing LCI databases that record biophysical inputs and outputs for crop production, which may not always be available for some regions or crops (Correa et al., 2022). To address these limitations, the research team met with stakeholders at different scales (national, provincial, and local). Thereby, the data sources were contrasted, and the results obtained were validated. These meetings also allowed for a better understanding of the information needs of the various actors to bridge the gap between research and policy.

Finally, it should be emphasized that there are uncertainties about the nexus outcomes of interest given that the simulation approach must assume certain factors remain unchanged. To the degree that both input and output prices are uncertain, the results related to the socio-economic analysis should be considered provisional. In addition their is uncertainty with respect to potential climate changes that would alter crop yields and water availability. There is also uncertainty with respect to future technological changes that would alter the relative profitability between different crop, thus changing future cropping patterns, land use, and accompanying water and energy requirements.

5. Conclusions

Nexus-coherent policies are at the core of achieving the SDGs and using scarce resources best. Although this is widely recognised, governments remain slow in achieving the SDGs in part due to a lack of comprehensible and actionable information. SDGs might be complementary in some contexts, but in others, they have competing or even conflicting objectives, so their synergies and trade-offs should be fully understood. As developed in this paper and applied to a specific case in Ecuador, a nexus approach can support the integrated realisation of sustainable development goals, especially if both multidisciplinary and transdisciplinary approaches are taken. The modelling toolkit incorporates a range of methods – a water resources modelling (WEAP), an environmental assessment (LCA), and a socioeconomic analysis – to evaluate water and energy demand, potential annual crop production, global warming potential, freshwater eutrophication, terrestrial acidification, fine particulate matter formation, net incomes, and labour use. More innovatively, this present study uses a participatory approach to define and evaluate future scenarios with stakeholders to ensure the relevance of scenarios for local decision-making. The underlying WEFE perspective provides the multidisciplinary framework to which one can add a transdisciplinary component, yielding an integrated toolkit based on the community context in which stakeholders are a significant source of information. Perhaps, a C should be added for community to the WEFE acronym – WEFEC – to reflect this transdisciplinary framework.

The outputs of the modelling tool presented here represent key evidence for policymakers to help them develop informed and coordinated policies for sustainable agricultural development. This present study focuses on several SDGs: food security (SDG2), clean water (SDG 6), affordable and clean energy (SDG 7), and climate action (SDG 13). This integrated approach can help decision-makers balance development priorities and provide evidence on how the Nexus approach can contribute to a low-carbon green transition in BRI countries. For example, in a policy scenario that aims to reduce carbon emissions, there is a cost, or trade-off, in terms of income and employment.

Moreover, knowing the impacts on energy use, global warming potential and freshwater eutrophication at the level of crop variety and irrigation technology, one can refine policies that influence individual farmers and other decision-makers within the broad scenarios addressed in this present study. Especially in the case of farmers, this would have implications for adopting cleaner production technologies. The nexus toolkit approach allows targeting specific problems, such as that identified here for banana production irrigated by sprinklers using diesel fuels. Once a broad, community-viable policy is defined and evaluated, the approach naturally opens the possibility of future research regarding specific problems and so permits concentrating on potential additional policy interventions for adopting cleaner technologies. For example, to address the notably deleterious WEFE impacts of bananas, especially under the irrigation-expansion scenario evaluated in the present case study, supplementary policies could be introduced to incentivise farmers to switch from diesel-driven sprinkler systems or to alter crop portfolios toward more sustainable production. As another example, the nexus exercise identifies maize as particularly stressful on water resources in the case of irrigation expansion, although less so in the case of the agro-export development scenario. This result opens the possibility of future work involving additional analytical focus on the policy drivers of water use and, therefore, on potential reforms that could lead to cleaner production.

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☒ 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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