Food and Agriculture Organization
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Water–energy–food–health nexus in Lebanon

Case study

SOLAW21 Technical background report

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by

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Contents

Figures:

TABLES

ACRONYMS

AETI	actual evapotranspiration and interception
AREC	Aadvancing Research Enabling Communities (AUB research station)
ASCE	American Society of Civil Engineers
AUB	American University of Beirut
CBA	Cost benefit analysis
CEDRO	Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon
CO_2	Carbon dioxide
EDL	Electricité du Liban
FAO	Food and Agriculture Organization of the United Nations
FAFS	Faculty of Agricultural and Food Sciences
GEF	Global Environment Facility
IRB	Internal Review Board (AUB)
MoA	Ministry of Agriculture
MoE	Ministry of Environment
NPP	Net primary productivity
PV	Photovoltaics
RefET	Reference evapotranspiration
RETI	Reference evapotranspiration and interception
UNDP	United Nations Development Programme
USDA	United States Department of Agriculture
WaPOR	Water Productivity Open-Access Portal (FAO)
WEF	Water–energy–food
WTA	Willingness to accept

EXECUTIVE SUMMARY

Water, energy and food securities are tightly interconnected and have direct implications for human health and well-being (Liu *et al.*, 2017; FAO, 2014; Giampietro *et al.*, 2013; Howells *et al.*, 2013; Mohtar and Daher, 2012, 2016). Addressing the challenges facing these resource systems must be grounded in an understanding of these interconnections, which can be utilized to support integrative planning (Daher and Mohtar, 2015). Trade-off analysis tools can play a critical role in catalysing cross-sectoral dialogues among the stakeholders who regulate, manage, and use these resource systems (Daher *et al.*, 2019). Such dialogues enhance the processes of planning the implementation of the United Nations Sustainable Development Goals (SDGs).

The EAT-lancet commission, striving toward balanced nutritious diets and sustainable food systems, has proposed a list of recommendations for healthy diets. The recommendations include substantial dietary shifts, whereby the global consumption of fruits, vegetables, nuts and legumes would have to almost double, and the consumption of foods, such as red meat and sugar, would have to be reduced by more than 50 percent (Willet *et al.*, 2019). A diet rich in plant-based foods and with fewer animal-sourced foods confers both health and environmental benefits. The Mediterranean diet converges with the EAT-Lancet diet to a high degree and has been shown to have beneficial health effects while leaving a smaller environmental footprint (Hwalla *et al.*, 2015; Naja *et al.*, 2011, 2012, 2013, 2018). The impact of relying heavily on plant-based diets differs according to the availability of water and energy resources and the requirements of food in a particular region. Given the scarcity of water and arable land in arid and semi-arid regions, for which several sectors compete, our research considers the sustainability of the Mediterranean diet. With a system-of-systems view, we also investigate the ways in which alternative water and energy sources could play a role in affecting the sustainability of this diet.

This study used a water-energy-food system-of-systems assessment to evaluate the sustainability of the Mediterranean diet in Lebanon. The specific aims were to: **1) identify and quantify** the critical interconnections between water, energy and food systems in Lebanon; **2) develop a nexus framework** to assess the trade-offs associated with adopting interventions within current water, energy and agriculture portfolios and practices; **3) evaluate stakeholder perceptions** around regional resource challenges and their willingness to implement proposed interventions.

The nexus framework was used to evaluate the trade-offs associated with scenarios involving different crop choices, water sources, and energy sources, with the ultimate goal of sustainability. In addition, due to the economic crisis and currency devaluation in Lebanon, we evaluated different currency conversion rates from US dollars (USD) to Lebanese pounds (LBP). The following criteria were used to evaluate the scenarios: **1) irrigation water (m^3)** required to produce one tonne (or ha) of a given crop, representing the net irrigation need and equivalent to evapotranspiration (ET) of crop – rainfall. To account for field losses unrelated to ET, this figure also reflected irrigation project efficiency; **2) land (ha)** required to produce one tonne of a given crop, calculated using local yield data; **3) energy (kJ)** includes two components –

energy for water and energy for agricultural production. *Energy for water (E_w)* considers surface and groundwater and treated wastewater as possible sources of water for irrigation. Different energy requirements are associated with the pumping, treatment and conveyance of each of these water sources (kJ/m^3). *Energy for agricultural production (E_a)* includes energy for harvesting, planting, spraying and tillage; **4) financial cost (USD)** captures the net cost associated with local production, importing and exporting different crops; **5) environmental impact** quantified CO_2 emissions associated with the different scenarios. The emissions depend on the source of energy needed to procure water for agriculture and the energy needed for agricultural production processes. The sources of energy considered include diesel, fuel oil, solar and wind; **6) nutrition (kcal)** quantifies the nutritional value of the crops according to energy (kcal), protein, fats, carbohydrates, fibre and sugar (value/100g); and **7) reliance (percent)** represents the proportion of imports included in the food basket, indicating the trade-offs expected with increased imports, as opposed to local production.

In addition to the technical evaluation, stakeholder perceptions were evaluated through a survey that targeted 200 farmers, landowners, and public officials in the local water and agriculture industries, mainly in the Beqaa valley.

The case study focuses on selected crops from the Mediterranean and EAT-Lancet diets. It included, for each food group, the main crops that constitute the diet and are produced in Lebanon. A list of 33 crops that make up the Lebanese diet and are consistent with EAT-Lancet recommendations was developed for the study.

The total cultivated land area in Lebanon is about 231 000 ha (MoA and FAO, 2010). The main agricultural areas are mainly found in the Beqaa Valley, representing 42 percent of Lebanon's agricultural land (Machayekhi *et al.*, 2017) where a multiplicity of grains, potatoes, stone fruits, vegetables, grapevine, and feed crops are grown (Haydamous and El Hajj, 2016). The Akkar and North Lebanon regions constitute 26 percent of the cultivated area and produce a range of cereal crops, pulses, vegetables and fruit trees, including olives. South Lebanon encompasses about 22 percent of the agricultural area, producing mainly citrus, olives, bananas, cereals and industrial crops such as tobacco. Mount Lebanon, with about 9 percent of the cultivated area, focuses on vegetable production, especially under greenhouses in the coastal areas, and on fruit trees in the mountains.

The concentration of agricultural activity in the Beqaa and Akkar zones imposes a heavy demand on water and energy resources. Overall, 60 percent of water in Lebanon is directed to agriculture. In the Beqaa valley, agriculture consumes 86 percent of available water resources from rivers, springs, and underground aquifers, and Akkar, over 45 percent of whose cultivated land is irrigated, uses most of its available water resources from rivers, springs and groundwater (El Amine *et al.*, 2018; MoA, 2010; World Bank, 2003). Despite drawing on some rivers, such as the Litani, Al-Kabir or Al-Bared, and hundreds of springs, farmers rely largely (around 80 percent) on groundwater pumping through public and private wells. The diminishing quantity and quality of water is a major challenge. Available water resources are threatened by decreasing precipitation, pollution, uncontrolled pumping, and wastewater seepage (El-Kareh *et al.*, 2018).

As for energy, although the agricultural sector uses diesel oil for most operations (e.g. to pump water, supply greenhouses and traction vehicles, etc.), this represents less than 9 percent of Lebanon's total energy demand (MoE, UNDP and GEF, 2016). The 2017 EDL (Electricité du Liban) electricity generation rate was 15 TWh, which was mainly generated from the use of fossil fuels (over 96 percent). Only 3 percent of electricity is generated from hydropower plants, and 0.35 percent from photovoltaic (PV) panels. Because Lebanon has minimal energy sources (solar, hydropower and wind) and because its potential oil and natural gas are largely unexploited, the country depends heavily on imported primary energy resources.

Another scenario relates to the exchange rate of the local currency. Given the uncertainty of future currency conversion rates, it was critical to identify a strategic food basket that can be produced locally in order to reduce reliance on foreign markets.

The results of the study allowed us to evaluate the sustainability of different scenarios from a resource and nutrition perspective, while accounting for the preferences of farmers as they manage their lands. We found that an investment in growing beans, lentils, chickpeas, and peas locally led to cost savings, increased nutritional value in the locally-produced food basket, and reduced reliance on foreign markets. However, this creates additional water, energy, land and carbon footprints, indicating a need to expand research on improving the yields of highly nutritious crops with low irrigation requirements. On the other hand, if the resources required for crops that exceed local self-sufficiency levels and are exported were reallocated to produce low self-sufficiency, high nutrition, low resource-intensive crops, the result could be reduced reliance on foreign markets and water, energy, cost and emission savings. Given the low yields of such crops, the other key trade-off would be more land allocation for agriculture. One option would be to look at intercropping or understory cropping systems to maximize land use; another option would be to restore marginal degraded land.

An additional objective of the study was to compare ET from field measurements with those from FAO's Water Productivity Open-Access Portal (WaPOR) database, specifically for the Beqaa Valley. This was to validate the output of WaPOR and to identify gaps and possible needs for validation through field data collection. The ET WaPOR validation, using RefET (reference evapotranspiration) from local stations, showed a high level of agreement, especially in semi-arid climates characterized by heterogeneous irrigated landscapes such as are found in the Beqaa Valley. Monthly ET averages were more accurate than the daily averages, especially during the wet seasons; overestimation of the monthly averages mostly occurred during the dry season.

Lessons learned from this study can inform policymaking and planning in Lebanon as the country works to implement the United Nations Sustainable Development Goals (SDGs). The study can be adapted and replicated in other countries in the Middle East and North Africa (MENA) region

I. INTRODUCTION

Building a sustainable economic and environmental future in Lebanon requires acknowledging the nexus between the water, energy and food sectors to simultaneously address water issues, food insecurity and natural hazards (Daher and Mohtar, 2015). Lebanon faces various constraints in access to water, energy, nutritious food and health care. These constraints are expected to increase with prevailing demographic and climate changes. Water, energy, and food security are tightly interconnected, which has direct implications for human health and well-being (Liu *et al*., 2017; FAO, 2014; Giampietro *et al.*, 2013; Howells *et al*., 2013; Mohtar and Daher, 2012, 2016). The links between primary resources systems carry high risks and great vulnerabilities.

Lebanon is one of the world's most water-scarce and food-insecure regions. While the country is considered to occupy a relatively favourable position as far as rainfall and water resources are concerned (FAO, 2008), the amount of renewable water has significantly dropped from more than 1 000 cubic metres/year/person to around 700 cubic metres/year/person in a period of ten years (2000 to 2009) (Machayekhi *et al*., 2017).

Food security is a national priority for Lebanon and many other countries in the region. It requires a water-energy-food (WEF) nexus approach that includes stakeholders beyond the agriculture sector, since unilateral approaches have failed to address the deep environmental and societal issues facing the region. Trade-offs between water, nutrition, and agriculture in Lebanon should be assessed using a WEF approach with the objective of enhancing opportunities for research and development and interventions.

In an effort to promote balanced nutritious diets and sustainable food systems, the EAT-Lancet Commission proposed a list of recommendations for a healthy diet. The recommendations imply substantial dietary shifts, whereby the consumption of fruits, vegetables, nuts and legumes would almost double, and consumption of foods like red meat and sugar would decrease by more than 50 percent (Willet *et al*., 2019). A diet that is rich in plant-based foods and with fewer animal sourced-foods offers both health and environmental benefits. The Mediterranean diet converges with the EAT Lancet diet to a high degree and has been shown to have beneficial health effects with a smaller environmental footprint (Hwalla *et al*., 2015; Naja *et al*., 2011, 2012, 2013, 2018). The feasibility of relying heavily on plant-based diets depends on the availability of water and energy resources and the requirements of food in a particular region. Given the scarcity of water and arable land in arid and semi-arid regions, for which several sectors compete, our research considers the sustainability of the Mediterranean diet. With a system-of-systems view, we also investigate the ways in which alternative water and energy sources could affect the sustainability of the Mediterranean diet.

Initially, the study was focused on the Beqaa valley as the main agricultural area in Lebanon, however, due to the scale of the data available and the type of analysis related to trade, it was decided to broaden the analysis to the national scale.
The study began with a literature review of the availability, uses, policies, governance, initiatives and gaps in knowledge around water and energy in agriculture and other sectors. Some of the challenges currently facing farmers include small farm holdings, which incur high production costs; infrastructure; shifts in temperature and precipitation patterns; reduced water and energy resources; and low incomes. Inefficient and/or unimplemented policies related to water and energy allocation compound the challenges. Stakeholders in the water-energy-food sectors were identified through the literature review and include institutions (governmental and secondary governmental authorities and non-governmental organizations), private suppliers and companies, consumers and end users.

The project was carried out by the Faculty of Agricultural and Food Sciences at the American University of Beirut between July 2019 and September 2020. The aims were to: 1) identify and quantify the critical interconnections between water, energy, and food systems in Lebanon; 2) develop a nexus framework to assess the trade-offs associated with adopting particular interventions in current water, energy, and agriculture portfolios and practices. The trade-offs will be shared with the aim of catalysing a multistakeholder dialogue and promoting integrated research and capacity building in support of health, water, food, and energy security; 3) evaluate stakeholder perceptions of regional resource challenges and assess the willingness to accept (WTA) changes in the production system by stakeholders.

The project also compared evapotranspiration from field measurements with those from FAO's WaPOR database, designed specifically for the Beqaa valley. The objective of this exercise was to validate the output of WaPOR and to identify gaps and possible needs for validation through field data collection.

II. OVERVIEW OF THE CURRENT STATUS

The total cultivated land area in Lebanon is about 231 000 ha (MoA and FAO, 2010). The main agricultural zone is the Beqaa Valley, representing 42 percent of Lebanon's agricultural land (Machayekhi *et al*., 2017); a multiplicity of grains, potatoes, stone fruits, vegetables, grapevine, and feed crops are grown here (Haydamous and El Hajj, 2016). Akkar and North Lebanon constitute 26 percent of the country's cultivated area, growing cereal crops, pulses, vegetables and fruit trees, including olives. South Lebanon represents about 22 percent of the agricultural area and produces citrus, olives, bananas, cereals and industrial crops such as tobacco. Mount Lebanon, covering about 9 percent of the cultivated area, focuses on vegetable production, especially under greenhouses in the coastal areas, and on fruit trees in the mountains. Most farms are smallholdings and do not exceed a single hectare.

The concentration of agricultural activity in the Beqaa and Akkar areas imposes a high demand on water and energy resources. Overall, 60 percent of water in Lebanon is directed to agriculture. In the Beqaa Valley, agriculture consumes 86 percent of available water resources (rivers, springs, and underground aquifers), and in Akkar, where over 45 percent of the cultivated land is irrigated, most of the available water resources from rivers, springs and groundwater are destined for farming (El Amine *et al*., 2018; MoA, 2010; World Bank, 2003). Despite drawing on some rivers, such as the Litani, Al-Kabir and Al-Bared, and hundreds of springs, farmers depend heavily (around 80 percent) on groundwater pumping from public and private wells. Nevertheless, the diminishing quantity and quality of water is a major challenge. Available water resources are threatened by decreasing precipitation, pollution, uncontrolled pumping and wastewater seepage (El-Kareh *et al*., 2018).

With regard to energy, while the agriculture sector uses diesel oil for operations, such as pumping water, drying grains, supplying greenhouses and traction vehicles, this represents less than 9 percent of Lebanon's total energy demand (MoE, UNDP and GEF, 2016). The 2017 EDL (Electricité du Liban) rate of electricity generation was 15 TWh, 96 percent of which came from fossil fuels, 3 percent from hydropower plants, and 0.35 percent from photovoltaic (PV) panels. Because Lebanon has minimal energy sources (solar, hydropower and wind) and because its oil and natural gas potential is largely unexploited, the country is highly dependent on imported primary energy sources. The energy used in agricultural production is divided between diesel (70 percent) and gasoline (30 percent).

The case study focuses on selected crops from the Mediterranean and EAT-Lancet diets that can be produced in Lebanon. Some crops, such as parsley and pine nuts, were not included, despite forming part of the diets, because their consumption and production are minor and detailed trade and national census data are not available. A list of 33 crops that are commonly used in the Lebanese diet and are consistent with EAT-Lancet recommendations was developed for the study. These include cereals (wheat and corn), vegetables (tomato, cucumber, zucchini, lettuce, potato, onion, garlic, pepper), fruits (apple, apricot, peaches, oranges, lemons, grapefruit, tangerines, banana, cherries, grapes, melon, watermelon, strawberries), nut trees (almond, walnut), olives, pulses (dry peas, green peas, dry beans, green beans, broad beans, chickpeas, lentils).

The self-sufficiency values of these selected crops are shown in Figure 1, where it can be seen that some crops, marked in red, have low self-sufficiency, i.e. they are mostly imported. These crops generally have low irrigation requirements and high caloric value or protein concentration. Low self-sufficiency crops include lentils, broad beans, olives, walnuts, peas, and chickpeas and these were included in the trade-off scenarios. These crops, which are mostly pulses, are classified as staple Mediterranean crops that contribute to many traditional dishes, as well as wheat, which is also considered a staple food.

Figure 1. Lebanon's self-sufficiency levels for selected crops

>100% self-sufficiency

Apple	230
Grapes	146
Banana	145
Oranges	136
Grapefruit	131
Peach	123
Cherries	116
Tangerines	110
Lettuce	110
Potato	109
Apricot	107
Lemons	103
Almond	101

> 90% self-sufficiency

Olives	100
Tomato	100
Cucumber	98
Melon	98
Watermelon	96
Zucchini	92

Cereals

Wheat	17
Corn	1

2017

Medium and low self-sufficiency

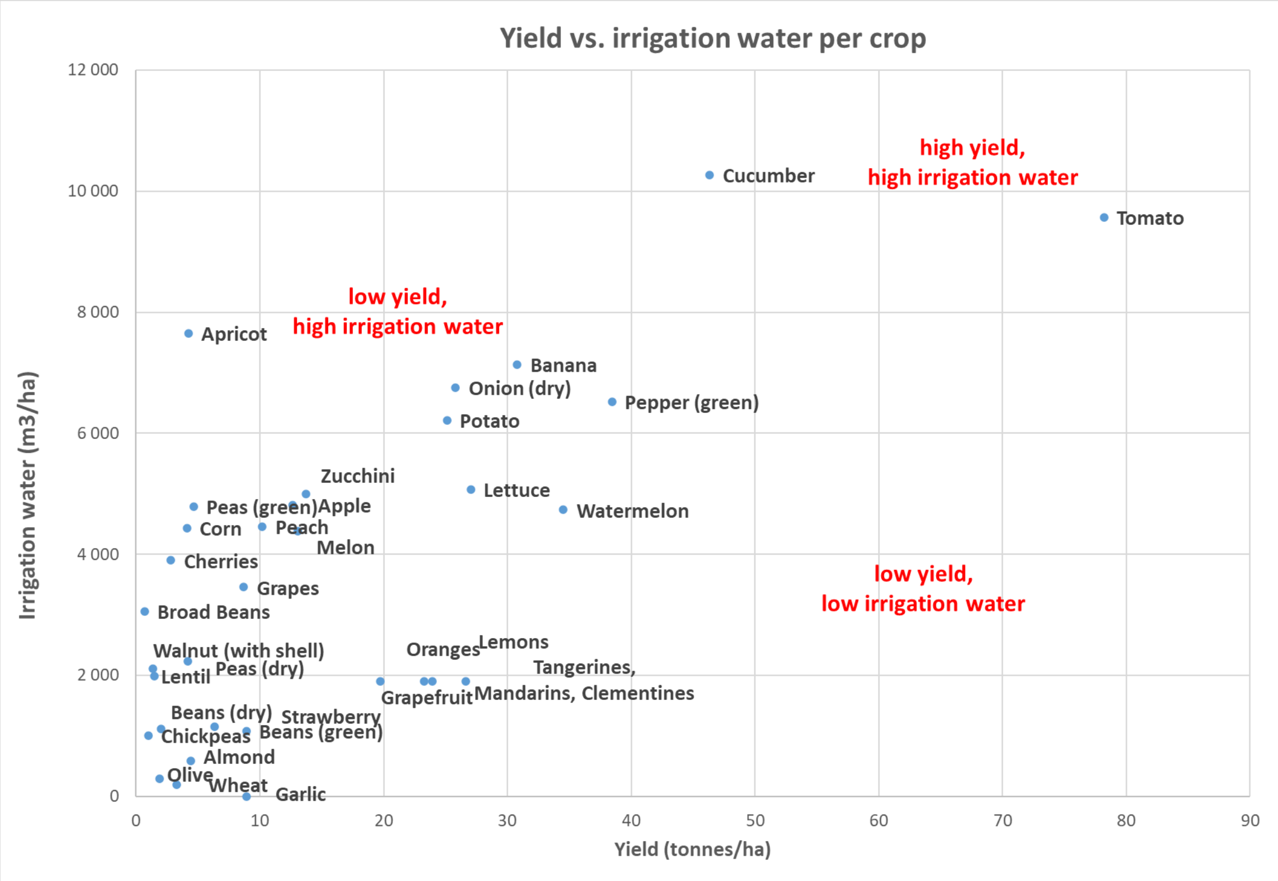
Peas (dry)	90
Beans (green)	89
Onion (dry)	89
Pepper (green)	80
Strawberry	73
Peas (green)	70
Walnut (with shell)	49
Beans (dry)	48
Garlic	25
Chickpeas	19
Lentil	7
Broad Beans	3

Source: Authors own elaboration

Calculated from evapotranspiration data, the three figures that follow (

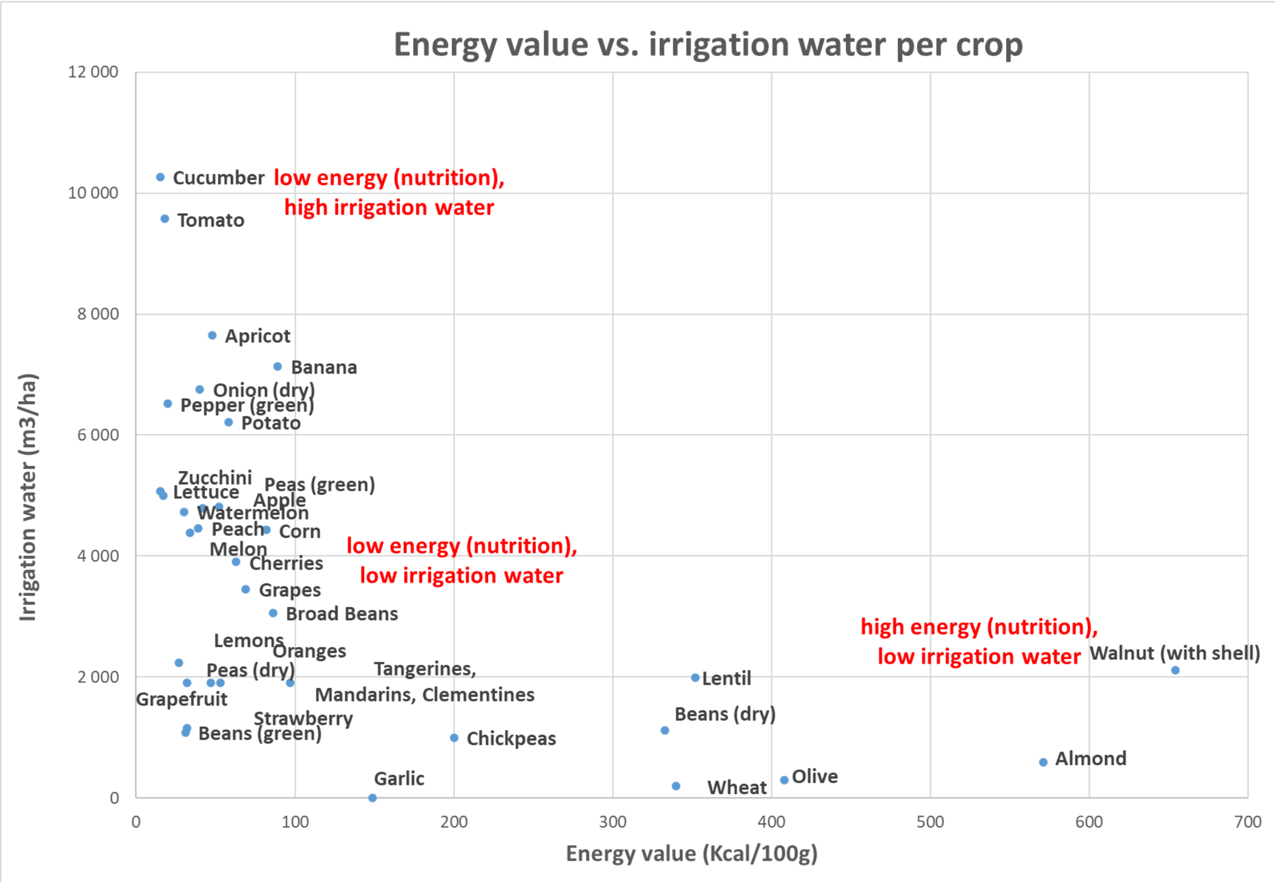
Figure 2,
Figure 3,
Figure 4) indicate the crops that have low irrigation requirements, are high in protein and caloric value and have potential to increase their acreage because they are produced on a small percentage of the agricultural land (more details on this data are presented in Appendix I).

Figure 2. Yield and irrigation water requirements for selected crops



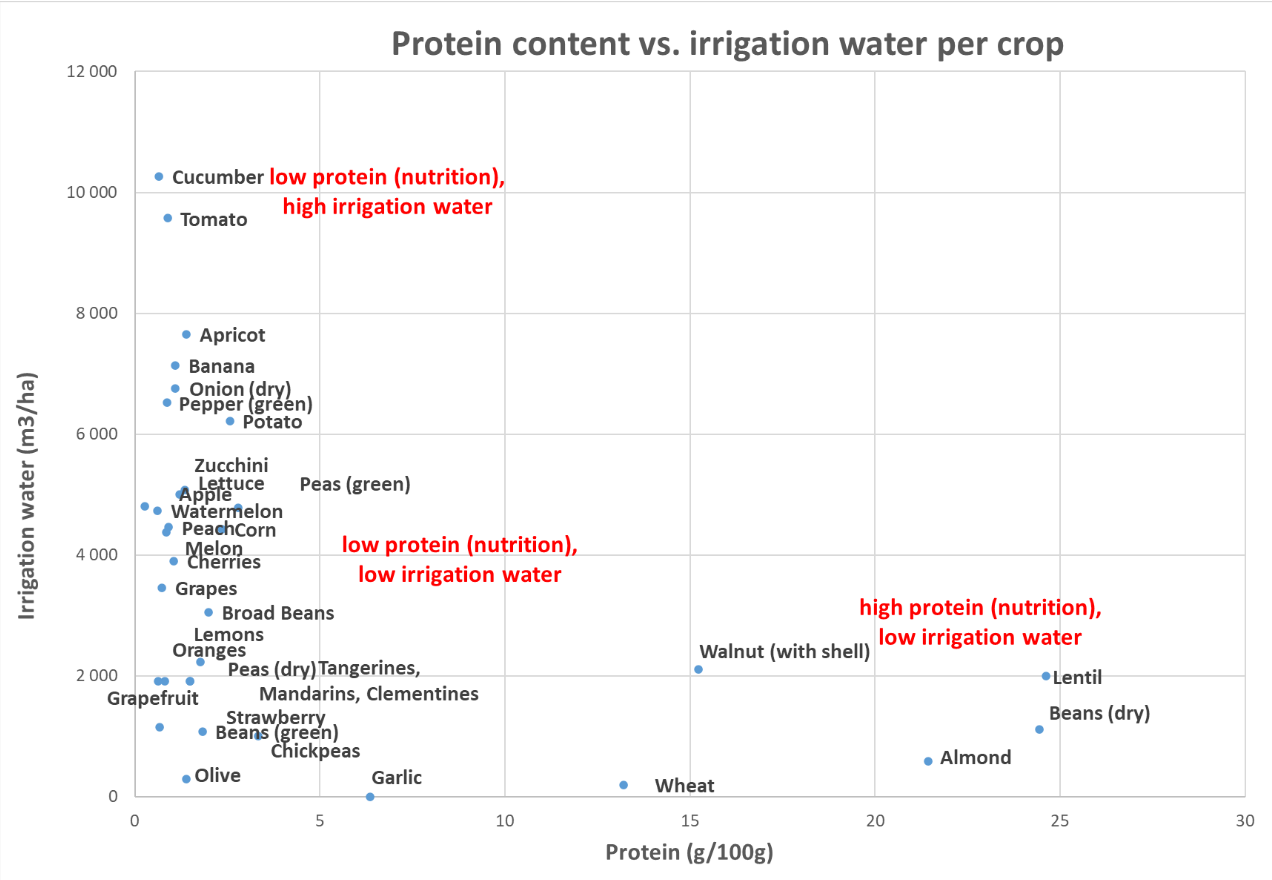
Source: Authors own elaboration

Figure 3. Energy value and irrigation water requirements for selected crops



Source: Authors own elaboration

Figure 4. Protein content and irrigation water requirements for selected crops



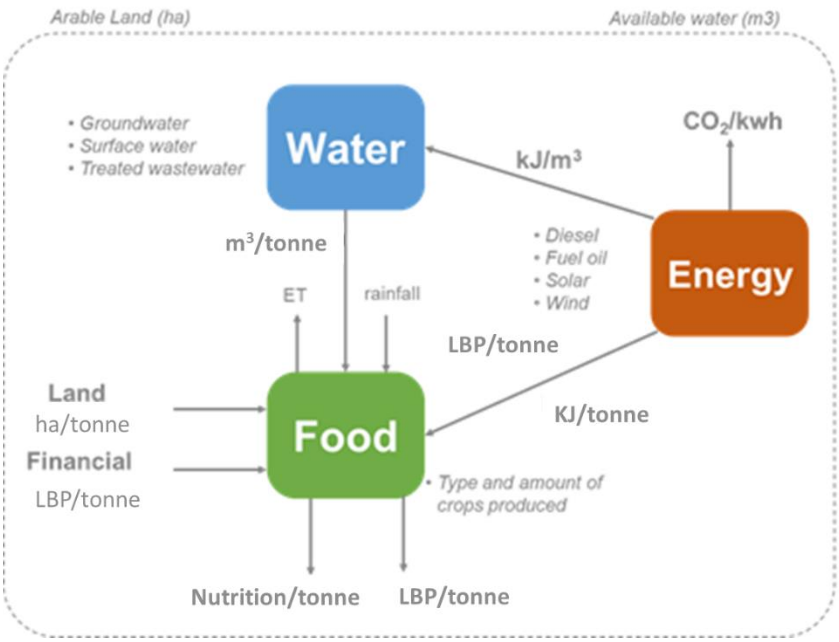
Source: Authors own elaboration

III. OVERARCHING FRAMEWORK AND METHODOLGY

1. Interconnections framework

Figure 5 provides a conceptual representation of the interconnections between the water, energy and food systems considered in this study. Decisions regarding each of the resource systems have an impact on others. Decisions related to the type and self-sufficiencies of crops grown in Lebanon were the basis for quantifying the interconnections across the resource systems. Depending on the resource requirements needed to produce the identified food basket, the choice of specific water and energy portfolios has an impact on the energy requirement, emissions and cost of a given scenario.

Figure 5. Interconnections framework

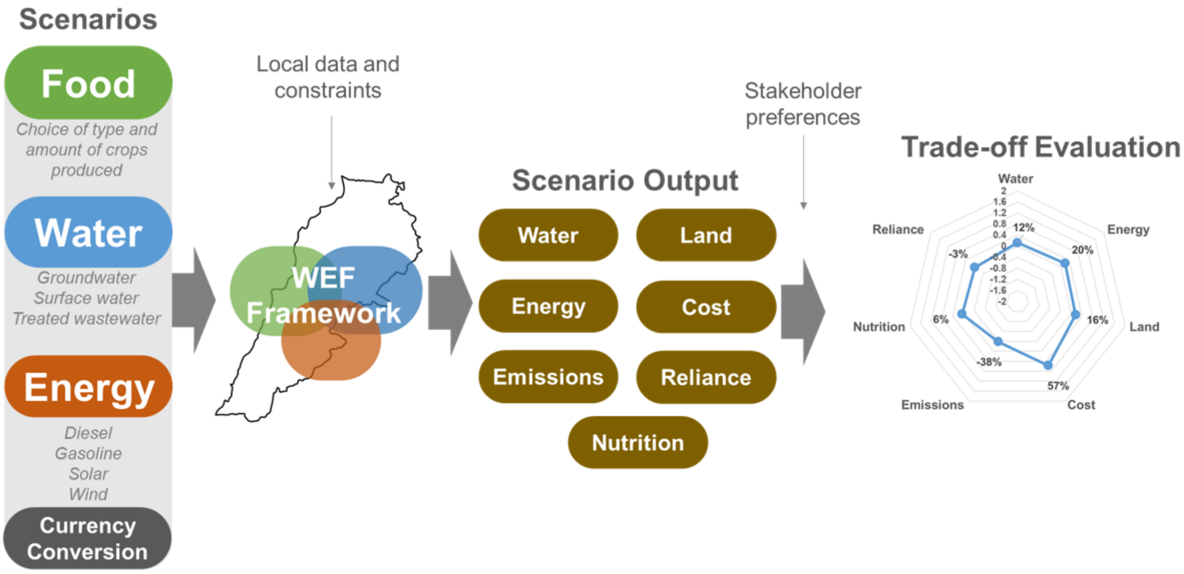


Source: Authors own elaboration

1.1. WEF framework structure

Building on the interconnections framework, this section introduces the WEF nexus scenario evaluation structure (see Figure 6). It outlines: 1) scenario inputs, 2) a sample of background data needs, 3) the list of scenario outputs, 4) and evaluation criteria.

Figure 6. WEF framework structure



Source: Authors own elaboration

1.2. Scenario inputs

1. ***Self-sufficiency:*** The self-sufficiency ratios of the crops are the main building block of the scenarios developed for this study. The user will have the chance to create a scenario with a defined self-sufficiency ratio per crop. Year 2017 data are used for the base case scenario. The choice of a higher or lower self-sufficiency will impact the resources required to produce a specific scenario.

   $\%\ \textit{self-sufficiency ratio}_i = (\textit{production}_i * 100) / (\textit{production}_i + \textit{import}_i - \textit{export}_i)$:
   Due to the lack of data on the spatial variability of soil productivity and suitability, the yield (tonne/ha) per crop was calculated to be equal to the total production (tonnes) divided by the total area harvested (ha) in base year 2017.

2. ***Water sources:*** The second input includes the ratios of water sources for irrigation, including groundwater, surface water and treated wastewater.

   $\%GW + \%SW + \%\ TWW = 100\%$ *irrigation water*

3. ***Energy sources:*** Similarly, the study identified the portfolio of energy sources. The energy sources considered were gasoline, diesel, wind and solar.

   $\%$ *gasoline* + $\%$ *diesel* + $\%$ *solar* + $\%$ *wind* = *100% of energy*

4. ***Currency conversion:*** Given the high dependence of the Lebanese economy on the US dollar, particularly as it relates to trade, and due to the recent

fluctuation in the conversion rate of the Lebanese pound to the dollar, the study explored scenarios under different exchange rates. The official conversion rate for base year 2017 was USD 1 = 1LBP 1 500. In 2020, this rate fluctuated between LBP 3 000 and 10 000 to the US dollar.

$$\% \text{ self-sufficiency ratio}_i = (\text{production}_i * 100) / (\text{production}_i + \text{import}_i - \text{export}_i)$$

1.3. Scenario outputs

The following describes resources and indicators used to assess different scenarios.

1. ***Irrigated water (W) (m³) required to produce a tonne (or ha) of a crop***: This represents the net irrigation need, equivalent to ET of crop – rainfall. This figure also takes into consideration an irrigation project efficiency to account for losses at the field not related to ET.

To calculate ET and irrigation requirements, weather data were collected from several stations across Lebanon. The main production regions for each crop were identified using the land use land cover map developed by the Center for Remote Sensing at the Lebanese Council for Scientific Research (CNRS) in 2017. Average weather data in the locations where each crop is mainly grown were used to first calculate reference ET (ET_o), using the FAO Penman Monteith equation, then crop coefficients from the FAO database (Allen *et al*., 1998) were used to generate crop ET:

$$ET_c = ET_o \times K_c$$

The same was done to determine the effective rainfall for each crop based on the location where it is most prevalent. Climatic datasets were available for the period 2010 to 2018 for most stations.

2. ***Land (ha) required for producing a tonne of a given crop***: This was calculated using local yield data.

$$Land_{crop\,i}\,(ha) = \Sigma\,[\text{production}_i\,(\text{tonne}) / \text{yield}_i\,(\text{tonne/ha})]$$

3. ***Energy (kJ)***: We considered two components: energy for water (Ew) and energy for agricultural production (Ea).

$$E\,(kJ) = E_w\,(kJ) + E_a\,(kJ)$$

Energy for water (E_w): Groundwater (GW), surface water (SF), and treated wastewater (TWW) are all possible sources of water for irrigation. There is a different energy tag associated with pumping, treatment and conveyance of different water sources (kJ/m³). Therefore, the choice of water sources for irrigation has different energy costs (E_w). Whether it is surface or groundwater pumping, treating water or wastewater or desalination, each has its respective energy footprint depending on the domestically-available plants and their efficiencies.

$$E_w (kJ) = \%GW \times E_{GW} (kJ) + \%SF \times E_{SF} (kJ) + \%TWW \times E_{TWW} (kJ)$$
$$\text{where } GW+SF+TWW = \text{irrigated water } W\ (m^3)$$

Energy for agricultural production (E_a): This includes the energy required for harvesting, tillage, planting and spraying. The total area of land needed for each crop and the total energy for each of four practices (harvesting, tillage, planting and spraying) was quantified for each scenario. The energy requirements for these practices are site-specific and would heavily rely on the type of technologies and machinery that are used. Data about energy requirements and current technologies were collected in meetings with farmers.

$$E_a = E_{tillage} + E_{harvesting} + E_{planting} + E_{spraying}$$
$$\text{where } E_{tillage} = \Sigma\ [tillage_{Crop\ i}\ (\text{kJ/ha}) \times \text{production}_{\text{crop i}} (\text{tonne}) / \text{yield}_{\text{crop i}} (\text{tonne/ha})\ ]$$
$$\text{Similarly, for } E_{harvesting} + E_{planting} + E_{spraying}$$

4. Cost (in Lebanese pounds – LBP): This represents the net cost of locally producing, importing and exporting relevant food products. The local production of crops is affected by the source of energy and water used to grow them.

$$Cost\ (LBP) = \Sigma\ [cost\ of\ local\ production_i] + \Sigma\ [cost\ of\ import_i] - \Sigma\ [export\ price_i]$$

5. Environmental impact: The CO_2 emissions associated with different scenarios were quantified. Emissions depend on the source of energy needed to secure water for agriculture, C_w (pumping, treatment, conveyance), and the energy that goes into the various agricultural production processes, C_a (tillage, harvest, spraying, planting). The sources of energy considered for irrigation were: gasoline, diesel, wind and solar, while the sources of energy for the other agricultural activities were gasoline and diesel.

$$C\ (\text{tonne } CO_2) = C_w + C_a$$
$$C_w = C_{GW} + C_{SW} + C_{TWW}$$
$$C_a = C_{tillage} + C_{harvest} + C_{spraying} + C_{planting}$$
$$C_{GW} (\text{tonne } CO_2) = \%\ E_{diesel} (\text{kwh}) \times \text{diesel} (\text{tonne } CO_2/\text{kwh}) + \%\ E_{gasoline} (\text{kwh}) \times \text{gasoline} (\text{tonne } CO_2/\text{kwh}) + \%\ E_{wind} (\text{kwh}) \times \text{wind} (\text{tonne } CO_2/\text{kwh}) + \%\ E_{solar} (\text{kwh}) \times \text{solar} (\text{tonne } CO_2/\text{kwh}),$$
$$\text{similarly, for } C_{sw}, C_{TWW}$$
$$C_{tillage\ i} (\text{tonne } CO_2) = [\text{production}_i (\text{tonne}) \times E_{tillage} (\text{kJ/ha}) \times C_{diesel/gasoline} (\text{tonne } CO_2/\text{kJ})\ ] / \text{yield}_i (\text{tonne/ha})$$
$$\text{similarly, } C_{harvest}, C_{spraying}, C_{planting}$$

6. Nutrition: The nutritional value of the crops was quantified according to their energy (kcal), protein, fats, carbs, fibre and sugar (value/100g) content. This assessment accounted for the nutritional value of the crops produced and consumed locally, while not accounting for the exported portion of the products.

$$E\ (\text{kcal}) = \text{energy content (kcal/100g)}_i \times \text{minimum [production}_i\ \text{(tonne), consumption}_i\ \text{(tonne)} \times (\%\ \text{edible}_i)] \times 10^4$$

Similarly, we calculated grams protein, fats, carbs, fibre and sugar.

7. Reliance: This indicator represented the proportion of imports that constitutes a consumed food basket. It is intended to indicate the trade-offs expected with increased imports, as opposed to local production.

$$\%\ \text{reliance} = [\Sigma\ [\text{import}_{\text{crop } i}] \ /\ \Sigma\ [\text{consumption}_{\text{crop } i}]] \times 100$$

Two main constraints were considered when developing the scenarios: available arable land (ha) and water available (m^3) for agriculture.

1.4. Collection of local data

To develop and evaluate these scenarios, it was necessary to collect local data on crops produced in Lebanon. This included information on available water and energy sources; water requirements for different crops; yields for different crops; energy requirements for water pumping, treatment and conveyance; energy requirements for tillage, harvesting, spraying and planting; and trade data. The data came from FAO databases, the Ministry of Agriculture's census report, the United States Department of Agriculture (USDA)'s food composition database, local weather data, surveys and other published work. Samples of the data can be found in Appendix I.

1.5. Evaluation criteria

The main goal of the framework was to evaluate trade-offs associated with different scenarios around crop choices, water sources, and energy sources. The framework allows the quantification of how much more, or less, output should be expected when comparing a new scenario to practices in 2017. One scenario might require more water, but less land. Another scenario might be more costly but require less energy. In addition, "preference coefficients" provide a weighting for the various scenario outputs. These coefficients reflect the readiness of farmers to switch to a proposed scenario and the relative importance of reducing each of the resource requirements (water, energy, emissions, land, financial). In other words, they help determine which costs under a given scenario are more important to reduce relative to others. The higher the importance of a particular coefficient, the more critical it will be to adopt a scenario with a lower respective resource requirement. In this report, we surveyed farmers as key stakeholders in the decision-making process. Moving forward, the goal is to use the analytics developed for this study to bring together cross-sectoral focus groups to reflect stakeholder preferences as we evaluate different pathways forward.

2. Survey and data collection

Water, energy, and food systems do not exist in a vacuum. They are managed, regulated and consumed by different actors making decision at various levels. These decisions are often influenced by the actors' preferences. This report focuses on farmers' preferences and their willingness to adopt different practices at the farm scale. Such practices include shifting to different crops, alternative water and energy sources. We surveyed 200 farmers in the Beqaa Valley to learn about farmers' priorities in terms of minimizing water, energy, land, emissions and cost, and maximizing nutritional value.

2.1. Survey sections and sample size

The farmer survey was divided into two sections: i) taking stock of current agricultural practices and data on crops, water use, fertilization, energy use and agricultural operations; and ii) quantifying the willingness of farmers to change their farming practices (e.g. by switching to alternative resources, changing cropping patterns, etc.). The survey was approved by the American University of Beirut (AUB)'s Internal Review Board (IRB). The survey can be found at Appendix II.

Before starting data collection, we conducted a sample size calculation to determine how many people needed to be interviewed to ensure the survey sample was representative of the target population. Given that no records are available on the number of farmers in the Beqaa Valley, the population size (total number of farmers) was estimated based on average holding size and total agricultural area. According to the 2010 agricultural census, the total farmed area in the Beqaa is about 99 274 ha distributed across 34 085 holdings or farmers, resulting in an average size of 2.9 ha per holding. Based on the number of farmers, a statistically representative sample size for data collection is between 200 and 245 farmers, with confidence interval of 95 percent and a 5 percent margin of error.

Participants in the survey were drawn from contacts involved in previous projects with AUB and Advancing Research Enabling Communities (AREC), an AUB research station.

2.2. Challenges in data collection

The survey revealed that a major gap was the quality and accuracy of data on farming practices since most farmers were only able to provide estimates. Many farmers lacked knowledge about the level of resources they consumed or used on their farms. For example, there were no flowmeters at the farm level or at water sources to quantify water use. The estimates provided by the farmers (e.g. number of irrigation hours, pipe sizes) were very rough, making it difficult to determine water use per crop. In addition, calculating on-farm energy consumption was challenging, given that the main sources of energy include diesel, public electricity (which is bundled with the house bill in many cases), or an 'unlisted' electricity source that is not accounted for in the energy bill. At most, a farmer would know how much they paid for diesel in a given year. That figure would include energy for irrigation, diesel for machinery, trucks and transportation. Nor do famers usually know much about their fertilizer inputs. They normally take a 'recipe' from fertilizer providers/agricultural engineers; this is rarely based on soil analysis, leading to overfertilization. Another challenge was to calculate the yields of vegetable producers, who harvest on a daily or weekly basis. because most farmers do not keep records. Instead, they would estimate how many boxes of vegetables they harvest per day that would then be converted to an estimate of yield.

As mentioned previously, the study initially aimed to focus on the Beqaa Valley as a case study. However, given the scale of available data, especially related to food trade and production, and the fact that that not all of the selected crops can be grown in Beqaa due to reasons of agroecology and suitability, it was decided to conduct the WEF framework analysis on a national scale and to focus data collection on farmers in Beqaa. It is important to note that the cost benefit analysis and the life cycle cost analysis were embedded in the calculation on the WEF framework and not carried out as separate exercises

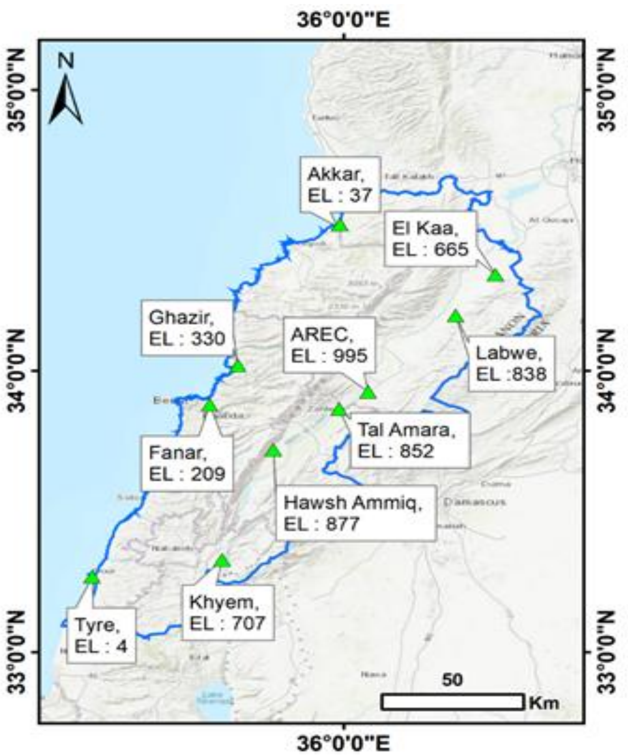
3. WaPOR data validation

3.1. Datasets

i. Ground data

Daily meteorological data were collected from ten weather stations across Lebanon: Akkar, El Kaa, Fanar, Ghazir, Hawsh Ammiq, Khyem, Labwe, Tal Amara, AREC and Tyr (see
Figure 7). The weather station data used for the study included daily minimum and maximum air temperature (°C), wind speed (m/s), solar radiation (MJ/m^2) (for AREC and Tal Amara only), and dew point (°C) for the study period 2009–2015 (for most of the weather stations), 2012–2020 (for AREC), and 2019–2020 (for Labwe). Some of the stations do not measure solar radiation; in this case, missing values were calculated using equations from Allen *et al*. (1998). The weather station data was used as an input to the ReFET software designed by Richard G. Allen (University of Idaho, United States of America). The ReFET software calculates solar radiation as suggested by the FAO 56 Penman-Monteith equation (see below).

Figure 7. Locations of the weather stations with their corresponding elevations



Source: Authors own elaboration, base map "ESRI Terrain map", 2020. www.arcgis.com/apps/mapviewer/index.html?layers=58a541efc59545e6b7137f961d7de883 , Modified to comply with UN. 2020.

ii. WaPOR reference evapotranspiration data

The analysis dataset was the daily reference ET–WaPOR V2.1 Level 1 product with a resolution of 20 km, which is available on the WaPOR portal (https://wapor.apps.fao.org/home/WaPOR_2/1). Reference evapotranspiration was calculated using the Penman-Monteith equation adapted to remote sensing input data. The Penman-Monteith equation (Monteith, 1965) uses the combined approaches of the energy balance and the aerodynamic equations (see Allen *et al*., 1998). WaPOR uses weather data input (air temperature, relative humidity, wind speed, air pressure and aerosol optical depth), obtained from ModernEra Retrospective Analysis for Research and Applications (MERRA) up to the start of 21 February 2014, and the Goddard Earth Observing System (GEOS-5) after 21 February 2014 (Rienecker *et al.*, 2011).

$$ET_o = \frac{\Delta\ (R_n - G)\ +\ \rho_{air}\, c_{air} \left(\frac{e_s - e_a}{r_a}\right)}{\Delta\ + \gamma\ \left(1\ + \frac{r_s}{r_a}\right)}$$

Where: λ: latent heat of evaporation (J kg^{-1}); ETo: evapotranspiration (mm/day); R_n: net radiation (W m^{-2}); G: soil heat flux (W m^{-2}); ρ_a: air density (kg m^{-3}); c_a: specific heat of dry air (J kg^{-1} K $^{-1}$); e_a: actual vapour pressure of the air (Pa); e_s : saturated vapour pressure (Pa); Δ: slope of the saturation vapour pressure vs. temperature curve (Pa K^{-1}); γ: psychrometric constant (Pa K^{-1}); r_a: aerodynamic resistance (s m^{-1}); r_s: bulk surface resistance (s m^{-1}). The soil heat flux G is net 0 for the whole day.
The aerodynamic equation for the reference crop is parametrized considering the crop height of 0.12m,

$$r_a = \frac{208}{u_{obs}}$$

Δ, γ, and ρ_a are a function of air temperature and elevation. The resistance to vapour flow from the transpiring reference crop is set to 70 s m^{-1}. The net radiation R_n is solved using the radiation balance:

$$R_n = (1 - \alpha_0)R_S - L^* - I$$

where α_o is the surface albedo (a fixed albedo of 0.23 is used for the reference crop); Rs is incoming solar radiation (W m^{-2}); L^* is net longwave radiation (W m^{-2}); I is the energy needed for interception (W m^{-2}), which is set at 0 for calculating RefET.

3.2. Accuracy assessment

Statistical analysis was performed between the RefET generated from the observed weather station data and the modelled WaPOR reference ET. Statistical metrics computed are as follows: the root mean square error (RMSE), the mean absolute error (MAE), the mean absolute percentage error (MAPE), the relative RMSE, the mean bias error (MBE), and the index of agreement (d).

IV. RESULTS AND DISCUSSION

1. Scenario evaluation

This section includes sample scenarios that were assessed using the evaluation framework. The goal was to highlight the trade-offs associated with different scenarios as the water, energy, and agricultural portfolios change relative to the base year 2017.

1.1. Base year scenario 2017

Table 1 shows the self-sufficiency (SS) ratios of the selected crops, water sources, energy sources and currency conversion rate in 2017.

Table 1. Self-sufficiency ratios, water sources, energy sources and currency conversion rate in 2017

Crops	2017 %SS	Crops	2017 %SS	Water sources	%	Energy for water	%
Wheat	17	***Watermelon***	96	***Groundwater***	80	***Diesel***	100
Corn	1	***Melon***	98			***Gasoline***	0
Potato	109	***Peach***	123			***Wind***	0
ra	110	***Apricot***	107			***Solar***	0
Tomato	100	***Grape***	146	***Surface water***	20	***Diesel***	100
Zucchini	92	***Bean (dry)***	48			***Gasoline***	0
Pepper (green)	80	***Bean (green)***	89			***Wind***	0
Cucumber	98	***Broad bean***	3			***Solar***	0
Onion (dry)	89	***Lentil***	7	***Treated wastewater***	0	***Diesel***	0
Garlic	25	***Chickpea***	19			***Gasoline***	0
Apple	230	***Pea (dry)***	90			***Wind***	0
Grapefruit	131	***Pea (green)***	70			***Solar***	0
Lemon	103	***Almond***	101	**Energy for food**		**Currency conversion**	
Orange	136	***Walnut (with shell)***	49	***Gasoline***	30%	***USD***	1
Tangerine, Mandarine, Clementine	110	***Cherry***	116	***Diesel***	70%	***LBP***	1500
Banana	145	***Olive***	100				
Strawberry	73						

Source: Authors own elaboration

Table 2. outlines the outputs for the base scenario, while Table 3 shows a breakdown of energy, cost, emissions and nutrition for the base scenario.

Table 2. Scenario outputs for base scenario 2017

2017		
Water	(m^3)	464 793 307
Energy	(GJ)	1 547.1
Land	(ha)	198 179
Cost	(billion LBP)	1 538.5
Emissions	(tonne CO_2)	105 743.8
Nutrition	(kcal)	1.4 E+14
Reliance	ratio (I/C)	0.45

Source: Authors own elaboration

Table 3. Breakdown of energy, cost, emissions, and nutrition for base case scenario

ENERGY (GJ)	**2017**	**EMISSIONS (tonne CO_2)**	**2017**
E 4 F (GJ)	34.46	**C 4 Food**	2 215.51
E4 Harvest	6.05	*C 4 Harvest*	388.77
E4 Tillage	21.23	*C 4 Tillage*	1 365.02
E 4 Planting	2.34	*C 4 Planting*	150.33
E 4 Spraying	4.84	*C 4 Spraying*	311.40
E 4 W (GJ)	1 512.62	**C 4 Water (tonne CO_2)**	103 236.65
COST (billion LBP)	**2017**	**NUTRITION**	**2017**
Local production	997.40	*Energy (kCal)*	1.4E+14
Import	564.26	*Protein (g)*	3.6E+12
Export	-155.56	*Fats (g)*	5.8E+12
Cost of energy for water	132.35	*Carbs (g)*	2.4E+13
		Fibre (g)	4.8E+12
		Sugar (g)	4.5E+12

Source: Authors own elaboration

Having established the different resource requirements and outputs for the base scenario, the following section will explore the impact of different interventions relative to the base year by changing the self-sufficiency of different crops and choosing different water and energy sources under different currency conversion rates.

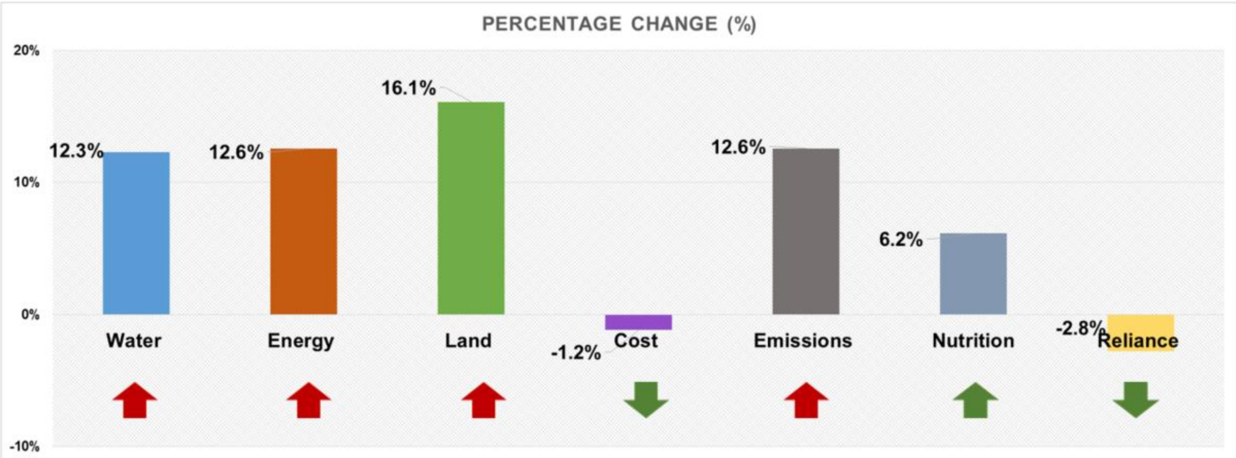
1.2. Scenario A. Nutrition-centric

Given the low self-sufficiency of beans, chickpeas and peas, despite their high nutritional content and low irrigation needs, this scenario explores increasing the self-sufficiency of these crops to 100 percent. The energy and water sources and ratios, as well as the currency conversion rates, are kept at 2017 values.

Scenario A. Summary

- **Increase** production of beans (green, broad, dry), lentils, chickpeas and peas (dry, green) to 100 percent SS.
- **Water:** 80 percent groundwater, 20 percent surface water;
- **Energy–water:** 100 percent diesel;
- **Energy–food:** 70 percent diesel, 30 percent gasoline;
- **Currency conversion**: USD 1 = LBP 1 500.

Figure 8. Percentage change in outputs relative to 2017 (Scenario A)



Source: Authors own elaboration

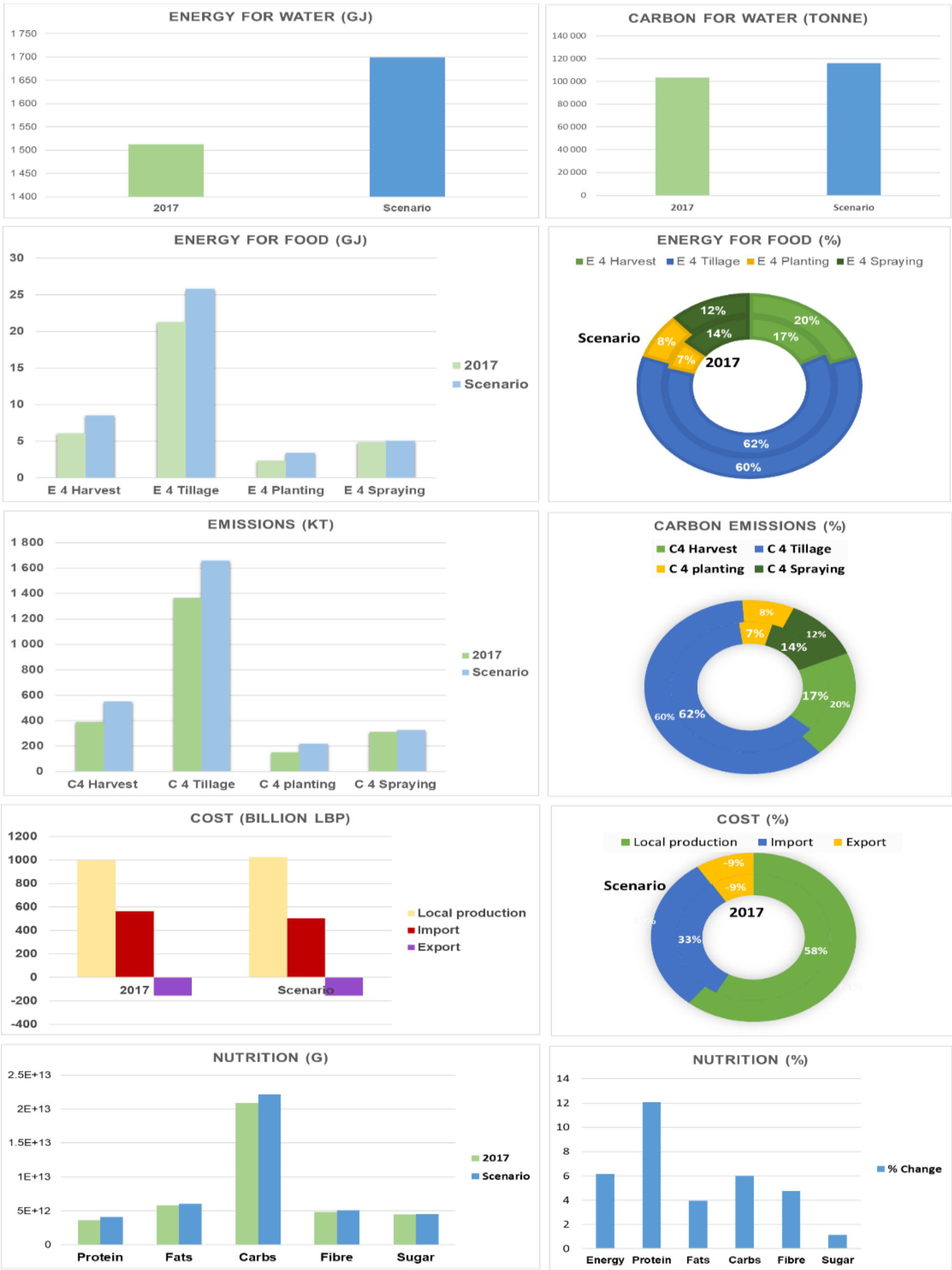
An analysis of this scenario shows that around 12 percent more water and energy and 16 percent more land is required to achieve full self-sufficiency for beans, lentils, chickpeas and peas (see Figure 8). The arable land required is estimated to be around 209 072 ha (CNRS, 2017). This scenario exceeds the arable limit by 10 percent. The additional land requirement could be achieved by restoring degraded or unexploited lands, which comes at a cost. Alternatively, improved management practices could increase the productivity of agricultural land and bridge the land gap. The 1.2 percent cost saving is due to the difference in costs incurred for local production versus imports. Given that the main source of energy in the base scenario is diesel, this scenario produces 12 percent more emissions. It also contributes to an increase of 6 percent in locally-produced kcal of the overall food basket. Furthermore, it reduces reliance on imports by 2.8 percent.

Key trade-offs

By investing in growing beans, lentils, chickpeas and peas, we see cost savings and increased nutritional value in the locally-produced food basket and reduced reliance on foreign markets. In return, this comes with additional water, energy, land and carbon footprints.

Figure 9 shows a breakdown of the scenario output as it compares to the 2017 base scenario in terms of amounts and percentages

Figure 9. Scenario A breakdown.



Source: Authors own elaboration

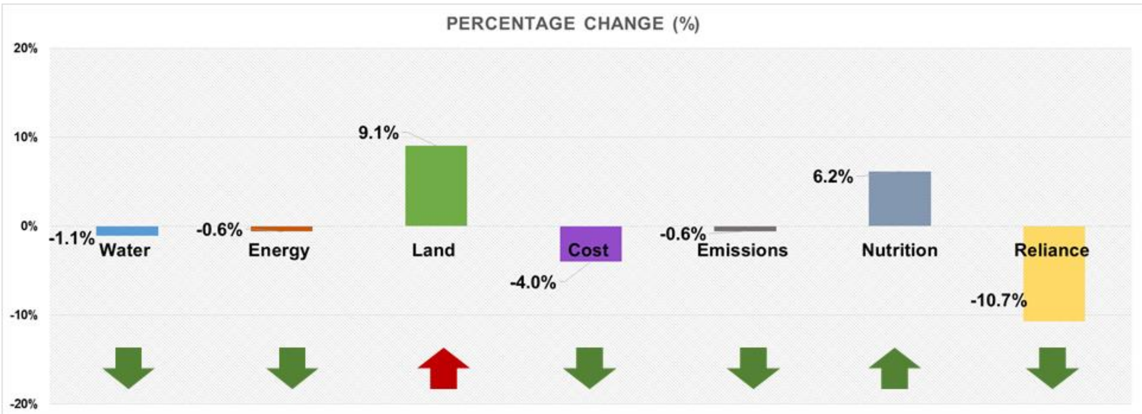
1.3. Scenario B1. Shifting from exports to more local production

This scenario explores the possibility of reducing the local production of crops that currently exceed full self-sufficiency (SS > 100 percent) and are exported. These include potatoes, lettuce, apples, grapefruit, citrus fruits, banana, grapes, apricots, peaches, almonds and cherries. As in Scenario A, Scenario B1 considers increasing the self-sufficiency of beans, lentils, chickpeas and peas to 100 percent. Water and energy sources and ratios as well as currency conversion are the same as in 2017.

Scenario B1. Summary

- **Increase** production of beans (green, broad, dry), lentils, chickpeas and peas (dry, green) to 100 percent SS.
- **Decrease** production of crops with SS > 100 percent to SS = 100 percent; no exports, no additional imports of these products.
- **Water:** 80 percent groundwater, 20 percent surface water;
- **Energy–water:** 100 percent diesel;
- **Energy–food:** 70 percent diesel, 30 percent gasoline;
- **Currency conversion**: USD 1 = LBP 1 500.

Figure 10. Percentage change in outputs relative to 2017 (Scenario B1)



Source: Authors own elaboration

In this scenario, we observe a decrease in water and energy requirements, initially allocated to locally-produced and exported crops in the base scenario. One of the key challenges of growing beans, lentils, chickpeas and peas is their low yield compared to other crops. Despite a reduction in the self-sufficiency of many currently-produced and exported crops, this scenario still requires a 9.1 percent increase in land compared to 2017 (see Figure 10). Innovative breeding to produce higher-yielding varieties will improve these estimates. The reduction in energy requirements comes with a reduction in carbon footprint. The increase in nutritional value is similar to that in Scenario A, but with a greater decrease in reliance on imports. This is attributed to limiting imports of some crops to 100 percent SS, which are also no longer exported according to this scenario. Our analysis shows a 4 percent decrease in cost due to the replacement of imported pulses with locally-produced

pulses. This decrease in cost was slightly higher than the losses resulting from the halt in exports, hence the 4 percent decrease.
shows the breakdown of Scenario B1 outputs.

Key trade-offs

By reallocating resources from crops currently produced at more than local full self-sufficiency and exported to produce low self-sufficiency, high nutrition, low resource-intensive crops, we can reduce reliance on foreign markets, while realizing water, energy, cost and emissions savings. Given the low yield of such crops, the other major trade-off will be more land allocation for agriculture.

Figure 11. provides a breakdown of Scenario B1 outputs

Source: Authors own elaboration

1.4. Scenario B2. Shifting from exports to more local production with currency fluctuation

The difference between scenario B1 and B2 is in the currency conversion rate of the USD to the Lebanese pound. This scenario explores a conversion rate of USD 1 = 4 000 LPB (compared to 1 USD = 1 500 LBP in 2017).

Scenario B2. Summary

- **Increase** production of beans (green, broad, dry), lentils, chickpeas and peas (dry, green) to 100 percent SS.
- **Decrease** production of crops with SS > 100 percent to SS = 100 percent; no exports, no additional imports of these products.
- **Water:** 80 percent groundwater, 20 percent surface water;
- **Energy–water:** 100 percent diesel;
- **Energy–food:** 70 percent diesel, 30 percent gasoline;
- **Currency conversion**: 1 USD = 4 000 LBP.

Figure 12. Percentage change in outputs relative to 2017 (Scenario B2)

Source: Authors own elaboration

This scenario highlights the impact of the new currency conversion rate on the cost indicator. It is no surprise that, given the 4 000/1 500 (2.67-fold) increase in the conversion rate, there is an overall cost increase relative to 2017 (see Figure 12). For this assessment, import costs and export revenues were calculated according to the new rate. Since many of the primary resources used on the farm are imported, it was assumed that the increase in local production costs would be equal to 50 percent of the increase between the 2017 rate and the new rate. Due to uncertainty around future currency conversion rates, it becomes ever more critical to identify a strategic food basket that can be produced locally to reduce reliance on foreign markets.

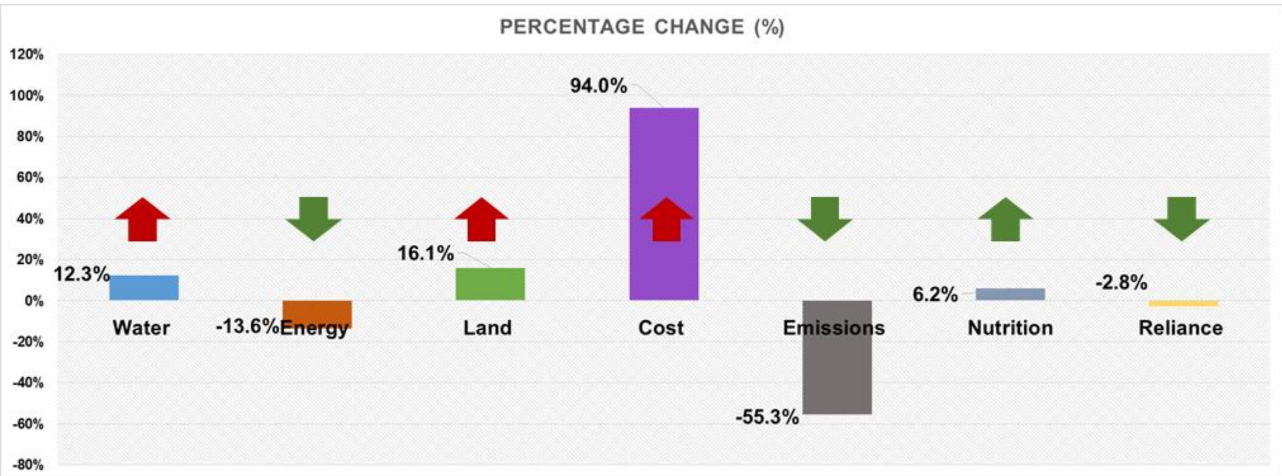
1.5. Scenario C. Scenario A + renewable energy + treated water + currency fluctuation

Scenario C explores the potential of diversifying the water and energy portfolios, building on the main components of Scenario A. This scenario includes shifting from diesel to solar energy as the main energy source for pumping water on farms. It also explores the impact of using treated wastewater as part of the irrigation portfolio.

Scenario C. Summary

- **Increase** production of beans (green, broad, dry), lentils, chickpeas and peas (dry, green) to 100 percent SS.
- **Water:** 60 percent groundwater, 20 percent surface water, 20 percent treated wastewater;
- **Energy–water:** 50 percent diesel, 50 percent solar;
- **Energy–food:** 70 percent diesel, 30 percent gasoline;
- **Currency conversion**: 1 USD = 4 000 LBP.

Figure 13. Percentage change in outputs relative to 2017 (Scenario C)



Source: Authors own elaboration

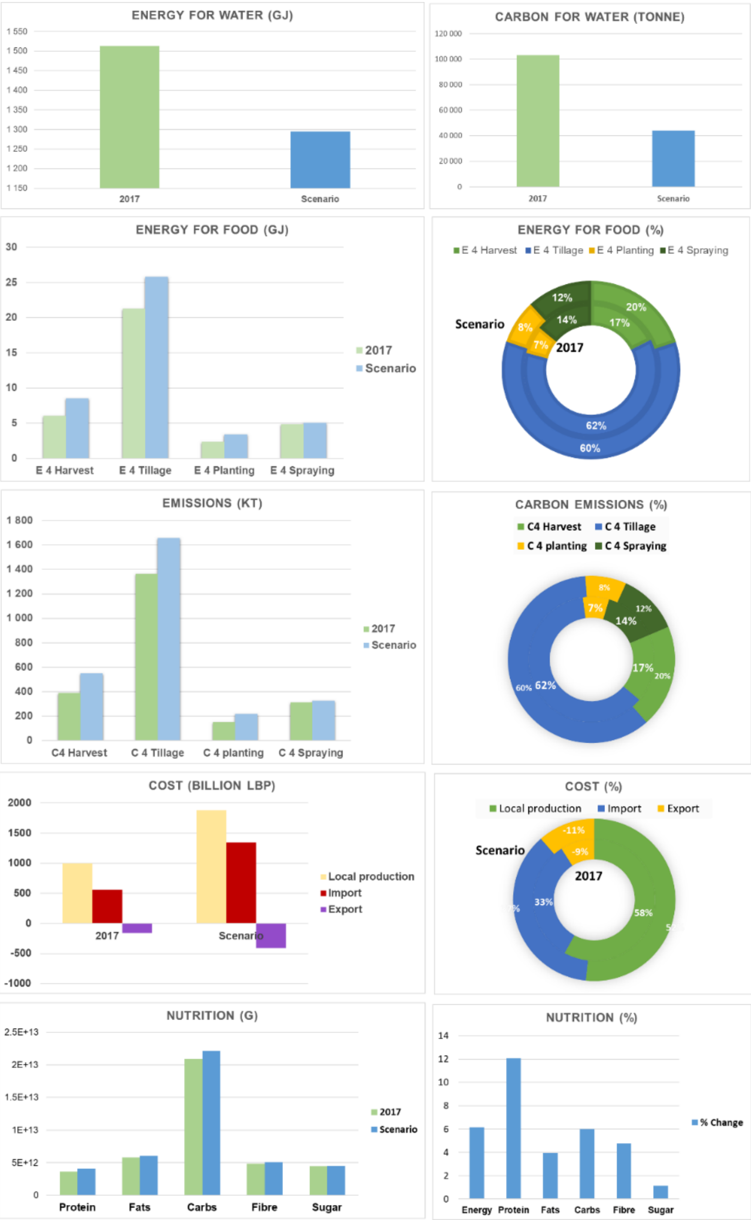
Like Scenario A, this scenario requires additional water and land, and provides additional nutrition and reduced reliance on imports. By shifting to lower energy intensive water sources (surface water and treated wastewater) the scenario results in around 13 percent energy savings. Increasing the use of solar energy for water pumping, conveyance, and treatment reduces emissions by 55 percent. Due to the new currency conversion rate, we see a major increase of 94 percent in net costs. Given the lower $/kwh of producing energy from solar as compared to diesel, producing more goods locally becomes more competitive than imports.

Key trade-offs

Energy requirements, carbon emissions and costs of local production could be reduced by shifting to less energy-intensive water sources for irrigation and renewable energy, making production more competitive compared to imports.

This assessment does not include initial investment costs for adopting new water and energy portfolio options. The future development of this framework would expand the cost function of the tool to include such costs.

Figure 14. provides a breakdown of Scenario C outputs



Source: Authors own elaboration

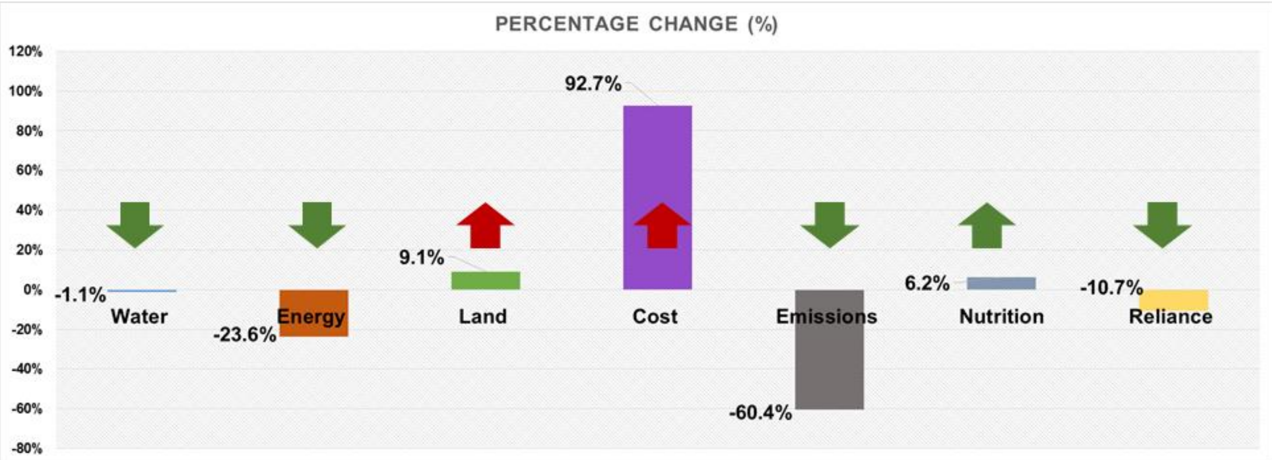
1.6. Scenario D: Scenario B + renewable energy + treated water + currency fluctuation

Scenario D builds on Scenario B, while diversifying water and energy portfolios under currency conversion change.

Scenario D. Summary

- **Increase** production of beans (green, broad, dry), lentils, chickpeas and peas (dry, green) to 100 percent SS.
- **Decrease** production of crops with SS > 100 percent to SS = 100 percent; no exports, no additional imports of these products.
- **Water:** 60 percent groundwater, 20 percent surface water, 20 percent treated water;
- **Energy–water:** 50 percent diesel, 50 percent solar;
- **Energy–food:** 70 percent diesel, 30 percent gasoline;
- **Currency conversion**: 1 USD = 4 000 LBP.

Figure 15. Percentage change in outputs relative to 2017 (Scenario D)



Source: Authors own elaboration

Similar to the trends in Scenario C, this scenario results in greater energy savings and emissions reduction. The key message is the potential for mitigating some negative trade-offs and improving resource savings by exploring new water and energy options for agriculture, making local production more competitive (see Figure 15).

Figure 16. Scenario C breakdown. Source: authors

Source: Authors own elaboration

2. Survey findings and willingness-to-adapt (WTA)

We conducted an in-person survey with 200 farmers in the Beqaa Valley in an effort to learn about the willingness of farmers to shift to different crops and alternative water and energy sources. We were also interested to learn about farmers' priorities in terms of minimizing water, energy, land, emissions and cost, and maximizing nutritional value as they made the decision to shift.

The surveys showed that:

- The average land size occupied by the surveyed farmers was 5.8 ha.
- 38.5 percent of the farmers reported that their main income came from agriculture.
- 57 percent of the farmers both owned and invested in their land; 37 percent owned land and 3.5 percent invested.

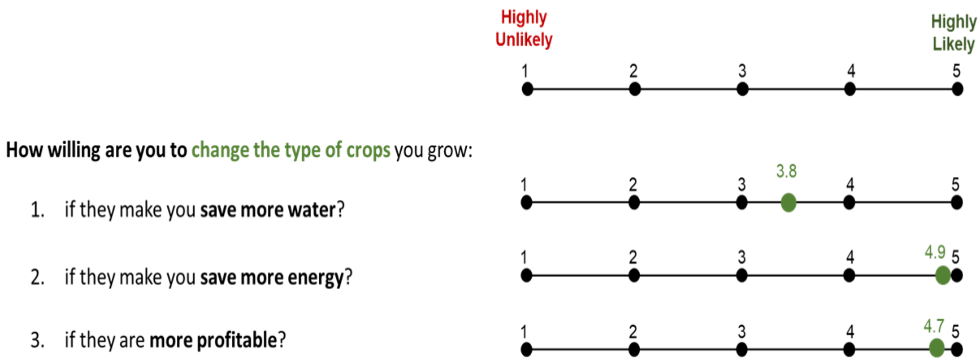
The ranking of decisions by farmers to use alternative energy, grow different crops or use alternative irrigation sort are shown in Figure 17, which clearly shows that such shifts are driven by profit increases before savings on energy or water resources. The *least* important driver of change for the farmers was the reduction of emissions and improving the nutritional value of their diets/crops.

Figure 17. Ranking the decisions farmers are most likely to make on their farm (willingness to adapt (WTA) changes)

Source: Authors own elaboration

The survey showed that farmers are willing to change the type of the crops they grow if they can save on energy use, which results in cost savings, or if the change in crop type is more profitable for them. Saving water as a motive to drive a change in cropping type ranked lower among farmers' choices than did energy and cost savings.

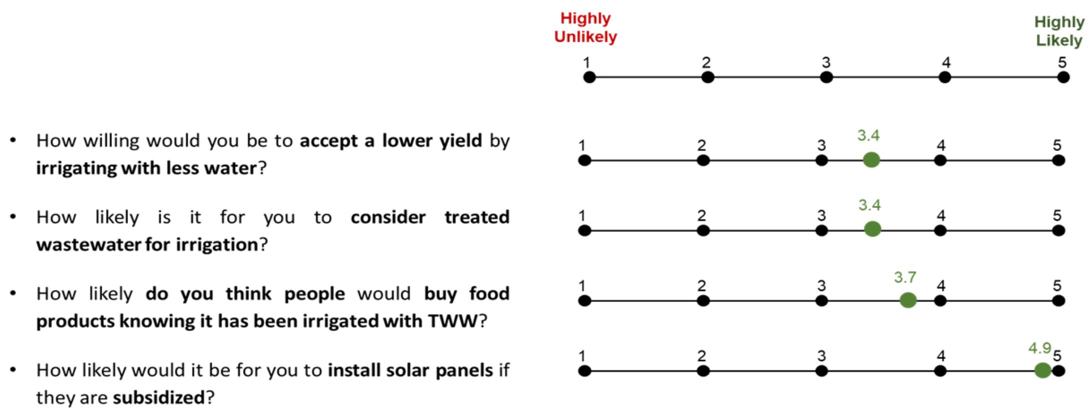
Figure 18. Farmers' willingness to change crops



Source: Authors own elaboration

The survey found that farmers were somewhat likely to be willing to accept a lower yield in order to save water, ranking 3.4/5 (see Figure 19). As far as considering the use of alternative water sources – specifically treated wastewater – the farmers were somewhat likely to do so, at an average of 3.4/5 (68 percent), and they held that people would be more likely than not to buy products irrigated with treated wastewater (3.7/5). These results indicate that considerations of water and energy sustainability are not completely rejected by farmers in the Beqaa Valley and that the incentive to change seems to be savings in production costs. Similarly, energy cost savings would be an incentive for farmers to use alternative energy sources such as installing solar panels (see Figure 19).

Figure 19. Farmers' willingness to accept lower yields and irrigate less



Source: Authors own elaboration

Asked to rank the options that they would be more likely to adopt, the farmers revealed that their main incentive to change would be profit which, in the Beqaa Valley, is usually linked to the use of alternative energy sources, since energy is one of the most expensive inputs in farming. Specifically, the survey found that farmers would most likely: i) use alternative energy sources as a first option; ii) grow different agricultural products as a second option; and iii) consider alternative irrigation sources (i.e. treated wastewater) as a last option (see Figure 20). This indicates that, while farmers are somewhat willing to adopt wastewater reuse as an irrigation source (3.4/5), (see Figure 19) they would prefer to change their energy source or to grow different crops.

Overall, the findings reveal that the use of a different water source is of interest *if* it results in financial profit. Any plans or policies that promote wastewater reuse in irrigation must consider the costs incurred by farmers, in particular, that the price of freshwater is highly undervalued and that most irrigation costs in Lebanon relate to energy costs for pumping.

It is important to note that the methodology used to analyse the survey questions was based on weighted frequencies, as shown in the total column in the following figures.

Figure 20. Ranking farmers' willingness to change.

Rank the decisions you are **most likely** to make

a. Grow different agricultural products

b. Use alternative irrigation water source

c. Use alternative energy source

n=196	Total	Rank
Grow different agricultural products	403	2
Use alternative irrigation water source	345	3
Use alternative energy source	428	1

Source: Authors own elaboration

Farmers were also asked what would make them change their crop types (see Figurw 21), the water source they use (see Figure 22), and the energy type (see Figure 23). The main incentive driving a change in crop types was profit and savings on energy; saving water resources was the fourth of six proposed factors that would motivate a cropping change. The farmers' priorities are unwavering, as can be seen in Figure 21. Profit is the first incentive for changing energy and water sources. Preserving groundwater came second to last as an incentive and reducing greenhouse gas emissions ranked last as an incentive.

Figure 21. Ranking farmers' incentives to change crops

Rank the decisions you are **most likely** to make

Change the crops they grow in an effort to:

a. save irrigated water

b. save energy

c. save land

d. reduce carbon emissions

e. improve profit

f. improve nutritional value of produced food

n=193	Total	Rank
to save water	684	**4**
to save energy	858	**2**
to save land	739	**3**
to reduce environmental impac	374	**5**
to increase profit	1156	**1**
to improve dietary value	242	**6**

Source: Authors own elaboration

Figure 22. Ranking farmers' incentives to use alternative irrigation water source

Rank the decisions you are **most likely** to make

Use **alternative irrigation water source:**

a. **to save groundwater**

b. **to save energy**

c. to **reduce carbon emissions**

d. to **increase profit**

n=196	Total	Rank
to save underground water	416	3
to save energy	441	2
to reduce emissions	334	4
to increase profit	769	1

Source: Authors own elaboration

Figure 23. Ranking farmers' incentives to use alternative energy source

Rank the decisions you are **most likely** to make

Use **alternative energy source** in an effort to:

a. **save water**

b. **reduce carbon emissions**

c. **increase profit**

n=196	Total	Rank
to save water	371	2
to reduce emissions	236	3
to increase profit	581	1

Source: Authors own elaboration

3. WaPOR validation

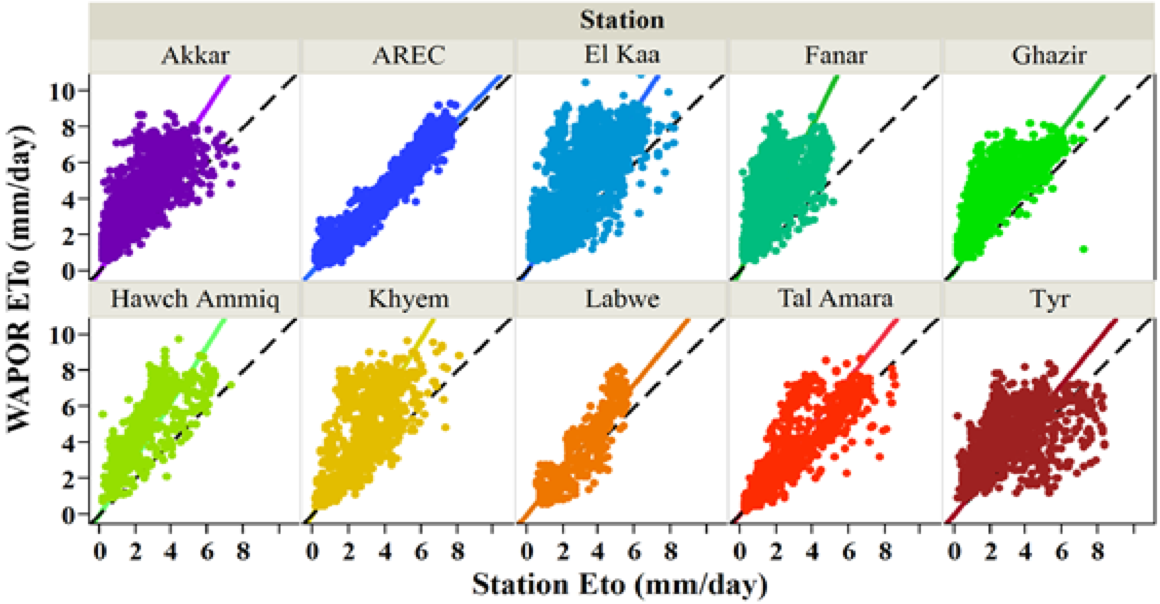
3.1. Direct validation

The results of the direct validation of the ETref–WaPOR to the *in situ* ET-ref on a daily basis using ten weather stations across Lebanon are shown in Figure 24 and Table 4 Ref ET (ETo) is overestimated compared to the studied weather stations with the values for RRMSE and MAPE higher than 20 percent, with the exception of the AREC station (see Table 5).

Our statistical analysis shows a substantial variation among the weather stations. A good linear relationship exists between the WaPOR and the station reference evaporation (see Table 4). Overall, a good index of agreement is found between the modelled and station reference evapotranspiration in all but the Fanar weather station. The AREC station's RefET matches well with WaPOR RefET and it is the best performing of the stations. The site is characterized by a semi-arid climate and heterogeneous irrigated landscapes. The second-best performing site is Tal Amara.

To further assess the performance of the WaPOR ETo against the station ETo, the station ETo data were divided into four groups: very low (0.16– 1), low (1– 2), medium (2– 5), and high (>5) Leaf Area Index (LAI) ranges. Our analysis shows an apparent overestimation of ETo at the Akkar, El Kaa, Fanar, Ghazir, Hawsh Ammiq stations in all ranges of ETo, an overestimation of ETo at high ETo range for Labwe, and an overestimation over the very low, low, and medium ranges and underestimation over the high ranges of ETo for the Tyr station.

Figure 24. Comparison between the modelled WaPOR reference evapotranspiration and the observed reference evapotranspiration from ten weather stations across Lebanon



Note: The dashed line represents the 1:1 line, Source: Authors own elaboration

Table 4. Fit line equations with their R2

Station	Fit line equation	R^2
Akkar	Y = 1.51*X	0.86
AREC	Y =1.05*X	0.98
El Kaa	Y =1.49*X	0.86
Fanar	Y = 2.03*X	0.80
Ghazir	Y = 1.55*X	0.90
Hawsh Ammiq	Y= 1.57*X	0.89
Labwe	Y= 1.21*X	0.96
Tal Amara	Y = 1.10*X	0.90
Tyr	Y = 1.21*X	0.75
Khyem	Y = 1.45*X	0.88

Source: Authors own elaboration

Table 5. Statistical analysis summary for direct validation of ETref-WaPOR to the in situ ET-ref

Weather stations	Statistical matrices						
	RMSE	MAE	MBE	d	RRMSE (%)	MAPE (%)	RE (%)
Akkar	1.91	1.55	1.51	0.73	91	118	72
El Kaa	2.42	1.91	1.77	0.70	92	105	67
Fanar	2.79	2.33	2.32	0.45	173	187	144
Ghazir	1.92	1.63	1.61	0.71	88	104	72
Hawsh Ammiq	2.19	1.74	1.65	0.68	98	117	74
Khyem	2.14	1.57	1.44	0.69	79	71	53
Labwe	1.18	0.94	0.62	0.90	37	34	20
Tal Amara	1.31	0.85	0.51	0.89	41	35	16
Tyr	2.06	1.71	1.22	0.66	69	82	41
AREC	0.52	0.40	0.17	0.99	14	16	6

Source: Authors own elaboration

3.2. Uncertainties in ETo assessment

The use of weather stations as a validation method for remote sensing has from 10–30 percent of inherent errors. The errors are related to scale and geolocation mismatch (a partial overlap between the remote sensing and point measurements from the weather stations), measurement uncertainties, and canopy heterogeneities (Allen, 2011).

3.3. Daily and monthly ETo comparisons

Table 6 shows the percent deviation between WaPOR and observed ETo across all stations on a daily basis. The average difference of daily ETo ranged from -4.2 percent at the AREC station to -59 percent at the Fanar station.

Table 6. Average daily ETo over the study period at all stations

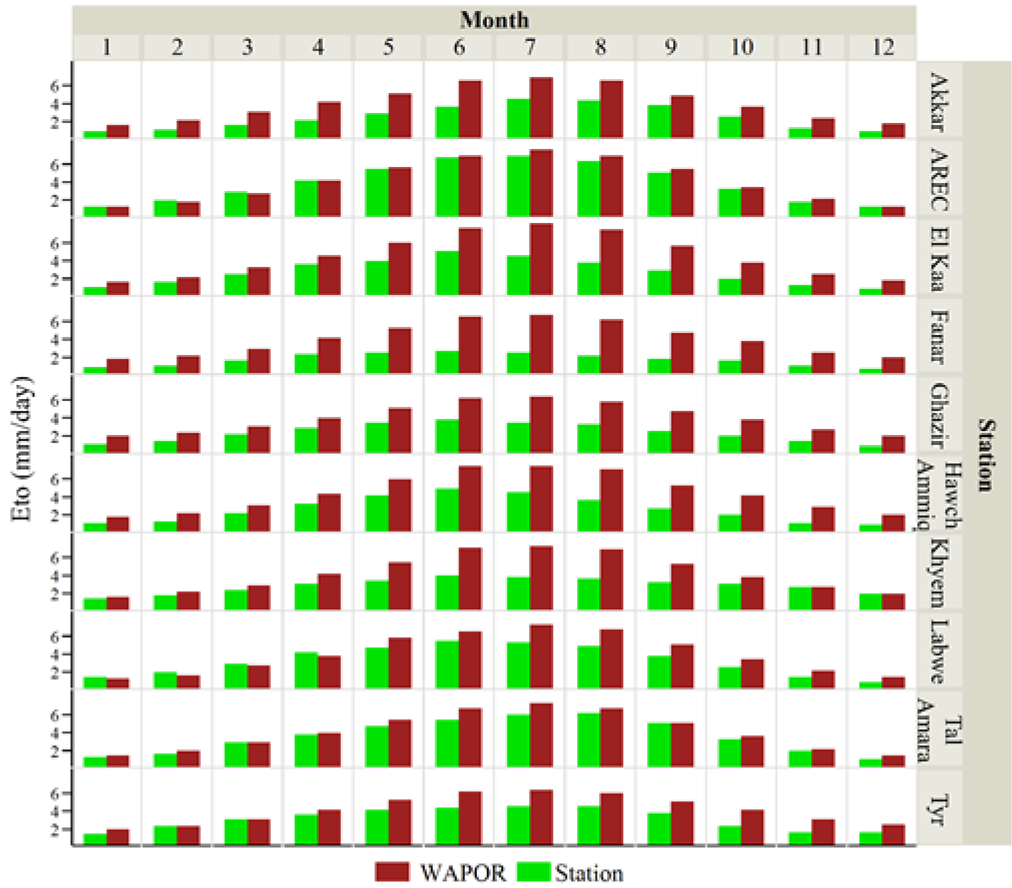
Weather stations	Station ETo (mm/day)	WaPOR ETo (mm/day)	% Difference
Akkar	2.13	3.61	-41.0
AREC	3.83	4.00	-4.2
El Kaa	2.64	4.41	-40.0
Fanar	1.61	3.93	-59.0
Ghazir	2.18	3.79	-42.6
Hawsh Ammiq	2.61	4.53	-42.5

Khyem	2.72	4.16	-34.6
Labwe	3.15	3.77	-16.5
Tal Amara	3.29	3.75	-12.3
Tyr	3.14	4.22	-25.5

Source: Authors own elaboration

With regard to mean monthly comparisons of WaPOR and station ETo, the results show that WaPOR overestimates ETo in all months at Akkar station. However, the percent deviation between WaPOR and observed ETo is less than +/- 20 percent during months 3 and 4 at El Kaa, months 10, 11, 12, 1, 2 and 3 at Khyem, months 1, 2, 3, 4, 5 and 6 at Labwe, and months 2, 3, 4 and 5 at Tyr station (see Figure 25). This shows that WaPOR works well during the wet seasons (winter and early spring), while overestimation occurs during the dry season.

Figure 25. Mean monthly WaPOR and station ETo at the studied weather stations



Source: Authors own elaboration

3.4. Comparison of WAPOR-derived yield to field data

We compared barley and barley/vetch yield to field data. To convert from WAPOR NPP to yield, we used a number of assumptions about harvest index and moisture content. For barley planted in AREC, the harvest index was adopted from Jaafar and

Ahmad (2015) as HI=0.49 and the moisture content was MC =11 percent, as adopted from Polat (2015). For vetch, HI=0.32 was used, within the range reported by Rao (2004) between 0.32 and 0.40. The moisture content used for vetch was MC =11 percent as adopted from Taser (2005). When barley and vetch were intercropped in some fields, we considered HI=0.49, MC=0.11 as reported for barley since the WaPOR NPP results showed higher accuracy than when the average indices were considered for the intercropped species. HI for oat was recorded by Peltonen-Sainio *et al*. (2007) as falling between 0.45 and 0.49, and the recorded MC=11 percent (White, 1999). However, oat was only intercropped with vetch in AREC. Therefore, for the yield validation of those intercropped fields, we relied on the indices specific to vetch with HI=0.32 and MC=11 percent.

Table 7. Harvest indices and moisture content of the different crops

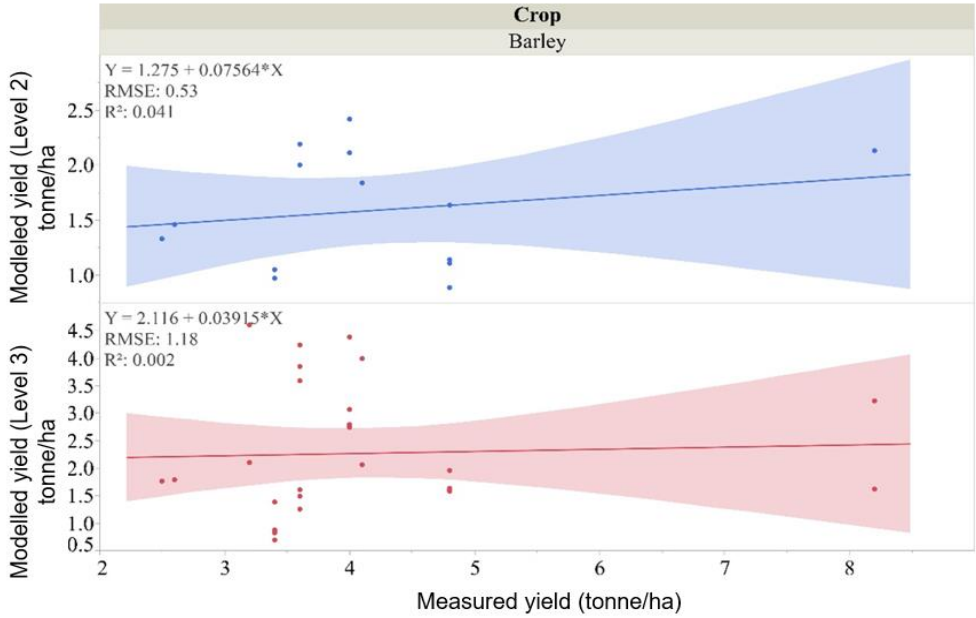
Crop	Harvest index	Moisture content (%)
Barley	0.49	11
Vetch	0.32	11
Oat/vetch	0.32	11
Barley/vetch	0.49	11

Source: Authors own elaboration

The accuracy of WaPOR NPP predictions for the five oat/vetch fields showed lower relative error percentages at Level 3 (24.82 percent) than at Level 2 (70.45 percent). RMSE values were also lower at Level 3 (1.94) than at Level 2 (3.44). Nevertheless, the R^2 values were higher at Level 2(0.18) than those at Level 3. One vetch field that was analysed also showed more accurate results at Level 3, according to both the relative error percentage and RMSE. Results showed that the relative error percentage at Level 3 (63.01 percent) was lower than recorded at Level 2 calculated by point (78.86 percent) or by using shape files (68.28 percent). The results of RMSE were also lower at Level 3 (3.27) than at Level 2 using point coordinates (3.94) or shapefiles (11.66). WaPOR NPP was estimated for 62 fields of barley/vetch at Level 3 and recorded a relative percentage error of 33.11 percent, an R^2 of 0.01 and an RMSE of 3.41.

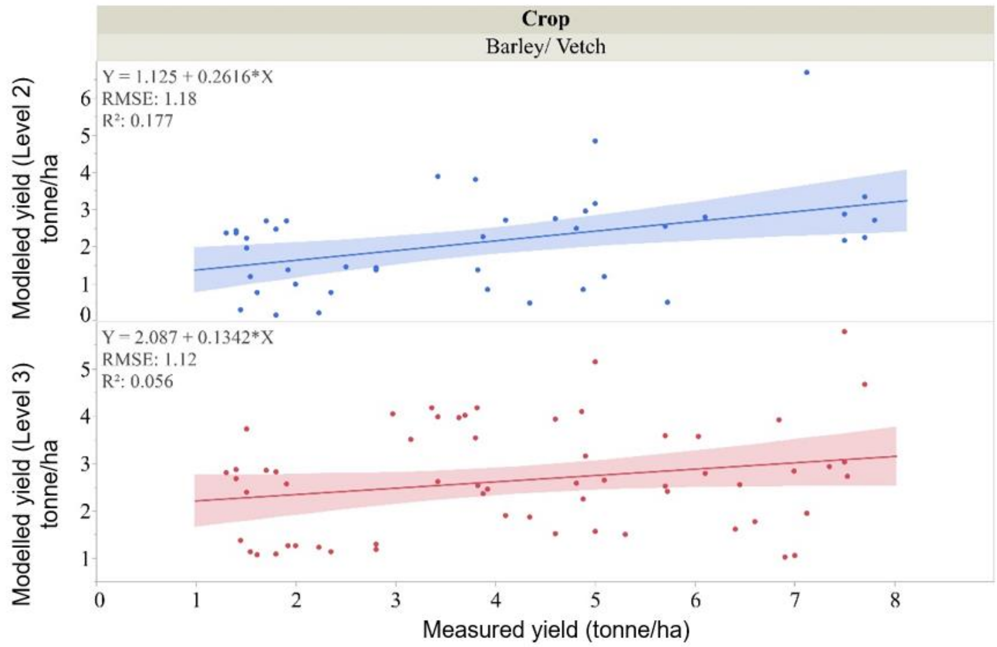
The accuracy of WaPOR NPP barley predictions for the 21 barley fields using point coordinates showed a relative error of 58.67 percent, a low R^2 of 0.01 and an RMSE of 2.69. The NPP barley predictions at Level 2 using shapefiles were done for 14 barley fields, and a relative error percentage of 61.97 percent, an R^2 of 0.04 and an RMSE of 2.92 were recorded. At Level 3, WaPOR NPP was estimated for 29 fields, where a relative error of 44.4 percent was recorded, an R^2 of 0.00 and an RMSE of 0.17. As for the barley/vetch fields, WaPOR NPP was calculated for 52 fields of barley/vetch at Level 2 using point coordinates, and a relative error percentage of 55.52 percent was recorded, as were an R^2 of 0.08 and an RMSE of 3.07. Estimations at Level 2 using shape files were calculated for 18 fields of barley/vetch and recorded a relative error percentage of 37.19 percent, an R^2 of 0.29 and an RMSE of 2.32. The 1:1 comparisons for the resulting yields are provided below.

Figure 26. Comparison between the modelled yield (at Level 2 and Level 3) and the observed barley yield



Source: Authors own elaboration

Figure 27. Comparison between the modelled yield (at Level 2 and Level 3) and the observed barley/vetch yield



Source: Authors own elaboration

V. CONCLUSIONS

The framework described in this report enumerates the interlinkages between water, energy and food in the Lebanese agricultural context and indicates that there are several opportunities to improve food security and sustainably produce the Mediterranean plant-based diet, which is known to be a healthy option.

Clear findings arose from the analytics and trade-off analyses and from the surveys undertaken in connection with this case study. Investing in renewable energy and exploring the use of treated wastewater in agriculture have the potential to improve the competitiveness of local production *vis-a-vis* imports. A self-sufficiency analysis showed that it is possible to reduce reliance on foreign markets by strategically reallocating resources from crops that exceed full self-sufficiency to less resource-intensive crops that are nutritionally rich with low self-sufficiencies.

It is clear that the willingness of farmers to change what and how they produce is driven by the potential for profit increase in the first instance, followed by reduced energy use and water use. The least important drivers of change from the farmers' perspective are improving environmental conditions and improving diet quality.

Moving forward with using WEF framework analysis, it will be important to account for spatio-temporal distribution, soil suitability maps, soil productivity maps, and variability and their roles in making trade-off decisions. This will allow the development of the framework as a scalable tool that uses customized WEF analytics to address questions at the country and regional levels. Using these analytics could help engage multiple stakeholders and catalyse cross-sectoral dialogue around trade-offs, future pathways forward and strategies for development. Integrative agricultural strategies need to account for barriers to implementation arising from existing farmer preferences. Understanding the preferences and perspectives of cross-sectoral stakeholders would allow a better evaluation of possible interventions and policy changes. Examples of possible policies are found in Appendix III.

On the technical side, the analytics can be improved by adding functions such as a cost assessment of different scenarios. Currently, these only concern the difference between the cost of local production and imports on one hand and revenues from exports on the other.

Future research should focus on improving the yields of highly nutritious crops with low irrigation requirements by exploring different varieties, cropping patterns, technologies, breeding approaches, etc. Irrigation efficiencies could be improved by better metering and accounting for water use on farms. Further study and analysis of existing incentive structures and their impact on preferences are also needed, as are reliable country- and basin-level data on water accounting, water resources, agronomic practices, energy use, food consumption, and other relevant parameters. Furthermore, the impact of using treated wastewater as an alternative water resource should be evaluated, especially in terms of soil health and impact on soil productivity.

It has been shown that there is a good index of agreement between WaPOR RefET and RefET from the weather stations, especially in regions characterized by a semi-arid climate and heterogeneous irrigated landscapes (AREC and Tal Amara in the Beqaa). While the accuracy of daily ETo from WaPOR was not high, the monthly averages showed that WaPOR works well during the wet seasons (winter and early spring), while overestimation occurs during the dry season. Such discrepancies are partly due to the scale and comparison of point measurements with a larger footprint from remote sensing. Further studies to compare WaPOR data to ET fluxes is important for more validation of the WaPOR.

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Appendix I. Crop data

	Crop	Consumption (2017)	Production (2017)	Export (2017)	Import (2017)	SS (2017)	Area harvested (2017)	Yield (2017)
		tonne	tonne	tonne	tonne	percent	hectares	tonne/ hectares
1	Wheat	76 8421	130 000	2 480	640 901	16.91 781	39 386	3.300 665
2	Corn	570 040	3 000	23	567 063	0.526 279	729	4.115 226
3	Potato	357 059	389 847	127 628	94 840	109.1 828	15 509	25.13 682
4	Lettuce	51 089	56 412	7 978	2 655	110.4 191	2 087	27.03 019
5	Tomato	298 259	298 003	815	1 071	99.91 417	3 810	78.21 601
6	Zucchini	29 692	27 444	526	2 774	92.42 894	1 999	13.72 886
7	Pepper (green)	28 558	22 824	349	6 083	79.92 156	593	38.48 904
8	Cucumber	154 167	151 695	264	2 736	98.39 654	3 274	46.33 323
9	Onion (dry)	78 618	70 151	5 132	13 599	89.2 302	2 721	25.78 133
10	Garlic	9 547	2 393	33	7 187	25.06 547	269	8.895 911
11	Apple	54 241	125 013	70 818	46	230.4 769	9 875	12.65 954
12	Grapefruit	5 459	7 135	1 682	6	130.7 016	298	23.94 295
13	Lemon	99 983	102 676	3 141	448	102.6 935	3 852	26.65 524
14	Orange	97 128	131 630	34 532	30	135.5 222	5 654	23.28 086
15	Tangerine, Mandarin, Clementine	25 972	28 632	2 661	1	110.2 418	1 453	19.70 544
16	Banana	49 834	72 234	25 135	2 735	144.9 492	2 347	30.77 716
17	Strawberry	2 130	1 562	15	583	73.33 333	247	6.323 887
18	Watermelon	68 934	66 013	647	3 568	95.76 261	1 913	34.50 758
19	Melon	13 475	13 171	40	344	97.74 397	1 009	13.05 352
20	Peach	25 277	31 138	5 877	16	123.1 871	3 050	10.20 918
21	Apricot	19 748	21 223	1 488	13	107.4 691	5 000	4.2 446
22	Grapes	46 542	68 129	21 675	88	146.3 818	7 843	8.6 866
23	Bean (dry)	1 892	912	5 361	6 341	48.20 296	449	2.03 118
24	Bean (green)	29 520	26 174	187	3 533	88.66 531	2 925	8.948 376
25	Broad bean	4 784	129	2 141	6 796	2.696 488	189	0.68 254
26	Lentil	15 417	1 076	401	14 742	6.979 309	727	1.480 055
27	Chickpea	17 047	3 183	1 108	14 972	18.67 191	3 241	0.982 104
28	Pea (dry)	4 053	3 633	0	420	89.63 731	867	4.190 311
29	Pea (green)	5 422	3 808	37	1 651	70.23 239	822	4.632 603
30	Almond	30 157	30 398	383	142	100.7 992	6 834	4.448 054
31	Walnut (with shell)	3 511	1 720	6	1 797	48.9 8889	1 289	1.334 368
32	Cherry	16 597	19 193	2 598	2	115.6 414	6 833	2.808 869
33	Olive	116 926	116 532	14	408	99.66 303	61 085	1.907 702

	Crop	Harvesting	Tillage	Planting	Spraying
		kj/ha	kj/ha	kj/ha	kj/ha
1	Wheat	72 968	196 350	29 850.52	6 633.45
2	Corn	116 749	179 766.5	44 444.11	13 266.9
3	Potato	161 856	307 792	44 444.11	26 533.8
4	Lettuce	0	149 916	0	6 633.45
5	Tomato	0	110 115.3	0	26 533.8
6	Zucchini	0	110 115.3	0	26 533.8
7	Pepper (green)	0	110 115.3	0	26 533.8
8	Cucumber	0	110 115.3	0	26 533.8
9	Onion (dry)	47 761	110 115.3	29 850.52	6 633.45
10	Garlic	47 761	110 115.3	29 850.52	6 633.45
11	Apple	0	45 107.45	0	33 167
12	Grapefruit	0	67661.18	0	33 167
13	Lemon	0	67 661.18	0	33 167
14	Orange	0	67 661.18	0	33 167
15	Tangerine, Mandarin, Clementine	0	67 661.18	0	33 167
16	Banana	0	0	0	0
17	Strawberry	0	96 848.35	0	33 167
18	Watermelon	0	110 115.3	0	26 533.8
19	Melon	0	110 115.3	0	26 533.8
20	Peach	0	45 107.45	0	33 167
21	Apricot	0	45 107.45	0	33 167
22	Grapes	0	45 107.45	0	33 167
23	Bean (dry)	79 601	110 115.3	44 444.11	6 633.45
24	Bean (green)	0	110 115.3	44 444.11	6 633.45
25	Broad bean	79 601	110 115.3	44 444.11	6 633.45
26	Lentil	79 601	153 896	29 850.52	6 633.45
27	Chickpea	79 601	153 896	29 850.52	6 633.45
28	Pea (dry)	79 601	110 115.3	44 444.11	6 633.45
29	Pea (green)	0	110 115.3	44 444.11	6 633.45
30	Almond	0	45 107.45	0	33 167.24
31	Walnut (with shell)	0	45 107.45	0	13 267
32	Cherry	0	45 107.45	0	33 167
33	Olive	0	45 107.45	0	33 167.24

	Crop	Water	Energy	Protein	Fats	Carbs	Fibre	Sugar	Edible
		%	kcal/100g	g/100 g	g/100 g	g/100 g	g/100 g	g/100 g	percent
1	Wheat	10.74	340	13.21	2.5	71.97	10.7	0.41	76
2	Corn		82	2.35	0.59	18.82	2.4	3.53	100
3	Potato	83.29	58	2.57	0.1	12.44	2.5		86
4	Lettuce	94.98	15	1.36	0.15	2.87	1.3	0.78	76
5	Tomato	94.52	18	0.88	0.2	3.89	1.2	2.63	90
6	Zucchini	94.79	17	1.21	0.32	3.11	1	2.5	95
7	Pepper (green)	93.89	20	0.86	0.17	4.64	1.7	2.4	82
8	Cucumber	95.23	15	0.65	0.11	3.63	0.5	1.67	95
9	Onion (dry)	89.11	40	1.1	0.1	9.34	1.7	4.24	78
10	Garlic	58.58	149	6.36	0.5	33.06	2.1	1	87
11	Apple	85.56	52	0.26	0.17	13.81	2.4	10.39	75
12	Grapefruit	90.89	32	0.63	0.1	8.08	1.1	6.98	73
13	Lemon	81.6	47	1.5	0.3	16	10.6	4.17	73
14	Orange	72.5	97	1.5	0.2	25	10.6		73
15	Tangerine, Mandarin, Clementine	85.17	53	0.81	0.31	13.34	1.8	10.58	73
16	Banana	74.91	89	1.09	0.33	22.84	2.6	12.23	88
17	Strawberry	90.95	32	0.67	0.3	7.68	2	4.89	90
18	Watermelon	91.45	30	0.61	0.15	7.55	0.4	6.2	55
19	Melon	90.15	34	0.84	0.19	8.16	0.9	7.86	52
20	Peach	88.87	39	0.91	0.25	9.54	1.5	8.39	76
21	Apricot	86.35	48	1.4	0.39	11.12	2	9.24	94
22	Grape	80.54	69	0.72	0.16	18.1	0.9	15.48	90
23	Bean (dry)	0	333	24.44	0	57.78	15.6	2.22	88
24	Bean (green)	90.32	31	1.83	0.22	6.97	2.7	3.26	100
25	Broad bean		86	2	1	19	1	1	88
26	Lentil	8.26	352	24.63	1.06	63.35	10.7	2.03	100
27	Chickpea		200	3.33	15	13.33	3.3	0	100
28	Pea (dry)		27	1.77	0	4.42	1.8	2.65	38
29	Pea (green)	88.89	42	2.8	0.2	7.55	2.6	4	67
30	Almond		571	21.43	50	21.43	10.7	3.57	55
31	Walnut (with shell)	4.07	654	15.23	65.21	13.71	6.7	2.61	53
32	Cherry	82.25	63	1.06	0.2	16.01	2.1	12.82	85
33	Olive		408	1.4	43.6	2.6	1.6		86

	Crops	Cost of production	Import cost	Export selling price
		LBP/tonne	USD/tonne	USD/tonne
1	Wheat	325 000	209.2 376	268.6 028
2	Corn	614 000	193.5 121	1 073.256
3	Potato	421 111.1111	458.7 398	228.162
4	Lettuce	175 000	911.7 867	1 195.741
5	Tomato	806 666.6 667	699.0 583	805.8 702
6	Zucchini	623 636.3 636	748.3 803	1 289.147
7	Pepper (green)	850 000	801.6 786	521.0 074
8	Cucumber	728 888.8 889	707.7 629	1 380.816
9	Onion (dry)	343 333.3 333	398.9 451	218.1 827
10	Garlic	525 000	860.4 664	2 323.232
11	Apple	400 000	854.3 647	225.4 669
12	Grapefruit	425 000	259.5 228	236.9 207
13	Lemon	425 000	259.5 228	236.9 207
14	Orange	425 000	259.5 228	236.9 207
15	Tangerine, Mandarin, Clementine	425 000	259.5 228	236.9 207
16	Banana	250 000	708.9632	470.9946
17	Strawberry	1 700 000	1 208.26	2 172.222
18	Watermelon	166 666.6 667	543.2 468	212.7 753
19	Melon	200 000	968.758	573.343
20	Peach	445 000	1 406.25	349.9 628
21	Apricot	391 428.5 714	1 642.422	459.8 312
22	Grapes	607 727.2 727	1 126.666	374.8 465
23	Bean (dry)	200 000	1 452.985	897.4 802
24	Bean (green)	540 000	542.0 968	558.2 511
25	Broad bean	700 000	879.0 438	1 392.413
26	Lentil	725 000	1 020.7	1 402.614
27	Chickpea	652 222.2 222	1 102.023	887.3 215
28	Pea (dry)	1 000 000	712.2 881	1 635.514
29	Pea (green)	1 000 000	1 932.955	1 711.969
30	Almond	356 000	4 485.308	1 154.13
31	Walnut (with shell)	7 142 857.143	3 805.677	2 217.563
32	Cherry	850 000	2 500	950
33	Olive	340 000	793.6435	2 037.219

	Tonne CO2/gal	$/KWh
Diesel	0.01	0.21
Gasolin e	0.00887	0.11
Wind	0	0.096
Solar	0	0.04

Appendix II: Farmers' survey

Date:

Part I : Data collection

Questionnaire number:	Location
Name:	Phone number:
Land ownership: owned/rented:	Total land area:
Household size/how many dependents:	Is agriculture the main source of income? yes/no

Water

1) Irrigated crops and area per crop: (Past 3–5 years)

a.	a.	a.	a.	a.
b.	b.	b.	b.	b.
c.	c.	c.	c.	c.

2) Rainfed crops and area per crop: (Past 3–5 years)

a.	a.	a.	a.	a.
b.	b.	b.	b.	b.
c.	c.	c.	c.	c.

3) Water source:
   a. river □
   b. pool □
   c. lake □
   d. well □
   e. canal □
   f. wastewater □

g. other: specify water source: _______________

4) Price of water:

a. LBP/m^3	
b. LBP/hr	
c. LBP/du	

5) Buys water from private suppliers? yes □ no □; If "yes", state frequency, capacity and fees:

____
____
____

6) Irrigation method:
   a. drip □
   b. surface □
   c. subsurface □
   d. sprinkle □
   e. other □

7) How much do you irrigate per crop?
   a. m^3/du ____________
   b. hr/du _____________ ; Flow rate ________________; Canal/pipe dimension: ______________

8) Irrigation duration and frequency (range), per crop:
   a.
   b.
   c.

9) Presence of water-holding structures (example: tanks, wells, etc…). If present, specify type and capacity:

____

10) Presence of a frost protection and crop cooling system. If present, specify how often the system is operated

____

11) Fertilizers and manure:

a. Type of fertilizers and/or manure per crop ____

b. Fertilizer rate (Kg/du) ____

c. Type of manure if used ____

Energy

1) Energy source:

   a. Renewable energy:

      - type: ______________________
      - power/capacity: ______________________
      - installing and maintenance fees: ______________________
      - supplies the electrical operations fully? yes □ no□; if "no", state the percentage that the system is providing for all the electrical operations.

   b. Power generator:

      - capacity/power: ______________________________
      - operating frequency (hours/day and months/year): __________________________________
      - estimated fuel consumption: ______________________________

   c. Electricity of Lebanon average fees: ________________________________

2) Equipment and machinery:

a. Water pump:
   - type: diesel □ electric □ solar □
   - power: ___________________
   - maximum water flow: _________________
   - operating frequency: __________________

b. Atmosphere control (fans, sprayers, heaters, etc…)
   - power: _____________________________
   - operating frequency: _______________________

c. Tillage
   - type of tillage: _________________________
   - frequency per season: ___________________________
   - area to be tilled: _______________________

d. Planting
   - manually □
   - planter/tractor-pulled seeder □

e. Fertilizer
   - with irrigation water □
   - with fertilizer spreader – frequency per season □
   - manually □

f. Pesticide
   - boom sprayer □
   - tanker □
   - hand/back sprayer □
   - frequency of application per season: ____________________________

g. Harvesting
   - machinery used: ___________________
   - estimate operation frequency upon harvesting: _________________

h. Transportation
   - distance from field to storage, and frequency of trips per harvesting season:

     ____

- distance from storage to usual selling point: ______________________________

Food

1) Estimated yield per crop

a. b. c.	a. b. c.	a. b. c.	a. b. c.	a. b. c.

2) Estimated loss of crops due to external factors (storms, pests, etc…).

____

____

Production cost

1) What is the average cost of production per tonne per crop?

____

2) What is the average selling price per tonne or kg crop?

____

3) What is the market retail price if known?

____

Part II – WTA survey

Land ownership: owned/rented:	Total land area:
Household size/how many dependents:	

Is agriculture the main source of income? yes/no

Prospects for WTA

Question	**1**	**2**	**3**	**4**	**5**
1. How willing are you to change the type of crops you grow if they save more water?					
2. How willing are you to change the type of crops you grow if they save more energy?					
3. How willing are you to change the type of crops you grow if they are more profitable?					
4. How willing would you be to accept a lower yield by irrigating with less water?					
5. How likely is it for you to consider treated wastewater (TWW) if it is within the safe standard limits?					
6. How likely do you think it is that people would buy food products knowing they have been irrigated with TWW?					
7. How likely would it be for you to invest in solar on your farm if it were not subsidized?					
8. How likely would it be for you to install solar panels if they were subsidized?					

1. Rank the following decisions from most likely to least likely for you to make on your farm:
    a. Grow different agricultural products.
    b. Use alternative irrigation water source.
    c. Use alternative energy source.

2. Rank the following decisions from most likely to least likely for you to make on your farm:
    a. Grow different agricultural products in an effort to save irrigated water.
    b. Grow different agricultural products in an effort to save energy.
    c. Grow different agricultural products in an effort to save land.
    d. Grow different agricultural products in an effort to reduce carbon emissions.
    e. Grow different agricultural products in an effort to improve profits.
    f. Grow different agricultural products in an effort to improve the nutritional value of produced food.

3. Rank the following decisions from most likely to least likely for you to make on your farm:
    a. Use alternative irrigation water source in an effort to save groundwater.
    b. Use alternative irrigation water source in an effort to save energy.

c. Use alternative irrigation water source in an effort to reduce carbon emissions.
d. Use alternative irrigation water source in an effort to improve profits.

4. Rank the following decisions from most likely to least likely for you to make on your farm:
    a. Use alternative energy source in an effort to save water.
    b. Use alternative energy source in an effort to reduce carbon emissions.
    c. Use alternative energy source in an effort to improve profits.
    d. Use alternative energy source in an effort to reduce land use.

Appendix III further sources.

Addressing Food Security Challenges in Lebanon: a Water-Energy-Food-Health Nexus Approach. Food and Agriculture Organization of the United Nations. Policy Brief September 2020. Roula Bachour, Sandra Yan-ni, Bassel Daher, Reem Khat-tar, Ali Olliek, Haydar Sleiman, and Rabi Mohtar.
https://drive.google.com/file/d/16gUuwevMw6SBkjBVZ6ONU4LnsQRh_X2Z/view

Evaluating farmer priorities and readiness to adopt new water, energy, and agricultural solutions in Lebanon. Food and Agriculture Organization of the United Nations. Policy Brief September 2020. Roula Bachour, Sandra Yan-ni, Bassel Daher, Reem Khat-tar, Ali Olliek, Haydar Sleiman, and Rabi Mohtar.
https://agrilife.org/wefnexus/files/2023/03/AUB-FAO_Evaluating-Farmer-Priorities.pdf

Water, energy and food securities are tightly interconnected and have direct implications for human health and well-being. Addressing the challenges facing these resource systems must be grounded in an understanding of these interconnections, which can be utilized to support integrative planning. Trade-off analysis tools can play a critical role in catalysing cross-sectoral dialogues among the stakeholders who regulate, manage, and use these resource systems. Such dialogues enhance the processes of planning the implementation of the United Nations Sustainable Development Goals (SDGs).

The EAT-Lancet Commission, striving toward balanced nutritious diets and sustainable food systems, has proposed a list of recommendations for healthy diets. The recommendations include substantial dietary shifts, whereby the global consumption of fruits, vegetables, nuts and legumes would have to almost double, and the consumption of foods, such as red meat and sugar, would have to be reduced by more than 50 percent. A diet rich in plant-based foods and with fewer animal- sourced foods confers both health and environmental benefits. The Mediterranean diet converges with the EAT-Lancet diet to a high degree and has been shown to have beneficial health effects while leaving a smaller environmental footprint. The impact of relying heavily on plant-based diets differs according to the availability of water and energy resources and the requirements of food in a particular region. Given the scarcity of water and arable land in arid and semi-arid regions, for which several sectors compete, our research considers the sustainability of the Mediterranean diet. With a system-of-systems view, we also investigate the ways in which alternative water and energy sources could play a role in affecting the sustainability of this diet.

This study used a water-energy-food system-of-systems assessment to evaluate the sustainability of the Mediterranean diet in Lebanon. The specific aims were to: 1) identify and quantify the critical interconnections between water, energy and food systems in Lebanon; 2) develop a nexus framework to assess the trade-offs associated with adopting interventions within current water, energy and agriculture portfolios and practices; 3) evaluate stakeholder perceptions around regional resource challenges and their willingness to implement proposed interventions.

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