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FOOD SECURITY AND THE WATER-FOOD NEXUS: AN OPTIMIZATION APPROACH

by
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AN ABSTRACT OF THE THESIS OF

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Water and food security is facing increased challenges with population increase, climate and land use change, as well as resource depletion coupled with pollution and unsustainable practices. Coordinated and effective management of limited natural resources have become an imperative to meet these challenges by optimizing the usage of resources under various constraints. In this study, an optimization model is developed for optimal resource allocation towards sustainable water and food security under nutritional, socio-economic, agricultural, environmental, and natural resources constraints. The core objective of this model is to maximize the composite water-food security status by recommending an optimal water and agricultural strategy. The model balances between the healthy nutritional demand side and the constrained supply side while considering the supply chain in between. It equally ensures that the population achieves recommended nutritional guidelines and population food-preferences by quantifying an optimum agricultural and water policy through transforming optimum food demands into optimum cropping policy given the water and land footprints of each crop or agricultural product. Through this process, water and food security are optimized considering factors that include crop-food transformation (food processing), water footprints, crop yields, climate, blue and green water resources, irrigation efficiency, arable land resources, soil texture, and economic policies. The model performance regarding agricultural practices and sustainable food security opportunities was successfully tested and verified both at a hypothetical and pilot scale levels.

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CHAPTER 1

INTRODUCTION

Food security, used historically as a measure of individuals' and societies' well-being, is a fundamental condition for human development. The food insecurity status constitutes a critical threat as it involves a deprivation of basic needs, may provoke multiple nutritional and health problems and retard in human and society development (Bickel et al., 2000). Pressures on food security are increasing from the supply side, including climate change, urbanization, globalization and land use change, and from the demand side including population increase, urbanization and changes in food types consumed (Misselhorn et al., 2012). The volatility of food prices in recent years has been considered as warning signs of future challenges (World Economic Forum, 2011b). As such, the challenge of achieving sustainable food security is multi-disciplinary calling for optimization as means to address it.

First category of optimization approaches targeting food security are the nutrition / diet problems: their general framework is to optimize the cost of food basket preferred in a certain nation and satisfying nutritional guidelines. Darko et al. (2013) developed a linear programming model to decide on the food selection that would save the cost of unnecessary items, given that in many developing countries, it is challengeable to meet the required nutrients' intake in the daily food diet due to limited budgets. The reported optimum food baskets and their costs vary among countries depending on the consumption habits and market prices, but the cost reduction induced may reach up to 40%. Likewise, Garille and Gass (2001) stated that diets recommended by professional dieticians are two to three times more costly than the minimum cost diet. Many additions have been applied to the diet problem, like constraining a minimum variety of foods and serving numbers per meal (Ford, 2006). By this, nutrition optimization problems are essentially concerned by the individual food security.

Second category is the food supply chain problem and comprises elements linking production with market from production facilities, distribution and storage facilities, transportation links and retailers, and also including the agricultural industry of crop/livestock processing. The optimization of food system operations aims to minimize the economic cost in all stages of the system under the constraints of production, demand and transportation. However, it has been expended to cover other criteria like time and food quality deterioration (Rong et al., 2011), and even to take account of environmental impacts like carbon footprint and greenhouse gas (GHG) emissions (Validi et al., 2014; Govindan et al., 2014) as an attempt to maintain a sustainable food supply. The consumption constraint in this model category is to meet the market demand, without involving the adequacy of this demand to food security conditions.

The agricultural production optimization problem is to manage the agricultural sector to ensure food supply under a minimum economic cost (or maximize profit), and subjected to resources constraint, mainly land and water constraints. But few of reported models incorporated constraint of food security. Manos et al. (2013) applied multi-criteria decision making (MCDM) techniques to formulate agricultural production model of multiple objectives (maximize gross margin, minimize labor, minimize fertilizers). Lu et al. (2013) developed interval-probabilistic agricultural production structure optimization model (IPAPSOM) that takes into account the economic profits, local food security and resources availability. Note that in IPAPSOM, (1) food security targeted at the local scale (region Dancheng in China), was exclusively equated with the policy of prohibited grain import, which is not a common regulation in non-agricultural countries. (2) Land resources allocation to cultivated crops doesn't consider the water criteria since no spatial variability of water demand due to climatic and soil factors was indicated. (3) The production of crops and meat is constrained to meet the society demand, and health constraints were not regarded. Havlik et al., (2011) developed a Global Biomass Optimization Model (GLOBIOM) concerned by the global agricultural and forest sectors. It optimizes the variables land use that maximize producers' and consumers' surplus, and achieve the global agricultural market equilibrium under resource and technological constraints. GLOBIOM, recursive dynamic partial equilibrium model, was originally developed to evaluate the GHG emissions caused by expending agricultural land areas, with no explicit inclusion of food security in the model. Then it was reapplied in Schneider et al. (2011) to assess the food market equilibrium under scenarios of population growth and economic development and the associated water and land scarcities. In Fuss et al., (2015), GLOBIOM investigated the impacts on global food security caused by climate change and crop yield volatility, and also under the resource and technological constraints in the context of stochastic optimization. But, food security was targeted at economic region scale by a single constrain of minimum vegetal calories required. Also in resource constraints, climate was involved as a mark of land suitability for cultivation more than spatial variability of irrigation water demand. Moreover, some agricultural optimization studies are oriented towards land management plans. Cobuloglu and Büyüktahtakın (2015) introduced a multi-objective mixed-integer agricultural optimization model to assess the impact of growing biofuel's cultivation on food supply security. The objective was to maximize economic and environmental benefits, where the considered environmental impacts include in addition to emissions, soil erosion and nitrogen pollution. Seeing the land competition between food and energy crops and to mitigate risk on food security supply, they recommend specifying priority policies that manage land allocation. Arnoult et al., (2010) studied the impacts of healthy diets' consumption on the agricultural production and land uses in England and Wales. First, they performed a quadratic minimization of difference between the actual and the optimized consumption levels of foods, weighted by their contribution to the total energy intake, and the model constraints were limited to nutrition constraints (intake recommendations of 13 essential nutrients). In a second separate step, Land Use Allocation Model (LUAM), developed by Jones et al., (1995), was applied to evaluate the changes in land use and food production. Note that, (1) food security conditions and water constraint are not explicitly addressed, and (2) the disconnected two-step optimization approach eliminates the interactions between demand and supply sides. Models and policies can operate such interactions to achieve higher food securities.

The linear programming model LUAM allocates land areas to different activities and optimizes the returns under constraints of land and labor availability, demand and policy. LUAM model belongs to the family of land use planning problems: land resources allocation to multiple conflicting usages that would result in the optimum resource productivity. The outputs of optimization are interpreted to generate land use strategies and provide support to land managers in their decisions. Gilbert et al. (1985) presented a multi-objective integer model to allocate land areas for development projects mainly based on criteria of cost and proximity to a certain land feature. In Wang et al. (2004), the environmental and economic optimum spatial distribution of land uses in a watershed was solved for by a GIS-based allocation model considering the existing land cover and the distance from sub-area to the surface water. To manage the land conversion due to urbanization and globalization in China, Cai et al. (2002) proposed optimization algorithm for optimum lands allocation that conserves economic growth and also maintains a certain level of land productivity and food self-sufficient rate.

Moreover, in the literature, the assessment of food security at large scales, national and global, relies on scenarios analysis. Sposito (2013) exposed the alternatives to increase food production and assessed their environmental impacts at the global scale. First alternative of additional land conversion would deteriorate ecosystem regulatory services and have serious risks on biodiversity, thus meeting future food demand is better accomplished by enhancing the productivity of existing croplands. Second, blue water resources have been excessively used in irrigation, and boosting water withdrawal would put serious pressures on ecosystems sustained by the resource, and is not a sustainable alternative to increase agricultural productivity. Then, the finest alternative is to enhance green water productivity on croplands: the productive flow (transpiration) of the whole evapotranspiration flow will have to increase versus a decrease in evaporation fraction. Rockstrom et al. (2007) evaluated the opportunity for developing countries to meet their future food demand, through quantifying the water demand (based on an acceptable standard diet) and identifying the water sources and the ecological impacts of agricultural land expansion, and concluding that improving water productivity (WP) is a real opportunity to release the pressures on water resources and mitigate ecological impacts in the future. Still a little conversion of land seems inevitable to achieve the target of foods self-sufficiency in those countries. Intensive agriculture, having higher water productivity than regular cultivation, is a way to achieve the sustainable agricultural development (Hoff, 2011). Wu et al., (2011) accomplished an assessment of future global food security under scenarios of socio-economic and climate change. Precise indicators of food security were used, where the per capita food availability and the total food production were calculated as representative of the "*status of food availability and stability*". Furthermore, the gross domestic product (GDP) was incorporated in the analysis to reveal the "*situation of food accessibility and affordability*". Hotspots of food insecurity, reflected by the two FS indicators, were associated with low food production and poverty. Thus, scenarios analyses clearly do not develop a tool to assist in making decisions, but are essential to establish frameworks for proposed programming models, identify the pressing constraints and analyze the results and generate policies.

Various attempts to address food security optimization were reported, however water, that constitutes the scarcest resource in many countries, was undervalued in most outlines. In fact, freshwater shortage constitutes the primary natural limitation on economic growth and must not be wasted or overused (World Economic Forum, 2011b). Water management deeply affects regulations in food, environmental and energy disciplines (Bates et al., 2008). Water footprint concept introduced in 2002, has proved to be an exceptional indicator of national water consumption because is able to relate consumption patterns with water resources use (Chapagain & Hoekstra, 2004), measures external water dependency and hence evaluate water security. Few optimization models in different sectors, as industrial sector, incorporate the water footprint into their formulations, but none in the agricultural sector. We present optimization programming model, the first that explicitly incorporate the water footprint notion in a water-food securities nexus optimization model under multiple objectives and scenarios.

In this study, the opportunity of achieving individual and national food and water securities simultaneously under demand pressures and resource constraints is assessed. Land and water resources availability and interactions were explored since land allocation is primarily based on spatial variability of water demand, also the relative weights of blue and green water in optimization were investigated. Our intention is to optimize the resource use efficiency in the agricultural sector while accounting for competing and overlapping goals (Figure 1).

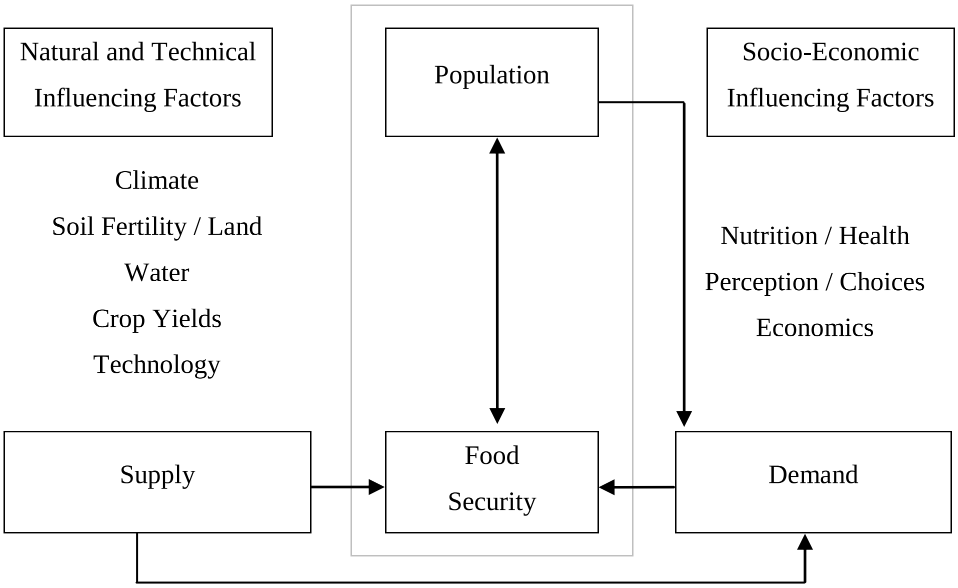


Figure 1. Problem Description: The main supply and demand pressures on food security as covered by the model

The model framework situates under the water-energy-food nexus approach (WEF), recognizing that the three areas are highly linked and interdependent and should be addressed as a one nexus because any approach that promotes one area security but restrict other areas securities is considered an unsustainable approach (Bizikova et al., 2013). Accordingly, business-as-usual approach will not achieve long-term WEF securities and thinking shift to match the nexus perspective and adopt new management techniques are needed (Coles & Hall, 2012). One way is raising the interaction among sectors and improving the overall production efficiency instead of the productivity of separated sectors (Hoff, 2011). The agricultural sector, accounting for more than 70% of the total water withdrawal worldwide, is an essential ingredient in the integrated solution (World Economic Forum, 2011a).

CHAPTER 2

METHODOLOGY

2.1.Food Security Definition

Food security (FS) has been addressed at multiple scales spanning from household to global scales. Firstly, the integration between nutritional security and food security is not always complete, due to non-food factors affecting the nutritional status of individuals such as water quality, infectious diseases, health care, lifestyle practices and physical activities (Krauss et al., 2000); hence, food security does not guarantee nutrition security. Concurrently, FAO provides a definition of household or individual food security, presented in (Table 1) (WHO, 1996), and the analysis of which is based on three terms: food availability, access, and utilization (World Food Programme, 2009). However, the definition did not identify the nutritional requirements needed to consider the person food secure, since any micronutrient deficiency, for instance iron deficiency, would make the individual food unsecure according to this definition (Andersen, 2009). As such, it is questioned whether the FAO definition is suitable to measure national food insecurity or to generate FS policies. Therefore, moving from individual to regional scale, defining food security (FS) has been a source of debate despite its criticality for every region to establish national FS policies or to claim that it is food secure. Multiple terms were used as equivalent to national food security like Self-Sufficiency status, Food Sovereignty and Economic Food Security (Table 1). Needless to say, all food availability indicators first do not guarantee equal food distribution and access for the most vulnerable and second are estimated based on calories requirement which is not a sufficient measure of healthy and nutritious diet.

Thus, food security is a critical concept and should be used with a clear understanding of its definitions and their limitations.

Table 1. Food Security Definitions

Concept		Definition
Household or Individual Food Security *		"Food security exists when all people, at all times, have *physical and economic access to sufficient, safe and nutritious food* to meet their dietary needs and food preferences for a healthy and active life"
Interpretation **	*Food Availability*	It is the physical presence of food in an area by way of production, trade, stock or transfer
	Food Access	Food accessibility is when households are able to acquire the needed food by own farm production, purchase, exchange, gift or food aid
	Food Utilization	Food utilization represents households' allocation of foods and ability to absorb and use of nutrients
	Food Preferences	It is analyzed as the food desired socially and culturally and accepted religiously and ethically
Nutritional Food Security ***		
Self-Sufficiency Status		Food consumed by the population is domestically produced, with minor level of attention to whether the food should satisfy the energy and nutritional requirements of inhabitants or just meet the economic demand at the local market.
Food Sovereignty		Measurement of the capability of a region to meet the food demand of its population regardless of domestic production or import sources.
Economic View of Food Security		Food security is a function of national incomes and food prices in the domestic market. The country is classified as food secure if has the capacity to acquire its food needed by domestic production or by import.

* (WHO, 1996); Definition agreed upon in the World Food Summit
** (World Food Programme, 2009)
*** (Andersen, 2009)
The terms in *Italic font* are integrated in the model formulation

This study considers five components from Table 1 as representative for the food security status and converts them into model formulation: (1) Sufficient and Nutritious Food (through nutritional guidelines prepared by global health organizations, like WHO), (2) Food Availability (through permissible food production and import), (3) Economic Food Access (food prices comparable to national average incomes), (4) Food

Preferences (current consumption patterns are respected representative of population preferences), and (5) National food security (taken equivalent to Self-sufficiency status in first objective function).

2.2.Model Components

After setting the model assumptions, we will describe how the main supply and demand constraints to the food security problem (Figure 1) were treated in the proposed model.

2.2.1. Nutrition

National food-based dietary guidelines were prepared by referring to the World Health organization (WHO), the Institute of Medicine (IOM) and the American Heart Association (AHA). WHO introduced, in its technical report No. 916 (WHO, 2013), of nutrient intake goals in the form of average intakes needed to preserve the population in good health, where the term “health” is defined by a low occurrence of diet-related diseases as obesity, type-2 diabetes, CVD, cancer, dental diseases and osteoporosis. The average intake ranges are established primarily for the three macronutrients, i.e. carbohydrates, proteins and fats, but these are not a sufficient marker of a balanced diet since the intake of other micronutrients is also a major concern. Therefore, they were complemented with recommended daily consumption of certain food categories, like fruits and vegetables, to ensure the intake of essential micronutrients, especially vitamins and minerals (WHO, 2013). The Institute of Medicine IOM provided gender and age sensitive dietary reference intakes (DRIs) for water, energy, macro- and micro- nutrients (Hellwing et al., 2006). For micronutrients

Table 2. Summary Table of WHO, IOM and AHA dietary guidelines

Macronutrients (% of total calories)	**WHO/FAO Report** [6]	**IOM Report** [7]	**AHA Report** [8]
Total Fat	15 – 30	20 – 35	15 – 30
Saturated fatty acids	< 10	As low as possible	<10
Polyunsaturated fatty acids (PUFAs)	6 – 10	5.6 – 11.2 (1)	
n-6 Polyunsaturated fatty acids (linoleic acid)	5 – 8	5 – 10	
n-3 Polyunsaturated fatty acids (α-linolenic acid)	1 – 2	0.6 – 1.2	
Trans fatty acids	< 1	As low as possible	As low as possible
Monounsaturated fatty acids (MUFAs)	< 24 (2)		
Protein	10 – 15	10 – 35	15 (≈ 50 to 100 g/day)
Total Carbohydrate (wide range)	55 – 75	45 – 65	55 – 70 preferred to be ≤60 (3)
Free sugars	< 10	< 25 (4)	As low as possible
Total dietary fiber	> 25 g/day (5)	25 – 38 g/day (6)	≥ 25 g/day
Non-starch polysaccharides (NSP)	> 20 g/day (5)		
Other Nutrients	**WHO/FAO Report** [6]	**IOM Report** [7]	**AHA Report** [8]
Cholesterol	< 300 mg/day	As low as possible	<300 mg/day
Sodium chloride (sodium)	< 5 g/day (< 2 g/day)	------- (< 1.5 g/day)	< 6 g/day (< 2.4 g/day)
Total Water (7)		2.7 – 3.7 L/day (6)	
Fruits and vegetables	> 400 g/day		*See AHA guidelines below*

Additional AHA general guidelines [8] (8)

- Include variety of foods from all the major food groups
- Consume 5 or more servings per day of variety of fruits and vegetables
- Consume 6 or more servings per day of a variety of grain products, including whole grains
- Consume 2 to 4 servings per day of low-fat dairy products
- Consume at least 2 servings of fish per week
- Limit alcohol intake to 2 drinks (men) and 1 drink (women) per day among those who drink.

(1) The intake range is calculated by summation of ranges of n-3 and n-6 polyunsaturated fatty acids
(2) The upper bound is calculated by subtract the intake of other fatty acids from the total fat intake
(3) Quoting: "Diets high in total carbohydrate (eg, .60% of energy) can lead to elevated triglyceride and reduced HDL cholesterol, effects that may be associated with increased risk for cardiovascular disease." [8]
(4) A sugar intake equivalent to 25% of total calories is not recommended for a healthful diet [7]
(5) The intake of fibers comes from consuming fruits, vegetables and wholegrain foods [6]
(6) Lower bound corresponds for females (19-70 years) and upper bound for males (19-70 years). This range was considered here as representative for the general population. The values presented are adequate intake (AI)
(7) Total water is the summation of drinking water and water contained in food
(8) AHA provides examples for servings size depending on the food type, for instance one serving of fish is equivalent to 3 oz of grilled fish, while one serving of grain products is equivalent to 1 oz of dry cereal. Next, these serving sizes, given in ounces and cups, were converted into grams and liters.

intake, the DRIs lists a large number of vitamins, elements and minerals, making it difficult to set as general population dietary guidelines. Regular consumption of a variety of foods from all the major food groups is indispensable to prevent any nutrient deficiency, thus the macronutrients guidelines were matched with complementary food-based dietary guidelines extracted from the American Heart Association AHA (Krauss et al., 2000). AHA provided general principles and specific guidelines to achieve and maintain four general population goals: (1) healthy eating pattern, (2) healthy body weight, (3) desirable blood cholesterol, and (4) normal blood pressure. These practical guidelines consist of recommendations for regular consumption of certain food categories expressed as number of servings per day/week and are valid for all persons older than two years (Krauss et al., 2000). In conclusion, the dietary guidelines of the three organizations are highly consistent (Table 2) and they will be used in a complementary way to set a more balanced and complete diet.

The recommended intake of most nutrients is typically related to the total calorie intake (Table 2). The recommended daily energy intake (kcal/day) depends on gender, age and physical activity level, and should be balanced with energy expenditure (activity level) in order to achieve better weight management (IOM, 2005).

2.2.2. Food

2.2.2.1. Food Consumption Data

Estimating national food security is based on national consumption data obtained from different kinds of surveys. There are three distinct techniques to collect food consumption data: food balance sheets (also named food supply surveys), household consumption surveys and individual dietary intake survey (Nasreddine et al., 2006). The resultant consumption data of these three approaches is not exactly the same due to losses and waste factors occurring at different stages. Food balance sheets (FBS) remain the best available source of national food data despite their limitations and uncertainties (WHO, 2003). FBS are provided by FAOSTAT and offer data about food availability per country on annual budget (FAOSTAT). The national food profile presented in FBS can be simplified by the following two equations:

Production + Import quantity+ Stock variation – Export quantity = ***Domestic supply quantity*** (1)

Domestic supply quantity = Feed + Seed + Waste + Processing + Other use + ***Food*** (2)

The “waste” entry in FBS represents the losses at the stages: farm, transportation, storage and market of the food system. The FBS data doesn’t account for the waste at the household level, hence it tends to overestimate the individual food consumption by around 15% in worst cases (WHO, 2003).

2.2.2.2.Food Lists

In regards to food lists, the foods are categorized into groups in accordance with FAOSTAT food classifications (FAOSTAT), of which the major groups are cereal and grain products, fruits and vegetables, legumes and nuts, dairy products, fish, poultry, and meats. Given the large variety of foods, only the food items commonly consumed by the local population are considered in the optimization model. These food types are principally derived from Food Balance Sheets in addition to local (Nasreddine et al., 2006; Nasreddine et al., 2010) and regional (WHO, 2003) studies that reflect the population food preferences and cover some important details missing from the FBS.

2.2.3. Crops

The following phase is to assess the input in primary crops to produce the processed foods. For vegetal foods, it is a direct evaluation of crops input into the production process, for instance sugar cane is a primary crop input of derived sugar. For livestock products, it is a composite evaluation of first the live animal heads required to produce the livestock food and second the feed and water quantities required to raise the animals. Here we must differentiate between the feed produced on croplands and Fodder growing in permanent grazing lands (Rockstrom et al., 2007). The production of the former is measured similar to other crops, whereas the only resource considered in the production of the latter is the arable land. Moving from the food list to the crop list is completed via "technical conversion factors" introduced by FAO (FAO, 2003), so that all the demand at this stage is expressed in terms of crops and water. The potential production of crops is primarily a function of climatic conditions, and natural resources, particularly water and land resources.

2.2.4. Climate and Crop Characteristics

2.2.4.1. Crop Evapotranspiration

The Food and Agricultural Organization (FAO) presented in its technical paper No. 56 a detailed method to calculate the crop evapotranspiration and then the crop water requirement over the entire growing period (Allen et al., 1998). The reference evapotranspiration (ET_0) is the evapotranspiration rate from the hypothetical reference surface that is a well-watered grass with specified characteristics, and is a function of only climatic conditions, calculated using the Penman-Monteith method. Then ET_0 is used to obtain the crop evapotranspiration under standard conditions (ET_c)

through the crop coefficient approach (K_c) with $ET_c = K_c * ET_0$, where the crop coefficient (K_c) is a function of crop characteristics. Moreover, ET_0 is used to obtain the crop evapotranspiration under non-standard conditions (ET_{cadj}) that accounts for crops growing in sub-optimal growth conditions caused by factors like water shortage, soil salinity or low soil fertility. In case of water shortage, ET_{cadj} is calculated with $ET_{cadj} = K_s * ET_c$; where the water stress coefficient (K_s) expresses the effect of soil water deficit on the crop evapotranspiration. In addition, FAO paper No. 33 describes a linear relationship between crop yield reduction and crop evapotranspiration reduction due to water shortage (Doorenbos & Kassam, 1979).

2.2.4.2. Crop Yields

The crop yields are presented as statistical data on FAOSTAT but should be used carefully, particularly in developing countries, where crops widely grow under sub-optimal conditions, thus resulting in low yield values. The disparities between current crop yields of nations are considerable with great potentials for agricultural development based on adequate technology and supporting soil fertility in under-yielding regions to diminish the yields gap (Tilman et al., 2011; Rockstrom et al., 2007). For instance, Rockstrom et al. (2007) conducted an experimental study to conclude that there is no hydrologic limitation to increase yield twofold, threefold or even more especially in under-yielding regions. On the other hand, Reynolds et al. (2000) recommended a more conservative approach by stating the maximum national yield as equal to the actual national yield multiplied by a factor of 1.2, which was adopted in several studies including the water footprint reports (Mekonnen & Hoekstra, 2010).

Still, the 1.2 factor may be subjected to improvements by accounting for country-specific conditions.

2.2.5. Land resources

Land resources are the total fertile land and comprise land that is actually cultivated or potential land for future exploitation. Globally, agricultural lands engage around 50 million Km^2 of permanent croplands, annual replanting croplands and permanent pastures (FAOSTAT). Different fertility levels may be associated with arable lands based on the biological, chemical and physical characteristics of the soil (Mekonnen & Hoekstra, 2010). The physical component consists mainly of soil texture and structure, and water holding capacity, while the chemical component comprises acidity, salinity and soil nutrients content particularly nitrogen, phosphorous and potassium. The biological component designates the activities of living organisms in soil as microorganisms, animals and plants. Soil fertility is maintained by a continuous cycle between organic and inorganic forms of nutrients (Abbott & Murphy, 2003). From this perspective, the soil fertility of most arable lands is susceptible for advancement if needed.

2.2.6. Water resources

The agricultural sector currently accounts for more than 70% of the total water withdrawal worldwide (World Economic Forum, 2011a). This immense use of water resources in food production implies, that food security is particularly linked to water security, and that assessing agricultural practices is vital for sustainable water management (Silva, 2013). Water resources constitute the main natural limitation on economic growth (World Economic Forum, 2011b), with the main challenges to attain sustainable water security status being: meeting essential needs, securing food supply and protecting ecosystems (Wouters, 2010). Thus to improve water withdrawal efficiencies, the concept of water footprint (WF) was introduced as equal to the total volume of water consumed and polluted at all production stages of a given product (Hoekstra et al., 2009). This perception allows water-scarce countries to follow trade policies that import water intensive products and export only water extensive products. Furthermore, it is important to track water origins by dividing the total WF between blue, green and gray WFs. Blue water resources are surface and groundwater resources, like lakes, rivers and aquifers, while green water is the water stored in the vadose zone of soil (Sposito, 2013). As such, proper utilization of green water (soil water) can decrease demands of blue water (irrigation) and positively impact national water security.

2.2.7. Irrigation

The efficiency of irrigation, is highly dependent on the system installed, that can be traditional surface, sprinkler or drip irrigation technique. Other important factors are the timing and amounts of water application, where a good management of these factors reduces excess irrigation (thus water losses) and water shortage (thus yield reduction) situations.

2.3.Model Formulation

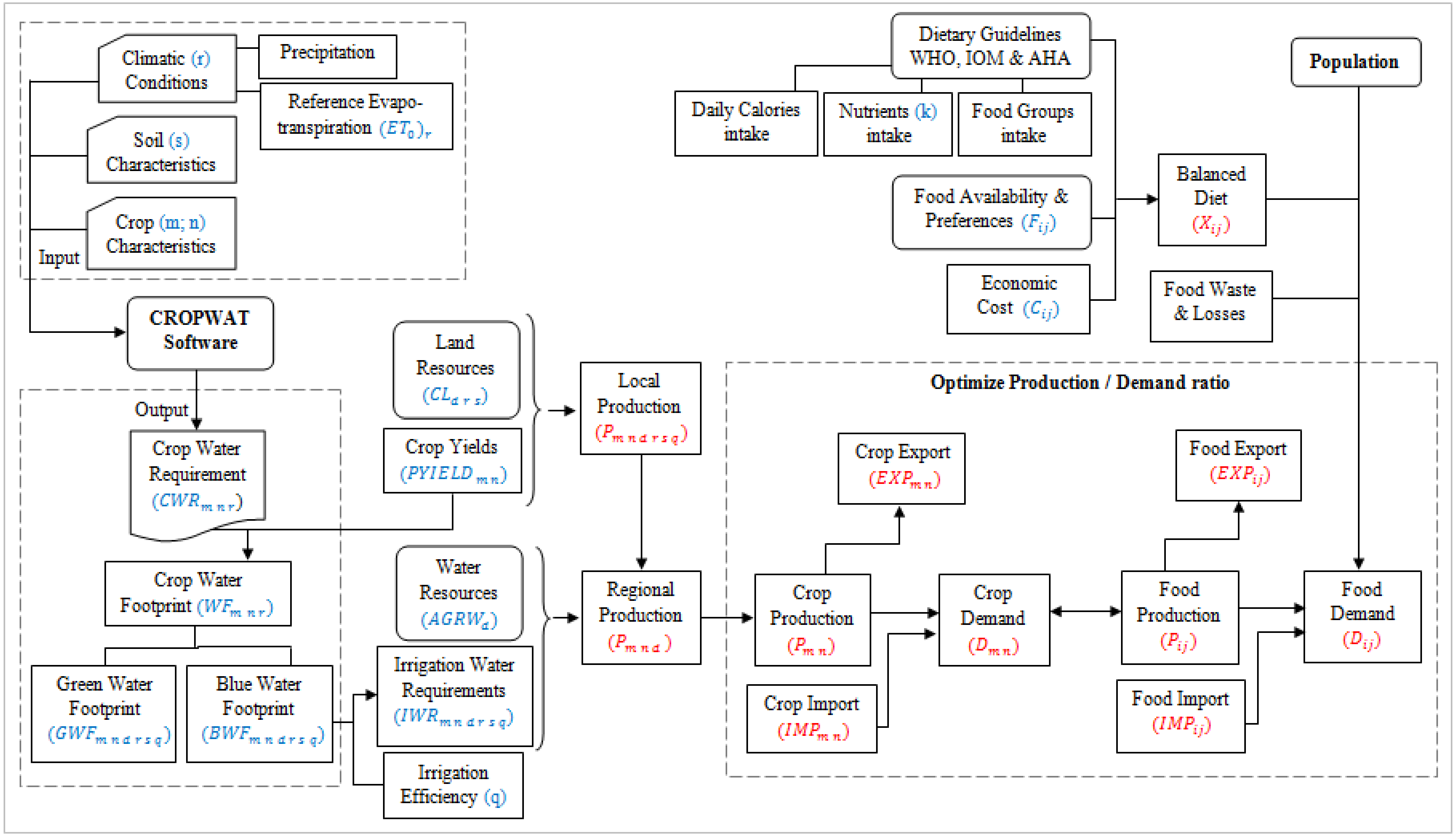
Here we present the model formulation for optimum food and water security at a regional scale, as presented in Figure 2, and consists of defining the model decision variables (DVs), objective functions (OFs) and constraints.

Spatially, the model has the fine resolution to represent different unit cultivation areas as affected by distribution of ecosystem components, field topography, soil characteristics and weather (Smith et al. 2007). However, the model has also a coarser resolution to provide results at district scale, more aligned with the overall objective of improving regional policy than taking decisions at farm scale. Thus, expected policies would not only manage the agricultural sector at national and regional scales via an integrated perspective, but also consider the specialty of farm scale and its optimum usage.

Temporally, we recognize that dealing with agricultural policies requires alignment along a wide range of temporal scales. Policies may involve a duration exceeding a ten year period, while decisions at farm scale are mostly set at annual or sub-annual scale depending on crop type. Furthermore, precipitation and reference evapotranspiration variables are best addressed as monthly averages, whereas cropping schedules and plants irrigation requirements are better addressed on weekly or daily scales. All of these distinct temporal scales are essential and must be linked in the food security model.

Clearly, the built model deals with fine scale from one end (individual food consumption, single food and crop items, unit agricultural land) while attending to coarser scale from the other end (regional consumption and production, country's agricultural sector). Introducing different decision variables at intermediate scales,

Figure 2. Model Framework



called auxiliary variables reduce the gap between the two ends and allow the model to treat food security at both national and individual levels.

2.3.1. Decision Variables

2.3.1.1. Food Consumption Decision Variables

A food decision variable, represented in the model as (X_{ij}), is the daily consumption per capita of food item j belonging to food group i (in g/day/capita). Given that i ϵ {1; 2; …; I} is the index of food groups, I is the total number of food groups, j ϵ {1; 2; …; J(i)} is the index of individual food items belonging to a corresponding food group i and J(i) is the total number of individual food items in group i. The total number of food consumption decision variables is equal to the total number of food items included in the study is $\sum_{i=1}^{I} J(i)$.

2.3.1.2. Food Policy Decision Variables

D_{ij} , P_{ij} , IMP_{ij} and EXP_{ij} are respectively national domestic demand, production, import and export quantities of food (i; j) per year in (ton/year). Similarly, the total number of each of these four decision variables is $\sum_{i=1}^{I} J(i)$. Note that the decision variables are distributed into main and auxiliary DVs. For instance, X_{ij} and D_{ij} are linearly related for every i and j, but both are kept in the model given their significance.

2.3.1.3. Crop Policy Decision Variables

The production quantities of crop (m; n) in ton/year are represented by $P_{m\,n}$. The indices (m; n) refer to the crops list to be differentiated from processed foods (i; j), with m ϵ {1; 2; …; M} being the index of primary crop groups, and n ϵ {1; 2; ….; N(m)} being the index of individual crop belonging to each crop group. We also define $D_{m\,n}$, $IMP_{m\,n}$ *and* $EXP_{m\,n}$ variables as domestic demand, import and export quantities of crop (m; n) per year in (ton/year). The total number of each of the four decision variables is $\sum_{m=1}^{M} N(m)$.

Remark that the import and export operations are supposed to occur at the crop and the food stage together; consequently the food domestically produced may be partially derived from local/foreign crop production.

2.3.1.4.Crop Production Decision Variables

The production variables are divided into partial components to account for different spatial characteristics. First, we define $P_{m\,n\,d}$ as the production quantity (ton) of crop (m; n) growing in district d ϵ {1; 2; …; D}. The total number of decision variables $P_{m\,n\,d}$ is $D\sum_{m=1}^{M} N(m)$. Next, we differentiate between crop productions in different cultivation conditions. The agro-climatic regions are denoted by the index r ϵ {1; 2; …; R}, where a climatic region is defined as region having homogenous average monthly precipitation and reference evapotranspiration values. Furthermore, the irrigation water requirements in a cropland are highly dependent on the soil texture s ϵ {1; 2; … S} and the irrigation criteria or technique used q ϵ {1; 2; Q=3}. As a result, $P_{m\,n\,\,d\,r\,s\,q}$ is the production quantity (ton) of crop (m; n) growing in district d, climatic region r, in cropland of soil texture s and under irrigation technique q. The total number of decision variables $P_{m\,n\,d\,r\,s\,q}$ is $DRSQ\ \sum_{m=1}^{M} N(m)$.

2.3.2. Model Objective Functions

The problem may be optimized with different objectives stressing on either water or food security.

2.3.2.1. First approach: Optimize water security

The first approach aims to minimize the blue water withdrawal (irrigation water). This minimization favors choosing crops with low water requirements.

$$Minimize \sum_{m=1}^{M} \sum_{n=1}^{N(m)} \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,s\,q}$$

Where $P_{m\,n\,d\,r\,s\,q}$ and $IWR_{m\,n\,d\,r\,s\,q}$ are respectively the crop production quantities (ton) and the irrigation water requirements (m^3/ton) of crop (m; n) growing in district d, climatic region r, in cropland of soil texture s and under irrigation technique q.

In this approach, the objective function must be associated with additional constraint that ensures a desired level of food security. Otherwise, the optimization will favor import of all foods and annul production. FAO define self-sufficiency ratio (SSR) as the “magnitude of production in relation to domestic utilization” (FAO, 2001):

$$Self\ Sufficiency\ (SSR) = \frac{Production}{Production + Import - Export} \qquad (3)$$

Self-sufficiency ratio may be calculated for individual food item or whole food group. If SSR is greater than 1, then the country is a net exporter of the food item in question, and in the opposite case (SSR<1) the country is a net importer of the food item. In general, the total SSR may be constrained to be greater than a specified value.

Furthermore, foods are classified into diverse priority levels ($Priority_{ij}$) ϵ {1; 2; 3; …} based on their nutritional value and criticality for food security status. Accordingly, different self-sufficiency constraints may be assigned for foods having different priority levels. This allows testing scenarios that maximize (SSR_{ij}) of essential foods like wheat products and relax the SSR constraint of some complementary foods like exotic fruits.

$$SSR_{ij} = \frac{P_{ij}}{P_{ij} + IMP_{ij} - EXP_{ij}} \geq \left(\text{SSR ratio associated to } Priority_{ij}\right) \quad \forall\, i \,\&\, j \qquad (4)$$

2.3.2.2. Second approach: Optimize food security

The second approach focuses on maximizing the self-sufficiency ratio defined previously. Similar to first approach, the self-sustainability of foods can be weighted by their priority level in the objective function formula.

$$Maximize \quad \frac{1}{\sum_{i=1}^{I} J(i)} \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \frac{SSR_{ij}}{Priority_{ij}}$$

Here, the renewable water constraint will ensure a sustainable agricultural water use.

In conclusion, the first approach prioritizes water security by minimizing irrigation withdrawal with certain level of food self-sufficiency, while the second approach prioritizes food security by maximizing food self-sufficiency given the available water. Both approaches ensure an optimal water-food security nexus.

2.3.3. Model Constraints

2.3.3.1. Balance Constraints

2.3.3.1.1. Food National demand

The national consumption of foods per year is calculated by moving from the individual scale (g/day/capita) to the national scale (ton/year/population). This establishes the total requirements to compare with the production capabilities under limited land and water resources. The national consumption accounts for the total population including the waste and losses factors.

$$D_{ij} = \frac{X_{ij} * Population * 365.25}{10^6 * \left(1 - waste\ factor_{ij}\right)(1 - Loss\ ratio_{ij})} \quad \forall\ i\ \&\ j \qquad (5)$$

The loss ratio represents the losses at the farm, transportation and market stages of the food system while the waste factor occurs at the household level.

A food balance constraint (in = out) at the inventory year is added assuming the storage change equal to zero.

$$P_{ij} + IMP_{ij} - EXP_{ij} = D_{ij} \quad \forall\ i\ \&\ j \qquad (6)$$

2.3.3.1.2. Food-Crop relating constraints

We introduce the matrix $A = \left[a_{m\,n\,,i\,j}\right]$ that links the original crops with the consumed foods. Every element $a_{m\,n\,,i\,j}$ represents the amount needed of crop (m; n) to produce a unit weight of food item (i; j) and is determined/calculated one to one as the inverse of "extraction rates" presented in FAO's Technical Conversion Factors paper (FAO, 2003). The dimension of matrix A is $\sum_{m=1}^{M} N(m) \times \sum_{i=1}^{I} J(i)$.

The domestic demand on crop (m; n) in ton/year $(D_{m\,n})$ needed for food production $\left(P_{ij}\right)$ is computed as follows:

$$(D_{m\,n}) = A \times \left(P_{ij}\right) \quad \forall\ m, n, i\ \&\ j \qquad (7)$$

The crop balance constraint at inventory year is the following:

$$P_{m\,n} + IMP_{m\,n} - EXP_{m\,n} = D_{m\,n} \quad \forall\ m\ \&\ n \qquad (8)$$

2.3.3.1.3. Crop Production Constraints

The production variables are the essential decision variables calculated by the optimization model. Here, two Balance Constraints are needed:

1. For every crop (m; n), the summation of crop production quantities across all the districts is equal to the total national production of this crop.

$$P_{m\,n} = \sum_{d=1}^{D} P_{m\,n\,d} \quad \forall\, m\ \&\ n \tag{9}$$

2. For every crop (m; n), the summation of crop production quantities in different croplands within the same district is equal to the total crop production in this district.

$$P_{m\,n\,d} = \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} \qquad \forall\, m, n\ \&\ d \tag{10}$$

2.3.3.2. Daily Per Capita Food Consumption Constraints

2.3.3.2.1. Daily Calories intake

The population-wide average energy intake ($Calorie\ intake_{av}$) is calculated by assuming a moderate or high activity level and by averaging the intake of all age groups, each weighted by its corresponding percentage. The calculated *Calorie Intake*$_{av}$ is then used in the following nutrition constraints to compute the lower and upper intake bounds of nutrients.

$$Calorie\ intake_{av} = \frac{\sum[Calorie\ intake\ by\ Age\ Group\ \times\ Age\ Group\ Count]}{Population} \tag{11}$$

2.3.3.2.2. Nutrition Constraints

By analyzing the nutrient intake goals presented in Table 1, we distinguish two classes of constraints.

A. Nutrient Intake constraints:

Based on Table 1, we ensure the intake of 16 nutrients ranked k starting with k = 1 for calorie intake as summarized in Appendix I. The content of nutrient type k in food (i; j), noted (NTR_{ijk}), is given per 100 gram of edible portion of foods, as extracted from the databases like USDA Nutrient database (USDA, 2014). Foods of the same type but produced in different countries may have different elements content caused by varied soil characteristics among croplands (Nasreddine et al., 2010). The daily intake of every nutrient type is summed for all the foods (i; j) consumed and is set between lower and upper bounds.

$$L_k \le \sum_{i=1}^{I}\sum_{j=1}^{J(i)} \frac{NTR_{ijk}}{100} * \left(\text{Edible portion of } X_{ij}\right) \le U_k \quad \forall\, k \in \{1; \ldots ; K = 16\} \qquad (12)$$

Where, k is the index of nutrients accounted for in the nutritional verification; NTR_{ijk} is the content of nutrient k (g or mg) present in 100 g of food type (i; j); and L_k and U_k are the lower and upper bounds on the daily intake of nutrient k (g or mg per day) respectively.

Note that the energy intake constraint (for k =1) is an equality constraint where the lower and the upper bounds are equal to the *Calorie Intake*$_{av}$ calculated previously. The lower and the upper bounds are extracted from the nutritional guidelines (Table 1) but are subjected to unit conversions (percentages, calories, grams, liters) to match the nutrient units used in the USDA database. The calculation steps are illustrated in Appendix I.

B. General food groups guidelines:

These constraints are general recommendations for the entire food group like the AHA guidelines presented in Table 1. The recommended number of servings per day or week was converted to equivalent weight in gram.

$$Min\ intake_i < \sum_{j=1}^{J(i)} X_{ij} < Max\ intake_i \quad \forall i \in \{\text{food groups covered by AHA}\} \quad (13)$$

Where Min and Max $intake_i$ guidelines (g/day) are the minimum and maximum intake guidelines of food group i integrated AHA guidelines.

Furthermore, the fraction of animal to vegetal calories in the recommended diet is not stated explicitly in the nutritional guidelines, but it is mainly determined by limiting the cholesterol intake at 300 mg per day, as cholesterol is only found in foods from animal sources. This is significant as while foods in general are water intensive commodities, water footprint for vegetal is much lower than that of animal foods. For instance, the global average water footprint of cereals is in the range of 1,500 liters/kg while it is in the range of 15,000 liters/kg for bovine meat (Chapagain & Hoekstra, 2004).

2.3.3.2.3. Energy density of the diet

The diet energy density (kcal/g) is a critical factor in the nutritious diet and depends on the intake proportions of the three macronutrients in addition to the food water content (Krauss et al., 2000). The foods are classified into low energy density foods (less than 1.5 kcal/g), medium energy density foods (1.5 to 4 kcal/g) and high energy density foods (more than 4 kcal/g). It is recommended to consume more foods with low or medium energy density as fruits, vegetables and cereals, and limit the consumption of foods with high energy density as butter and oils. A diet with foods of low energy density would moderate the intake of excess calories and enhance the overall nutrient density of the diet. The energy density of the model output diet must be checked and compared with the original diet energy density. It is calculated as the total calories intake (Kcal/day) divided by the total weight of the diet (g/day).

$$Diet\ energy\ density\ \ (Kcal/g) = \left(\sum_{i=1}^{I}\sum_{j=1}^{J(i)}\frac{NTR_{ij\ (k=1)}}{100} * X_{ij}\right) / \left(\sum_{i=1}^{I}\sum_{j=1}^{J(i)} X_{ij}\right) \quad (14)$$

2.3.3.2.4. Population Preferences Constraint

This constraint sets α_{ij} (%) as the maximum allowable change in the diet for food item (i; j) to limit the difference between the original and target (optimum) diets, so that no extreme dietary changes are taken and the food preferences of the population will be respected to the maximum extent. Let F_{ij} be the amount of food (i; j) currently consumed by the population in g/day/capita, which can be null value if considering foods that were not initially consumed. The following constraint exists for every food item (i; j) where $F_{ij} > 0$

$$-\alpha_{ij} \leq \frac{F_{ij} - X_{ij}}{F_{ij}} \leq \alpha_{ij} \qquad \forall\ i\ \&\ j \qquad (15)$$

In addition, the food preferences constraint would oblige the model to comprise a good variety of foods in the output diet. However, we also introduced, in Appendix I, a specific constraint for food varieties in the form of an integer problem.

2.3.3.2.5. Diet Economic Cost Constraint

The market value of total food items incorporated in the diet should have a lower bound to ensure minimum accepted variety as well as an upper bound that is less than the food share in the income, to ensure an economically-feasible and nutritious diet accessible to the most vulnerable population. The lower bound can be the food share (expenditure) at the poverty line in a region whereas the upper bound can be the food share from the average national expenditure report (in the absence of a national or international target). For every food item (i; j), a cost coefficient C_{ij} (US$ per g) will be associated.

$$Lower\ bound \leq \sum_{i=1}^{I} \sum_{j=1}^{J(i)} C_{ij} * X_{ij} \leq Upper\ bound \quad (16)$$

Where,

$$\text{Lower bound} = \frac{\text{Food Share (\% of income)} * \text{ Poverty Line Income (\$/capita/year)}}{365.25 \text{ (days/year)}} \quad (17)$$

$$\text{Upper bound} = \frac{\text{Food share } * \text{Average National Income}}{365.25} \quad (18)$$

2.3.3.3. Resource Constraints

2.3.3.3.1. Land Constraints

In the model, the crop production quantities will be computed under two crop yield scenarios:

1. Current crop yields ($YIELD_{m\,n}$) in ton/ha of crop (m; n)
2. Potential crop yields ($PYIELD_{m\,n}$) in ton/ha

The target of the second scenario is to assess role of technology and agricultural development in the potential improvement to water-food security status by reducing the gap existing between actual and potential yields.

In any region, the land area cultivated by a crop is equal to the crop production (ton) in this region divided by the crop yield (ton/ha). The summation of these land areas over all crops should be less than or equal to the total available land for cultivation (ha). Here we define $CL_{d\,r\,s}$ and $CL_{m\,n\,d\,r\,s\,q}$ respectively as the land available for cultivation in the district d, climatic region r and soil texture s and that cultivated in crop (m; n) under irrigation technique q.

$$\frac{P_{m\,n\,d\,r\,s\,q}}{PYIELD_{m\,n}} = CL_{m\,n\,d\,r\,s\,q} \qquad \forall\, m, n, d\,, r, s\ \&\ q \tag{19}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N(m)}\sum_{q=1}^{Q} CL_{m\,n\,d\,r\,s\,q} \le CL_{d\,r\,s} \qquad \forall\, d\,, r\ \&\ s \tag{20}$$

The summation of cultivated areas in all regions is equal to the total national cultivated land area TCL in ha.

$$\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{s=1}^{S} CL_{d\,r\,s} = TCL \tag{21}$$

Land is classified into three major categories: Actual cultivated land, Potential agricultural but not cultivated land (arable land) and Non-fertile land. It is recommended to run the model with *TCL* equal to the actual cultivated lands, and if land resource proved to be the limiting constraint, new unexploited land can be added to *TCL*. The constraint on grazing lands for animals depends on the country environment.

Furthermore, a constraint can be added to distinguish between lands cultivated with permanent crops (trees) and those cultivated with annual field crops (like cereals). The purpose is to impose a penalty cost for the conversion of permanent crops lands into others cultivation types in case the model proposed this conversion. To do so, any hectare reduction in the actual agricultural lands of trees will have a dollar cost ($/ha).

2.3.3.3.2. Water Constraints

The two main water concerns of this project are crop water footprint and irrigation water demand, both could be calculated via the CROPWAT model provided by FAOSTAT database (FAO, 2014a), and based on the two FAO technical papers No. 56 (Allen et al., 1998) and No. 33 (Doorenbos & Kassam, 1979). CROPWAT combines various climatic, crop and soil data to compute the crop water requirement (CWR) over the entire growing period, and consequently irrigation demands and schedules (FAO, 2014a). Climatic data for ET_0 Penman-Monteith evapotranspiration and precipitation can be obtained from FAO's CLIMWAT global database (FAO, 2014b), whereas standard crop and soil data files are provided with CROPWAT in absence of local data. The daily cropfield evapotranspiration $(ET_c)_{m\,n\,r}$ in different agro-climatic zones is equal to:

$$(ET_c)_{m\,n\,r} = (K_c)_{m\,n} * (ET_0)_r \qquad \forall\, m, n \,\&\, r \qquad (22)$$

Moreover, the irrigation requirements are accurately evaluated by applying the soil water balance method (Allen et al., 1998) to consider all outflows and inflows to the root zone (Figure 3). The soil water balance equation is expressed in terms of the root zone depletion (Dr), that is the water shortage in the root zone with respect to field capacity (in mm):

Depletion *(end of day i)* = ***Depletion*** *(end of day i-1)* + ***Crop Evapotranspiration*** *(day i)* – ***Net Irrigation*** *(day i)* – ***Precipitation*** *(day i)* + ***Runoff*** *(day i)* – ***Capillary Rise*** *(day i)* + ***Deep Percolation*** *(day i)* (23)

CROPWAT then calculates the total crop water and irrigation requirements and as the summation over the growing period. The CROPWAT data input, output and irrigation criteria are presented in Appendix II.

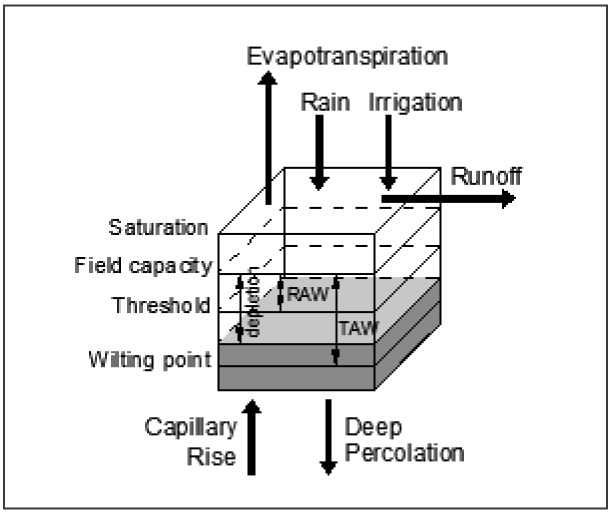


Figure 3. Unit volume of the root zone with the water balance elements, adapted from (Allen et al., 1998)

A. Crop Water Footprint:

Potential Water Use per crop (m; n) in region r ($PWU_{m\,n\,r}$) is calculated by CROPWAT in mm over the entire growing period.

$$PWU_{m\,n\,r} = \sum_{\substack{growing \\ period}} (ET_c)_{\,m\,n\,r} \qquad \forall\, m, n \,\&\, r \tag{24}$$

The crop water requirement in m^3/ha (converted from $PWU_{m\,n\,r}$ in mm):

$$CWR_{m\,n\,r} = 10 * PWU_{m\,n\,r} \qquad \forall\, m, n \,\&\, r \tag{25}$$

Since the crops are assumed to be growing under optimal conditions where the crop water requirements are fully met, the actual water use per crop is equated with the CWR and the water footprint of crop (m; n) in m^3/ton is calculated as follows:

$$WF_{m\,n\,r} = \frac{CWR_{\,m\,n\,r}}{PYIELD_{\,m\,n}} \qquad \forall\, m, n \,\&\, r \tag{26}$$

Obviously, the water footprint value doesn't depend on the district (location of cropland) but more on climatic conditions r,

$$WF_{m\,n\,d\,r} = WF_{m\,n\,r} \qquad \forall\, d \tag{27}$$

B. Crop Irrigation Water Requirement:

The total water footprint is divided into blue (*BWF*) and green (*GWF*) water footprint, where the BWF represents irrigation water extracted from surface and ground waters while the GWF represents the soil moisture available in the root zone from effective rainfall. The relative weight of the two WFs is a function of total precipitation over the growing period (depends on the region r), soil texture and irrigation technique q: convenient cultivation conditions result in higher contribution of green water. The treated gray water can also be added if used for irrigation in significant amounts.

$$WF_{m\,n\,d\,r\,s\,q} = BWF_{m\,n\,d\,r\,s\,q} + GWF_{m\,n\,d\,r\,s\,q} \tag{28}$$

The irrigation water requirements in m^3/ton:

$$IWR_{m\,n\,d\,r\,s\,q} = \frac{BWF_{m\,n\,d\,r\,s\,q}}{efficiency\ of\ irrigation\ technique\ q} \tag{29}$$

The total irrigation water should be limited by the agricultural water share in the region, which is determined by an integrated management plan of renewable water resources under the Water-Energy-Food nexus approach. There are diverse scenarios that might be adopted to calculate this agricultural water share, including FAO's irrigation water withdrawal thresholds of 40% and 20% of the total renewable water resources, to be considered a critical or impending water scarcity status, respectively [26]. Here, we define $AGRW$ and $AGRW_d$ as the water share (m^3/year) devoted/available for agricultural sector use by country and by district respectively, and can be derived from blue and gray water resources. Thus:

$$\sum_{m=1}^{M}\sum_{n=1}^{N(m)}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,s\,q} + WLA \le AGRW_d \qquad \forall\, d \tag{30}$$

$$\sum_{d=1}^{D} AGRW_d = AGRW \qquad (31)$$

Where, WLA is the water required for raising live animals that are processed into livestock food products, and is mainly the summation of drinking and service water consumed during the animals lifespan. The complex process to evaluate the value of WLA is presented in Supplement information.

2.3.3.4. Economic Policies Constraints

Several constraints can be added to regulate the agricultural policies in the region. For example, production can be constrained with maximum agricultural budget (Eq. 32), and export and import policies can be set via minimum export revenue and maximum import expenditure (Eq. 33 and Eq. 34), respectively.

$$\sum_{m=1}^{M}\sum_{n=1}^{N(m)} \text{Unit Production Cost} * P_{m\,n} \leq \text{ maximum agricultural budget} \qquad (32)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J(i)} \text{Unit Export Profit} * EXP_{ij} \geq \text{minimum economic revenue from food export} \qquad (33)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J(i)} \text{Unit Import Cost} * IMP_{ij} \leq \text{maximum national expenditure on foods import} \qquad (34)$$

2.3.3.5. Non-negativity constraints

All decision variables are non-negative variables.

Finally, the built model includes a combination of different forms of constraints to address the multi-disciplinary problem, all of them are linear constraints unlike the non-linear formulation of SSR in the objective function.

2.3.3.6. Impact of the Time Variable:

The impact of time variable on the problem conceptualization is discussed in this section along with the associated formulation.

2.3.3.6.1. Monthly Population and Production variables

There are two major reasons to consider a variable population across the year: the monthly population increase and the seasonal change in inhabitants (foreign workers in winter season and tourists in summer season). In the same way, the national average diet (Xij) can be taken as annual or seasonal (two distinct diets per year) average diets.

We define the index t to represent the time steps per year, here considered on monthly scale; thus $t \in \{1; 2; \ldots; T = 12\}$

$$D_{ij\,t} = \frac{X_{ij} * Population_t * 30.5}{10^6 * (1 - waste\ factor_{ij})(1 - Loss\ ratio_{ij})} \quad \forall\ i, j\ \&\ t \qquad (35)$$

Where $Population_t$ and $D_{ij\,t}$ are the population count and the national demand of food (i; j) in month t. As for the food balance constraint in month t, storage is allowed throughout the year.

$$P_{ij\,t} + IMP_{ij\,t} - EXP_{ij\,t} + STK_{ij\,(t-1)} - STK_{ij\,t} = D_{ij\,t} \quad \forall\ i, j\ \&\ t \qquad (36)$$

Where $STK_{ij\,(t-1)}$ and $STK_{ij\,t}$ are respectively the stock variables at the end of months t and (t-1), $P_{ij\,t}$, $IMP_{ij\,t}$ and $EXP_{ij\,t}$ are the production, import and export quantities of food (i; j) in month t (ton/month). We still suppose that the overall delta storage of the inventory year is zero, thus stock variables in months 1 and 12 are null:

$$STK_{ij\,(t=1)} = STK_{ij\,(t=12)} = 0 \quad \forall\ i\ \&\ j \qquad (37)$$

Same discussion and formulation is repeated for crops, but note that the production time of crops may belong for years before that of foods, as in case of livestock feeds.

$$(D_{m\,n\,t}) = A \times \left(P_{ij\,t}\right) \quad \forall\, m, n, i, j \,\&\, t \tag{38}$$

$$P_{m\,n\,t} + IMP_{m\,n\,t} - EXP_{m\,n\,t} + STK_{m\,n\,(t-1)} - STK_{m\,n\,t} = D_{m\,n\,t} \quad \forall\, m, n \,\&\, t \tag{39}$$

$$STK_{m\,n\,(t=1)} = STK_{m\,n\,(t=12)} = 0 \qquad \forall\, i \,\&\, j \tag{40}$$

2.3.3.6.2. Seasonal Land Cultivation

In crop production variables, t represents the harvest date (month):

$$P_{m\,n\,t} = \sum_{d=1}^{D} P_{m\,n\,d\,t} \quad \forall\, m \,\&\, n \tag{41}$$

$$P_{m\,n\,d\,t} = \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q\,t} \qquad \forall\, m, n \,\&\, d \tag{42}$$

For the cultivation period of crops, we introduce the index τ ϵ {first cultivation month; final / harvest month}

$$\frac{P_{m\,n\,d\,r\,s\,q\,t}}{PYIELD_{m\,n}} = CL_{m\,n\,d\,r\,s\,q\,\tau} \qquad \forall\, m, n, d\,, r, s \,\&\, q \tag{43}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N(m)}\sum_{q=1}^{Q} CL_{m\,n\,d\,r\,s\,q\,\tau} \le CL_{d\,r\,s} \quad \forall\, d\,, r \,\&\, s \tag{44}$$

At this stage, we must differentiate between annual and perennial crops. For the first category, the cropland may be exploited more than once a year since most grains, vegetable, legumes and roots and tubers have a flexible cultivation / seeding date. Early and late cultivation periods enable two harvests per year of the same crop, for example, tomato crop have a life span of four to five months and a cultivation date from January to May in Mediterranean regions (Allen et al., 1998). But to maintain high soil fertility, land rotation between two or more crops is adopted. Some rounds may extend to a period of two or four years, for example, cultivation of sugar beet and wheat in the first year and of potatoes and vegetables in the second year. In model formulation, the same crop cultivated in different weathers have different water footprint and irrigation needs, and thus distinct decision variables are defined to each (for instance: Tomato1 and Tomato2). No general constraints are set for those cultivation options, since they are based mainly on traditional agricultural practices, for crops with non-overlapping growing periods (τ). For the second category of perennial trees, the period (τ) persist all over the year, the existing cultivated lands ($CL_{m\,n\,d\,r\,s\,q\,\tau}$) are recognized and limitedly changed (or penalized), and their cultivation requires a policy of long-term horizon to meet the future food demand.

2.3.3.6.3. Water Availability

Water balance is not accurate expressed at the annual scale due to non-uniform temporal water availability, and should be addressed at finest temporal scale (month). This allows the potential crop evapotranspiration ($PWU_{m\,n\,r}$) to be evaluated at monthly scale as follows:

$$PWU_{m\,n\,r\,t} = \sum_{\text{month t}} (ET_c)_{\,m\,n\,r} \qquad \forall\, m, n, r \,\&\, t \tag{45}$$

Then,
$$PWU_{m\,n\,r} = \sum_{t=1}^{T} PWU_{m\,n\,r\,t} \qquad \forall\, m, n \,\&\, r \tag{46}$$

$BWF_{m\,n\,d\,r\,s\,q\,t}$ is calculated for each month t via CROPWAT.

$$IWR_{m\,n\,d\,r\,s\,q\,t} = \frac{BWF_{m\,n\,d\,r\,s\,q\,t}}{\text{efficiency of irrigation technique q}} \qquad \forall\, m, n, d, r, s, q \,\&\, t \tag{47}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N(m)}\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,s\,q\,t} + WLA \;\leq AGRW_t \quad \forall\, t \qquad (48)$$

Where, $AGRW_t$ is the water available for agricultural use in month t. And finally the irrigation by crop over the entire year:

$$IWR_{m\,n\,d\,r\,s\,q} = \sum_{\mathrm{t}=1}^{\mathrm{T}} IWR_{m\,n\,d\,r\,s\,q\,t} \qquad \forall\, m, n, d, r, s \;\&\; q \qquad (49)$$

CHAPTER 3

VALIDATION WITH HYPOTHETICAL CASE STUDY

3.1.Case Study Description

To demonstrate the effectiveness of the proposed model, we present a simple generic case study that consists of limited varieties of all variables.

The study area is formed of one district distributed into three climatic regions, climate1 (interior) being the wettest region, climate2 (coastal), and climate3 (arid). The area is also characterized by a single soil type and irrigation technique (70% efficiency), (Table V-1). For the foods and crops data, we consider four types of food (wheat flour, tomatoes, oranges, dry beans) in addition to the drinking water. Thus, the crops considered are also four (wheat, tomatoes, oranges and beans). To further simplicity, only four nutrients are considered (total water, total calories, carbohydrates and protein intakes), as shown in Table V-2.

This results in a problem with 17 principal decision variables out of a total 57 D.Vs. (Table V-3). Not all of the constraints are integrated here, rather we considered just the essential balance (Eq.5, 6, 7, 8 & 10), nutrition (Eq.12) and resources constraints (Eq.19 & 29); their number is 34 constraints (Tables V-4 & V-5). Three objective functions are addressed: (OFa) attempt to maximize the food security by means of the nonlinear formula of foods self-sufficiency ratios (SSR), while (OFb) and (OFc) aim to linearly minimize the water and land resources exploited, respectively. The model is incorporated into and solved by Microsoft Excel spreadsheets.

3.2.Results and Sensitivity Analysis

3.2.1. Water Footprint of Crops

The crops water footprint and irrigation needs were calculated for each climatic region r by CROPWAT model and are presented in Table V-7, and was found to be lowest for the first climate, where the average WF for climate1 is lower by 20% and 45% than that of climate2 and climate3, respectively. The difference is farther amplified for the irrigation water, where the climate1 gives values lower by about 35% and 75% than climate2 and climate3 respectively. In regard to crops, the oranges inclose the maximum WF (average 5400 m^3/ton) that is about 50 times greater than the min WF (average 110 m^3/ton) recorded for tomatoes. however, almost all water requirements for tomatoes comes from irrigation sources due to its unfavorable cultivation in dry season, whereas orange is a perennial crop that benefits from rainfall water in wet season, which reduces the gap in irrigation water (m^3/ton) between the two extreme crops to 33 times.

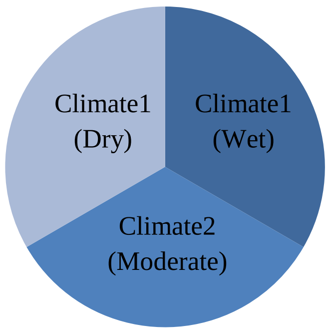
3.2.2. Scenario 1: Resources Abundance

For a population of 100 inhabitants, we introduce Scenario 1 by assuming all resources required to sustain the population are abundant, so that the foods are domestically produced. We decided on 30 hectares of agricultural lands equally distributed among the three climates (10 ha for each) along with 50,000 m^3 of freshwater available for irrigation (Figure4).

Region
100 inhabitants
50,000 m^3 Irrigation Water
30ha Agricultural Lands

Crops
Wheat
Oranges
Tomatoes
Beans

Nutrients
Water
Calories
Protein
Carbohydrates



1 Soil type (loam)

1 Irrigation technique (70% efficiency)

Figure 4. The study area in Scenario 1 consists of 100 inhabitants, 30 ha agricultural lands and 50,000 m^3 irrigation water

3.2.2.1.First Objective Function (OFa)

$$(\mathrm{OF_a}) \qquad Maximize \ \frac{1}{\sum_{i=1}^{I} J(i)} \sum_{i=1}^{I} \sum_{j=1}^{J(i)} SSR_{ij} \ , \qquad \text{where} \ \ SSR_{ij} = \frac{P_{ij}}{P_{ij} + IMP_{ij} - EXP_{ij}}$$

Multiple starting points were checked to ensure the optimality of the results obtained by the first objective function with its nonlinear formulation. Export is firstly set equal to zero, and since this scenario is resource abundant, we expect the production to meet the demand, thus the maximum SSR can reach one (zero import). The tested starting points provided multiple optimum solutions but within a stable range, with a moderate deviation in decision variables values, grace to nutritional constraints. The average consumption variables (X_{ij}) are about 370g/capita/day of wheat flour, 120g of oranges, 1100g of tomatoes and 205g of beans (Table3).

Cultivated lands concentrated in the most favorable climate1 with the entire 10 ha being exploited (binding resource constraint), then the model shifts to use some agricultural lands in the next desired climate2 (3.8 ha) and almost zero lands in the arid climate3 (0.1 ha), so the constraints of these two land resources are not binding. The water constraint is also binding where the whole 50,000 m^3 were withdrawn.

Table 3. Summary Table of results of Scenario 1

		OFa	OFb	OFc	OFa with Export
Food Variables (Xij)	Wheat Flour (g)	370	390	390	563
	Oranges (g)	120	1	1	10
	Tomatoes (g)	1100	1200	1200	1190
	Beans (g)	205	200	200	10
	Drinking Water (L)	2	2	2	2
Resources	Water Withdrawn (m^3)	50,000	29,170	47,500	50,000
	(%)	100	60	95	100
	Land Exploited (ha)	13.8	10.4	10.2	15.4
	(%)	46	35	34	51
	Land Climate1 (ha)	10	10	3.4	10
	Land Climate2 (ha)	3.8	0.4	3.4	5.4
	Land Climate3 (ha)	0.1	0	3.4	0

Export Variables:

Keeping the same conditions, we add the Export as principal decision variables which their number becomes 21 D.Vs. Now, SSRij may go larger than one with OFa that aims to maximize the average SSR of all foods. What the model will basically do is increasing the production (also export) and diminishing the demand of a certain crop to obtain high ratio between the two numbers, and consequently SSR could reach infinitely high values. To prevent this possibility and ensure that production will cover the domestic demand before starting to export foods, we added constraints on individual food items (SSRij > 0.999) and we required a minimum consumption of all foods (10 grams).

The optimum solution obtained is SSR = 10.8, with increased consumption of wheat flour (563g) and tomatoes (1190g), and minimum consumption of beans and oranges (10g) (Table 3). OFa (average SSR) was maximized through the export of beans (24.8 tons) with SSR_{beans} is about 50 and is one for other foods (Figure 5). Observing the change in consumption variables (X_{ij}), the model has limited the domestic consumption of certain foods in order to achieve higher SSR. This choice could be justified and evaluated only in light of economic benefits, and thus decide if exporting 25 tons of beans is significant to almost exclude the oranges from domestic consumption.

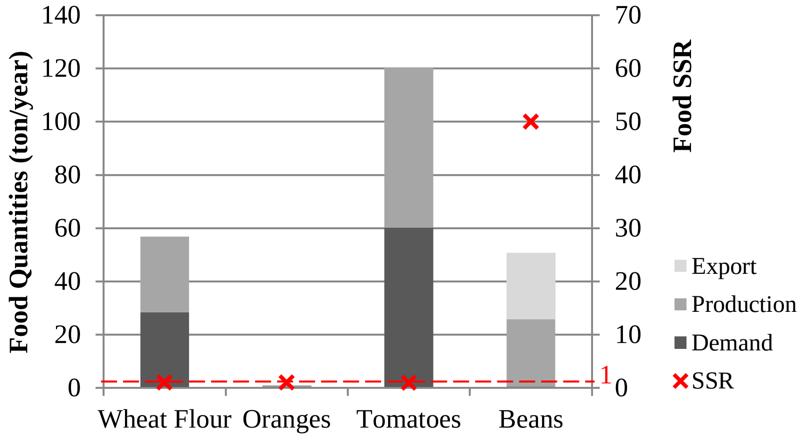


Figure 5. Demand, Production and Export variables of food items (based on Table V-9)

3.2.2.2. Second Objective Function (OFb)

$$(OF_b) \quad Minimize \sum_{m=1}^{M} \sum_{n=1}^{N(m)} \sum_{d=1}^{D} \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,s\,q}$$

$$\text{With:} \quad SSR_{ij} = \frac{P_{ij}}{P_{ij} + IMP_{ij} - EXP_{ij}} \geq \text{minimum ratio} \quad \forall\, i\, \&j$$

The second objective function linearly minimizes the irrigation water volume under the constraint of full food local production; with SSRij set greater than 0.999. A unique optimum solution of 29,170 m^3 irrigation water is needed to achieve the same optimum food security level by withdrawing only 60% of the total available water. The evident following step is to examine what was changed in the model's decisions regarding the foods consumption, the crops production and the resources reallocation.

The model obviously prefers the crops of lower WFs as long as the nutritional constraints are met. The consumption of orange is abandoned due to its highest irrigation water demand and substituted by extra-consumptions of wheat (additional 20g) and tomatoes (additional 100g) (Table3). This substitution resulted also in requiring fewer lands for agricultural production.

Moreover, we performed a Sensitivity Analysis of the right hand side of the water constraint and the three land constraints using the linear OFb. Here, the water resource constraint becomes a non-binding constraint and the land resources constraints remain as binding for climate1 and non-binding for climate2 and climate3 (Tables V-9 & V-10). The shadow price of the single binding constraint (climate1) is about -1225 m^3, indicating that every unit increase (1 ha) in this resource will induce a 1225 m^3 decrease in the objective function (irrigation water), which represents about 4% of the current optimum value. Accordingly, water and land are interdependent, if more land is available thus less water is needed because agriculture would be applied in favorable conditions. As for the ranges of optimality, the allowable decrease of resources in condition of maintaining the same optimum value of OFb, is obviously zero for the binding constraint and equal to the slack of the non-binding constraints: 9.7ha for the climate2, 10ha for the climate3 and 20,800 m^3 for the water constraint.

3.2.2.3.Third Objective Function (OFc)

$$(\mathrm{OF}_c) \qquad Minimize \sum_{d=1}^{D} \sum_{r=1}^{R} \sum_{s=1}^{S} CL_{d\,r\,s}$$

With: $SSR_{ij} = \dfrac{P_{ij}}{P_{ij} + IMP_{ij} - EXP_{ij}} \geq \text{minimum ratio} \quad \forall\, i \,\&j$

The third objective function was applied to linearly minimize the agricultural lands exploited, under the constraint of food SSRij > 0.999 and maximum water availability of 50,000 m^3. The optimum solution is total lands equals 10.41 ha distributed in either way among the three regions since the crop yield was taken unchanged among regions (Table V-6). This minimum land is obtained by choosing the crops of higher yields regardless of the location cultivated in as long as the one condition of not exceeding the water budget is satisfied. Therefore, there is unique optimum solution of consumption variables X_{ij} , of same values of those in OFb (Table3), but there are infinite optimum solutions of P_{mndrsq} variables. Even though the water volume used may reach 50,000 m^3 in certain solutions, still the water is not considered a binding resource in this problem since there are always other optimum solutions giving lower values of water volume. Thus, OFc didn't go further than OFb in the optimization process with regard to studying the water constraint.

3.2.3. Resource Scarcities

3.2.3.1.Scenario2: Land Scarcity

After we addressed the food security status (OFa) in view of abundance resources, we consider the problem extremes being water and land scarcities. In Scenario 2, the land resource was gradually reduced from 30 ha to 3 ha by decreasing 3ha at each step. The equal division of lands between the three climates along with the water resource was preserved.

While the consumption (X_{ij}) of the low-yield orange crop decreased progressively from its initial value of 120g to zero at 9ha available land, the high-yield tomatoes consumption increased from 1100 to 1200g (Figure 6). This monotonic change in food variables X_{ij} reveals the stability of the optimization model realized via the nutritional constraints.

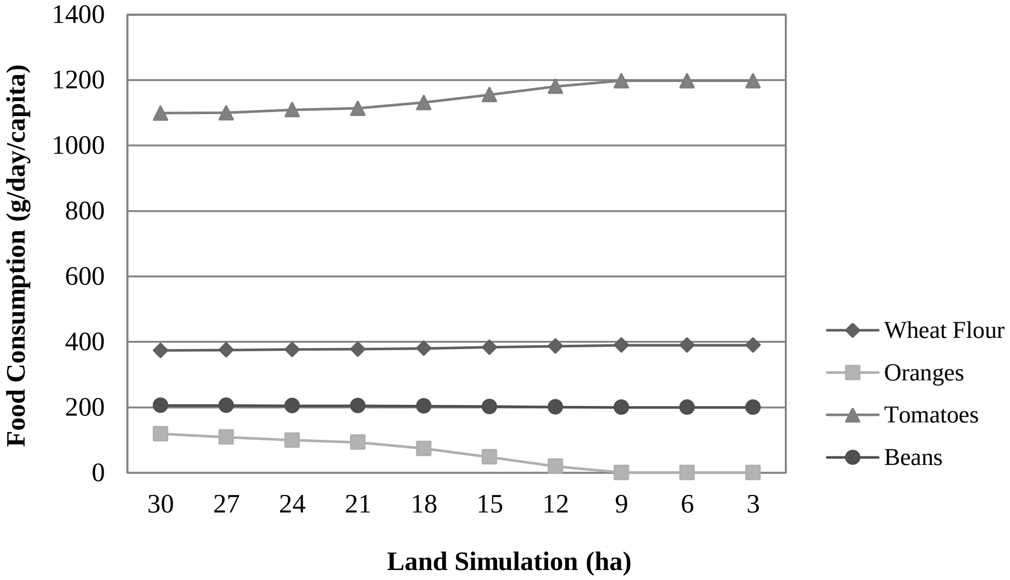


Figure 6. The change in consumption variables X_{ij} (g) in consequence of agricultural lands (ha) reduction (based on Table V-11)

At the 9 ha stage, we attained the imbalance between the supply and demand of the land resource, and the lands were totally used in the three climates (Figure7). Correspondingly, the water was originally fully exploited until the 9ha stage as less than 50,000m^3 was withdrawn and the excess quantity remained of no use. At this point, the water resource becomes ineffective and unable to compensate the sharp reduction of lands, leading to SSR shrinking. Actually, the optimum solution in the first simulations has maintained its top value with SSR equal to one, but it decreases in the last three runs to 0.96 at 9ha, 0.88 at 6ha and 0.6 at 3ha (Figure7).

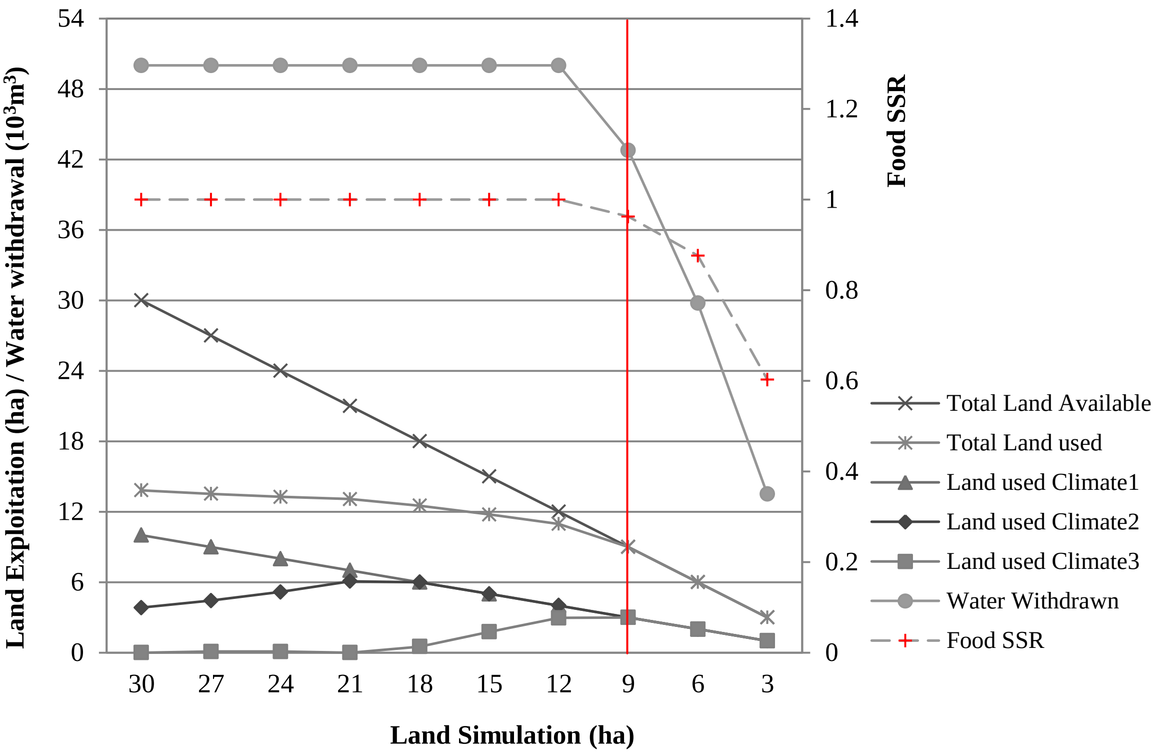


Figure 7. Variation of Land Exploitation per Climate (ha) with respect to Total Land Availability (ha). At the 18ha stage we started to use lands in climate 3 and at the 9ha stage all the lands offered were used (based on Table V-12)

3.2.3.2.Scenario3: Water Scarcity

In Scenario 3, the first objective function OFa is applied to assess the water constraint in a simulation of ten different levels varying from 50,000 to 5,000 m^3, with keeping the agricultural lands intact. As we diminish the water volume, the consumption variables X_{ij} follow the same pattern noticed in the land scarcity exercise, regarding the variation in oranges and tomatoes consumption (Figure8), plus a little change was occurring after the fifth run (at 30,000 m^3).

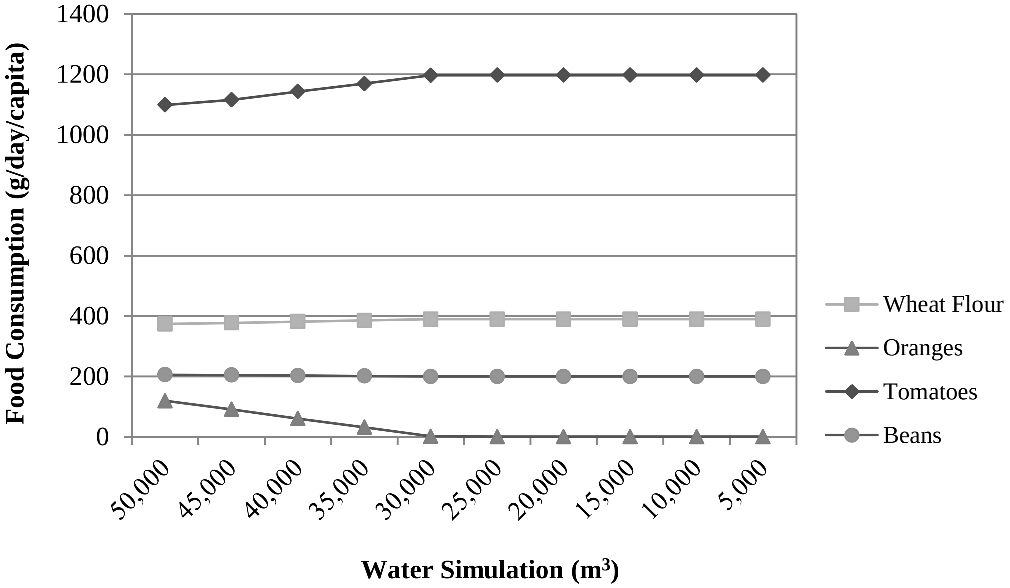


Figure 8. The change in consumption variables X_{ij} (g) in consequence of irrigation water (m^3) reduction, (based on Table V-13)

The water shortage happens in the last five runs, the model uses less than 10 ha of lands and hence becomes satisfied with the climate1-lands, and the SSR gradually drop from the value 1 to 0.95 at 25,000 m^3 and to finally reach 0.66 at 5,000 m^3 passing by intermediate levels (Figure9). Under such severe water scarcity, the decision to produce or to import the foods consumed depends on the irrigation needs of crops, accordingly the orange crop having the highest water footprint is never locally produced. Whereas at 25,000 m^3, the wheat crop - of the second highest WF - comes partly from domestic production (18%) and partly from import sources (82%). In subsequent simulations, the wheat import ratio is even amplified to 41% at 20,000 m^3, then to 64% at 15,000 m^3 and 86% at 10,000 m^3. At the 5,000 m^3 stage, all the wheat consumed is imported and we also start to import tomatoes (35%) (Figure10).

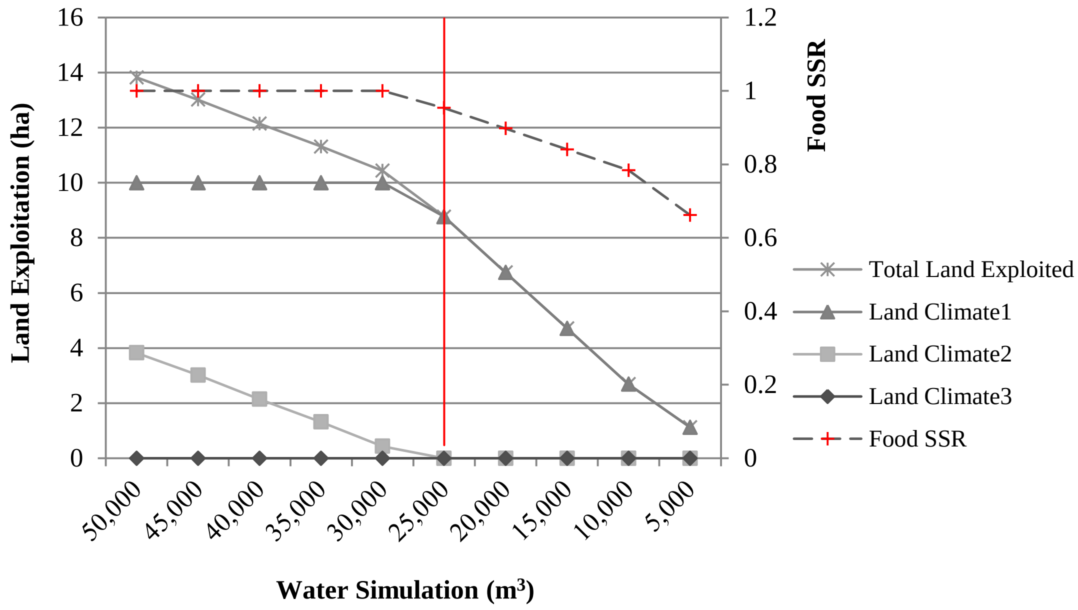


Figure 9. Variation of Land Exploitation per Climate (ha) with respect to Water Availability (m^3); At the 25,000m^3 stage the lands of Climate1 become sufficient and Food SSR starts to decrease (based on Table V-14)

3.2.3.3. Linearization Impact

The built optimization model aims to address large scale problems of national food security and would involve thousands of decision variables and constraints. Such application requires the linearization of the objective function of maximum food security (non-linear SSR formula). As an alternative objective function (OFd), we suggest minimizing the difference between demand and production quantities of foods instead of maximizing their ratios (OFa), and the impact of this linearization will be investigated in this section. With zero export and storage, the difference between demand and production would be covered by equivalent import.

$$(\mathrm{OF_d}) \qquad Minimize \sum_{i=1}^{I}\sum_{j=1}^{J(i)}(D_{ij} - P_{ij}) \equiv Min \sum_{i=1}^{I}\sum_{j=1}^{J(i)} IMP_{ij}$$

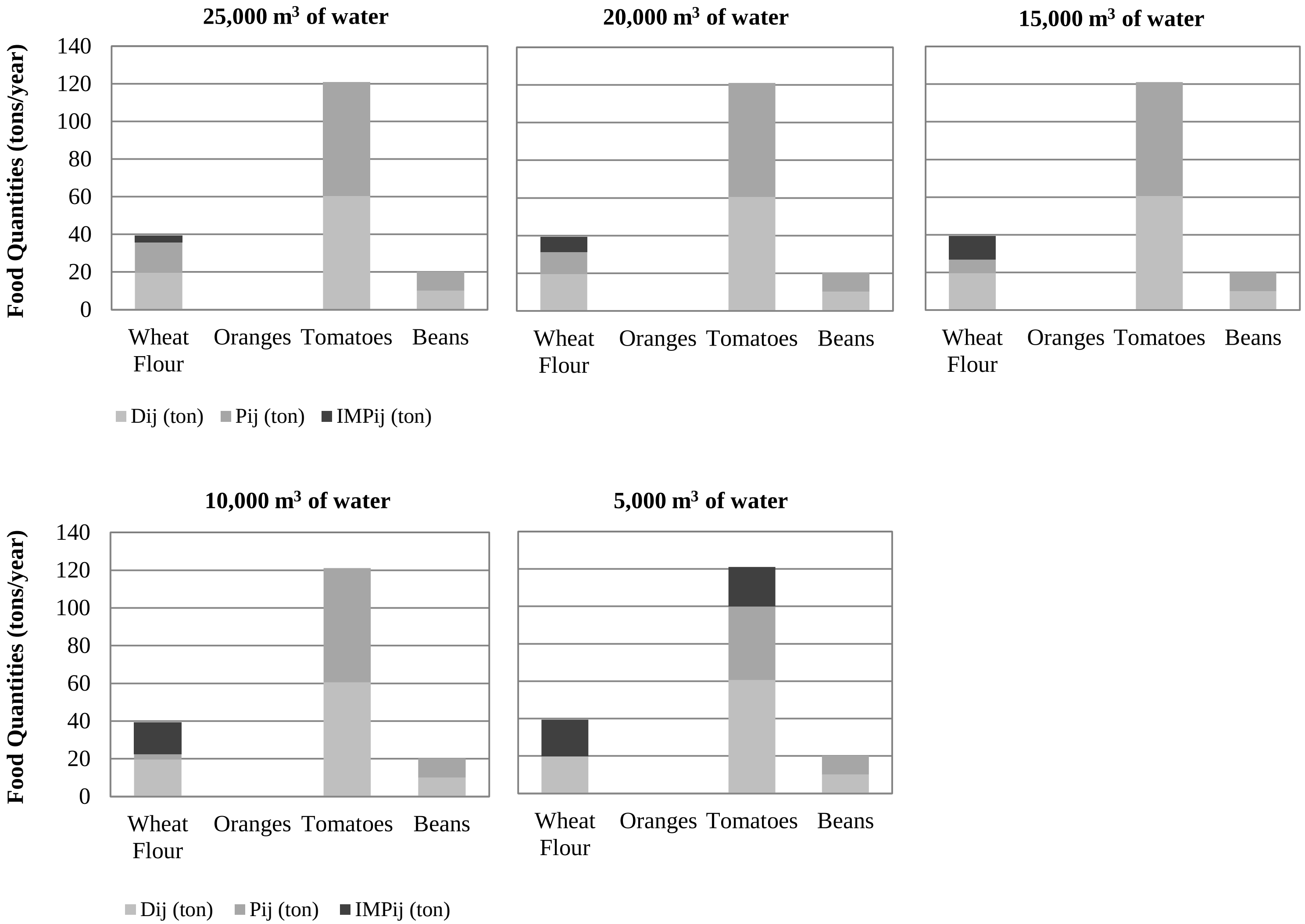


Figure 10. Demand, Production and Export variables of foods in the final 5 simulations of water scarcity (from 25,000 to 5,000 m^3) under OFa

OFd is first applied under Scenario1 of abundance resources, where the optimum solution of zero (D – P) is achieved with multiple optimum values of decision variables due to the flexible allocation of abundance resources, and the range of optimum D.V.s is similar to that obtained in the case of OFa. Therefore, the difference between OFa and OFd is better assessed through simulations of resources scarcity.

By applying OFd under Scenario3 of water scarcity, we observe that food consumption variables (Xij) and land exploitation varies following the same pattern noticed with OFa in Figures 8 and 9 (see Figures V-1 & V-2). However, the change in self-sufficiency ratios (SSRij) is excluded from this statement (Figure11): even though both curves of SSR in function of water availability are monotonic decreasing curves, but are different in main two aspects. Firstly, With OFa (Scenario3), SSR is subjected to a progressive decrease delineated by a concave-downward curve decreasing at accelerated rate: low values of SSR would be obtained only at severe scarcity where almost all food is imported. For instance, SSR in OFa conserves a fairly high level (0.66) even at a very low water availability status (5,000 m^3). The same was noticed with OFa in scenario 2 of Land scarcity with a SSR of 0.6 at 3ha available land. On the opposite, OFd traces brutal and non-regular decrease in SSR in function of water availability. The levels achieved of SSR are found much lower, where water scarcity at 5,000 m^3 induces SSR equal to 0.22. On the other hand, the increase in import (D – P) accompanied with water shortage is identical and progressive for (OFa) and (OFd). The single significant difference noticed is in the final simulation (5,000 m^3) where OFd provides an optimum solution of import less by 5 tons of that provided by OFa, which is equivalent to 13% of total import and 6% of total demands quantities.

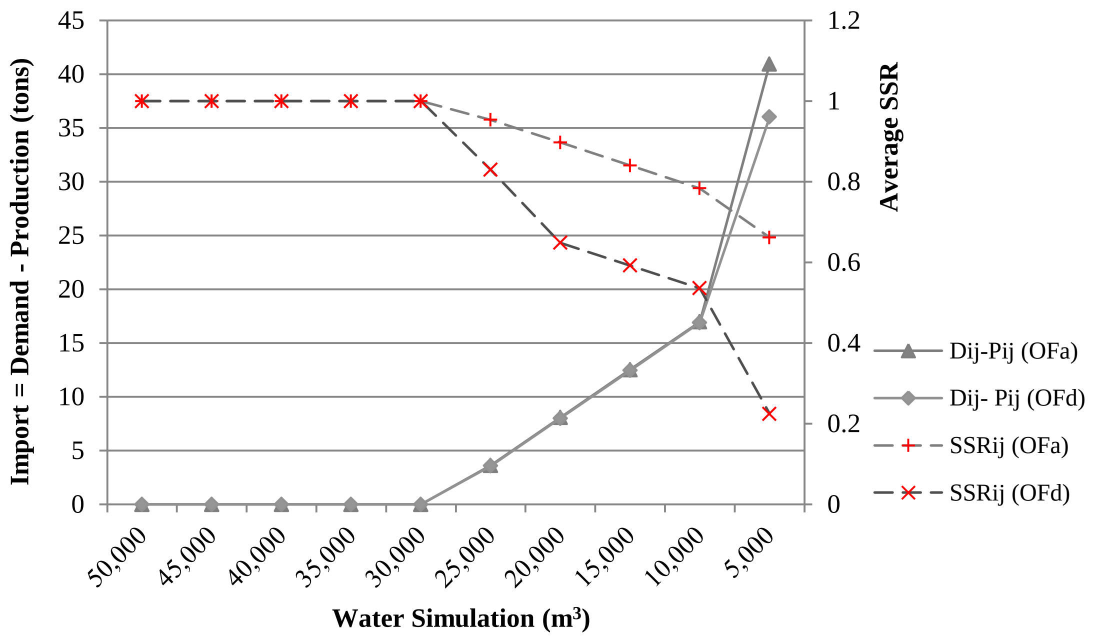


Figure 11. The change in food security indicators, SSR and D – P, with respect to water availability (m^3) for the nonlinear (OFa) and linear (OFd) objective functions (based on Table V-17)

Observing OFa formula and Figure 10, we notice that the optimization model will first intend to satisfy the demand of crops of little consumption (here oranges then beans) because it would lead to a non-negligible increase in overall Foods SSR (here 0.25 due to the small food count 4). With OFd, the model will not follow the same direction in minimization, it rather tends to produce more foods in total, thus the priority will be strictly for crops of low water needs (here tomatoes) seeing the water shortage (Figure12). Thus, the major difference between the two model applications is expected to be occurring at the level of production and import decisions. In Figures 10 and 12 at the final simulation (5,000 m^3), OFa and OFd yield the same demand quantities of foods, however for OFa all wheat and a considerable portion of tomatoes (35%) are imported, while for OFd the model imports all wheat, beans then a minor part of tomatoes (10%).

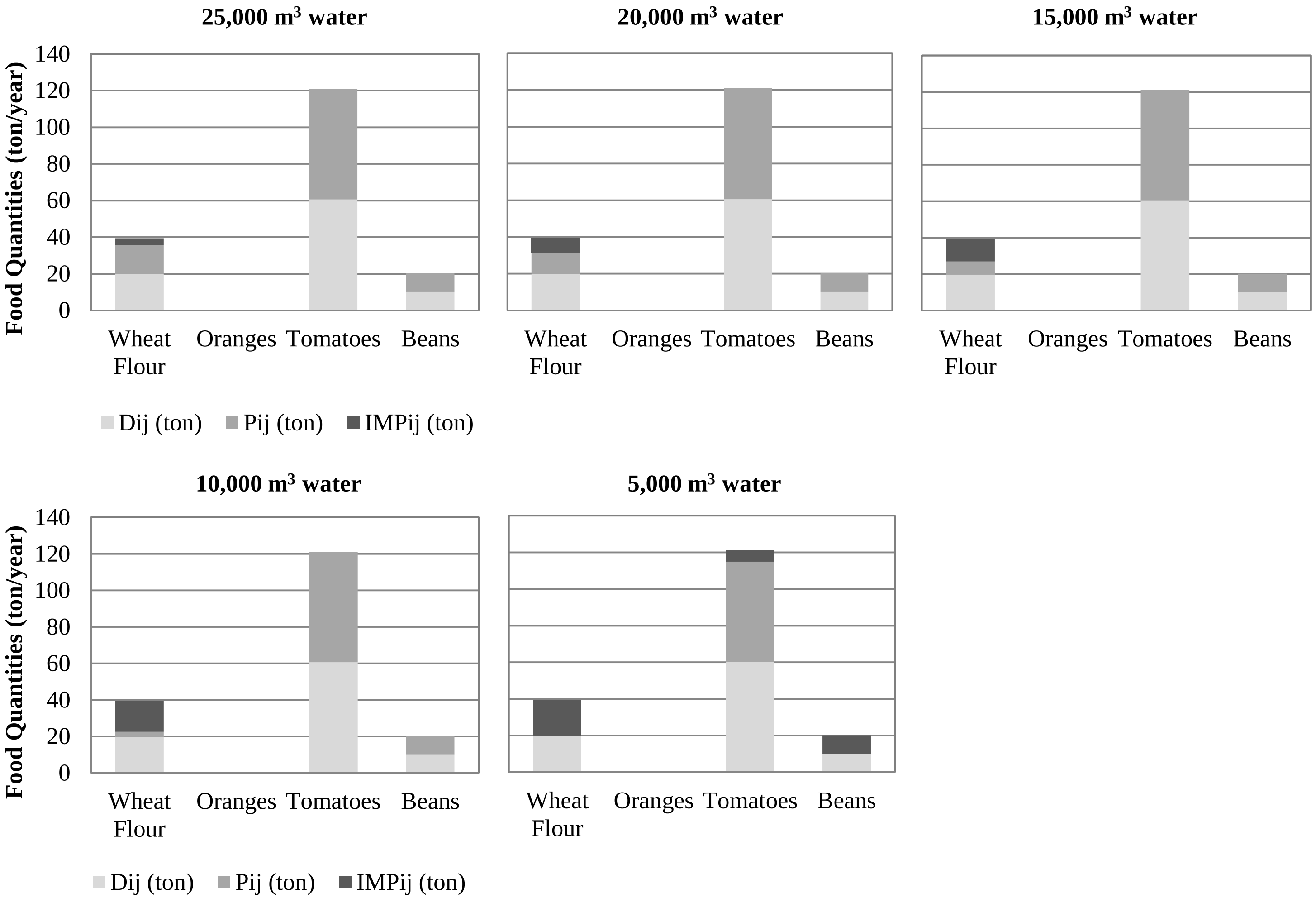


Figure 12. Demand, Production and Export variables of foods in the final 5 simulations of water scarcity (from 25,000 to 5,000 m^3) under OFd

As conclusion, the linear objective function is less representative: SSR is directly linked with national food security status, while the sum of import quantities of foods can hardly say something about the FS status. Also, linearization results in loss of information, presented in simulations for production, import, export and demand variables. However, the analysis of results of OFa and OFd applications reveals that both provide significant results and recommended to be considered.

3.2.4. Scenario4: Land Resources Assessment

In this exercise, we look into the variant water productivity related to cultivation in different climates. What we did is three successive runs of the model as we alternately allocate the entire 30 hectares of lands to a single climatic area in each run.

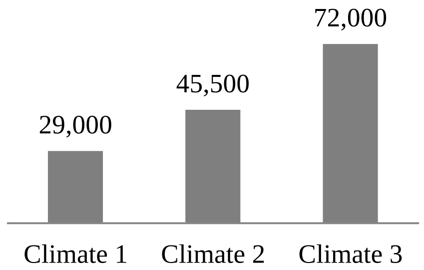
By applying the first OFa, the three runs resulted in significantly different optimum consumption variables X_{ij} (Table V-18). The Climate1 run is the most flexible in choosing its crops, where the solving process settled on consumption of crops regardless of their high WF and low yield (considerable orange consumption). Climate2 run, being more restricted in water resources, has selected more tomatoes crop characterized not by only low irrigation needs but also in high yields, thus the total lands utilized tends to be lower than those in climate1 (15 ha decreased to 11 ha). As for climate3, the model found that 50,000 m^3 of water are not even sufficient to find a feasible solution within the proposed crops. Similar to what we concluded before, there are multiple aspects of resources abundance, the same quantity of water may be considered abundant in one condition but scarce in another, depending on the climate and the crops cultivated.

Also in Scenario 4, the second function OFb that minimizes water with the constraint SSR>0.999 is applied and the obtained optimum X_{ij} in the three runs are equal to each other and to those obtained in Scenario1/OFb. In addition, since we adopted similar crop yields across the three regions, then the land resources used are the same (10.4 ha). The minimum water needed for agriculture is 29,000 m^3 in climate1, 45,500 in climate2 and 72,000 in climate3 (Table V-18). Hence, the water volume is amplified around 1.6 times in the second run and 2.5 times in the second time, which may be well considered as the ratios of water productivity among the three climates (Figure13).

Population of 100 person

Food Basket	Kg/day
Flour of wheat	0.4
Oranges	0
Tomatoes	1.2
Beans	0.2

Agricultural Land Exploited
10.4 ha



Blue Water withdrawn (m^3/year)
in either climate

Figure 13. The quantity of blue water input (irrigation water) varies in the three climates to produce the same Food basket. The water productivity in climate1 decreases by 33% in climate2 and 60% in climate3. This food combination satisfies the basic nutritional constraints and consists of the minimum blue water footprint according to the model output.

Scenario5, presented in Appendix V, considers the cultivation under non-standard conditions due to water shortage and concludes about the rainfed agriculture as alternative for water scarcity. Also, the constraints of monthly water balance were tested and presented in Appendix V.

CHAPTER 4

VALIDATION WITH CASE STUDY ON LEBANON

4.1.Introduction

An optimization model addressing the food security at regional scale in the context of water-food nexus was developed in Chapter II. The model performance was verified in a case study with several inclusive scenarios in Chapter III. In this chapter, the application is extended to a country scale to review the current water and food securities status and evaluate the potential opportunities under the limited resources of land and water.

Water and land are directly linked to food security perceiving that food production is the most demanding for both resources. Globally, the agricultural sector accounts for around 70% of total water withdrawal, followed by the industrial and domestic sectors with 16 and 14%, respectively (World Economic Forum, 2011b). Although water resources are available in sufficient quantities for utilization, the disparity in water quality and distribution constitutes an essential problem (Wouters, 2010). The Middle East region suffers from the most severe water scarcity in the world (Bou-Zeid & El-Fadel, 2002). The basin having a water availability per capita that is less than 1000 m^3 / year is considered a water-stressed basin, as in most of the basins located in the Mediterranean region (Bates et al., 2008). In this context, precipitation in Lebanon is higher than levels in surrounding countries, but is still inferior to the threshold of 1000 m^3/capita/year. The water problem will be intensified in the future because the annual renewable water resources per capita will continue to decrease due to population growth (Bou-Zeid & El-Fadel, 2002). Considering the shortage in natural

Table 4. Summary of data, description and sources

Data Type	**Data Description**	**Adopted Sources**
Population	Population count and age group distribution	United Nations Department of Economic and Social Affairs (2013)
Food Consumption data	Food Basket (Food lists) Daily food consumption Waste / losses factors	FBS from (FAOSTAT) Regional (WHO, 2003) and local (Nasreddine et al, 2006 ; 2010) studies
Food Nutrient Content	The food content in 16 essential nutrients	USDA National Nutrient database (2014)
Crops – Foods relation	Technical conversion factors from primary crops into processed food Edible portion of crops directly consumed Animals Feeds (types and quantities) and Productivity of livestock foods	FAO technical conversion factors report (FAO, 2003)
Crop parameters	Planting and harvest date Length of the four growth stages Crop coefficient, rooting depth, critical depletion fraction, yield response factor and crop height.	FAO paper 56 (Allen et al., 1998) Local Sources and farmers WF Reports (Chapagain & Hoekstra, 2004; Hoekstra et al., 2009; Mekonnen & Hoekstra, 2010; Hoekstra & Mekonnen, 2012)
Climatic regions within Lebanon	Locations and areas of eco-climatic zones distinguished by different topographic features, temperature levels and rainfall criteria	The National Meteorological service (MoA, 2003) Ministry of Environm. (2011) FAO (Asmar, 2011)
Climatic data	Long-term average meteorological data (temperature, humidity, wind, sun hours) Reference evapotranspiration ET_0	CLIMWAT (FAO, 2014b)
Precipitation	Long-term average rainfall data on a monthly, decade or daily basis	CLIMWAT (FAO, 2014b)
Soil data	Soil texture Field capacity, welting point, maximum infiltration rate, maximum rooting depth and initial soil moisture depletion	GIS geotechnical maps
Land Resources	Potential and actual cultivated land in different climatic regions	CDR (2005) GIS land use maps
Renewable water Resources	Renewable water available for irrigation usage	AQUASTAT (Frenken, 2009)
Irrigation Techniques	Irrigation criteria System Efficiency	AQUASTAT (Frenken, 2009)

resources along with the conflicting needs, optimization is liable to ensure a wise exploitation, as required in general agricultural policies.

4.2.Materials

The model was applied to assess the food-water securities status in Lebanon. A wide collection of data was needed to calculate the model parameters as summarized in Table 4.

4.2.1. Nutrition

The food consumption pattern in Lebanon was investigated and assessed recently by Nasreddine et al. (2006) using the method of individual dietary intake survey (Nasreddine et al., 2006). Analyzing the mean consumption of foods showed that the actual diet is different from the dietary recommendations, where high fraction of fat intake, low fish consumption and relatively low fruits and vegetables intake were detected. This result implies that the population may be at risk of suffering from some diet-related diseases, such as obesity and cardiovascular diseases. This conclusion was confirmed by a subsequent study revealing inadequate iron intake for a wide portion of the Lebanese population (Nasreddine et al., 2010). Change in dietary pattern showed an increase in meat consumption since the 1960s versus a decrease in cereal consumption (Nasreddine et al., 2006). These findings required an adjustment to the population diet as a part of the food security policy. To set the new diet, the nutritional contents of foods are extracted from the USDA nutrient database (USDA, 2014) due to lack of similar national database.

4.2.2. Food and Crop Consumption

For Lebanon, the food lists derived from the 2009 Food Balance Sheets (FBS) were used. 56 representative food items (out of a total list of 96 items majorly consumed) and categorized into 16 groups (Appendix III), were chosen using the following criteria: some of the foods of similar nutritional values as well as foreign crops were eliminated, and keeping the local crops of important production. This was done to reduce the number of decision variables in addition to get more practical and simpler recommended diet. The calculation of waste and losses factors is presented in Appendix III.

The crop lists were then prepared based on the food lists, i.e. we included the crops that are the input/constituents in processing the listed food items. The final number of crops is 36, three of them are forage crops appropriate for animal feeds usage only. Crops were categorized according to two approaches; first classification into 9 groups is based on the crops usage and the foods produced, and the second classification into 12 groups is based on the growing characteristics of plants (Appendix IV).

4.2.3. Regional Data

4.2.3.1. <u>Districts</u>

The six administrative districts of Lebanon were regoruped into 4 districts (Figure 14.a) of total surface areas stated in the Table 5.

Table 5. Districts (d) in Lebanon

District	Region	Surface Area (km^2)	Percentage of Total Area (%)
D1	North	1973.2	19.3
D2	Bekaa	4258.4	41.6
D3	Mount Lebanon and Beirut	1991.2	19.4
D4	South and Nabatieh	2023.4	19.7

4.2.3.2. Lebanese Climate

Most of the precipitation, in Lebanon, falls during winter season, whereas little or no rain occurs in the summer period where the evapotranspiration requirements and demand for irrigation water increases to their optimum (El-Fadel et al., 2000). The Lebanese landscape characterized by its various elevation levels sustain extremely rich biodiversity conditions (CDR, 2005) and hence promote variety agriculture and delimit diverse microclimatic zones (Frenken, 2009). Precipitation varies considerably from 200 to 1400 mm per year in different Lebanese regions (Ministry of Environment, 2011). As a result, the National Meteorological service identifies eight eco-climatic zones (r) in Lebanon based on the rainfall criteria (Ministry of Agriculture, 2003). Other approaches use the mountains feature to distinguish five different bio-climatic zones [MoE, 2011; Asmar, 2011).

Climatic data recorded in 15 climate stations over the Lebanese land, extracted from online-database CLIMWAT (FAO, 2014b) as long-term monthly mean values, reflect a remarkable spatial variability of precipitation and reference evapotranspiration: The yearly average reference evapotranspiration (Et_0) varies from a minimum 2.81 mm/day recorded at Al-Arez to a maximum 4.19 mm/day recorded at Chlifa. Likewise, the annual precipitation (P in mm/year) varies from minimum 404 recorded at Chlifa to a maximum at 1322 at Bhamdoun. After considering the vegetal and meteorological traits of different Lebanese regions, mainly based on (MoA, 2011), we adopted a general but also inclusive categorization, with four distinct climatic regions (coastal, interior, mountains and arid), intended to allow uncomplicated application of the model (Figure 14.b). Data for each region r was obtained from a representative station located within the same region (Tables 6.a and 6.b).

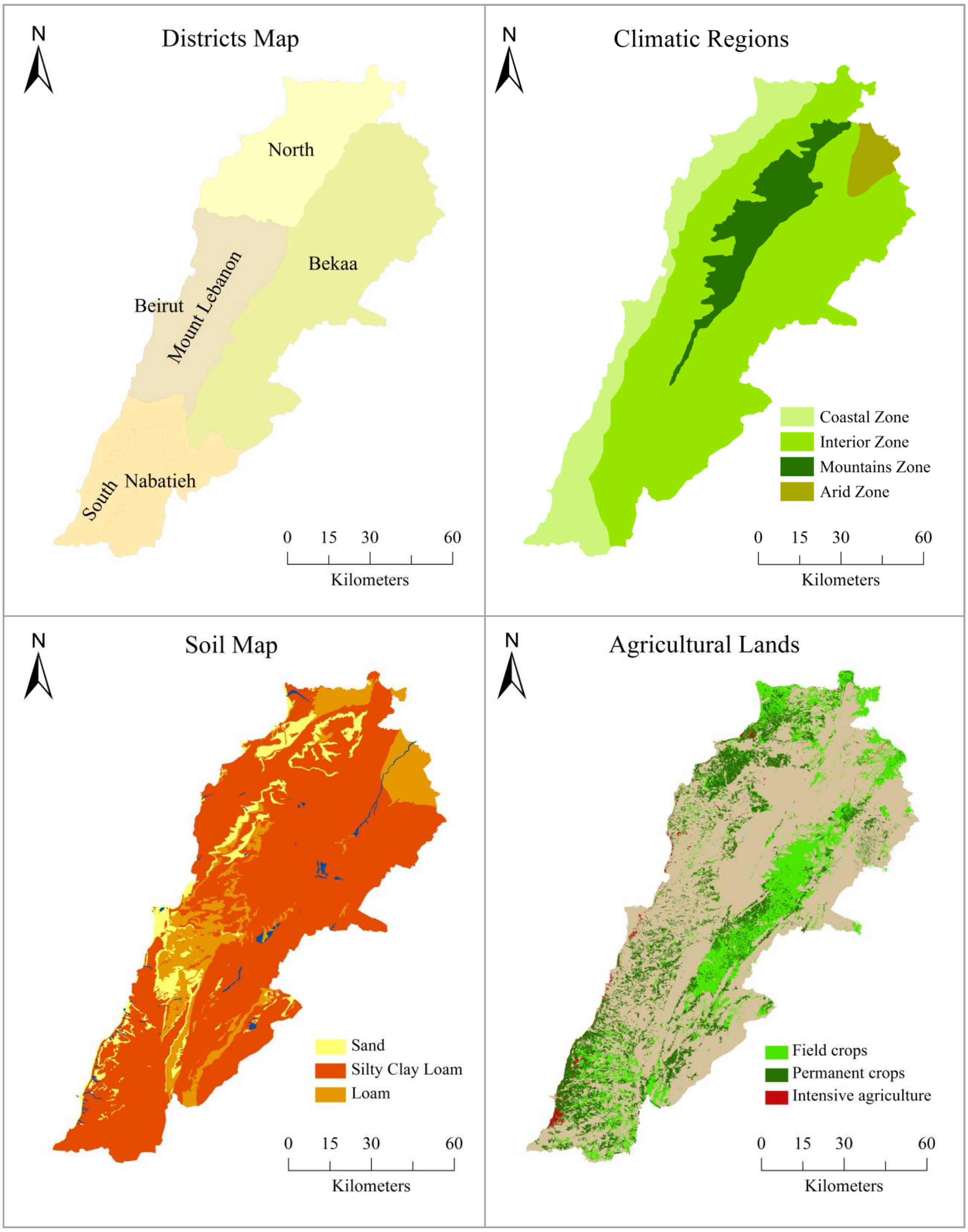


Figure 14. Maps of Districts (14.a), Climate (14.b), Pedology (14.c) and Agricultural Lands (14.d) in Lebanon
(Prepared by Geographic Information System)

Table 6. Regional info of meteorological stations (5.a), total rainfall in mm per month and average monthly reference evapotranspiration in mm per day (5.b)

Table 5.a

Zone	Station	Altitude (meter)	Latitude (North)	Longitude (East)
Coastal Zone	**Beyrouth**	35	33.9	35.48
Interior Zone	**Merdjayoun**	773	33.36	35.58
Mountains Zone	**Al-Arz**	1916	34.25	36.05
Arid Zone	**Chlifa**	1000	34.08	36.06

Table 5.b

Station / Month	January	February	March	April	May	June	July	August	September	October	November	December	Total (mm/year)	Average (mm/day)
Total rainfall in mm per month														
Beyrouth	195	116	107	48	18	1	1	0	9	35	149	148	**827**	
Merdjayoun	193	181	129	73	26	1	1	1	3	24	91	162	**885**	
Al-Arz	239	207	145	68	32	5	1	1	5	32	93	158	**986**	
Chlifa	96	80	53	31	14	1	0	0	1	7	47	74	**404**	
Average monthly reference evapotranspiration in mm per day														
Beyrouth	1.73	2.03	2.58	3.43	4.47	5.56	5.87	5.54	4.39	3.31	2.27	1.74	**1308.8**	**3.58**
Merdjayoun	1.56	1.85	2.59	3.39	4.59	5.48	5.12	4.99	4.54	3.97	2.82	1.88	**1304.4**	**3.57**
Al-Arz	1	1.27	1.8	2.7	3.64	4.43	4.99	4.8	3.61	2.62	1.69	1.17	**1029.1**	**2.81**
Chlifa	1.52	1.9	2.78	4.07	5.27	6.9	7.85	7.25	5.43	3.58	2.14	1.56	**1533.5**	**4.19**

4.2.3.3. Pedology

Soil types, present in the Pedology map of Lebanon, were converted into the basic soil textures (sand, clay, silt and loam) of USDA soil classification, by means of principles of soil conversion described in FAO-UNESCO's report Soil map of the World (FAO, 1974). The three soil textures adopted in the final soil map were sand, loam and silt clay loam (Figure 14.c). Next, the soil physical characteristics (field capacity, welting point and total available soil moisture) were derived from FAO Paper 56 (Allen et al., 1998). The average characteristics of soils are summarized in the Table 7. The maximum rain infiltration rate was taken 40 mm/day for the three soil types and the nutrients content of soil and its fertility were supposed uniform.

Table 7. Soil types (s) and characteristics considered in study

Soil Type	Field capacity θ_{FC} (m^3/m^3)	Welting point θ_{WP} (m^3/m^3)	Total Available Soil Moisture (m/m)
Sand	0.12	0.05	0.07
Silt clay loam	0.33	0.21	0.12
Loam	0.26	0.11	0.15

4.2.3.4. Agricultural Land Resources in Lebanon

For Lebanon, the CDR report (2005) stated that around one half of the surface area of Lebanon can be cultivated with different fertility levels. Yet, the actual cultivated lands constitute roughly one third of the country surface area (32% equal to 3300 km^2), and are classified into field crops (50%), permanent crops (48%) and intensive agriculture (2%) (Figure 14.d). This agricultural area is larger than that reported in some other global and local sources where it is changing from 2500 to 2800 Km^2 (FAO, 2014c; MoA, 2005). Table 8 shows the distribution of agricultural lands with different soil types and climatic regions between the four districts.

Table 8. Summary Table of Land Resources (Km^2)

District (d)	Climatic Zone (r)	Soil (s)			Total Area (km^2)	(%)
		Soil1	Soil2	Soil3		
District1 (North)	**Zone1**	89.43	267.83	52.67	**409.93**	**23%**
	Zone2	25.85	204.10	65.55	**295.50**	
	Zone3	4.00	37.40	7.19	**48.59**	
	Zone4	-	-	-	**-**	
	Total (km^2)	**119.29**	**509.33**	**125.41**	**754.02**	
District2 (Bekaa)	**Zone1**	-	-	-	**-**	**41%**
	Zone2	13.92	1,146.98	59.60	**1,220.49**	
	Zone3	1.41	21.53	1.98	**24.92**	
	Zone4	-	5.09	106.13	**111.23**	
	Total (km^2)	**15.33**	**1,173.60**	**167.72**	**1,356.65**	
District3 (Mount Lebanon & Beirut)	**Zone1**	12.89	52.47	8.96	**74.31**	**10%**
	Zone2	40.34	65.68	133.16	**239.18**	
	Zone3	0.46	10.61	10.05	**21.12**	
	Zone4	-	-	-	**-**	
	Total (km^2)	**53.68**	**128.75**	**152.17**	**334.61**	
District4 (South & Nabatieh)	**Zone1**	65.02	354.55	-	**419.57**	**26%**
	Zone2	9.07	346.66	63.57	**419.29**	
	Zone3	-	-	-	**-**	
	Zone4	-	-	-	**-**	
	Total (km^2)	**74.09**	**701.20**	**63.57**	**838.86**	
Total Agricultural Lands = 3284.14 km^2						

The variables presented in the table are:
$CL_{d\,r\,s}$: Available land for cultivation in district d, region r and soil texture s in Km^2;
TCL: Total national cultivated land area in Km^2.
Legend:
Districts d ϵ {1 = North ; 2 = Bekaa ; 3 = Mount Lebanon ; 4 = South}
Climatic-Regions r ϵ {1 = Coastal ; 2 = Interior ; 3 = Mountain ; 4 = Semi-Arid}
Soil Textures s ϵ {1 = Sand ; 2 = Silty clay loam; 3 = Loam}

4.2.3.5. Irrigation in Lebanon

Irrigated lands constitute only 42% of total cultivated lands varying from a minimum 27% in South to a maximum 52% in Bekaa (MoA, 2005). The three different types of irrigation used in Lebanon are surface, sprinkler and localized (surface) irrigation covering 63.5%, 28% and 8.5% of total equipped area for irrigation, respectively (Frenken, 2009). The percentage of irrigation methods for all districts, extracted from Atlas Agricole du Liban (MoA, 2005), is given in Table 9. The same distribution of irrigation methods is assumed in the model application, thus the land variable ($CL_{d\,r\,s}$) is further discretized into ($CL_{d\,r\,s\,q}$) to account for the irrigation variable (q). The source of irrigation water, surface water or groundwater, is not considered in the model.

Table 9. Distribution of Irrigation Methods (%)

District	q1- Surface	q2- sprinkler	q3- Drip	Total
D1- North	91.5	6.1	2.4	**100**
D2- Bekaa	37.5	50.6	11.9	**100**
D3- Mount Leb.	87.3	0.9	11.8	**100**
D4- South	93.9	1.6	4.5	**100**
Lebanon	**63.6**	**27.9**	**8.5**	**100**

Legend: Irrigation Criteria q ϵ {1 = Surface ; 2 = Sprinkler ; 3 = Drip}

The efficiency of water application at the field level is provided, by FAO's report Irrigation Water Management (FAO, 1989), for surface (60%), sprinkler (75%) and drip (90%) irrigation methods. The efficiency of water transport in canals to the field (conveyance efficiency) is not added.

4.2.4. Water resources in Lebanon

In Lebanon, the long-term average annual renewable water is 4.503 km^3 per year. The total withdrawal in all sectors is equal to 1.3 km^3 for the year 2005 and it is divided among the three sectors (agricultural, municipal and industrial) with respective percentages of 60%, 29% and 11% (Frenken, 2009). This distribution is clearly different from the global average water withdrawal distribution. Lebanon has large external water footprint (73%), which means that its population rely heavily on external freshwater resources. Therefore, attaining water security status requires governments to develop trade policies that ensure safe import of needed commodities (Hoekstra & Mekonnen, 2012). We will adopt in this model the same amount of water withdrawn in agricultural sector (0.78 km^3/year), this value includes in addition to irrigation water, the water offered for farm animals raised locally. This amount withdrawn constitutes around 17% of the total renewable water resources in Lebanon (Frenken, 2009), very close to the threshold of impending water scarcity (20%) (Khan & Hanjra, 2009).

4.2.5. Crops Evapotranspiration

The crops evapotranspiration are calculated via CROPWAT model based on climate and soil data input in addition to crops characteristics data (Supplement Information) collected from numerous local and global sources, and adjusted according to the Lebanese environmental and cultivation calendars. Here, one yield value by crop is adopted across all regions. The output of 432 run (36 crops, 4 regions and 3 soil textures) is a large data set of crops potential evapotranspiration, irrigation needs and rain efficiencies in different regions and soils (Supplement Information).

4.3.Methods

4.3.1. Assumptions of Model Application

In this study, we restrict the model to natural resources management and relax the economic constraints. Crop and food Export variables are given current real values (or null values) as optimizing those as decision variables requires full consideration of economic constraints. The allowable change in food item consumption is set α = 50% to respect the food preferences. The permissible reduction in national production of permanent crops (trees) is taken 50% (Supplement Information), and the crops potential yields are taken equal to 1.2 actual yields, as recommended in the literature (Reynolds et al., 2000), due to potential enhancement in irrigation water application. In addition, fish production is not studied here and the water and land resources input to produce them were not computed; so the production quantity is limited to actual production (Supplement Information).

4.3.2. Model Summary Tables and Size

The optimization model, developed in Chapter II, is summarized here in Tables10, 11 and 12, considering the specialties of this case study.

Table 10. Decisions Variables (D.Vs.)

Symbol	Type	Description	Unit	Number	Count
X_{ij}	Principal*	daily consumption of food (i; j)	g/day/capita	$\sum_{i=1}^{I} J(i)$	56
D_{ij}	Auxiliary**	National domestic demand of food (i; j)	ton/year	$\sum_{i=1}^{I} J(i)$	56
P_{ij}	Principal	National production quantity of food (i; j)	ton/year	$\sum_{i=1}^{I} J(i)$	56
IMP_{ij}	Auxiliary	National import quantity of food (i; j)	ton/year	$\sum_{i=1}^{I} J(i)$	56
EXP_{ij}	***	National export quantity of food (i; j)	ton/year	$\sum_{i=1}^{I} J(i)$	56
$D_{m\,n}$	Auxiliary	National domestic demand of crop (m; n)	ton/year	$\sum_{m=1}^{M} N(m)$	36
$P_{m\,n}$	Auxiliary	National production quantity of crop (m; n)	ton/year	$\sum_{m=1}^{M} N(m)$	36
$IMP_{m\,n}$	Auxiliary	National import quantity of crop (m; n)	ton/year	$\sum_{m=1}^{M} N(m)$	36
$EXP_{m\,n}$	***	National export quantity of crop (m; n)	ton/year	$\sum_{m=1}^{M} N(m)$	36
$P_{m\,n\,d}$	Auxiliary	Production quantity of crop (m; n) growing in district d	ton/year	$D\sum_{m=1}^{M} N(m)$	144
$P_{m\,n\,d\,r\,s\,q}$	Principal	Production quantity of crop (m; n) growing in district d, climatic region r, cropland of soil texture s and irrigation technique q	ton/year	$DRSQ\sum_{m=1}^{M} N(m)$	5184
SSR_{ij}	FS. indicator	Self- sufficiency ratio of food (i; j)	ton/ton	$\sum_{i=1}^{I} J(i)$	56

$$\text{Principal D.V. Number} = 2\sum_{i=1}^{I} J(i) + \text{DRSQ}\sum_{m=1}^{M} N(m) = \mathbf{5296\ D.V}$$

$$\text{Total D.V. Number} = 4\sum_{i=1}^{I} J(i) + (3 + \text{D} + \text{DRSQ})\sum_{m=1}^{M} N(m) = \mathbf{5660\ \ D.V}$$

* Principal D.V.: variables determined by the optimization approach
** Auxiliary D.V.: variables calculated outside the model in function of principal D.V.
*** Export variables: Reduced to be input of the model in this case study
With:
i ϵ {1; 2; 3; …; I=16} is the index of food groups
j ϵ {1; 2; 3; …; J(i)} is the index of individual food items belonging to each food group i
m ϵ {1; 2; 3; …; M=9} is the index of primary crop groups
n ϵ {1; 2; ….; N(m)} is the index of individual crops belonging to each crop group m
d ϵ {1; 2; 3; D=4} is the index of the districts
r ϵ {1; 2; 3; R=4} is the index of the agro-climatic regions
s ϵ {1; 2; S=3} is the index of soil textures
q ϵ {1; 2; Q=3} is the index of the irrigation criteria/technique used

4.3.2.1.Decision Variables

If considering the original complete lists of foods (96 items) and crops (59 items) along with the 6 districts and the 5 climatic regions, the total number of main decision variables is around 16,850 variables, which is beyond the capacity of most optimization engines. Thus the extent of the problem was reduced as explained before: The food items number $\sum_{i=1}^{I} J(i)$ is 56, the crops items number is $\sum_{m=1}^{M} N(m)$ is 36, with 4 districts (D), 4 agro-climatic regions (R), 3 soils (S) and 3 irrigation criteria (Q). The principal decision variables of the model are X_{ij} , P_{ij} and $P_{m\,n\,d\,r\,s\,q}$ and count 5296 variables (Table 10). Among them, there are 1728 null D.Vs. due to non existed combinations.

4.3.2.2.Constraints

The total number of balance constraints (equalities) is 7529 and are adjusted by spreadsheet cells, number of normal constraints (inequalities) is 309 and are incorporated into the solver engine, and number of bound constraints (non-negativity) is 5296 ones (Tables 11 and 12). Therefore, this problem was solved by Frontline Premium Solver Platform that can treat large optimization problems up to 8000 D.Vs., 8000 constraints and 16000 bounds if the model is a linear one. Accordingly, the following step is the linearization of objective functions.

Table 11. Model Constraints

Constraint Name		Eq.#	Constraint	Variables	Number	Count
Food Balance Sheets		#1*	*Production + Import quantity+ Stock variation – Export quantity =* ***Domestic supply quantity***	-----		
		#2*	*Domestic supply quantity = Feed + Seed + Waste + Processing + Other use +* ***Food***	-----		
Objective Function Constraints		#3*	$Self\ Sufficiency\ (SSR) = \frac{Production}{Production + Import - Export}$	-----		
		#4**	$SSR_{ij} = \frac{P_{ij}}{P_{ij} + IMP_{ij} - EXP_{ij}} \geq (\text{SSR ratio associated to } Priority_{ij})$	i & j		
Balance Constraints	Food National demand Constraints	#5	$D_{ij} = \frac{X_{ij} * Population * 365.25}{10^6 * (1 - waste\ factor_{ij})(1 - Loss\ ratio_{ij})}$	i & j	$\sum_{i=1}^{I} J(i)$	56
		#6	$P_{ij} + IMP_{ij} - EXP_{ij} = D_{ij}$	i & j	$\sum_{i=1}^{I} J(i)$	56
	Food-Crop relating Constraints	#7	$(D_{m\,n}) = A \times (P_{ij})$	m, n, i & j	$\sum_{m=1}^{M} N(m) \times \sum_{i=1}^{I} J(i)$	2016
		#8	$P_{m\,n} + IMP_{m\,n} - EXP_{m\,n} = D_{m\,n}$	m & n	$\sum_{m=1}^{M} N(m)$	36
	Crop Production Constraints	#9	$P_{m\,n} = \sum_{d=1}^{D} P_{m\,n\,d}$	m & n	$\sum_{m=1}^{M} N(m)$	36
		#10	$P_{m\,n\,d} = \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q}$	m, n & d	$D \sum_{m=1}^{M} N(m)$	144
Daily Per Capita Food Consumption Constraints	Daily Calories intake	#11*	$Calorie\ intake_{av} = \frac{\sum[\text{Calorie intake by Age Group} \times \text{Age Group Count}]}{\text{Population}}$	-----		
	Nutrition Constraints	#12	$L_k \leq \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \frac{NTR_{ijk}}{100} * (Edible\ portion\ of\ X_{ij}) \leq U_k$	k	2K	26

		#13	$Min\ intake_i < \sum_{j=1}^{J(i)} X_{ij} < Max\ intake_i$	$i \in \{1; 4; 9; 10; 13; 15\}$	2*6	12
	Energy density of the diet	#14*	$Diet\ energy\ density = \left(\sum_{i=1}^{I}\sum_{j=1}^{J(i)} \frac{NTR_{ij\ (k=1)}}{100} * X_{ij}\right) / \left(\sum_{i=1}^{I}\sum_{j=1}^{J(i)} X_{ij}\right)$	-----		
	Population Preferences Constraint	#15	$-\alpha_{ij} \leq \frac{F_{ij} - X_{ij}}{F_{ij}} \leq \alpha_{ij}$	$i\ \&\ j$	$2\sum_{i=1}^{I} J(i)$	112
	Diet Economic Cost Constraint	#16**	$Lower\ bound \leq \sum_{i=1}^{I}\sum_{j=1}^{J(i)} C_{ij} * X_{ij} \leq Upper\ bound$	-----		
		#17*	$Lower\ bound = \frac{Food\ Share\ *\ Poverty\ Line\ Income}{365.25}$	-----		
		#18*	$Upper\ bound = \frac{Food\ share\ * Average\ National\ Income}{365.25}$	-----		
Resource Constraints	Land Constraints	#19	$\frac{P_{m\,n\,d\,r\,s\,q}}{PYIELD_{m\,n}} = CL_{m\,n\,d\,r\,s\,q}$	$m, n, d, r, s\ \&\ q$	$DRSQ\sum_{m=1}^{M} N(m)$	5184
		#20	$\sum_{m=1}^{M}\sum_{n=1}^{N(m)} CL_{m\,n\,d\,r\,s\,q} \leq CL_{d\,r\,s\,q}$	$d, r, s\ \&\ q$	$DRSQ$	144
		#21	$\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} CL_{d\,r\,s\,q} = TCL$	-----	1	1
	Water Constraints	#22*	$(ET_c)_{m\,n\,r} = (K_c)_{m\,n} * (ET_0)_r$	$m, n\ \&\ r$		
		#23*	***Depletion*** *(end of day i)* = ***Depletion*** *(end of day i-1)* + ***Crop Evapotranspiration*** *(i)* – ***Net Irrigation*** *(i)* – ***Precipitation*** *(i)* + ***Runoff*** *(i)* – ***Capillary Rise*** *(i)* + ***Deep Percolation*** *(i)*	-----		
		#24*	$PWU_{m\,n\,r} = \sum_{\substack{growing \\ period}} (ET_c)_{m\,n\,r}$	$m, n\ \&\ r$		

	#25*	$CWR_{m\,n\,r} = 10 * PWU_{m\,n\,r}$	$m, n \,\&\, r$		
	#26*	$WF_{m\,n\,r} = \frac{CWR_{m\,n\,r}}{PYIELD_{m\,n}}$	$m, n \,\&\, r$		
	#27*	$WF_{m\,n\,d\,r} = WF_{m\,n\,r}$	d		
	#28*	$WF_{m\,n\,d\,r\,s\,q} = BWF_{m\,n\,d\,r\,s\,q} + GWF_{m\,n\,d\,r\,s\,q}$	$m, n, d, r,$ $s \,\&\, q$		
	#29*	$IWR_{m\,n\,d\,r\,s\,q} = \frac{BWF_{m\,n\,d\,r\,s\,q}}{efficiency\ of\ irrigation\ technique\ q}$	$m, n, d, r,$ $s \,\&\, q$		
	#30	$\sum_{m=1}^{M} \sum_{n=1}^{N(m)} \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,s\,q} + WLA \leq AGRW_d$	d	D	4
	#31	$\sum_{d=1}^{D} AGRW_d = AGRW$	-----	1	1
Economic Policies Constraints	#32**	$\sum_{m=1}^{M} \sum_{n=1}^{N(m)}$ Unit Production Cost $* P_{m\,n} \leq$ maximum agricultural budget	-----		
	#33**	$\sum_{i=1}^{I} \sum_{j=1}^{J(i)}$ Unit Export Profit $* EXP_{ij} \geq$ minimum economic revenue from food export	-----		
	#34**	$\sum_{i=1}^{I} \sum_{j=1}^{J(i)}$ Unit Import Cost $* IMP_{ij} \leq$ maximum national expenditure on foods import	-----		
Non-Negativity Constraints		All decision variables are non-negative variables	Principal D.V.s		5296
				Balance Constraints	7529
				Daily per Capita Food Consumption constraints	150
				Resources Constraints	145
				Non-Negativity Constraints	5296

Table 11 includes all the equations introduced in chapter II. They are either:
Constraints applied in Lebanon case study,
* Equations are not model constraints, but are calculation methods of some parameters and performed outside the model
** Constraints are not applied in Lebanon case study
Thus, the column Count is calculated only for the applicable constraints.
The model constraints at monthly time step are not shown in the table.
Notes:
1) The Land constraints #20 and #21 are not exactly the same as those defined in Chapter1 since the irrigation techniques distribution in Lebanon are considered in the model, so the variable $CL_{d\,r\,s}$ is replaced by $CL_{d\,r\,s\,q}$
2) The constraints #30 and #31 are combined in one water constraint at the country scale.
3) In this application, we add the constraints on maximum fish production (4 constraints), allowable change in trees cultivation (9 constraints of olives, oranges, apples, grapes, bananas, cherries, peaches, almonds and walnuts) and the exclusion of rice cultivation in Lebanon (1 constraint).

Table 12. Terms Definition

Section	Term	Description	Unit
Food Security	$Priority_{ij}$	Priority level associated with food (i; j)	Unitless
Crop-Food	A	Matrix $A = [a_{m\,n\,,i\,j}]$; with $a_{m\,n\,,i\,j}$ represents the amount needed of original crop (m; n) to produce processed food item (i; j)	ton/ton
Nutrition	$Calorie\ intake_{a}$	Population-wide average of recommended daily energy intake	Kcal/day
	NTR_{ijk}	amount of nutrient k present in 100 g of food type (i; j)	g or mg /100g
	L_k	Recommended lower bound on the daily intake of nutrient k	g or mg /day
	U_k	Recommended upper bound on the daily intake of nutrient k	g or mg /day
	$Min\ intake_i$	Minimum intake guideline of food group i	g/day
	$Max\ intake_i$	Maximum intake guideline of food group i	g/day
Food Preferences	F_{ij}	Amount of food (i; j) currently consumed by the population	g/day/capita
	α_{ij}	Maximum allowable change between the original diet and the target diet for food item (i; j)	%
Diet Cost	C_{ij}	Cost coefficient associated to food item (i; j)	US$/g
Land Resources	$YIELD_{m\,n}$	Current yield value of crop (m; n)	ton/ha
	$PYIELD_{m\,n}$	Potential yield value of crop (m; n)	ton/ha
	$CL_{d\,r\,s\,q}$	Available land for cultivation in district d, region r, soil texture s and supplied by irrigation technique q	ha
	TCL	Total national cultivated land area	ha
Water Resources	$(ET_0)_{\,r}$	Reference evapotranspiration in climatic zone r	mm
	$(K_c)_{\,m\,n}$	Crop coefficient of crop (m; n)	Unitless
	$(ET_c)_{\,m\,n\,r}$	Crop evapotranspiration under standard conditions of crop (m; n) growing in climatic region r	mm
	$PWU_{m\,n\,r}$	Potential water use over the entire growing period of crop (m; n) growing in region r	mm
	$CWR_{m\,n\,r}$	Crop water requirement of crop (m; n) growing in climatic region r	m^3/ha
	$WF_{m\,n\,r}$	Water footprint of crop (m; n) growing in climatic zone r	m^3/ton
	$BWF_{m\,n\,d\,r\,s\,q}$	Blue water footprint of crop (m; n) growing in district d, climatic region r, cropland of soil texture s and under irrigation technique q	m^3/ton
	$GWF_{m\,n\,d\,r\,s\,q}$	Green water footprint of crop (m; n) growing in district d, climatic region r, cropland of soil texture s and under irrigation technique q	m^3/ton
	$IWR_{m\,n\,d\,r\,s\,q}$	Irrigation water requirements of crop (m; n) growing in district d, climatic region r, cropland of soil texture s and under irrigation technique q	m^3/ton
	$AGRW$	Water share devoted/available for agricultural sector use by country	m^3/year
	$AGRW_d$	Water share devoted/available for agricultural sector use by district	m^3/year

With:
$Priority_{ij} \in \{1; 2; 3\}$
k $\in$ {1; 2; … ; K=13} is the index of nutrients

4.3.3. Linear Objective Function

4.3.3.1. Optimize Food Security

The best way to optimize food security is perhaps by maximizing the self-sufficiency ratio of foods weighted by their priority level. However, this expression is a non-linear method that can't be used for a large-size problem. Therefore, we will attempt to minimize the difference between Consumption and Production quantities. Given that Export is never a decision variable (equal zero or actual values), thus we are trying to minimize the Import quantities.

$$Minimize \sum \{Demand - Production\} \equiv Minimize \sum \{Import\}$$

There are multiple expressions to describe this objective function, of which we adopt four formulas:

1) Minimize the import quantities of final food products (ton/year). This means that domestic food production can be equally based on locally grown or imported crops without differentiation; the same concept applies for animal feeds that could be either produced or imported.

$$\text{(OF1)} \quad Minimize \sum_{i=1}^{I} \sum_{j=1}^{J(i)} IMP_{ij}$$

2) Minimize the total import quantities of foods and crops (ton/year). This means that we equate between all foods and crops in their values by simply adding their weights.

$$\text{(OF2)} \quad Minimize \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J(i)} IMP_{ij} + \sum_{m=1}^{M} \sum_{n=1}^{N(m)} IMP_{m\,n} \right\}$$

3) Minimize the total import quantities of foods and crops (ton/year) with foods being weighted by their extraction rates from original crops (Supplement Information).

The extraction rate, that is equal to the weight ratio of input crop by output food, varies from 1 for vegetables and fruits (crops directly consumed) to reach around 45 for bovine meat (livestock products have high ratio of feed input/food output).

$$\text{(OF3)}\ \ Minimize\ \left\{\sum_{i=1}^{I}\sum_{j=1}^{J(i)} Weighted\_IMP_{ij}\ + \sum_{m=1}^{M}\sum_{n=1}^{N(m)} IMP_{m\,n}\right\}$$

$$\text{Where,}\ \ Weighted\_IMP_{ij} = Extraction\ Rates * \ IMP_{ij}$$

4) Minimize the total import quantities of foods and crops, each weighted by their priority levels. The priorities are assigned based on market demand and nutritional values (Appendix III and IV).

$$\text{(OF4)}\ \ Minimize\ \left\{\sum_{i=1}^{I}\sum_{j=1}^{J(i)} \frac{IMP_{ij}}{Priority_{ij}}\ + \sum_{m=1}^{M}\sum_{n=1}^{N(m)} \frac{IMP_{m\,n}}{Priority_{m\,n}}\right\}$$

4.3.3.2. <u>Optimize Water security</u>

Regarding the water security concern, Lebanon is a water-scarce country and the share of water resource devoted for agricultural sector usage is very limiting. Therefore, the attempt to limit water withdrawal in agricultural sector was substituted by a minimization of the national water footprint for foods, along with an upper limit for domestic waters equal to 20% of annual renewable water. We can recognize three objective function formulas in this matter:

5) Minimize the total water footprint of food consumption.

$$\text{(OF5)}\ \ Minimize\ \left\{\sum_{i=1}^{I}\sum_{j=1}^{J(i)} Local\_WF_{ij} *\ P_{ij} + Global\_WF_{ij} *\ IMP_{ij}\right\}$$

$$\text{Where,}\ \ Local_{WF_{ij}} = \text{ Green WF + Blue WF } = \text{effective soil moisture}$$
$$+ \text{(effecttive irrigation + domestic animals water + drinking water)}$$

and $Global\_WF_{ij}$ is the global average of water footprint of food (i; j)

6) Or minimize the internal water footprint of food consumption, thus rely more on external water resources and saves local water for other uses. This form of objective function represents a zero scenario.

$$(\text{OF6}) \quad Minimize \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J(i)} Local\_WF_{ij} * P_{ij} \right\}$$

7) Or at contrary, minimize the external water footprint of food consumption, that is equal to virtual water import, and thus achieve more water independency.

$$(\text{OF7}) \quad Minimize \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J(i)} Global\_WF_{ij} * IMP_{ij} \right\}$$

4.4.Results and Discussions

4.4.1. Food Security Optimization

Frontline solver provided almost instantaneous results after a short solving time of the model despite the inclusion of thousands of variables. The main outputs calculated for all the objective functions are summarized in Tables 13, 14 and 15. Tables 13 comprise Food profile variables at individual (Table 13.a and 13.b) and national scales (Table 13.c). The current real data presented in Table 13.c are derived from food balance sheets (FAOSTAT), where it include more food groups that are uncovered in this study and considers multiple usages of food (feed, seed, processing and other usage). Accordingly, real individual consumption data in Table 13.a was recalculated after accounting for household waste (15%), and found that the weight of foods consumed and the daily diet calories are about 1.96Kg and 2680Kcal per capita per day respectively. The daily calories intake in the model was calculated as a population average by applying the Eq.11 defined in Chapter 1 on the Lebanese population, assuming moderate physical activity level, and found equal to 2310 Kcal/capita/day. This value is significantly lower than that considered in national studies evaluating the amounts of food demand (Rockstrom et al., 2007), in the range of 3000Kcal, because they usually tend to overestimate the needed calories intake for conservative reasons.

One observation is that drinking water quantity complements food weights, since their weights added together is in the range of 3.7 kg/day for all OFs (Table 13.a). The diet, obtained by OF6 optimization, with the lowest drinking water quantity (1.52 L/day) and the greater weight (2234 g/day) is also characterized by a large intake of foods of high water content (1043 g/day of vegetables and fruits) and low intake of foods of low water content (170 g/day of cereals) (Table13.b). On the other end, the diet with the lowest weight (1458 g/day), given by OF7 optimization, comprises around 500 g/day intake of vegetables and fruits and 253 g/day intake cereals intake.

For all OFs except OF1, the vegetal food share is in the range of 80% in weight of total foods, making the animal share ranges around 20 % which is analogous to actual conditions (Table13.a). As for OF1, by minimizing the import of food products only, it adopts a different concept than the three following OFs that consider both foods and crops import, and thus OF1 would provide divergent results. This minimization doesn’t cover the feed import quantities in background that are required for live animal raisings, thus tends to increase the animal food share to 28%.

The total food consumptions computed are in the range of 4000 (1000ton) for all scenarios, and are all larger than the actual data (3540), which is most probably due to the waste and loss factors incorporated here for conservative purposes.

Table 13. Food individual consumption variables (13.a and 13.b) and national policy variables (13.c)

Table 13.a

Food Consumption per capita per day					
	Drinking Water	**Total Food Weight**	**Total calories**	**Vegetal F. Percentage**	**Animal F. Percentage**
Units	**Liter**	**g/day/cap**	**Kcal/day/cap**	**%**	**%**
Actual*		1962	2680	77.3	22.7
OF1	1.94	1798	2310	71.9	28.1
OF2	2.11	1622	2310	82.3	17.7
OF3	2.19	1544	2310	81.6	18.4
OF4	2.11	1621	2310	82.3	17.7
OF5	2.06	1682	2310	80.2	19.8
OF6	1.52	2234	2310	78.4	21.6
OF7	2.28	1458	2310	77.2	22.8

The results of each OFi optimization are presented in row i
* The actual data were derived from food balance sheets (FAOSTAT)

Table 13.b

Consumption per Food Groups					
	Cereals	**Vegetables**	**Fruits**	**Meats**	**Milk products**
Units	**g/day/cap**			**g/day/cap**	
OF1	180	316	249	83	384
OF2	195	367	220	78	170
OF3	195	316	186	78	170
OF4	185	367	220	78	170
OF5	212	374	220	78	205
OF6	170	746	298	78	364
OF7	253	316	186	78	205

Table 13.c

National Food Consumption per year						
	Total Food Consumption	**Vegetal F. weight**	**Animal F. weight**	**Total Food Production**	**Total Food Export**	**Total Food Import**
Units	**1000 ton / year / population**			**1000 ton / year / population**		
Actual*	3539			3354	667	2491
OF1	4343	3401	942	3805	0	538
OF2	4012	3480	532	3174	0	838
OF3	3860	3334	526	2938	0	922
OF4	4022	3490	532	3171	0	851
OF5	4122	3505	616	2938	0	1184
OF6	5235	4337	897	352	0	4883
OF7	3712	3096	616	2589	0	1123

* The actual data were derived from food balance sheets (FAOSTAT)

In Table 14.a, food self-sufficiency ratio (SSR) was computed by two methods. SSR1 calculates the overall food SSR based on total weights, while SSR2 consists of the average of SSR ratios of food items.

$$SSR1 = Overall\ SSR = \frac{All\ Foods\ Production}{All\ Foods\ Consumption} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J(i)} P_{ij}}{\sum_{i=1}^{I}\sum_{j=1}^{J(i)} D_{ij}} * 100$$

$$SSR2 = Average(SSRij\ ratios) = \frac{1}{Food\ Count}\sum \frac{Food\ item\ Production}{Food\ item\ Demand}$$
$$= \frac{1}{\sum_{i=1}^{I} J(i)} \sum_{i=1}^{I}\sum_{j=1}^{J(i)} \frac{P_{ij}}{D_{ij}} * 100$$

As we notice in Table 14.a, the two formulas lead to very different results. Hence, estimating food security level is depending on calculation method adopted and the agricultural policy must enclose an integrated perspective to formulate the food security problem. We presumed that SSR2 is more convenient for representing food security issue as it conserves foods specialties, and the rest of SSR calculation is based on this method.

Table 14. Self-sufficiency ratio of foods (14.a) and (14.b)

Table 14.a

	SSR formula 1 and 2		**SSR according to Priority Groups****		
	SSR1	**SSR2**	**SSR First Priority**	**SSR Second Priority**	**SSR Third Priority**
Units	**%**	**%**	**%**	**%**	**%**
Actual*		60.39			
OF1	87.61	71.06	70.94	70.35	73.03
OF2	79.12	61.45	53.54	61.10	66.74
OF3	76.12	61.80	66.67	63.60	54.25
OF4	78.83	54.06	57.37	56.93	44.43
OF5	71.27	60.83	33.33	58.64	81.82
OF6	6.72	12.71	0.00	17.97	5.27
OF7	69.74	72.34	50.00	73.33	81.82

* For actual conditions (FAOSTAT), SSR was calculated only for the food groups considered in this study but all usage of products are included as in calculation of Table 12 variables.
** The SSR by priority levels were calculated by means of SSR2 method

Table 14.b

	Vegetal Food			Animal Foods and the input feed			
	SSR of Vegetal Foods	**SSR of Cereals**	**SSR of Vegetables and Fruits**	**SSR of Animal Foods**	**Total Feeds weight**	**(%) of Feed from Local Origin**	**(%) of Feed from import origin**
Units	**%**	**%**	**%**	**%**	**1000 ton**	**%**	**%**
Actual	62.42			56.33			
OF1	70.09	6.40	99.06	73.33	13114	11.68	88.32
OF2	76.02	30.32	99.06	27.12	994	87.99	12.01
OF3	66.43	25.00	97.59	50.89	8327	94.65	5.35
OF4	65.49	36.05	97.59	27.12	994	87.73	12.27
OF5	80.58	25.00	91.71	14.29	176	0.00	100.00
OF6	18.10	0.00	25.84	0.00	0	0.00	0.00
OF7	87.88	25.00	100.00	35.71	7508	58.78	41.22

OF1 offers the highest sufficiency ratio for animal foods (73.33%) since it directly seeks minimizing the import of final food products. But we must be aware of the fact that approximately 90% of feed comes from foreign origins, and consequently raising animals under such condition is an unsafe option. By opposite, the three following OFs (OF2, OF3 & OF4) achieve much less sufficiency in animal foods (27% for OF2 and OF4 and 51% for OF3) but with around 90% of feeds have been grown locally. OF3 that is distinguished by inserting the extraction rates of foods was proved to be a very meaningful concept that yields significant results. To examine if the nation is self-sustained in meat production, it is best to consider OF3 scenario, where only 5% of feed quantity is acquired from abroad and the obtained self-sufficiency is 51% in livestock products and 66% in vegetal products. This outcome is possibly the ultimate level of security would be achieved under current circumstances.

The former results highlight two conclusions. First, Lebanon is in no doubt unable to accomplish satisfactory food security levels in view of limited water resources. Second, and based on first observation, policies should stress on the priorities. Therefore, we treat the problem from priority perspective, thus we categorized the crops and foods into three priority groups (Appendix III and IV), and calculated the average SSR of each of these groups for all the OFs cases.

In view that OF1 provides the highest value of average SSR of total foods, this reality expands to cover the average SSR of priority groups, which is attributable to the same justification elucidated before: the SSRij indicator does not take account of the import happening at the crop level (Figure3). We conclude that when we equate between foods importance in a food security problem, the model will always favorite to produce more livestock foods processed from animal raised on imported feeds.

OF2 and OF4 are both considering for crops and foods import quantities. The only difference between them is that OF4 incorporates the priorities of foods and crops in its method. Their outputs in relation to animal food production are particularly similar. But the difference appears in SSR of priority groups. OF2 results in SSR levels equal to 53%, 61% and 67% for food groups of priority 1, 2 and 3 respectively. Whereas OF4 bias the results for priority 1 group (57%) advantage on the expense of priority 3 group (44%), leaving priority 2 group approximately at its former level (57%). Thus OF4 supplies the optimization model with more control on the output.

4.4.2. Water Security Optimization

Given that water is always a liming resource in the food production process, reducing water withdrawal in the agricultural sector would be on the expense of food security in Lebanon. Therefore the water footprint (WF) of the population was considered as an indicator of the water security status.

The national water footprint of crops is taken equal to the arithmetic average of WF across the diverse regions in Lebanon, and the national WF of food products are calculated based on these averages (Supplement Information). There is a minor difference (about 15% in average) between the calculated national WFs and the previous findings in literature (Chapagain & Hoekstra, 2004a), which is quite acceptable given that the intra-variability within Lebanon of WFs from a climatic region to another is exceeding 40% in average (Supplement Information).

The Water Report No.16 (Chapagain & Hoekstra, 2004a) found that water footprint of agricultural products in Lebanon equals 5.63 km^3/year (Table 15.a) out of 6.44 total national water footprint, which implies a major contribution that exceeds 87% from these water intensive products. Later, Water Report No.50 (Mekonnen & Hoekstra, 2011) detailed WF calculation to consider green, blue and grey WF. The WF of agricultural products consumed is equal to 7.543 km^3/year to constitute about 94% of Total national WF (8.058 Km^3/year), and is divided into internal WF (1.954 Km^3) and external WF (5.589 km^3), where internal and external WF are the fractions of total WF that comes from local and foreign water resources, respectively.

The yearly per capita water footprint calculated in Chapagain and Hoekstra (2004a), equal to 1310 m^3, is greater than that provided by all OFs of the model that ranges from 960 to 1032 m^3/cap/year, i.e. between 2.5 and 2.9 m^3/day (Table 15.a). The reason is that agricultural products considered in the former study may include non-edible products such as leather.

The vegetal and animal food shares in total WF are very close for all OFs (50 - 50 %) except for the first one that assigns two thirds of water footprint to animal foods (Table15.b), and the evident reason is that OF1 provides the food diet with the larger animal foods (about 30% in weight) (Table 11.a). The direct drinking water is always a minor participant in the total WF of the diet (roughly 0.1%), underlining the importance of virtual water (VW) concept.

Obviously, the smallest national WF in food products is obtained by OF5 that aimed to minimize this variable leading to a value equals 3.72 km^3/year, by reducing the food self-sufficiency ratio attained by the four food security OFs (Table 14.a). Note however, that this scenario OF5 doesn't guarantee the optimum water security level from a national perspective, as we need to check the internal and external WFs and their ratios.

We observe that the internal WF is always considerably lower than the external WF, even when we tried to minimize the virtual water import in OF7. The ultimate local virtual water amounts incorporated in food products can reach 1.59 km^3 / year in the most optimistic scenarios (OF7). Still, it is exceeded by just about one and half times by the VW import quantity. The "water self-sufficiency" concept, introduced as equal to the ratio of internal WF divided by total WF (Chapagain & Hoekstra, 2004a), was applied and found ranging from 25 to 35% for the first four OFs and reaches its highest extent 41% for OF7. This fact means that "water import dependency" method, also introduced by Chapagain & Hoekstra (2004a) and equal to ratio of external over total WF, is always larger than 59%. Consequently, the water security status in Lebanon is under question according to its definition reported before. Furthermore, the calculated national water footprint in foods, varying between a maximum value 5.16 and a minimum 3.72 km^3/year, is considered too large in comparison to the average annual renewable water equal to 4.503 km^3 per year. Therefore, policies ought to set priorities among different usages of water resources.

OF6 has contradictory concept to that of OF7, as it intends to minimize the sum water footprint of foods domestically produced. Thus, OF6 reduces the internal WF to reach as low as 0.33 km^3/year and OF7 minimizes the external WF to arrive at 2.28 km^3/year (Table 15.a). In the same manner, OF6 and OF7 have provided the extreme values (min and max) of food consumption variables (Table 11.a). As expected, the zero scenario OF6 leads to the minimum national food production and maximum import amounts (Table 11.b). In fact, this scenario consists only of obliged cultivation by the constraint of permanent trees.

As a conclusion, we could encounter the illusion of food security status if the local food production is based on imported crops or feeds (as in OF1), and the illusion of water security status if we ignore the virtual water import in the balance equation between renewable water resources and national water withdrawal/consumption.

Table 15. National Water Footprint (15.a) and its components Blue (15.b) and Green (15.c) WF

Table 15.a

	Water Footprint in food products			**Distribution of Water Footprint**			**Internal and External WF**	
	Daily Individual WF	**Yearly Individual WF**	**National WF**	**Vegetal Foods Share**	**Animal Foods Share**	**Drinking Water Share**	**Local Virtual Water**	**Virtual Water Import**
Units	**m^3/day/cap**	**m^3/year/cap**	**km^3/year**	**%**	**%**	**%**	**km^3/year**	**km^3/year**
Actual 1*		1310	5.632				1.707	3.925
Actual 2			7.543				1.954	5.589
OF1	2.78	1014.4	5.159	36.272	63.660	0.068	1.239	3.920
OF2	2.65	968.3	4.026	47.333	52.573	0.094	1.065	2.961
OF3	2.63	959.8	4.413	50.411	49.500	0.089	1.501	2.912
OF4	2.67	974.4	4.649	54.334	45.584	0.082	1.096	3.553
OF5	2.58	941.0	3.729	47.698	52.202	0.099	0.884	2.845
OF6	2.83	1032.1	4.868	51.384	48.560	0.056	0.332	4.535
OF7	2.64	965.9	3.872	48.105	51.788	0.106	1.591	2.281

* The actual data above correspond to “Water Footprint in Consumption of agricultural goods”; i.e. may include non-edible crops and livestock products as leather. Data 1 is collected from (Chapagain & Hoekstra, 2004a) returns to the period 1997 – 2001 with the population is roughly the same. Data 2 is collected from (Mekonnen & Hoekstra, 2011) returns to the period 1996 – 2005.

Table 15.b

	Water Withdrawal in Agricultural Sector and BWF Distribution					
	Water Withdrawal	**Water for live animals**	**Gross Irrigation**	**Effective Irrigation**	**Irrigation Losses**	**Blue Water Footprint**
Units	**km^3/year**	**km^3/year**	**km^3/year**	**km^3/year**	**km^3/year**	**km^3/year**
OF1	0.78	0.027	0.753	0.542	0.211	0.572
OF2	0.78	0.002	0.778	0.554	0.224	0.560
OF3	0.780	0.015	0.765	0.527	0.237	0.547
OF4	0.780	0.002	0.778	0.551	0.227	0.557
OF5	0.764	0.002	0.762	0.552	0.210	0.558
OF6	0.242	0.000	0.242	0.194	0.048	0.197
OF7	0.780	0.015	0.765	0.545	0.220	0.564

Table 15.c

	Green Water Distribution			Internal WF Distribution	
	Soil water in irrigated Lands	**Soil Water in Grazing Lands**	**Green Water Footprint**	**Blue Water**	**Green Water**
Units	**km^3/year**	**km^3/year**	**km^3/year**	**%**	**%**
OF1	0.400	0.267	0.667	46.2	53.8
OF2	0.502	0.004	0.505	52.6	47.4
OF3	0.715	0.239	0.954	36.4	63.6
OF4	0.536	0.004	0.540	50.8	49.2
OF5	0.326	0.000	0.326	63.1	36.9
OF6	0.135	0.000	0.135	59.3	40.7
OF7	0.800	0.226	1.026	35.5	64.5

4.4.3. Blue and Green Water

The results of Table 15.b and 15.c must be analyzed in view of the water footprint map illustrated in the Figure 15. First, we must differentiate between water withdrawal and blue water footprint (BWF). The water withdrawal in agricultural sector is distributed between irrigation water and water required for raising live animals. The irrigation water is divided into effective irrigation water utilized by the plants (transpiration), and irrigation losses through evaporation and percolation. On the other hand, blue water footprint is computed as the summation of effective irrigation, water used by live animals and drinking water. Accordingly, the total internal virtual water, equal to the sum of green and blue WFs, may exceeds the water withdrawal (0.78) by a significant amount due to the considerable contribution of soil moisture to the total WF of crops. Note that no rainfed cultivation was considered in this study except for the grazing grasses where the green water is the only water available for those rangelands.

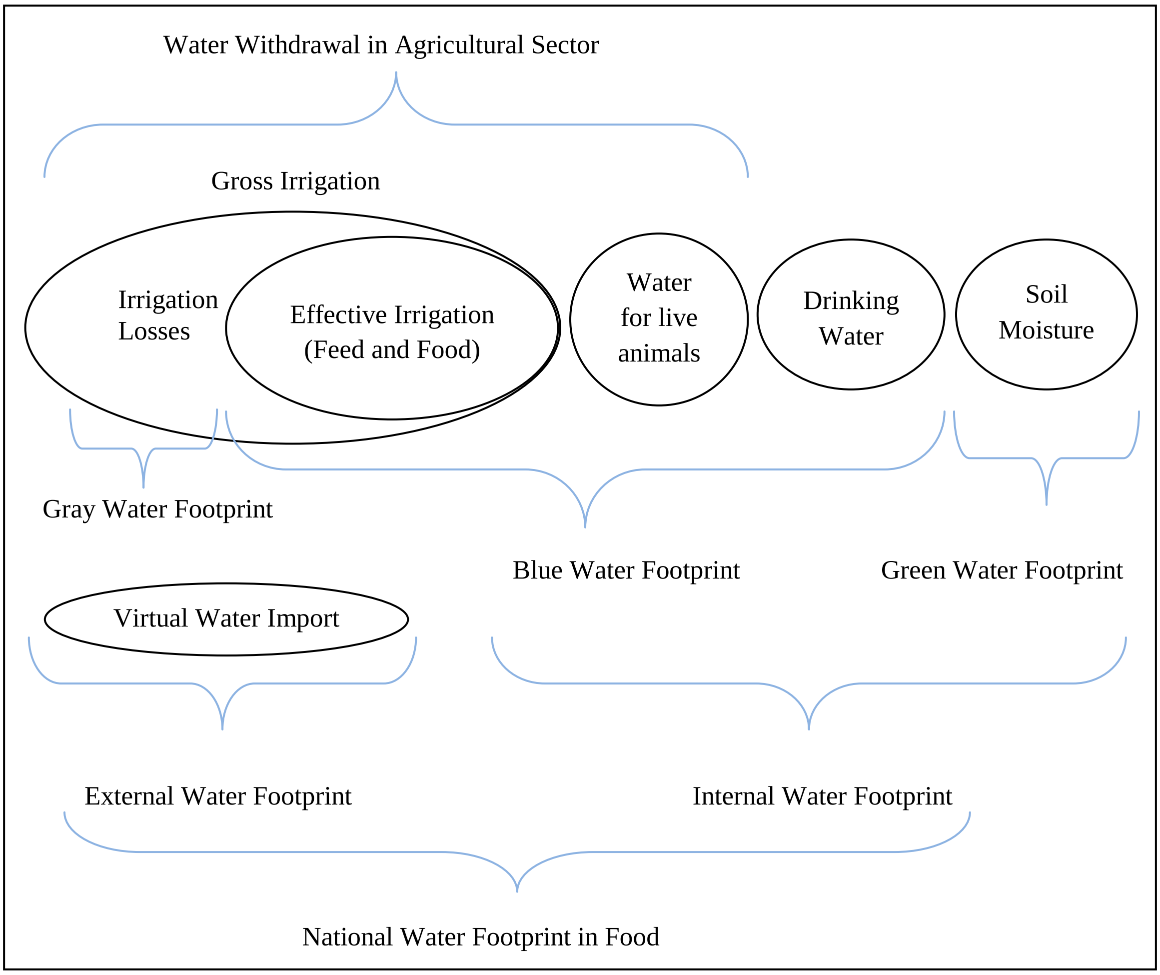


Figure 15. Water Footprint Map of food products as calculated by the model

In Table 15.b, the direct water demand for animals is always negligible in front of irrigation water, even when OF1 decided that 70% of livestock products are locally made. So the reason behind the high WF of most livestock products is above all the total virtual water content of feeds supplied for farm animals. Thus, the decision to import ready livestock products or to raise animals and import feeds not only depends on water resources availability but also relies on other inputs as land, economic, or even human resources.

Ratio of effective irrigation to gross irrigation is varying according to irrigation systems equipped in croplands: drip (90%), sprinkler (75%) and surface irrigation (60%). The optimization process will intend to cultivate first in irrigation systems with highest efficiency then moving to the lowest. Thus the average irrigation efficiency decreases when cultivation quantity increases (varying from 70% to 80%) where the maximum irrigation efficiency (80.2%) is attained by OF6 through its attempt to minimize the internal WF. Irrigation losses are left outside the blue water footprint account and consequently are not directly incorporated in the OF5, OF6 and OF7 optimizations. Controlling the losses and its outcome of reducing the water withdrawal may be investigated through sensitivity analysis study.

The maximum percentage of BWF is 63% and given by OF5 that doesn't differentiate between the two components of total WF to subsequently allocate a precious value for the blue water. On the opposite side, the best possible contribution of green water in internal WF reaches 64.5% for OF7 scenario, representing the ultimate productive use of soil moisture. The rest of OFs provides values in between of the two stated extremes indicating that green and blue waters have close participations in most scenarios. Note that those calculations are made under the fundamental assumption of the model that crops are grown in normal conditions of evapotranspiration needs fully met.

The actual water footprint in production of agricultural products, as computed by Report No.50 [59], comprises water for crops (1.734 km^3/year) added to green water for grazing (1.604 km^3/year) and blue water for animals (0.008km^3/year). In its turn, the actual water footprint profile for crops is as follows: blue WF equals 0.767 Km^3 /year, green WF equals 0.821 Km^3/year and grey WF equals 0.146 km3/ year (Mekonnen & Hoekstra, 2010a). Notice that the grey water footprint, that constitutes 8% of the total WF of crops, comes mostly from irrigation losses and is not taken into account in the current study. Furthermore, green water participates in around 47% of total WF of crops produced in Lebanon; however this percentage was proved to be much higher in global average (78%) (Mekonnen & Hoekstra, 2010a). The realistic reason is that Lebanon locates in semi-arid zone characterized by a climate with a long hot and dry period (6 month yearly), causing irrigation to be vital for crops cultivation.

4.4.4. Regional Analysis

Amid the first four food security OFs and the last three water security OFs, we chose to perform the regional analysis for the scenario that combines the ultimate results. Accordingly, OF3 was considered a representative objective function because it gives very acceptable values of the other OFs (Table VI-1), and the following output analysis is done based on this scenario.

4.4.4.1 <u>Crop Production</u>

The production amounts of crop groups are presented in Figure 16.a in 1000 tons per year, while Figure 16.b shows the production distribution among the four districts for five main groups. The national production of fodder crops is by far the highest amounts produced (around 6.3 million tons), yet it is concentrated in one district, where 71% of this production is originating in Bekaa (Figure 16.b and Table VI-2). In fact, agriculture in Bekaa is vital for several crop groups: sugar crops (100%), treenuts (44%), vegetables (56%) and fruits (52%). On the other side, more than 50% of cereals production originates from south, while north district has its considerable weight in treenuts (56%), oilcrops (46%) and fruits (36%) production.

4.4.4.2. Cultivated Lands by District

While the first analysis is done based on tones of quantity produced (yield), the second and the third analysis are done based on hectares of land cultivated. Obviously, analyses on production basis and land basis are different because of the diverse crops yields (ton/ha). The crop yields of items belonging to the same crop group are close in their values (Supplement Information), hence we could treat the whole group as one unit and execute the analysis at this large scale.

Figure 17 presents, in pie charts, the distribution of cultivated lands and of productions of crops at national scale. The cereals constitute only 2% in total production weight but they occupy 33% of lands cultivated. The paradox is that fodder crops also occupy 33% of lands but compose 69% in weights. Similarly vegetables and fruits constitute equal proportions of cultivated land (7%) but they have distinct fractions of total production, 7% and 4% respectively. Thus, distinct production-based and land-based agricultural policies would be developed from the multiple analyses of results.

The land pie chart in Figure 17 is divided into four parts illustrated in Figure 18.a, where the outer pie is the same original one, and the inner pie pieces are the relative fraction of each district for the crop groups.

Also, the lands cultivated in cereals, indicated before as 33% of national lands, constitute 73% of south and 53% of north agricultural lands. Whereas, the 33% associated to fodder lands is concentrated in Bekaa to constitute 60% of the land there. Further, 35% of Mount Liban land is devoted for roots and tubers. (Table VI-3).

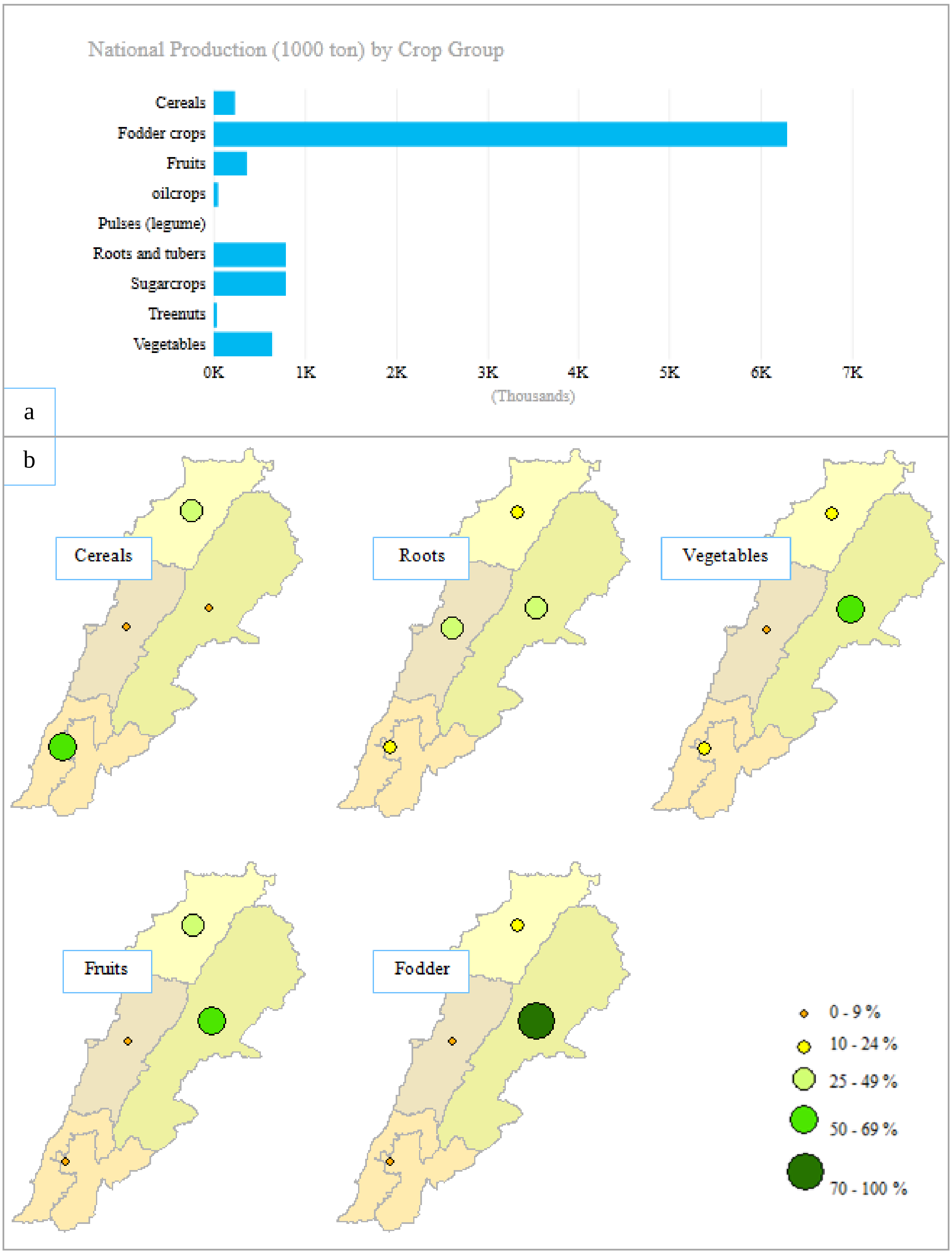


Figure 16. National Agricultural Production in 1000 tons (16.a) of major crop groups and the production distribution among the districts (16.b)

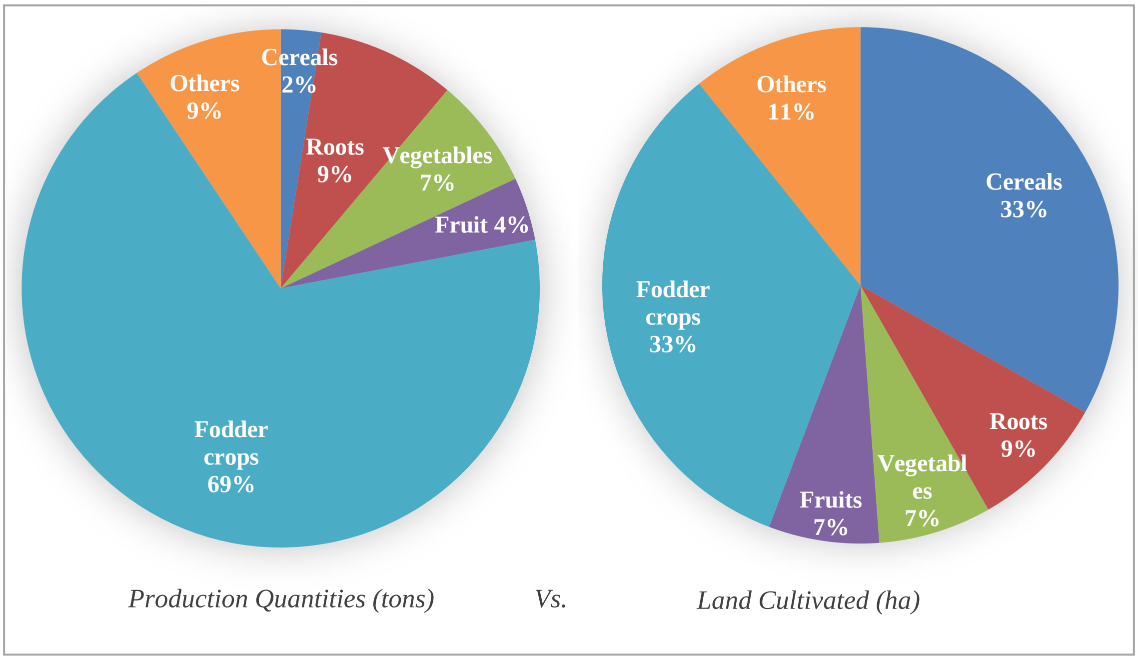


Figure 17. The charts to the left and to the right stand respectively for the production quantities and cultivated Lands of crops (in percentages)
"Others" category consists of sugarcrops, pulses, treenuts and oilcrops

In regard to agricultural lands, the North, Mount and South districts, having close total surface area (around 2000 km^2 in Table VI-4), but they include different available agricultural areas (North 750km^2, Mount 340 km^2, South 840 km^2) mostly due to the different geology and lands fertility frequent in the districts. Bekaa is by far having more land resources (1350 km^2 and about 41% of total agricultural land) (Table VI-4 and Figure 18.b) which supplies this district with the biggest weight in agriculture, therefore it is not an unexpected result that Bekaa lands provide a chief contribution in production of five crop groups out of nine groups (Table VI-5). The least involved district in agricultural production is Mount Lebanon due to its limited agricultural lands even so the mountains climate is in general little water demanding given its lower ET0 and higher precipitation amounts.

The decisions stated in section 1 and 2 are all fitted based on local natural circumstances, they outline an agricultural policy aims to optimize natural resources exploitation. Figure 18.a can be regarded as an agricultural policy map derived from land and water maps.

4.4.4.3.Climatic Regions and Crops Parameters

This analysis would provide a clarification of the decisions presented in the two previous sections because they are affected by the major factors climate and plants characteristics. The model considers the particularities of these two factors to fit the crops into the regions. The new categorization of crops is based on report 56 classification (Allen et al., 1998), where it consists of twelve categories each of them comprises plants of relatively similar characteristics such as fruit trees group, cereals group, vegetables cucumber family and solanum family (Appendix IV). The distribution of cultivated lands for these categories is illustrated in pie chart Figure 19.

The model verifies one general condition and another specific condition. The general condition is the crop water requirements versus the evaporation power of the atmosphere (ET0) and the precipitation in the region. Hence, the crop water footprint and the soil moisture availability are compared and the model will reasonably choose to cultivate crops of low WF in more arid zones and those of higher WF in more humid zones. The specific condition is the appropriation between the crop growing period and the region dry / wet seasons across the year. The best fitting occurs when the ultimate transpiration needs of the crop in its development and mid-season periods (where the Kc values are the highest) mach the region wet season. In these two ways, the soil moisture (green water) is effectively exploited by a productive transpiration and the irrigation needs (blue water) are as minimum as possible.

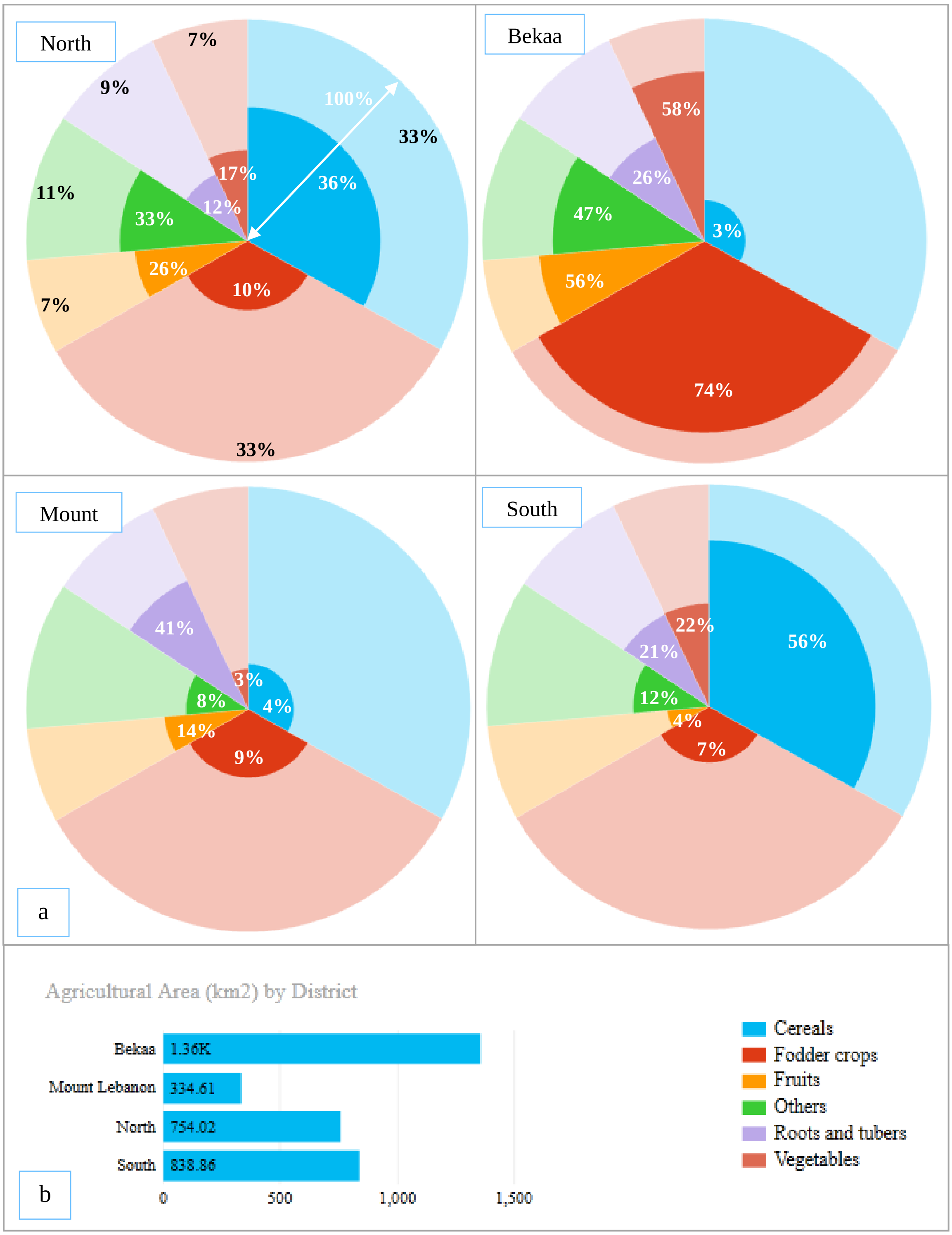


Figure 18. The distribution of lands cultivated in crops (%) among districts (18.a) and the agricultural area cultivated (km^2) by district (18.b) (based on Table VI-5)

The pie chart is read as follows: the outer pie (the same as figure 17) is the distribution of lands cultivated by crop groups; their percentages are in black font. The inner pie sectors are the relative fraction of each district in crops lands, the percentages are in white font and they differ between the four charts. The ratio of inner sector area to the outer sector area is representative of this percentage (white font).

It is correct that crop water footprint may vary from region to another by around 40%, yet the irrigation needs could vary even more than 100% (Supplement Information). Therefore, the model will choose to cultivate each crop in the region that demands minimum irrigation, and that is applicable only if the agricultural lands are sufficient there. However, with also restricted land resources, the solution adopted is the one that provides the maximum saving in the two resources and optimum food security.

Figure 19 is as well divided into four charts associated to the agro-climatic zones: coastal, interior, mountains and arid (Figure 20.a). First observation is that, unlike the crops distribution in all districts, there is a little division of crops among the regions where five groups are totally produced in a single region (Figure 20.a and Table VI-6). This note means that there is always a particular climate preferred for a certain crop, because crops of similar types are grown in the same conditions.

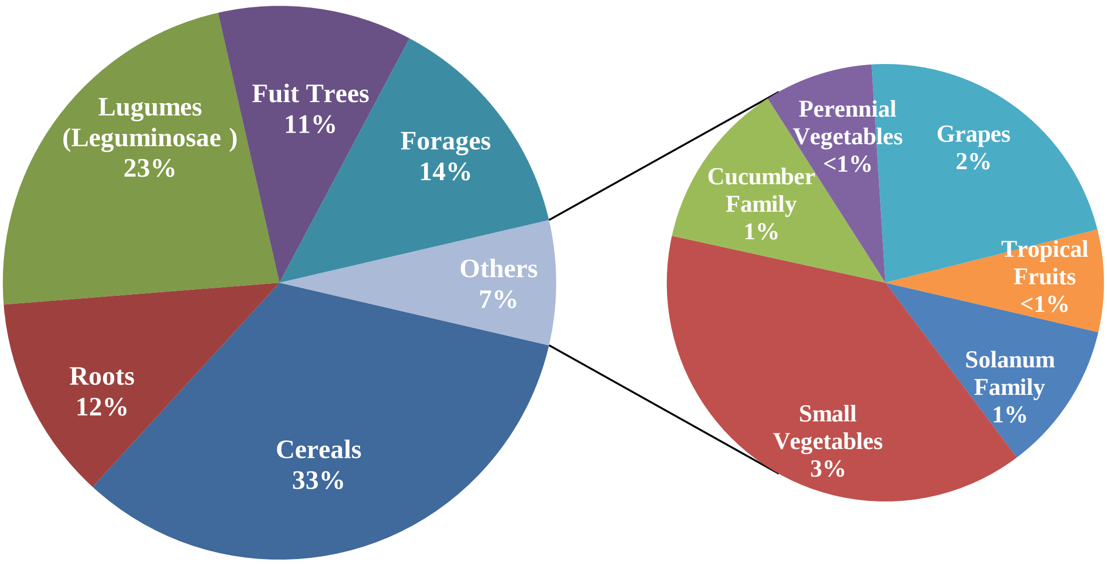


Figure 19. Distribution of cultivated lands according to crop groups

The fruit trees, producing crops of high water footprint (in the range of 1000m3/ton), needs water particularly in summer season (Supplement Information), accordingly they are cultivated in mountains, coastal and interior regions (Figure 20.a and Table VI-6). At opposite in arid zone, the model selected to cultivate forage crops (alfalfa), cereals (barley) and some small vegetables since they have low water footprint, and the summer crops are not recommended at all. The crops cultivated there are almost mutually exclusive with those in mountains. The cultivation in this dry region is an option only because of limited lands in the other three regions. In addition, the coastal zone participates in cultivating fraction of cereals, forages, small and perennial vegetables, and mainly fruit trees and tropical fruits.

The majority of agricultural lands locates in the interior climatic region (66% in Figure 20.b and Table VI-7), which is less humid than the coastal and mountains regions. The interior region constitutes a safe environment for growing diverse kinds of crops, thus it participates in growing almost all kinds of crops (Figure 20.a).

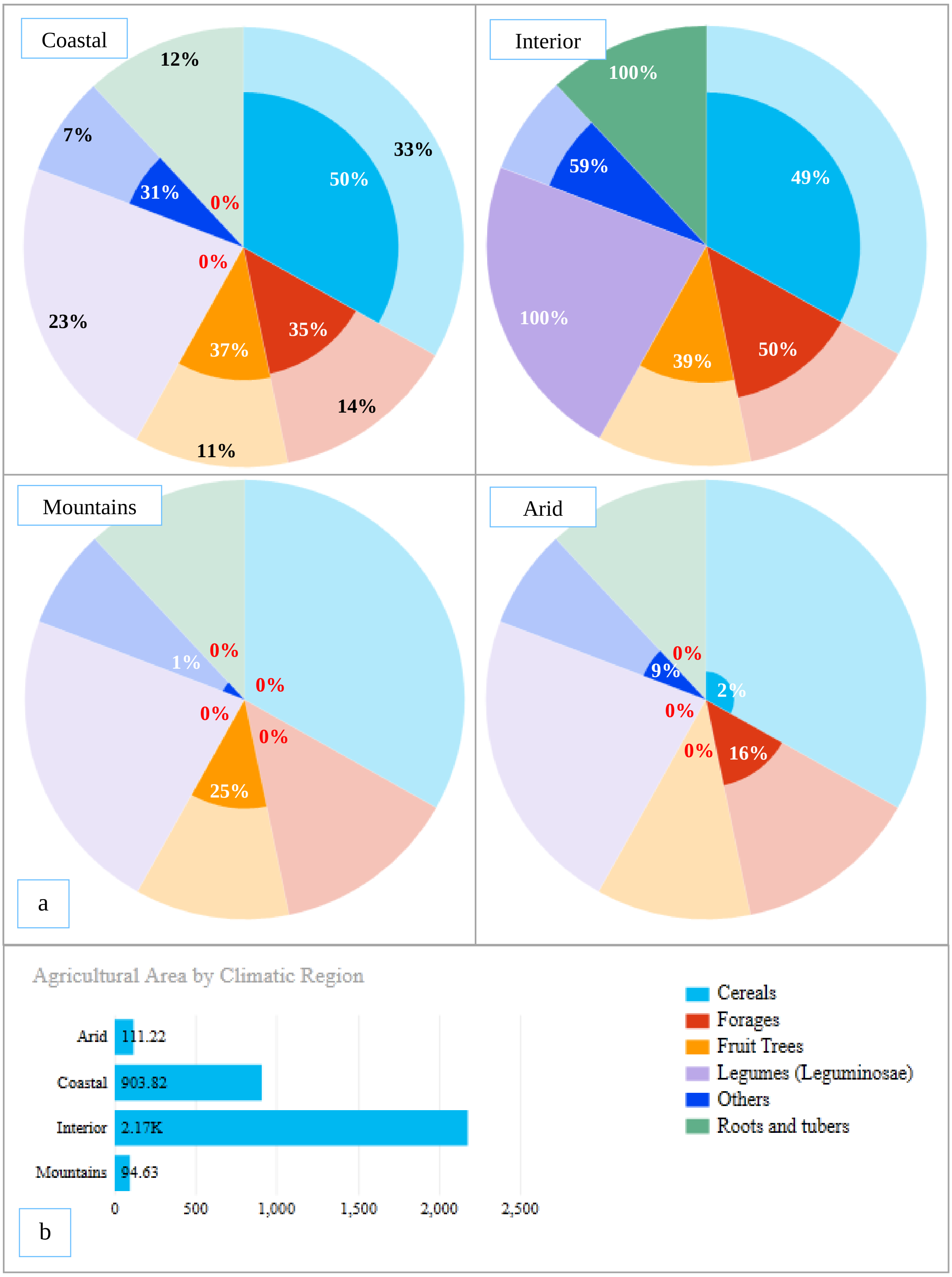


Figure 20. The distribution of lands cultivated in crops (%) among climatic regions (20.a) and the agricultural area cultivated (km^2) by region (20.b)

4.5. Conclusions and Recommendations

As a conclusion, and based on the altering results of different scenarios, the main concern of the country is provided for either food or water securities depending on the present conditions. And the decision to reallocate water from other sectors to be used in the agricultural sector requires considering the composite security.

The problem of limited resources might be avoided by the alternative solution of using advanced technology in cultivation to “produce more with less”. The proper technology would diminish disease effects in cropfields, increase crops yields and reduces loss rates at farmer and transportation stages. It also involves irrigation equipments that provide a water-conserving supply.

This study has introduced a model performing a particularly accurate evaluation of food security opportunities. The model application in Lebanon permits a study of the optimal food security along with the associated agricultural policies. An assessment of the current situation compared by the potential food security reflects a peculiar image: The export of foods with high water footprint (fruits) on the expense of producing essential foods for nutritional and food securities (cereals) might be interpreted only from economic background. The economic constraints and profits have not been incorporated in the model application, mainly for purposes linked to results clarity and analysis. Were the food security issue addressed from economic perspective, the main question would be how much food security is expected to worth in terms of revenue.

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APPENDICES

Appendix I – Nutrition Guidelines

Table I- 1. Nutrient intake goals

Rank k	Nutrient	Lower bound	Upper bound	Unit
1	Energy [a]	Energy x	Energy x	kcal per day
2	Total Fat[b]	15	30	% of total energy
3	Saturated fatty acids[b]	0	10	% of total energy
4	Polyunsaturated fatty acids[b]	6	10	% of total energy
5	n-6 Polyunsaturated fatty acids[b]	5	8	% of total energy
6	n-3 Polyunsaturated fatty acids[b]	1	2	% of total energy
7	Trans fatty acids [b]	0	1	% of total energy
8	Monounsaturated fatty acids [b]	0	24	% of total energy
9	Protein[b]	10	15	% of total energy
10	Total Carbohydrate[b]	55	75	% of total energy
11	Free/added sugars [b]	0	10	% of total energy
12	Cholesterol [b]	0	300	mg per day
13	Sodium chloride (sodium)[b]	0 (0)	5 (2)	g per day
14	Total dietary fiber [b]	25	-------	g per day
15	Non-starch polysaccharides [b]	20	-------	g per day
16	Total water[c]	3.2*	-------	liter per day

[a]Calculated for the entire population based on daily calorie (IOM, 2005)

[b]Population goals extracted from WHO technical report 916 (WHO, 2013)

[c]Adequate intake (AI) extracted from IOM report series of dietary reference intake (DRIs) (Hellwing et al., 2006)

* 3.2 is the arithmetic average of 2.7 (AI for females between 19—70 years) and 3.7 (AI for males between 19—70 years)

Table I- 2. Sample of nutrient data extracted from the USDA Nutrient database

Rank k*	Nutrient	Unit**
Proximates		
16	Water	g
1	Energy	Kcal
9	Protein	g
2	Total lipid (fat)	g
10	Carbohydrate	g
14	Total Fiber	g
11	Total Sugars	g
Minerals		
13	Sodium, Na	mg
Lipids		
3	Total saturated fatty acids	g
8	Total monounsaturated fatty acids	g
4	Total polyunsaturated fatty acids	g
7	Total trans fatty acids	g
12	Cholesterol	mg

* The rank k assigned to nutrients in this table has the same order provided in the intake goals table

** The value (in g or cal) of nutrient is given by 100 g of edible portions of food

Thus, the nutrient intake goals presented in the first table were converted to match the units of data extracted from the USDA database:

- From "percentage of total energy" to calorie: multiply by the daily calorie intake (kcal/day).
- From calorie to its equivalent gram: divide the intake of each of the three macronutrients by their densities (Kcal/g).The fat density is 9 kcal/g whereas the carbohydrate and protein densities are 4 kcal/g [8].
- From liter to gram: multiply by the water density 10^3 g/liter.

Table I- 3. Lower and upper bounds of nutrients

Rank k	Nutrient	Lower bound	Upper bound	Unit
1	Energy	x	x	kcal per day
2	Total Fat	x/60	x/30	g per day
3	Saturated fatty acids	0	x/90	g per day
4	Polyunsaturated fatty acids	x/150	x/90	g per day
5	n-6 Polyunsaturated fatty acids	x/180	x/112.5	g per day
6	n-3 Polyunsaturated fatty acids	x/900	x/450	g per day
7	Trans fatty acids	0	x/900	g per day
8	Monounsaturated fatty acids	0	x/37.5	g per day
9	Protein	x/40	3x/80	g per day
10	Total Carbohydrate	11x/80	3x/16	g per day
11	Free/added sugars	0	x/40	g per day
12	Cholesterol	0	300	mg per day
13	Sodium chloride (sodium)	0 (0)	5 (2)	g per day
14	Total dietary fiber	25	-------	g per day
15	Non-starch polysaccharides	20	-------	g per day
16	Total water	3200	-------	g per day

The variety constraints (Integer Problem):

In optimization, the solver may choose to include only one food item that, from its perspective, serves better the optimal solution, especially that the nutrition constraints do not cover all micronutrients intake. Thus, to ensure that mixture of foods is selected from all major food groups, the variety constraints in food consumption are introduced as follows:

First, food items are consumed from all the food groups:

$$\sum_{j=1}^{J(i)} X_{ij} > 0 \qquad\qquad \forall\, i \in \{1;\ 2;\ \dots\ ;\ I\}$$

This constraint is particularly significant for groups not included in the previous “general food groups guidelines”.

Furthermore, we suggest that at least half of food types j in every group i should be included in the diet. This constraint requires integer variables. We define Y_{ij} binary integer variables ϵ {0; 1}, such that:

$$Y_{ij} = \begin{cases} 1 & if\ item\ (i;j)\ \ is\ selected \quad \equiv X_{ij} > 0 \\ 0 & if\ otherwise \quad \equiv X_{ij} = 0 \end{cases}$$

Thus, $X_{ij} + \ M * \left(1 - Y_{ij}\right) > 0$ where M is a very large number

Interpretation:

- $If\ Y_{ij} = 1\ \rightarrow$ the constraint is active and $X_{ij} > 0$
- $If\ Y_{ij} = 0\ \rightarrow$ the constraint is redundant

$$\sum_{j=1}^{J(i)} Y_{ij} \geq\ 0.5\ * J(i) \qquad\qquad \forall\, i \in \{1;\ 2;\ \dots\ ;\ I\}$$

Given the large size of the model and for simplification purposes, it is preferable to dispense of integer formulation usage through manual variety formulations, i.e. to set constraints of minimum consumption for some selected food items in each food group.

$X_{ij}\ \geq \min(i;j)$ for essential foods

Appendix II – CROPWAT Model

Data input:

- Module **Climate/ET_0**: Long-term average meteorological data: minimum and maximum temperature, humidity, wind, sun hours and ET_0 Penman-Monteith evapotranspiration.
- Module **Rain**: long-term average rainfall data on a monthly, decade or daily basis.
- Module **Crop**: The crop parameters are planting and harvest date, length of the four growth stages (initial, development, mid-season, late season), crop coefficient K_c, rooting depth, critical depletion fraction, yield response factor and crop height. All of these coefficients vary along the growth stages.
- Module **Soil**: The soil data are field capacity, welting point, maximum infiltration rate, maximum rooting depth and initial soil moisture depletion.

Output:

The major outputs are potential and actual water use by crop (mm), total and effective rainfall over the growing period (mm), gross and actual irrigation requirement (mm) and yield reduction due to water shortage, if any (%). Effective rainfall (P_{eff}) is the fraction of rainfall stored in the root zone after excluding runoff and deep percolation.

Irrigation Criteria:

First, the *timing of irrigation process*, as recommended by CROPWAT, is "irrigate at critical depletion" where irrigation is applied each time soil moisture decrease to reach the threshold of critical depletion (figure 4). Second, the recommended *amount of irrigation water* is to "refill soil to field capacity", thus net irrigation will be equated with the root zone depletion. Any excess water in net irrigation above field capacity level is lost by deep percolation and should be avoided. Third, the *irrigation efficiency* is concerned by water losses through evaporation and runoff caused by a shortage in the irrigation system. The irrigation efficiency set by default is equal to 70% for "normal well-managed gravity irrigation".

By adopting the recommended options in CROPWAT, we have assumed that "automatic irrigation" is available, that is an accurate evaluation of the required water volume and its application at the exact time by differential amounts at different areas of the field due to non-uniform water needs.

Appendix III - Foods List

56 food items are categorized into 16 groups as shown in the table below. The nomenclature is identical to that of FAO food lists

Table III- 1. Foods list

Food Group		Rank	Item name	Priority
i = 1 Cereals	Wheat	j=1	Flour of Wheat	1
		j=2	Bread	1
		j=3	Bulgur	1
	Rice (Milled Equivalent)	j=4	Rice Husked	2
		j=5	Rice Milled	2
	Barley	j=6	Pot Barley	1
	Maize	j=7	Flour of Maize	2
i = 2 Roots and tubers	Potatoes	j=1	Potatoes	2
i = 3 Sugarcrops	Sugar Beet	j=1	Sugar beet	3
i =4 Sugar and Sweeteners	Sugar (Raw Equivalent)	j=1	Beet sugar, raw, centrifugal	3
		j=2	Sugar Refined	3
i = 5 Pulses (legume)	Beans	j=1	Beans, dry	2
	Peas	j=2	Peas, dry	2
	Pulses, Other	j=3	Broad beans, horse beans, dry	2
i = 6 Treenuts	Nuts	j=1	Pistachios	3
		j=2	Almonds Shelled	3
		j=3	Walnuts Shelled	3
i = 7 oilcrops	Soyabeans	j=1	Soyabeans	3
	Sunflowerseed	j=2	Sunflower seed	3
	Sesame seed	j=3	Sesame seed	3
	Olives	j=4	Olives Preserved	2
i = 8 Vegetable Oils	Soyabean Oil	j=1	Soyabean oil	3
	Sunflowerseed Oil	j=2	Sunflower oil	3
	Olive Oil	j=3	Olive oil, virgin	2
i = 9 Vegetables	Tomatoes	j=1	Tomatoes	2
	Onions	j=2	Onions, dry	2
	Vegetables, Other	j=3	Lettuce and chicory	2
		j=4	Spinach	2
		j=5	Cauliflowers and broccoli	2
		j=6	Pumpkins, squash and gourds	2
		j=7	Beans, Green	2
		j=8	Peas, Green	2
i = 10 Fruits	Oranges, Mandarines	j=1	Oranges	2
	Bananas	j=2	Bananas	2
	Apples	j=3	Apples	2

	Pineapples Grapes	j=4 j=5	Pineapples Grapes	3 2
	Fruits, Other	j=6 j=7 j=8 j=9	Cherries Peaches and nectarines Strawberries Watermelons	2 2 3 3
i = 11 Meat	Bovine Meat	j=1	Beef and Veal Boneless	1
	Mutton & Goat Meat	j=2 j=3	Sheep meat Goat meat	2 2
	Poultry Meat	j=4	Chicken meat	1
i = 12 Animal Fats	Butter, Ghee	j=1	Butter Cow Milk	3
i = 13 Milk - Excluding Butter	Milk	j=1 j=2 j=3 j=4	Cow milk, whole, fresh Milk Skm of Cows Yoghurt Cheese of Whole Cow Milk	1 1 2 2
i = 14 Eggs	Eggs	j=1	Hen eggs, in shell	2
i = 15 Fish, Seafood	Freshwater Fish	j=1	Frwtr Diad F	2
	Pelagic Fish	j=2	Pelagic Fresh	2
	Marine Fish, Other	j=3	Marine nes F	2
	Crustaceans	j=4	Crstaceans F	2
i = 16 Water		j=1	Waters,ice etc	1

Losses and Waste Ratios:

The loss ratio represents the losses at the farm, transportation and market stages of the food system. An average loss ratio will be calculated for each food group, thus all foods in the same group will have the same loss ratio which is calculated by dividing the "waste" entry in the food balance sheets (FAOSTAT) over the domestic supply quantity.

$$\text{Loss ratio} = \frac{\text{Waste entry}}{\text{Domestic supply quantity}}$$

After calculating the losses ratio in Lebanon for the year 2009, they are found ranging from 0% (sugars group, vegetable oils group…) to 14% (fruits group; eggs group). (Supplement Information) The waste factor represents the waste at the household stage and is taken equal to 15% as stated previously.

Appendix IV - Crops List

36 crops are categorized into 9 groups as shown in the table below.

Table IV- 1. Crops list

Crop Group	Rank	Crop Name	Priority
m=1 Cereals	n=1	Wheat	1
	n=2	Rice, paddy	2
	n=3	Barley	1
	n=4	Maize	2
m=2 Roots and tubers	n=1	Potatoes	2
m=3 Sugarcrops	n=1	Sugar beet	3
m=4 Pulses (legume)	n=1	Beans, dry	2
	n=2	Peas, dry	2
	n=3	Broad beans, horse beans, dry	2
m=5 Treenuts	n=1	Almonds, with shell	3
	n=2	Walnuts, with shell	3
	n=3	Pistachios	3
m=6 oilcrops	n=1	Soyabeans	3
	n=2	Sunflower seed	3
	n=3	Sesame seed	3
	n=4	Olives	2
m=7 Vegetables	n=1	Tomatoes	2
	n=2	Onions, dry	2
	n=3	Lettuce and chicory	2
	n=4	Spinach	2
	n=5	Cauliflowers and broccoli	2
	n=6	Pumpkins, squash and gourds	2
	n=7	Beans, Green	2
	n=8	Peas, Green	2
m=8 Fruits	n=1	Oranges	2
	n=2	Bananas	2
	n=3	Apples	2
	n=4	Pineapples	3
	n=5	Grapes	2
	n=6	Cherries	2
	n=7	Peaches and nectarines	2
	n=8	Strawberries	3
	n=9	Watermelons	3
m=9 Fodder crops	n=1	Vetches	2
	n=2	Alfalfa for Forage+Silag	2
	n=3	Grasses nes, Forage+Silag	2

Table IV- 2. Crops classification as presented in FAO paper 56 (Allen et al., 1998)

Crop Categories	Crops
1- Cereals	Wheat Rice, paddy Barley Maize
2- Roots and Tubers	Potatoes Sugar beet
3- Legumes (Leguminosae)	Beans, dry Peas, dry Broad beans, horse beans, dry Soyabeans Beans, Green Peas, Green Vetches
4- Oil Crops	Sunflower seed Sesame seed
5- Vegetables - Solanum Family (Solanaceae)	Tomatoes
6- Small Vegetables	Onions, dry Lettuce and chicory Spinach Cauliflowers and broccoli
7- Vegetables - Cucumber Family (Cucurbitaceae)	Pumpkins, squash and gourds Watermelons
8- Perennial Vegetables (with winter dormancy)	Strawberries
9- Fruit Trees	Oranges Apples Cherries Peaches and nectarines Almonds, with shell Walnuts, with shell Pistachios Olives
10- Grapes and Berries	Grapes
11- Tropical Fruits and Trees	Bananas Pineapples
12- Forages	Alfalfa for Forage +Silag Grasses nes, Forage +Silag

Appendix V – Generic Case Study

Regional Data

Table V- 1. Meteorological data

Month / Region	January	February	March	April	May	June	July	August	September	October	November	December	Total (mm/year)	Average (mm/day)
Table V-1 (a). Rainfall, total mm per month														
Climate1	239	207	145	68	32	5	1	1	5	32	93	158	**986**	
Climate2	195	116	107	48	18	1	1	0	9	35	149	148	**827**	
Climate3	96	80	53	31	14	1	0	0	1	7	47	74	**404**	
Table V-1. (b). Reference Evapotranspiration, average monthly, mm per day														
Climate1	1	1.27	1.8	2.7	3.64	4.43	4.99	4.8	3.61	2.62	1.69	1.17	**2.81**	**1029.1**
Climate2	1.73	2.03	2.58	3.43	4.47	5.56	5.87	5.54	4.39	3.31	2.27	1.74	**3.58**	**1308.8**
Climate3	1.52	1.9	2.78	4.07	5.27	6.9	7.85	7.25	5.43	3.58	2.14	1.56	**4.19**	**1533.5**

These data are recorded in three meteorological stations located in Lebanon, having a Mediterranean (or winter-rainfall semi-tropical) climate.

Table V-1 (c). Soil data

Soil Type	Field capacity θ_{FC} (m^3/m^3)	Welting point θ_{WP} (m^3/m^3)	Total Available Soil Moisture (m/m)
Loam	0.26	0.11	0.15

Initial soil moisture = 50% of field capacity

Irrigation field efficiency is taken constant and equal 75%

Foods and Crops Data

Table V- 2 (a). Foods list

Group Rank	Group Name	Item Rank	Item Name
i=1	Cereals	j=1	Flour of wheat
i=2	Vegetables	j=1	Tomatoes
i=3	Fruits	j=1	Oranges
i=4	Pulses	j=1	Dry Beans
i=5	Water	j=1	Drinking Water

Total foods number = $\sum_{i=1}^{I} J(i)$ = 5
Suppose waste factor = loss factor = 15%

Table V-2 (b). Nutrients List with their concentrations per 100 gram of food

Nutrient rank	k=1	k=2	k=3	k=4
Nutrient name	**Water**	**Energy**	**Protein**	**Carbohydrate**
Unit	**(g)**	**(Kcal)**	**(g)**	**(g)**
Flour of wheat	11.92	364	10.33	76.31
Oranges	86.75	47	0.94	11.75
Tomatoes	94.52	18	0.88	3.89
Dry Beans	11.32	333	23.36	60.27
Drinking Water	99.9	0	0	0

$\text{Calorie intake}_{av} = 2600$ kcal/capita/day

Table V-2 (c). Crops list

Group Rank	Group Name	Item Rank	Item Name
m=1	Cereals	n=1	Wheat
m=2	Vegetables	n=1	Tomatoes
m=3	Fruits	n=1	Oranges
m=4	Pulses	n=1	Beans

Total crops number = $\sum_{m=1}^{M} N(m)$ = 4

Decision Variables

Table V- 3. Decision variables

Symbol	Type	Number
X_{ij}	Principal	$\sum_{i=1}^{I} J(i)$ = 5
D_{ij}	Auxiliary	$\sum_{i=1}^{I} J(i)$ = 5
P_{ij}	Auxiliary	$\sum_{i=1}^{I} J(i)$ = 5
IMP_{ij}	Auxiliary	$\sum_{i=1}^{I} J(i)$ = 5
EXP_{ij}	Auxiliary	$\sum_{i=1}^{I} J(i)$ = 5
$D_{m\,n}$	Auxiliary	$\sum_{m=1}^{M} N(m)$ = 4
$P_{m\,n}$	Auxiliary	$\sum_{m=1}^{M} N(m)$ = 4
$IMP_{m\,n}$	Auxiliary	$\sum_{m=1}^{M} N(m)$ = 4
$EXP_{m\,n}$	Auxiliary	$\sum_{m=1}^{M} N(m)$ = 4
$P_{m\,n\,d}$	Auxiliary	$D\sum_{m=1}^{M} N(m)$ = 4
$P_{m\,n\,d\,r\,s\,q}$	Principal	$DRSQ\sum_{m=1}^{M} N(m)$ = 12
SSR_{ij}	FS. indicator	$\sum_{i=1}^{I} J(i)$ = 5

$$\text{Principal D.V. Number} = \sum_{i=1}^{I} J(i) + \text{DRSQ}\sum_{m=1}^{M} N(m) = \mathbf{17}\ \boldsymbol{D.V}$$

$$\text{Total Number} = 5\sum_{i=1}^{I} J(i) + (4 + \text{D} + \text{DRSQ})\sum_{m=1}^{M} N(m) = \mathbf{57}\ \boldsymbol{D.V}$$

Constraints

Table V- 4. Constraints

Type	Constraint	Number
Balance Constraints	$D_{ij} = \frac{X_{ij} * Population * 365.25}{10^6 * (1 - waste\ factor)(1 - Loss\ ratio)}$ $\forall\ i\ \&\ j$	$\sum_{i=1}^{I} J(i) = 5$
	$P_{ij} + IMP_{ij} - EXP_{ij} = D_{ij}$ $\forall\ i\ \&\ j$	$\sum_{i=1}^{I} J(i) = 5$
	$(D_{m\,n}) = A \times (P_{ij})$ $\forall\ m, n, i\ \&\ j$	$\sum_{m=1}^{M} N(m) = 4$
	$P_{m\,n} + IMP_{m\,n} - EXP_{m\,n} = D_{m\,n}$ $\forall\ m\ \&\ n$	$\sum_{m=1}^{M} N(m) = 4$
	$P_{m\,n} = \sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q}$ $\forall\ m\ \&\ n$	$\sum_{m=1}^{M} N(m) = 4$
Nutrition Constraints	$L_k \leq \sum_{i=1}^{I}\sum_{j=1}^{J(i)} \frac{NTR_{ijk}}{100} * X_{ij} \leq U_k$ $\forall\ k$	$\sum_{k=1}^{K} k = 4$
Resources Constraints	$\sum_{m=1}^{M}\sum_{n=1}^{N(m)}\sum_{q=1}^{Q} \frac{P_{m\,n\,d\,r\,s\,q}}{PYIELD_{m\,n}} \leq CL_{d\,r\,s}$ $\forall\ d, r\ \&\ s$	DRS= 3
	$\sum_{m=1}^{M}\sum_{n=1}^{N(m)}\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,s\,q} \leq AGRW$	1
Monthly Water Balance	$\sum_{m=1}^{M}\sum_{n=1}^{N(m)}\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,t\,s\,q} \leq AGRW_t$ $\forall\ t$	$\sum_{t=1}^{T} t = 12$
	$IWR_{m\,n\,d\,r\,s\,q} = \sum_{t=1}^{T} IWR_{m\,n\,d\,r\,t\,s\,q}$ $\forall\ m, n, d, r, s\ \&\ q$	1
Total Number $= 2\sum_{i=1}^{I} J(i) + 3\sum_{m=1}^{M} N(m) + 2\sum_{k=1}^{K} k + DRS + 1 =$ $\mathbf{34\ Constraints}$		

- No economic constraints
- The balance constraints (equality form) are adjustable by cells of excel spreadsheet while the other constraints (inequality form) must be incorporated in the solver engine.

Table V- 5. Matrix A with size 4*4

	Wheat Flour	Orange	Tomato	Bean
Wheat	1/0.79	0	0	0
Oranges	0	1	0	0
Tomatoes	0	0	1	0
Beans	0	0	0	1

Objective Functions Formulas

$$(1) \quad Maximize \ \frac{1}{\sum_{i=1}^{I} J(i)} \sum_{i=1}^{I} \sum_{j=1}^{J(i)} SSR_{ij} \quad ; \quad \text{Where} \quad SSR_{ij} = \frac{P_{ij}}{P_{ij} + IMP_{ij} - EXP_{ij}} \quad \forall\, i \,\&j$$

$$(2) \quad Minimize \sum_{m=1}^{M} \sum_{n=1}^{N(m)} \sum_{d=1}^{D} \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{q=1}^{Q} P_{m\,n\,d\,r\,s\,q} * IWR_{m\,n\,d\,r\,s\,q} \ ; \ \text{With } SSR_{ij} \geq \text{minimum ratio}$$

$$(3) \quad Minimize \sum_{d=1}^{D} \sum_{r=1}^{R} \sum_{s=1}^{S} CL_{d\,r\,s} \quad ; \quad \text{With} \quad SSR_{ij} \geq \text{minimum ratio}$$

Yield:

Table V- 6. Crops yield

Crop	Yield (ton/ha)
Wheat	2.8
Oranges*	1.6
Tomatoes**	65.1
Beans	20.7

The lowest yield is for orange crop and the highest is for the tomato crop

<u>Results</u>

Virtual Water

Table V- 7. Water footprint and irrigation water calculated by CROPWAT for cultivation in standard conditions

Climate	Crop	Potential Water Use (mm)	WF (m3/ton)	Actual Irrigation needs (mm)	Gross Irrigation Water (m3/ton)
Climate 1	Wheat	522	1877	185	887
	Oranges	650	4164	324	2768
	Tomatoes	556	85	449	92
	Beans	321	155	192	123
Climate 2	Wheat	679	2441	303	1453
	Oranges	785	5029	433	3702
	Tomatoes	662	102	594	122
	Beans	395	191	283	182
Climate 3	Wheat	815	2933	488	2341
	Oranges	1088	6973	760	6492
	Tomatoes	904	139	857	176
	Beans	500	242	434	279

In all climates, lower WF and irrigation needs were recorded for tomatoes and the highest for oranges

Scenario 1

Table V- 8. Food variables in scenario of OFa with export

	Xij (g/day)	Demand (ton)	Production (ton)	Import (ton)	Export (ton)
Wheat Flour	562.6	28.4	28.4	0.0	0
Oranges	10.0	0.5	0.5	0.0	0
Tomatoes	1190.4	60.2	60.1	0.1	0
Beans	10.0	0.5	25.3	0.0	24.8
Drinking Water	2000.0	101.1	101.1	0.0	0

Sensitivity Analysis:

Table V- 9. OFb answer report

Name	Cell Value	Status	Slack
Land 1	10	Binding	0
Land 2	0.32	Not Binding	9.68
Land 3	0.00	Not Binding	10
Water	29,172	Not Binding	20827.62

Table V- 10. OFb sensitivity report

Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
Land 1	10	-1225.33	10	0.322	0.166
Land 2	0.32	0.00	10	1E+30	9.678
Land 3	0.00	0.00	10	1E+30	10
Water	29,172	0	50000	1E+30	20827.62

Scenario 2: Land Scarcity

Table V- 11. Consumption variables Xij in function of land resource

Food (Xij) in g	30 ha	27 ha	24 ha	21 ha	18 ha	15 ha	12 ha	9 ha	6 ha	3 ha
Wheat Flour	374	375	377	377	380	383	387	390	390	390
Oranges	119	109	100	93	74	48	20	1	1	1
Tomatoes	1099	1100	1109	1114	1131	1155	1181	1198	1198	1198
Beans	206	206	205	205	204	202	201	200	200	200
Drinking Water	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000

Table V- 12. Model variables in function of land resource

Simulation Resource Variable	30 ha	27 ha	24 ha	21 ha	18 ha	15 ha	12 ha	9 ha	6 ha	3 ha
Land available in each climate	10	9	8	7	6	5	4	3	2	1
Land used Climate1	10	9	8	7	6	5	4	3	2	1
Land used Climate2	3.82	4.43	5.17	6.08	6	5	4	3	2	1
Land used Climate3	0	0	0	0	0.51	1.77	2.96	3	2	1
Total Lands used	13.82	13.53	13.26	13.08	12.51	11.77	10.96	9	6	3
Water	50,000	50,000	50,000	50,000	50,000	50,000	50,000	42,769	29,758	13,502
Food SSR	1	1	1	1	1	1	1	0.963	0.876	0.603

Scenario 3: Water scarcity

Table V- 13. Consumption variables Xij in function of water resource

Simulation Food Variable Xij	50,000 m^3	45,000 m^3	40,000 m^3	35,000 m^3	30,000 m^3	25,000 m^3	20,000 m^3	15,000 m^3	10,000 m^3	5,000 m^3
Wheat Flour	374	377.7	382	385.5	390	389.6	390	389.7	390	389.6
Oranges	119	91.2	61	32.1	2	1.0	1	1.0	1	1.0
Tomatoes	1099	1115.8	1143	1169.5	1197	1197.7	1198	1197.7	1198	1197.7
Beans	206	204.7	203	201.6	200	199.9	200	199.9	200	199.9
Drinking Water	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000

Table V- 14. Model variables in function of water resource

Simulation Resource Variable	50,000 m^3	45,000 m^3	40,000 m^3	35,000 m^3	30,000 m^3	25,000 m^3	20,000 m^3	15,000 m^3	10,000 m^3	5,000 m^3
Land Climate1	10	10	10	10	10	8.77	6.74	4.71	2.69	1.12
Land Climate2	3.82	3.02	2.14	1.31	0.44	0	0	0	0	0
Land Climate3	0	0	0	0	0	0	0	0	0	0
Total Land exploited	13.82	13.02	12.14	11.31	10.44	8.77	6.74	4.71	2.69	1.12
Water used	50,000	45,000	40,000	35,000	30,000	25,000	20,000	30,000	10,000	5,000
Food SSR	1	1	1	1	1	0.953	0.898	0.840	0.784	0.662
Import (Dem – Prod)	0	0	0	0	0	3.63	8.08	12.53	16.98	40.95

Linearization Impact

Table V- 15. Change of food consumption with respect to water availability for OFd

Simulation Food Variable Xij	50,000 m^3	45,000 m^3	40,000 m^3	35,000 m^3	30,000 m^3	25,000 m^3	20,000 m^3	15,000 m^3	10,000 m^3	5,000 m^3
Wheat Flour	375	378	382	389	390	390	390	390	390	390
Oranges	113	89	61	29	1	1	1	1	1	1
Tomatoes	1098	1135	1144	1172	1198	1198	1198	1198	1198	1198
Beans	206	204	203	200	200	200	200	200	200	199
Drinking Water	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000

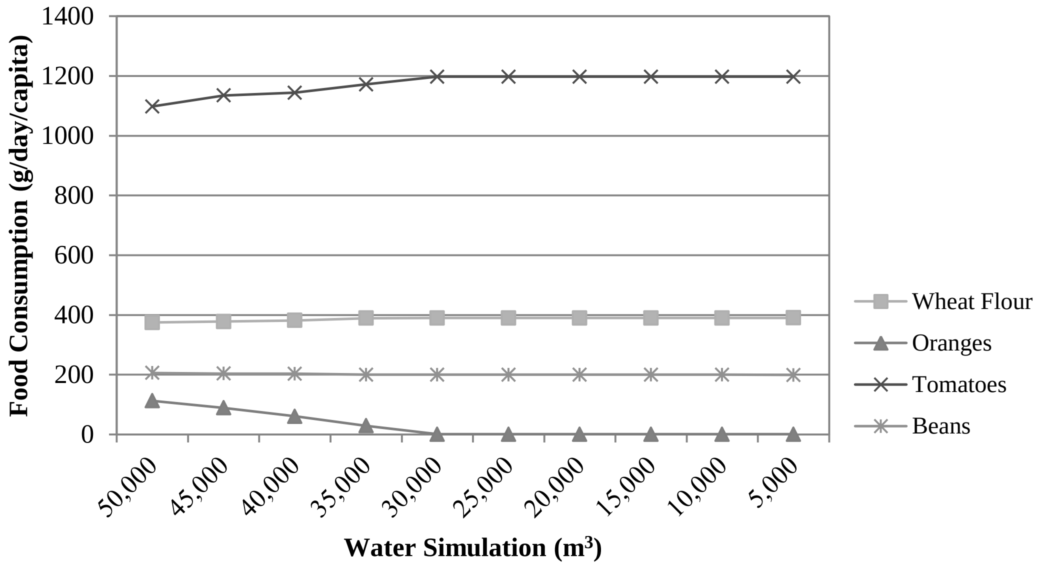

Figure V- 1. Change of food consumption with respect to water availability for OFd

Table V- 16. Change in land exploitation and food SSR with respect to water availability for OFd

Simulation Resource Variable	50,000 m^3	45,000 m^3	40,000 m^3	35,000 m^3	30,000 m^3	25,000 m^3	20,000 m^3	15,000 m^3	10,000 m^3	5,000 m^3
Land Climate1	10	10	10	10	10	8.79	6.76	4.74	2.71	0.84
Land Climate2	3.38	2.96	2.13	1.27	0.43	0	0	0	0	0.00
Land Climate3	0	0	0	0	0	0	0	0	0	0
Total Land exploited	13.38	12.96	12.13	11.27	10.43	8.79	6.76	4.74	2.71	0.84
Water used	50,000	45,000	40,000	35,000	30,000	25,000	20,000	15,000	10,000	5,000
Food SSR	1	1	1	1	1	0.830	0.649	0.593	0.536	0.225
Import (Dem – Prod)	0	0	0	0	0	3.59	8.01	12.46	16.91	36.03

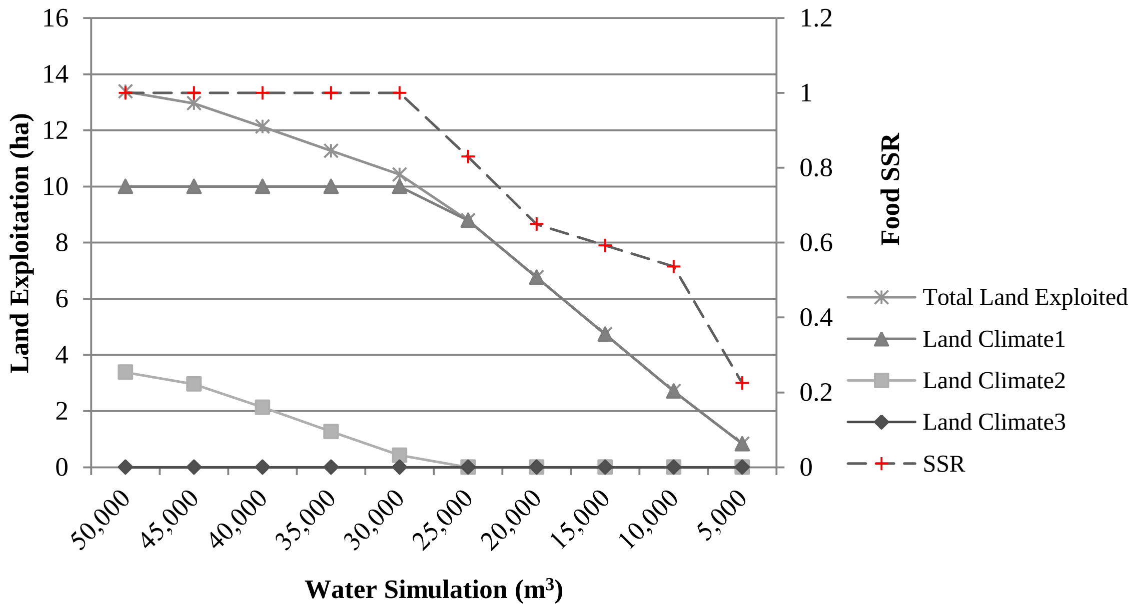

Figure V- 2. Change in land exploitation and food SSR with respect to water availability for OFd

Table V- 17. Change in food SSR and food import with respect to water availability for OFa and OFd

Variable	50,000 m^3	45,000 m^3	40,000 m^3	35,000 m^3	30,000 m^3	25,000 m^3	20,000 m^3	15,000 m^3	10,000 m^3	5,000 m^3
SSRij (OFa)	1	1	1	1	1	0.95	0.90	0.84	0.78	0.66
Dij-Pij (OFa)	0	0	0	0	0	3.63	8.08	12.53	16.98	40.95
SSRij (OFd)	1	1	1	1	1	0.830	0.649	0.593	0.536	0.225
Dij- Pij (OFd)	0	0	0	0	0	3.59	8.01	12.46	16.91	36.03

1.1.Triple runs

Table V- 18. Model variables with respect to land allocation in the three climates

	OFa			OFb		
Foods (Xij) in g	**Climate 1**	**Climate 2**	**Climate 3**	**Climate 1, 2 & 3**		
Flour of wheat	413	386	402	390		
Oranges	146	27	63	1		
Tomatoes	1063	1174	1878	1198		
Beans	189	201	166	200		
Drinking Water	2000	2000	2000	2000		
Lands (CLdrs) in ha	**Climate 1**	**Climate 2**	**Climate 3**	**Climate 1, 2 & 3**		
	15.5	11.2	13.2	10.4		
Water in m^3	**Climate 1**	**Climate 2**	**Climate 3**	**Climate 1**	**Climate 2**	**Climate 3**
	50,000	50,000	80,000	29,023	45,545	72,024

<u>Discussion</u>

Sensitivity Analysis of OFc:

We intended to find the unit worth of water resource in terms of land (shadow price) by performing a sensitivity analysis. So we have updated other version of OFc to maximize the agricultural lands of the least favorable climate3 under same conditions of water and SSR of foods. In this attempt, the water limitation prevented the model from being satisfied by the agricultural lands of the dry climate3. This has lead to optimum solution of maximum 5.29 ha used in climate3, in addition to exploiting additional lands in climate1 (5.12 ha) and withdrawing the total water resource (50,000 m3) making it a binding constraint. The Shadow Price of water resource is 0.00025 that is equal to the increase in climate3-lands when the water augments by one unit (Tables V-19 & V-20).

In other words, if the water augments by 1000 m3 then we may save 0.25 ha in climate1-lands for the sake of other essential landcovers, such as urbanization. Expressing the worth of water in terms of land and vice versa underlines the complimentarily of the two resources. Hopefully, the model application contributes to a better understanding of links existing between the water-land-food nexus.

Table V- 19. OFc answer report

Name	Cell Value	Status	Slack
Land1	5.12	Not Binding	4.9
Land2	0.00	Not Binding	10
Land3	5.29	Not Binding	4.7
Water	50,000	Binding	0

Table V- 20. OFc sensitivity report

Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
Land1	5.12	0.00	10	1E+30	4.9
Land2	0.00	0.00	10	1E+30	10
Land3	5.29	0.00	10	1E+30	4.7
Water	50,000	0.00025	50000	16845	19399

Scenario5: Cultivation under Non-Standard Conditions:

Another feature of water scarcity is the cultivation under nonstandard conditions, where the crops are subjected to shortage in irrigation water that involves a certain reduction in yields. The evaluation of water savings versus the yields shrinkage will determine whether this alternative is recommended in case of a severe water insufficiency, as we will do in Scenario 5.

First, we decided that irrigation deficit will arise from applying the irrigation water once the soil moisture reaches 150% critical depletion level, which is late enough to expose the plant to a certain water stress. Consequently, the reduction in water depth withdrawn (mm) due to this irrigation delay is a function of crop characteristics, like rooting zone depth, along with climatic conditions. Compared with the initial amounts calculated in standard conditions (Table V-7), the irrigation reduction is found changing between 6% and 60% in the different crop/climate situations, with an overall average equals to 24% (Table V-21).

Second, yield reduction was varying from 5% to 20% with an overall average equals to 9.8% (Table V-21). The yields are affected by the water stress to an extent related to the "yield response factor" (Ky) (see Formula(4) Appendix). Ky factor of the perennial trees (oranges) is constant across the year but is varying for the annual crops (like wheat) according to the stage of the growing period, noting that the highest vulnerability takes place at the mid-season.

Proceeding from these two figures, we calculated the irrigation water needs per crop's weight (m^3/ton) and the new crop yield (ton/ha) to perceive the change in resources, land and water, input to produce the same ton of crop. First, the irrigation waters (m^3/ton) are found lower than those of the standard conditions in ten out of twelve crop/climate situations, and second the new yields are always lower than the original ones (Table V-21). Thus in this problem, less water and more land are needed to produce the same amounts of crops, which illustrates new feature of land-water interdependencies. The two exceptions of the first observation are the tomatoes and beans in climate3: they are summer crops grown in arid region where any diminution in irrigation will induce relatively high yield shrinkage and hard to be compensated. In fact, yield reduction is most critical in climate3 with an average 12%. Also, tomatoes and beans, in all climates, are subjected to a little change in irrigation (m^3/ton) or none due to this kind of agriculture (Table V-21). On the contrary, this alternative is found quite beneficial for the winter crop wheat and the perennial crop orange with average irrigation reduction 522 and 926 m^3/ton respectively.

Table V- 21. Yield and irrigation water reductions calculated by CROPWAT for cultivation in nonstandard conditions

	Crop	Actual Irrigation needs (mm)	Gross Irrigation (mm)	Irrigation Reduction (%)	Yield Reduction (%)	Adjusted Yield (ton/ha)	Irrigation Water needs (m3/ton)	Irrigation Change (m3/ton)
Climate 1	Wheat	71	94	62	11.3	2.47	382	506
	Oranges	248	331	23	6.3	1.46	2263	505
	Tomatoes	415	553	8	7.6	60.16	92	0
	Beans	145	193	24	10.3	18.58	104	19
Climate 2	Wheat	223	298	26	5.2	2.64	1129	324
	Oranges	247	329	43	5.7	1.47	2235	1466
	Tomatoes	542	723	9	8.5	59.58	121	0
	Beans	241	321	15	13.4	17.93	179	4
Climate 3	Wheat	266	355	45	20.4	2.21	1604	737
	Oranges	588	784	23	11.6	1.38	5684	808
	Tomatoes	801	1068	7	7.7	60.10	178	-2
	Beans	406	541	6	9.6	18.72	289	-10

Irrigation is applied at 150% critical depletion of soil, rather than apply it at 100% level as in standard conditions.
The yield response factor (Ky) affect the plant vulnerability to water stress as follow:
(1 - Ya/Ymax) = Ky (1 - ETc adj / ETc)
If Ky increase, the induced reduction in yield also increases.

At this stage, we solved the optimization problem using the second objective function (OFb) concerned by irrigation water minimization, with considering the option of cultivation under non-standard conditions within the decision variables. The optimum solution of water used is 18,880 m^3 that is equal to 38% of the water available (50,000 m^3), suggesting that this alternative has provided unchanged food security level but with consuming the least amount of water as compared with all the former scenarios. Also, a modest increase in agricultural lands exploited was noticed and was justified by yield reduction, where 10ha of climate1 and 1.56ha of climate2 were cultivated. Therefore, reducing the irrigation water may become, not excessively harmful but rather, a real opportunity to save water once was applied on a convenient crop, being well-located and at the right growing stage. The saving amounts in water are decided on in accordance with the scarcity extent of resources. However, rainfed agriculture remains too risky in such climates.

Monthly Water Balance:

By considering the meteorological data of the three climatic regions (Table1), we find that the climates selected comprise a wet season (from October to March) and a dry season (from April to September). In all of the three climates, about 90% of the precipitation happens in the wet season and just 10 % in the dry season. In addition, the average of monthly reference evapotranspiration over the dry season is twofold greater than that of the wet season, making the plants' transpiration needs even more critical during the former period. Precipitation is the major source of national renewable water, of which the long-lasting storage is not perfectly realizable either naturally or artificially. Therefore, the water mostly exists in one season and the evapotranspiration needs are larger in the other season. Thus, the supply/demand imbalance in irrigation water at monthly basis is by far more severe than the annual one. The 50,000 m^3 of water offered won't be enough to attain food security if we apply the monthly balance constraints. This issue makes the water resource even scarcer and more requiring for sustainable management.

Appendix VI – Lebanon Case Study

Objective Functions Values:

Table VI- 1. Values of objective function (OFj) for the minimization of (OFi) given in row i and column j

	OF1	OF2	OF3	OF4	OF5	OF6	OF7
Unit	**1000 ton**				**Km^3**		
OF1	538	12121	12121	6560	5.173	1.253	3.920
OF2	838	957	4172	678	4.038	1.077	2.961
OF3	917	1368	1555	994	4.405	1.493	2.912
OF4	851	973	4188	616	4.659	1.106	3.553
OF5	1184	1360	4777	1070	3.743	0.898	2.845
OF6	4883	4883	8682	2699	4.886	0.350	4.535
OF7	804	4218	4615	2552	3.863	1.582	2.281

The highlighted numbers represent the minimum values of OFs.

Regional Results:

Table VI- 2. Total national production (1000 tons) of crop groups and its distribution among districts (%)

	D1	D2	D3	D4	Total
Units	**%**	**%**	**%**	**%**	**1000 ton**
Cereals	36	3	4	56	230
Roots and tubers	11	26	41	21	789
Sugarcrops	0	100	0	0	778
Pulses (legume)	0	0	0	0	0
Treenuts	56	44	1	0	36
Oilcrops	46	14	16	24	43
Vegetables	12	56	10	23	633
Fruits	36	52	9	3	361
Fodder crops	12	71	10	8	6282

Table VI- 3. Total land cultivated by districts (ha) and its distribution between the crop groups (%)

	D1	D2	D3	D4
Cereals	53	3	14	73
Roots and tubers	4	5	35	7
Sugarcrops	0	8	0	0
Pulses (legume)	0	0	0	0
Treenuts	5	2	0	0
oilcrops	11	2	8	5
Vegetables	5	10	2	6
Fruits	8	9	10	1
Fodder crops	14	60	31	8
Total (ha)	**75402**	**135664**	**33462**	**83887**

Table VI- 4. Agricultural land (Km^2) by districts

District	Total Land (Km^2)	Agricultural Land (Km^2)
D1	1973.2	754.02
D2	4258.4	1356.65
D3	1991.2	334.61
D4	2023.4	838.86

Table VI- 5. Total national land cultivated (Km^2) by crop groups and its distribution among districts (%)

	D1	D2	D3	D4	Total
Units	**%**	**%**	**%**	**%**	**Km2**
Cereals	36	3	4	56	1089
Roots and tubers	11	26	41	21	282
Sugarcrops	0	100	0	0	111
Pulses (legume)	0	0	0	0	0
Treenuts	55	45	1	0	69
oilcrops	46	14	16	24	173
Vegetables	17	58	3	22	233
Fruits	26	56	14	4	227
Fodder crops	10	74	9	6	1101

Table VI- 6. Total land cultivated (Km^2) by crop groups and its distribution among climatic region (%)

	R1	R2	R3	R4	Total (km2)	Percent (%)
Cereals	50	49	0	2	1089	33
Roots and Tubers	0	100	0	0	392	12
Lugumes (Leguminosae)	0	100	0	0	745	23
Oil Crops	0	0	0	0	0	0
Vegetables - Solanum Family	0	100	0	0	26	1
Small Vegetables	52	24	0	24	92	3
Vegetables - Cucumber Family	0	100	0	0	30	1
Perennial Vegetables	100	0	0	0	19	1
Fuit Trees	37	39	25	0	373	11
Grapes and Berries	0	100	0	0	53	2
Tropical Fruits and Trees	33	52	15	0	18	1
Forages	35	50	0	16	446	14

Table VI- 7. Agricultural Land (Km^2) by Climatic Region

Region	Agricultural Land (Km^2)	% of total Land
R1	904	28
R2	2174	66
R3	95	3
R4	111	3
Total	**3284**	**100**