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Changing the cropping pattern in a catchment to reduce blue water scarcity and increase nutritional and economic water productivity, would it?

Abstract

Water-stressed countries need to plan their food security and reduce the pressure on their limited water resources. Agriculture, the largest water-using sector, has a major role in addressing water scarcity and food security challenges. While there has been quite some attention to water management solutions like soil mulching and improved irrigation, less attention has been paid to adapting the cropping pattern to save water. Here, we investigate how a change in which crops are grown where and when can influence the green and blue water footprint (WF) of crop production, save blue water, reduce blue water scarcity and increase both food and cash crop production, using FAO's AquaCrop model. The performance of two potential solutions, first a strategy of mulching plus drip irrigation, and second a strategy with changing the cropping pattern in addition to mulching and drip irrigation, were compared in one of the most water-stressed catchments in the world, the Upper Litani Basin in Lebanon. Our results show a substantial potential for more efficient use of green water resources for food production while saving scarce blue water resources. Whereas mulching and drip irrigation together decrease the blue WF in the basin by 4.5%, changing the cropping pattern as well can decrease it by 20.3%. Food and cash production could increase by 3% and 50% by the changing the cropping pattern, compared to 1.5% and 2.1% by mulching and drip irrigation. Changing the cropping pattern could thus significantly reduce water scarcity and enlarge food and cash production in the basin.

Keywords: water scarcity, food security, economic blue water productivity, nutritional blue water productivity, sustainability assessment, blue water saving

1. Introduction

Increasing global demand for food has resulted in continued agricultural expansion and intensification during the past decades (FAO, 2017b; Godfray and Garnett, 2014; Tilman et al., 2011). This has helped to increase crop yields and total food production, but has not been without environmental consequences, including widespread overexploitation and pollution of limited freshwater resources. Most water-stressed countries have promoted better agricultural and water management practices, like soil mulching to reduce unbeneficial soil evaporation and pressurized irrigation to reduce water needs (Ali et al., 2017; Nakawuka et al., 2018; Quemada and Gabriel, 2016), but this has been insufficient to halt the growing scarcity of water in many places on earth (Kummu et al., 2016). Food security in water-stressed countries is highly dependent on irrigation (Belloumi and Matoussi, 2008; Dixon et al., 2001; FAO, 2003) that supplies by blue water resources like aquifers, streams and lakes, which paradoxically means that blue water demands are highest where blue water availability is lowest (Mekonnen and Hoekstra, 2016).

The quantity and spatial distribution of green and blue water resources in a catchment, together with national targets of food security and self-sufficiency, are key factors to decide where, when and what crops to cultivate. A sustainable farming scheme that not only plans the timing of plantation and spatial distribution of crops, but also takes into account crops' nutritional and economic productivity (e.g. replacing low-value crops by high-value ones) could be part of a long-term solution (Davis et al., 2017a; Davis et al., 2017b; Schyns and Hoekstra, 2014).

Crop redistribution based on spatial patterns of crop suitability and water availability can help to reduce water shortages and produce more food (Haouari and Azaiez, 2001; Matthews et al., 2013; Osama et al., 2017). Several studies in arid and semi-arid regions like Iran, Morocco or different parts of China reported higher crop water productivity, smaller water footprint and more potentials for water saving, and conceivably less environmental damage and more socio-economic gain by crop redistribution (Fasakhodi et al., 2010; Schyns and Hoekstra, 2014; Sun et al., 2014; Wang et al., 2014; Zhang et al., 2014). A long-term study (1990-2010) on the impact of cropping pattern modifications on the water demand of irrigated farming in Beijing Metropolitan Area showed a significant change in blue water consumption of the agricultural sector (Huang et al., 2012). A recent study claimed that rearranging crop distribution on a global scale can feed an additional 825 million people, which would be a 10% increase in the global nutritional productivity. Concurrently, their recommended cropping pattern could decrease green and blue water consumptions by 13.6% and 12.1%, respectively (Davis et al., 2017b).

To improve sustainable management of scarce water and land resources, various studies suggest combining crop redistribution practices with multi-cropping (growing two or more crops on the same field in sequence in different growing seasons of a year), this combination can substantially increase crop water productivity. In areas with a pronounced dry summer and wet winter season, multi-cropping facilitates cultivating rainfed crops outside the summer growing season, thus making better use of the available green water resources in the wet winter period; this can result in higher water productivity in the region and takes water-stressed countries one step closer to food security.

To assess how agricultural management strategies can assist coping with food and water crises in a dry region, we selected Upper Litani Basin in Lebanon, one of the most water-stressed basins in the world, for this study. Multi-cropping is a common practice in this basin, whereby particularly summer crops contribute to high blue water scarcity. We evaluated the impact of mulching, drip irrigation and crop redistribution in combination with multi-cropping on the WF of crop production in the catchment considering crop varieties and heterogeneity in soil and climate. We employed the global WF assessment standard (Hoekstra et al., 2011) and AquaCrop-OS model, the open-source MATLAB version of AquaCrop developed by FAO (FAO, 2017a) to assess the green and blue WF of major crops in the region and the influence of alternative agricultural practices on their total, green and blue WF. We suggested two water saving scenarios in comparison to the reference scenario (current practice), for which we take the period 2011-2016. In one scenario, we reflected the effect of introducing mulching and drip irrigation of the summer crops; in the other scenario we assessed the impact if we additionally improve the cropping pattern. We investigated how these scenarios can contribute to the reduction of blue water scarcity and the increase of nutritional and economic productivity of the catchment.

2. Method and data

2.1. Site description

The Upper Litani Basin - ULB in Lebanon (33° 54' 42.7680" N, 36° 0' 48.8880" E) measures 1500 km^2. The Upper and Lower Litani Basin together form a total area 2180 km^2 (Figure 1). The Litani River, around 182 km long, originates in the Bekaa plain in the north of the ULB and drains to Qaraoun Lake, continues south through the Lower Litani Basin and then deviates west and flows to the Mediterranean Sea. The ULB is a narrow basin, with the Bekaa plain stretched between two parallel mountain ranges. The ULB has a Mediterranean climate, with wet winters (November-May) and extended dry summers (April-October). However, its topographic features and the nearby Mediterranean Sea and Syrian Desert result in a variety of microclimates. The mean annual temperature in Bekka Valley is about 16 °C - ranging from 5 °C in winter to 26 °C in summer - and the mean annual precipitation varies between 700 and 1100 mm (Ramadan et al., 2012, 2013; Shaban et al., 2014).

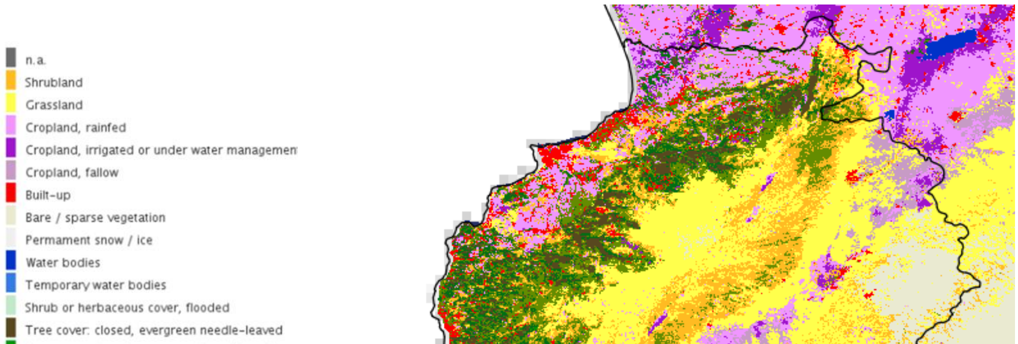


Figure 1. Land Cover Classification Map (year 2014) of Lebanon extracted from WaPOR – FAO (https://wapor.apps.fao.org/home/WAPOR_2/2)

Farming management practices at the ULB including irrigation method, irrigation depth, efficiency of each method and the proportion of the cultivated area under each irrigation method were extracted from our field survey and the available literature; mean values are summarised in Table 1 (FAO, 2017b; Nouri et al., 2019; USAID, 2014).

Table 1. Irrigation management at the ULB

Irrigation type	**Crop**	**Alfalfa**	**Barley**	**Chickpeas**	**Corn**	**Fava beans**	**Early potato**	**Late potato**	**Tobacco**	**Tomato**	**Wheat**
	Total cultivated area at ULB (ha)	**700**	**3200**	**2800**	**3800**	**2000**	**4400**	**3200**	**2800**	**4300**	**7800**
Surf ace	Area proportion (%)	57	100	90	96	53	100	100	57	79	100

	Irrigation depth (mm)	93	76	67	75	76	63	71	67	49	76
Sprinkler	Area proportion (%)	21	0	0	4	39	0	0	21	17	0
	Irrigation depth (mm)	116	95	84	94	95	79	89	84	61	95
Drip	Area proportion (%)	22	0	10	0	8	0	0	22	4	0
	Irrigation depth (mm)	78	63	56	63	63	53	59	56	41	63

2.2. Water footprint of agricultural crops

We considered water consumption of all sectors in the ULB, including the domestic, industrial, forestry and agricultural sectors during the period 2009-2016. Data on the water consumption of the domestic, industrial and forestry sectors were extracted from available literature (see Nouri et al. (2019)). Water consumption in crop cultivation was estimated using the open-source MATLAB version of AquaCrop, FAO's crop water productivity model (Foster et al., 2017).

From our field survey and the available literature of the ULB, we learned that there are 10 major crop types (wheat, early potato, late potato, alfalfa, barley, chickpea, corn, fava bean, tobacco and tomato), 4 major soil types (Orthents, Xeralfs, Xerepts and Xerolls – based on TAXOUSDA classification system) and 6 major climate zones (using Thiessen Polygons) at the ULB. In combination of crop type, soil type and climate zone, was divided this basin into 240 LUs, each of which represents a unique combination of crop, soil and climate. However, 15 of the 240 possible combinations are not available in the catchment. The ten major crops together cover 94% of the cultivated area in the ULB.

Per crop and land unit (total of 225 LU), evapotranspiration (ET) over the growing period and crop yield were estimated with AquaCrop. Soil moisture and ET were partitioned into green and blue components on daily basis, with green soil moisture and green ET referring to water originating from rainwater, and blue soil moisture and blue ET referring to water originating from irrigation water, i.e. water withdrawn from surface water or groundwater. This partitioning was done following the method of Chukalla et al. (2015). Per crop and per LU, the green and blue water footprint of the crop (in m^3/t) was calculated as the green or blue ET over the growing period divided by the crop yield, following the global WF assessment standard (Hoekstra et al., 2011).

AquaCrop was designed to be applicable under different soil and climate conditions, with no necessity for calibration once it has been parameterized for a specific crop species. Since our study is limited to the crops that already had been parameterized in the AquaCrop, the outcomes of the model were reliable (Chukalla et al., 2015; Steduto et al., 2012). However, to validate the outcomes for the specific conditions of Litani Basin by using the local data from the ground, initialization, parameterisation and validation were performed following the guideline by the FAO - AquaCrop manual: parameterization, calibration, and validation procedure (Steduto et al., 2012). Data on soil, climate, irrigation, field management and cropping patterns were collected during the field visit of the Litani Basin funded by the FAO-WaPOR project (FRAME consortium) in June - July 2017 and the available literature (Nouri et al., 2019).

The simulation period, based on data availability, was from January 2009 to December 2016. The first two calendar years (2009-2010) were used for initialization of the model. Since LUs were either used for a single summer or winter crop or for both, the model was initialized in the first one or two seasons. Summer crops were fully grown in one year and could thus be run for 7 years while winter crops are grown in two calendar years so only 6 simulation years was possible (i.e. winter crops in 2016 could not run the entire crop cycle). The model needed one year of initialization, which was not included in the water accounting of the ULB. To harmonize the water accounting periods of summer and winter, the initialization of summer crops was calculated for 2 years. For LUs with both summer and winter crops, the accounting period started at the beginning of the second winter crop season. This is why the water accounting was accounted for six years for all LUs. By iteration and assessment of results, we learned that after two years of simulation, the soil water balance was near field capacity at the start of the cropping season. So, the initial soil water status was at the field capacity for all simulations. This procedure was done by starting simulations with estimated parameters from the literature and comparing outputs with measured/observed values, then adjusting the parameters and run the simulation again. This procedure was repeated until our simulated results closely agreed with the measured/observed data. The Root Mean Square Error (RMSE) was used as the indicator to evaluate the model performance presenting the deviation between simulations and observations. Table 2 present the summary of the model performance for each crop; it confirmed the reliability of the outcomes of the model.

Table 2. The summary of model performance per crop type

Crop	**Wheat**	**Barley**	**Chickpeas**	**Corn**	**Fava beans**	**Potato**[1]	**Tobacco**	**Tomato**	**Alfalfa**
RMSE (%)	17.25	2.93	5.53	3.46	5.81	6.25	7.12	4.35	NA

[1] *Sum of early (58%) and late potato (42%) corrected for their areas.*

2.3. Nutritional and economic blue water productivity of crops

The blue water productivity of each crop in terms of t/m^3 is the inverse of the blue WF (m^3/t). The nutritional blue water productivity (NBWP, in kcal/m^3) and economic blue water productivity (EBWP, in USD/m^3) of each crop were calculated as follows:

$$\text{NBWP} = \frac{1}{\text{WF}_{\text{blue}}} \times \text{nutritional value} \tag{1}$$

$$\text{EBWP} = \frac{1}{\text{WF}_{\text{blue}}} \times \text{economic value} \tag{2}$$

Nutritional values of all crops were obtained from nutritional tables (DFC, 2017) and economic values from the FAOSTAT. The economic value of each crop varied over the study period (2011-2016); we took annual values for each individual crop. Where FAOSTAT was lacking data for Lebanon, data were taken from countries for which prices are most similar to Lebanon: barley from Turkey, corn from Jordan, and chickpeas, fava beans, tobacco and wheat from Iran. The economic and nutritional values of the crops are summarised in Table 3.

The nutritional production (kcal/y) was calculated per crop by multiplying the production (kg/y) with the nutritional value per crop (kcal/t). The economic production of each crop (USD/y) was calculated by multiplying the production (t/y) with the economic value per crop (USD/t).

Table 3. Nutritional and economic values of the major crops in the Upper Litani Basin.

	Year	**Alfalfa**	**Barley**	**Chick peas**	**Corn**	**Fava beans**	**Potato**	**Tobacco**	**Tomato**	**Wheat**
Nutritional value (million kcal/t)	-	2.9	33	16	35	3.9	8.5	0	1.9	33
Economic value (USD/t)	2011	66	263	1082	253	2475	269	3372	417	321
	2012	66	291	1672	218	1705	364	7106	445	391
	2013	66	267	1376	230	1937	460	8358	469	391
	2014	66	284	738	305	1331	440	4368	507	391
	2015	66	216	866	199	1462	417	7828	506	232
	2016	66	216	866	199	1462	417	7828	506	232

Food demand in the ULB was estimated by multiplying the number of inhabitants of the region by required calories per person. The population was estimated to be 375,000 in 2010 and is expected to reach 450,000 by 2030 (USAID, 2014). To suggest a sustainable scenario, we assumed that 50% of the required energy/calorie will be provided by crops by 2030. Considering 2355 kcal as the daily required calorie for a moderately active person with an average bodyweight, and assuming that major crops are only sources of carbohydrates (fat and protein sources are mainly imported to Lebanon and were not included in this study), the total food demand for the ULB was estimated at 193.5 billion kcal/y (2355 × 365.25 × 450 000 × 0.5) by 2030.

2.4. Blue water availability and water scarcity

Blue water availability in ULB was estimated on a monthly basis by deducting the environmental flow requirement from the natural runoff (Hoekstra et al., 2011). We assumed here the Availability+ scenario as described in Nouri et al. (2019), in which blue water availability is defined based on environmental flow requirements at 60% of natural runoff, plus a moderate level of fossil water abstractions, plus the availability from water storage from a newly planned irrigation scheme.

Blue water scarcity in the catchment is defined per month as the ratio of the blue water footprint in that month to the blue water available (Hoekstra et al., 2011; Hoekstra et al., 2012).

2.5. Two scenarios

Two scenarios, S1 and S2, were formulated and compared with the current situation (reference scenario) in the ULB. S1 includes organic mulching of the soil for all crops and drip irrigation for summer crops; details of this scenario and its impact of the WF, water scarcity and food security of the ULB was reported by Nouri et al. (2019). Our results revealed that implementation of S1 had positive but minor impact on the water saving and consequently more food production of the ULB. Mulching could decrease the blue WF of the ULB by 3.6%, and when drip irrigation of summer crops was added, it was reduced by 4.7% in total. This evidenced that further action is required to alleviate the WF of the basin and enhance the efficiency of water use to save more water for more crop production. S2 suggested a change in the cropping pattern in addition to what was done in S1 (mulching and drip irrigation of summer crops). The cropping pattern was redesigned taking into account the nutritional and economic values of each crop and their green and blue water consumptions. As a basis for the design of an alternative cropping pattern, we identified the months in which water scarcity is highest and which crops contributed most to this water scarcity. To formulate S2, we prioritised the value of crops in the context of Lebanon food security; we divided ten major crops of the ULB into three groups of cash crops (fava beans, tomato and tobacco), food crops (early potato, late potato, chickpeas, barley and wheat) and feed crops (alfalfa and corn). We assessed the contribution of each crop to food and cash production. In order to achieve food security and improve the economic status of the basin, we developed S2 such that sufficient food is produced (the 193.5 billion kcal/y mentioned earlier) and that the remaining water is allocated to high-value crops. The feed crops were considered as the first to be reduced or removed from the basin's cropping pattern. Table 3 list summer and winter crops in crop rotation in a particular cropping plan at the reference scenario against our recommendation with replaced crops in scenario 2 (S2). For instance, corn and alfalfa were considered feed crops in the ULB with the least priority in the food security, or tomato had a large blue WF; these crops were replaced with cash crops or suggested to remain uncultivated to save water.

Table 3. Overview of crop relocation in S2 compared to the reference scenario

Reference scenario		**S2**	
Summer	***Winter***	***Summer***	***Winter***
Fava beans	Alfalfa	Fava beans	Tobacco
Fava beans	Corn	Fava beans	Tobacco
Fallow	Corn	Wheat	Fallow
Wheat	Corn	Wheat	Fallow
Fallow	Tomato	Wheat	Fallow
Fallow		Wheat	Fallow

3. Results and discussion

3.1. Water footprints and nutritional and economic blue water productivity of crops

The average green and blue WFs of the major crops cultivated in the ULB are presented in Figure 2, as well as the nutritional blue water productivity (NBWP) and economic blue water productivity (EBWP). The results show that wheat scores best in terms of NBWP and fava beans in terms of EBWP. These two crops are winter crops, which explain the relatively large share of green water in the total WF. After wheat, corn has the highest NBWP, but corn is mainly used as feed for livestock and does not directly contribute to human food supply. Alfalfa, another feed crop, has a very low NBWP. Interesting results are found for tomato: according to (USAID, 2014), tomato is mainly planted in the basin for its cash value, but its EBWP is actually quite low. Tomato had indeed the highest amount of US$ per tons (Skaf et al., 2019). However, the EBWP is very low due to high blue WF. Tomato has a low NBWP as well. Since food security is the goal the peroject, the main focus is one more food production (and cash production for food import purposes) than feed production. Since meat and dairy products were assumed unnecessary in food security purposes, the lowest value were given to feed crops.

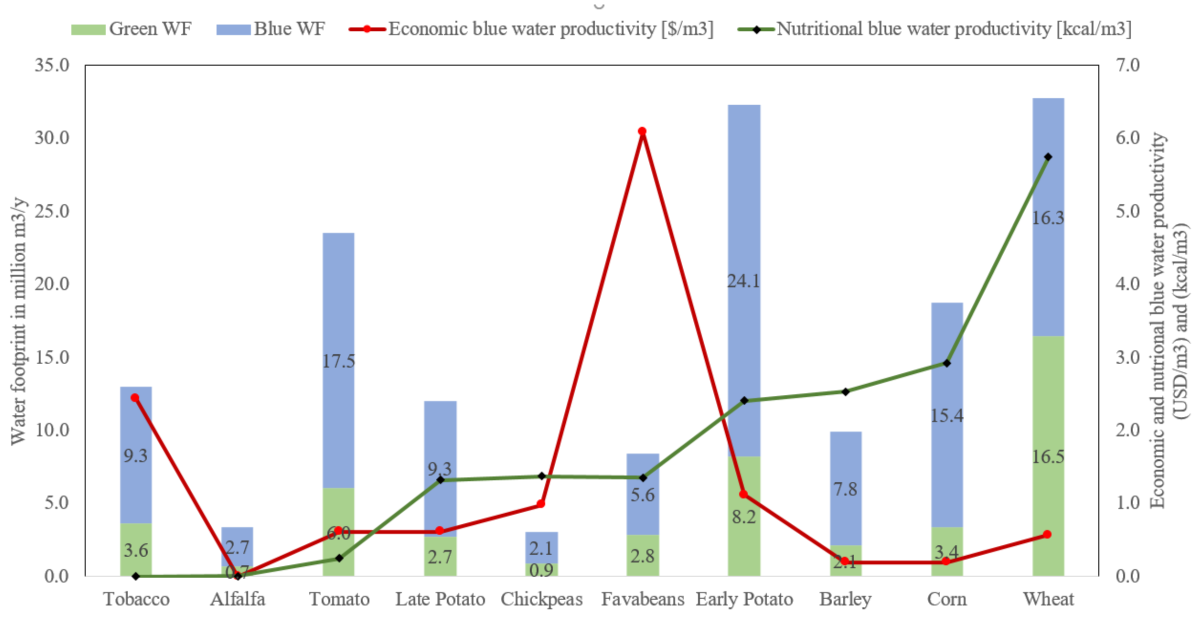


Figure 2. Annual green and blue water footprint of major crops in the Upper Litani Basin and their nutritional blue water productivity and economic blue water productivity in the period 2011-2016.

Annual production of food crops (in kcal/y) and cash crops (in USD/y) and the current food demand in the basin are shown in Figure 3. The current food production is estimated at 186 billion kcal/y and the cash production is 67 million US$/y. Wheat gives the largest contribution in the basin to total production of food-kcal, while fava beans contribute most to cash crop production. Tomato has a relatively high annual blue WF in the basin, but contributes relatively little to cash production. The food production can be increased most efficiently by wheat production. Tobacco and fava beans deliver the most US$ per cubic meter of water.

Higher food production is essential at the ULB since the food demand is not met currently, as presented in Figure 3. This is supported by the recent study on food security and sustainable agriculture in Lebanon that claimed about 80% of the food demand is imported (Skaf et al., 2019; UNHCR, 2017). Our results suggest that most priority should be given to wheat and potato whereas corn, alfalfa and tomato are the last in the list. Mourad et al. (2019) reported that animal production in MENA increased by 50% compared to the last decade, about half of the feed crops produce locally. This study recommended a shift in the diet to reduce WF.

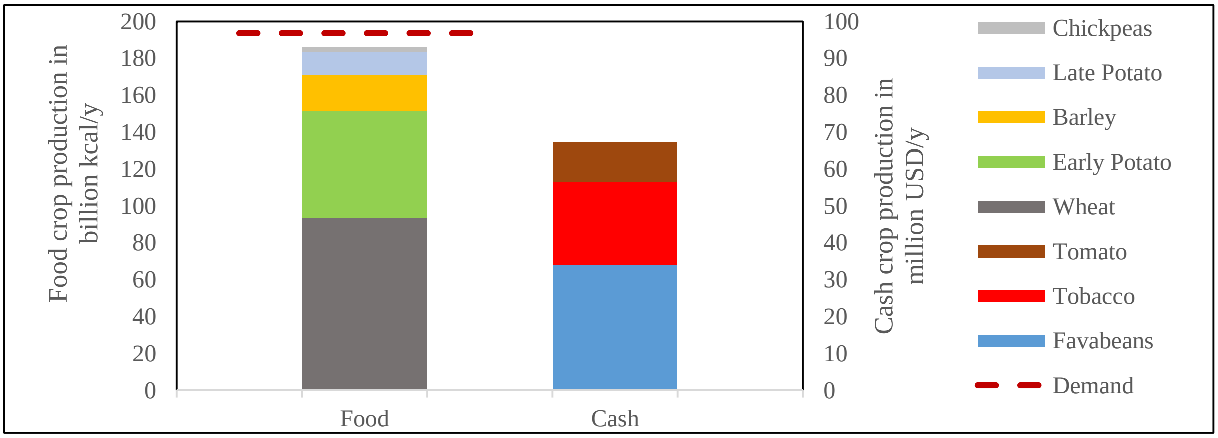


Figure 3. Annual food crop and cash crop production in the Upper Litani Basin in the period 2011-2016, and its food demand.

3.2. Changing the cropping pattern

Since the food demand of the ULB is more than local food supply (food trade is not included in this study), higher food production is desirable. Besides, blue water footprint in the summer is to be reduced to become sustainable, as the basin suffers significant to severe blue water scarcity in the months July to September (as presented in the reference scenario in Figure 5 – The black line presenting the water availability of the ULB placed lower than the average monthly blue WF during this period). The summer crops of corn and alfalfa are feed crops (lower priority) and they have large blue WFs in times when the water scarcity is highest. Tomato is a cash crop with low EBWP and large blue WF in the dry summer months. This means that these three crops have the least priority/value in terms of food security of the basin. If these three crops could be replaced by crops with higher nutritional and/or economic values (food or cash crops), the ULB could save a substantial amount of water while increasing food security and economic benefits.

Based on the WFs of all major crops and their economic and nutritional values, scenario S2 has been formulated such that wheat production in the wintertime is increased as well as tobacco cultivation in summertime. Wheat production is increased as a way to increase food production, tomato production in summer is stopped, and the summer crops corn and alfalfa are replaced by tobacco. Table 5 shows the spatial and temporal cropping pattern in both the reference scenario and scenario S2. In the reference, there is a total of 6,500 hectares of fallow land, which we cut down to 3,920 hectares in S2. Part of these fallow lands could be cultivated in winter without impact on blue water use in the driest months.

Table 5. Overview of cropping patterns in different land-use types in the Upper Litani Basin in the reference scenario and under scenario S2.

Reference (current situation)													
Land use type	Area(ha)	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct

1	700	Fallow								Corn			Fallow
2	4300	Fallow							Tomato				Fallow
3	4400	Fallow			Early potato						Fallow		
4	5500	Wheat								Fallow			
5	500	Fava beans							Fallow				
6	2300	Wheat								Corn			Fallow
7	3200	Barley								Late potato			
8	2800	Chickpeas							Tobacco			Fallow	
9	700	Fava beans							Alfalfa				Fallow
10	800	Fava beans							Fallow	Corn			Fallow
11	6500	Fallow											

Scenario S2 (changed cropping pattern)

Land use type	Area (ha)	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
3	4400	Fallow			Early potato						Fallow		
4	15480 [a]	Wheat								Fallow			
5	500	Fava beans							Fallow				
7	3200	Barley								Late potato			
8	2800	Chickpeas							Tobacco			Fallow	
11	3920 [b]	Fallow											
12	1500 [c]	Fava beans							Tobacco			Fallow	

[a] Extended area compared to the reference.

[b] Reduced area compared to the reference.

[c] New land use type compared to the reference.

The food and cash production for the reference and two alternative practices of S1 and S2 for major crops are shown in Figure 4. Wheat represents the highest share of food production; this is in line with the latest study in Lebanon (Nasrallah et al., 2020) . The harvested area of wheat was increased in S2 in order to produce more food; this set-up led to the fulfilment of the food demand of the region. In terms of economic production, S2 yields slightly higher benefits compared to the current situation and S1 as a result of the growth in tobacco cultivation.

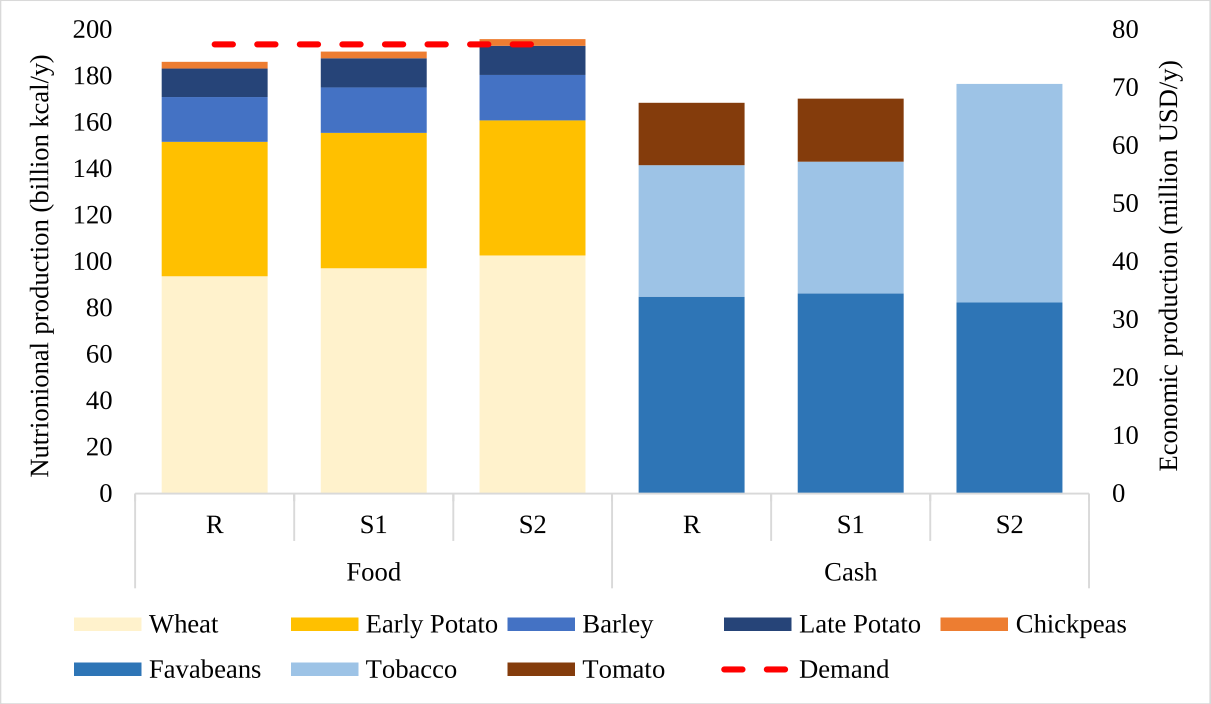
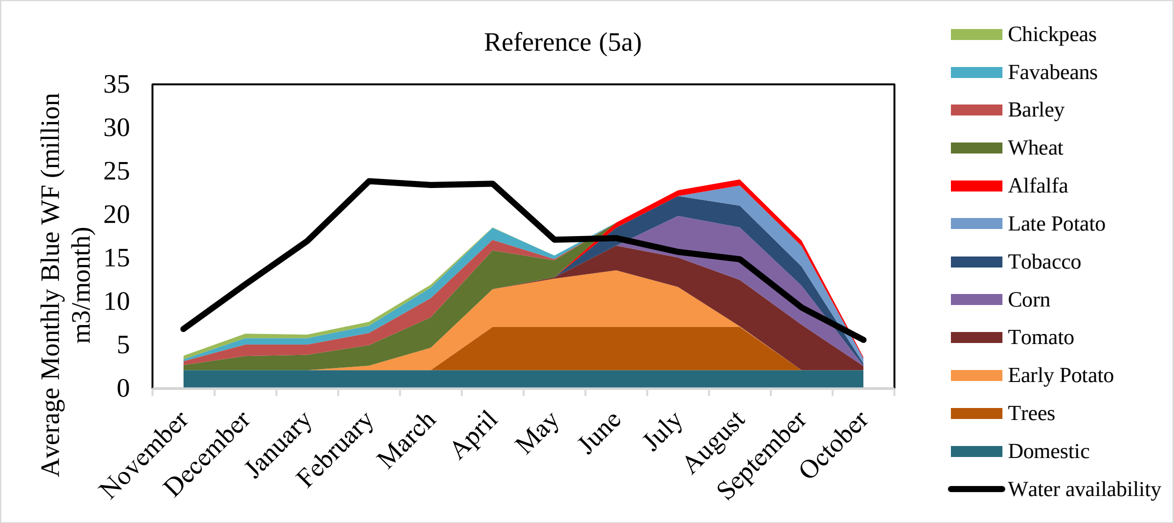
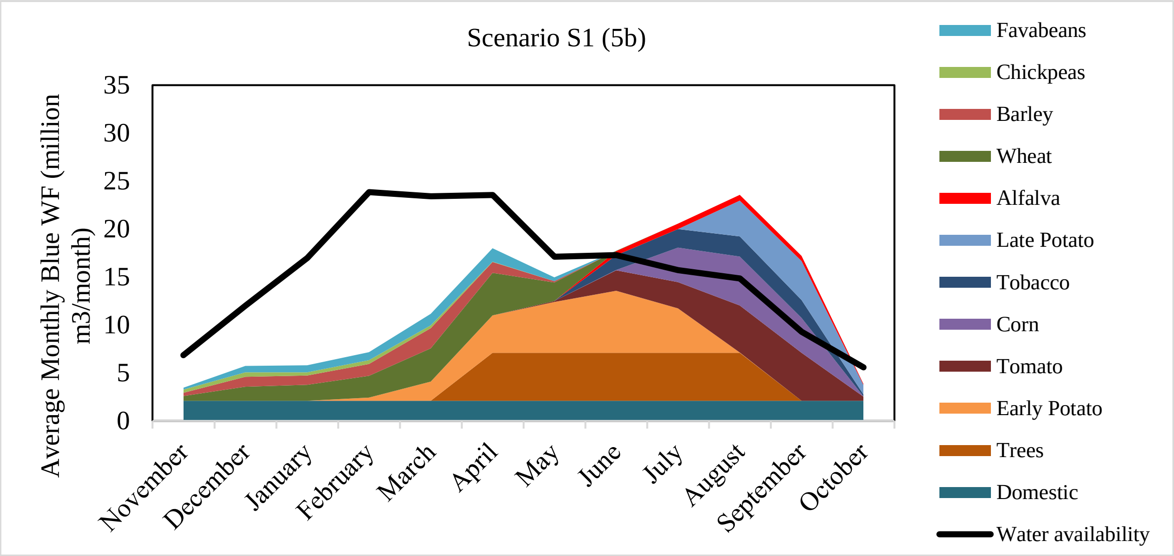


Figure 4. Food and cash production per crop type in the Upper Litani Basin in the reference (R), scenario S1 (mulching and drip irrigation), and scenario S2 (mulching and drip irrigation plus change in cropping pattern).

3.3. Blue water saving and water scarcity reduction

Figure 5 shows the average monthly blue WF of major crops and forestry and the domestic blue WF for the reference scenario, scenario S1 (mulching and drip irrigation) and scenario S2 (mulching and drip irrigation plus changing cropping pattern). The summer crops are irrigation dependent, while most winter crops are rainfed (Nasrallah et al., 2020). In S2, the low-value crops of corn, alfalfa and tomato were replaced with high-value crops of wheat (nutrient value) and tobacco (economic value). This change yielded a reduction in cultivation area during the dry summer and an increase in the harvested area during the wet winter. As shown in Figure 5, the change of cropping pattern in S2 reduces the blue WF in the summer months sufficiently to ensure that the blue WF remains below water availability, while in the reference scenario and S1, the blue WF in the summer months exceeds blue water availability. Details of the impact of different irrigation practices on each crop were lengthily discussed by (Nouri et al., 2019).





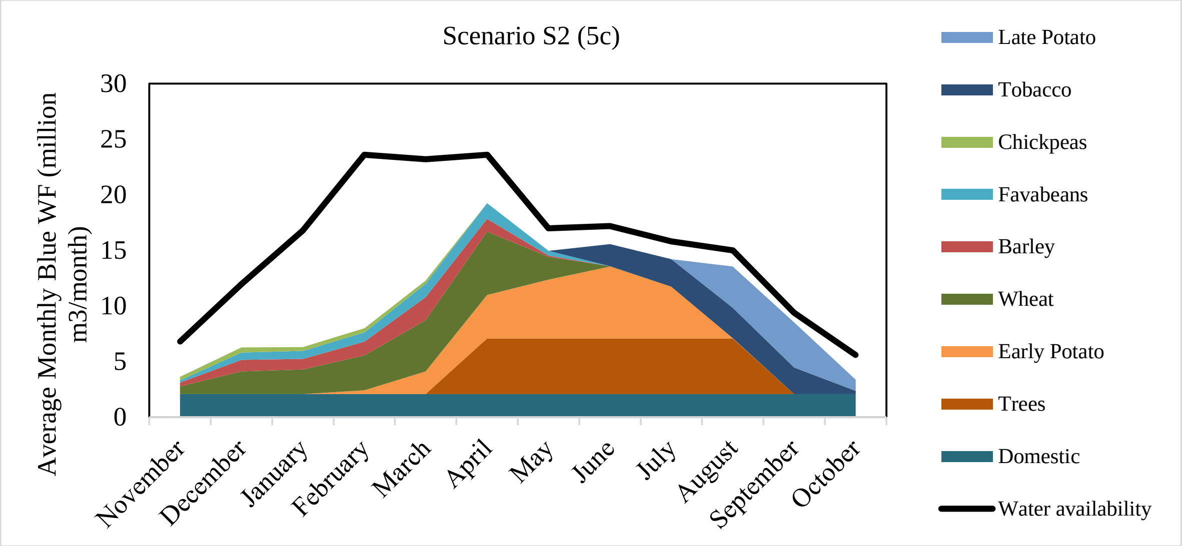


Figure 5. Average monthly blue WF versus water availability in the Upper Litani Basin in the reference (5a) and under scenario S1 - mulching and drip irrigation (5b) and scenario S2 - mulching and drip irrigation plus change in cropping pattern (5c). The black line presents the water availability of the ULB throughout the year.

Table 6 shows how scenarios S1 and S2 differ from the reference scenario in terms of the annual green and blue WF and the total nutritional and economic production of the region. Scenario S2 takes full benefit from the available green water resources in the ULB, while reducing the consumption of blue water resources. Mulching and drip irrigation (S1) result in a blue water saving of 8 million m^3/y. An additional change in cropping pattern (S2) results in a total blue water saving of 36 million m^3/y. The latter scenario also results in the highest nutritional and economic production.

Table 6. Annual green and blue WF, blue water saving, and crop production in the Upper Litani Basin for the reference and two scenarios.

Annual WF and crop production	**Reference**	**Scenario S1**	**Scenario S2**
Green WF (million m^3/y)	47	48	71
Blue WF (million m^3/y)	177	169	141
Blue water saving (million m^3/y)	-	8	36

Nutritional production (billion kcal/y)	186	190	196
Economic production (million US$/y)	67	68	102

Average blue water scarcity per month in the reference and scenarios S1 and S2 is presented in Table 7. In the reference and in scenario S1, the blue water footprint exceeds blue water availability for four months per year. This means that the ULB faces moderate to severe water scarcity in summer with the current cropping pattern and crop calendar, no matter what mulching practice or irrigation technique is used. Through a changed cropping pattern as in S2, low water scarcity is achieved throughout the year, with the blue water footprint remaining below the threshold of maximum water availability.

Table 7. Monthly blue water scarcity in the Upper Litani Basin in the reference scenario and the two scenarios.

Scenario	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Reference	0.60	0.60	0.42	0.37	0.60	0.88	1.00	1.25	1.64	1.83	2.13	0.70
Scenario **S1**	0.55	0.54	0.39	0.35	0.56	0.85	0.97	1.15	1.47	1.79	2.15	0.76
Scenario **S2**	0.58	0.59	0.43	0.39	0.62	0.92	0.97	1.00	0.99	0.99	1.00	0.65

Green-coloured months have low scarcity (≤1.0); yellow-coloured months have moderate water scarcity (1.0-1.5); orange-coloured months have significant water scarcity (1.5-2); red-coloured months have severe water scarcity (>2.0).

4. Conclusion

This research investigated the impact of changes in management practice and the cropping pattern on the annual green and blue WF, blue water saving, water scarcity, and food and economic production in the Upper Litani Basin in Lebanon. The existing situation was compared with two scenarios: organic mulching and drip irrigation (S1) and cropping pattern change in addition to mulching and drip irrigation (S2). Our results show that implementing mulching and drip irrigation will have a minor impact on the annual green and blue WF, blue water saving, water scarcity, and food and economic production compared to the significant positive impact of changing the cropping pattern. Mulching and drip irrigation together could increase green WF by 2.1%, decrease blue WF by 4.5% and increase food and economic production by 2.1% and 1.5%, respectively, compared to the current situation, while a change in cropping pattern could increase green WF by 51%, decrease blue WF by 20.3% and increase food and economic production by 3% and 50%, respectively.

This research demonstrates the potential of changing the cropping pattern in enhancing water and food security in a semi-arid region. Also, this promotes a plant-based diet and encourages taking half of the required daily calorie from food crops; this is in line with the Food-Based Dietary Guideline (FBDG) manual to promote healthy eating in Lebanon (Bahn et al., 2018).

The outcome of this study showed that careful consideration is needed in development and implementation of alternative agricultural management practices with food and water security purposes. No optimal scenario can be found to work for all basins; local studies are needed to evaluate possible scenarios and their potential impacts on water and food resources considering their environmental, social and economic impacts. This study can help policy makers, water managers and farmers for the sustainable management of water resources as one of main drivers of food security.

In terms of future development, the outcomes of this paper and the coupled paper by this team (Nouri et al., 2019) will further investigate the economic perspective of water footprint reduction under adaptive management practices in the case of mulching, drip irrigation and crop redistribution scenarios. Further investigation is needed to consider virtual water trade of the region and better understand trade-offs between a certain level of food self-sufficiency and local water saving. Also, the robustness of changing the cropping pattern under climate change needs to be studied.

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References

Ali, T., Huang, J., Wang, J., Xie, W. (2017) Global footprints of water and land resources through China's food trade. Global Food Security 12, 139-145.

Bahn, R.A., Nisr, R., El Labban, S., (2018) Food Policy in Lebanon, Reference Module in Food Science. Elsevier.

Belloumi, M., Matoussi, M.S. (2008) Water Scarcity Management in the MENA Region from a Globalization Perspective. Development 51, 135-138.

Chukalla, A.D., Krol, M.S., Hoekstra, A.Y. (2015) Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching. Hydrol. Earth Syst. Sci. 19, 4877-4891.

Davis, K., Seveso, A., Rulli, M., D'Odorico, P. (2017a) Water Savings of Crop Redistribution in the United States. Water 9, 83.

Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P. (2017b) Increased food production and reduced water use through optimized crop distribution. Nature Geoscience 10, 919-924.

DFC, (2017) Nutritional tables, Dutch Food Centre. the Netherlands.

Dixon, J., Gulliver, A., Gibbon, D., (2001) Farming Systems and Poverty - Improving Farmers' Livelihoods in a Changing World, in: Food and Agriculture Organization of the United Nations (FAO) (Ed.), Rome, Italy.

FAO, (2003) Trade reforms and food security: Conceptualizing the linkages in: Food and Agriculture Organization of the United Nations (Ed.), Rome, Italy.

FAO, (2017a) AquaCrop - Reference Manual. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, (2017b) The future of food and agriculture – Trends and challenges., in: Food and Agriculture Organization of the United Nations (FAO) (Ed.), Rome, Italy.

Fasakhodi, A., Nouri, S.H., Amini, M. (2010) Water Resources Sustainability and Optimal Cropping Pattern in Farming Systems; A Multi-Objective Fractional Goal Programming Approach. Water Resources Management 24, 4639-4657.

Foster, T., Brozović, N., Butler, A.P., Neale, C.M.U., Raes, D., Steduto, P., Fereres, E., Hsiao, T.C. (2017) AquaCrop-OS: An open source version of FAO's crop water productivity model. Agricultural Water Management 181, 18-22.

Godfray, H.C.J., Garnett, T. (2014) Food security and sustainable intensification. Philosophical transactions of the Royal Society of London. Series B, Biological sciences 369, 20120273-20120273.

Haouari, M., Azaiez, M.N. (2001) Optimal cropping patterns under water deficits. European Journal of Operational Research 130, 133-146.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M. (2011) The water footprint assessment manual: Setting the global standard. Earthscan, London, UK

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D. (2012) Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability. PLOS ONE 7, e32688.

Huang, J., Ridoutt, B.G., Xu, C.-c., Zhang, H.-l., Chen, F. (2012) Cropping Pattern Modifications Change Water Resource Demands in the Beijing Metropolitan Area. Journal of Integrative Agriculture 11, 1914-1923.

Kummu, M., Guillaume, J.H.A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., Siebert, S., Veldkamp, T.I.E., Ward, P.J. (2016) The world’s road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Scientific Reports 6, 38495.

Matthews, R.B., Rivington, M., Muhammed, S., Newton, A.C., Hallett, P.D. (2013) Adapting crops and cropping systems to future climates to ensure food security: The role of crop modelling. Global Food Security 2, 24-28.

Mekonnen, M.M., Hoekstra, A.Y. (2016) Four billion people facing severe water scarcity. Science Advances 2, e1500323.

Mourad, R., Jaafar, H.H., Daghir, N. (2019) New estimates of water footprint for animal products in fifteen countries of the Middle East and North Africa (2010–2016). Water Resources and Industry 22, 100113.

Nakawuka, P., Langan, S., Schmitter, P., Barron, J. (2018) A review of trends, constraints and opportunities of smallholder irrigation in East Africa. Global Food Security 17, 196-212.

Nasrallah, A., Belhouchette, H., Baghdadi, N., Mhawej, M., Darwish, T., Darwich, S., Faour, G. (2020) Performance of wheat-based cropping systems and economic risk of low relative productivity assessment in a sub-dry Mediterranean environment. European Journal of Agronomy 113, 125968.

Nouri, H., Stokvis, B., Galindo, A., Blatchford, M., Hoekstra, A.Y. (2019) Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation. Science of The Total Environment 653, 241-252.

Osama, S., Elkholy, M., Kansoh, R.M. (2017) Optimization of the cropping pattern in Egypt. Alexandria Engineering Journal 56, 557-566.

Quemada, M., Gabriel, J.L. (2016) Approaches for increasing nitrogen and water use efficiency simultaneously. Global Food Security 9, 29-35.

Ramadan, H.H., Beighley, R.E., Ramamurthy, A.S. (2012) Modelling streamflow trends for a watershed with limited data: case of the Litani basin, Lebanon. Hydrological Sciences Journal 57, 1516-1529.

Ramadan, H.H., Beighley, R.E., Ramamurthy, A.S. (2013) Sensitivity analysis of climate change impact on the hydrology of the Litani Basin in Lebanon. International Journal of Environment and Pollution 52, 65-81.

Schyns, J.F., Hoekstra, A.Y. (2014) The Added Value of Water Footprint Assessment for National Water Policy: A Case Study for Morocco. PLOS ONE 9, e99705.

Shaban, A., Telesca, L., Darwich, T., Amacha, N. (2014) Analysis of long-term fluctuations in stream flow time series: An application to Litani River, Lebanon. Acta Geophysica 62, 164-179.

Skaf, L., Buonocore, E., Dumontet, S., Capone, R., Franzese, P.P. (2019) Food security and sustainable agriculture in Lebanon: An environmental accounting framework. Journal of Cleaner Production 209, 1025-1032.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., (2012) FAO Irrigation and drainage paper 66 - Crop yield response to water - AquaCrop parameterization, calibration, and validation guide, in: Nations, F.a.A.O.o.t.U. (Ed.), Rome, Italy.

Sun, S.K., Wu, P.T., Wang, Y.B., Zhao, X.N. (2014) Impact of changing cropping pattern on the regional agricultural water productivity. The Journal of Agricultural Science 153, 767-778.

Tilman, D., Balzer, C., Hill, J., Befort, B.L. (2011) Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences 108, 20260-20264.

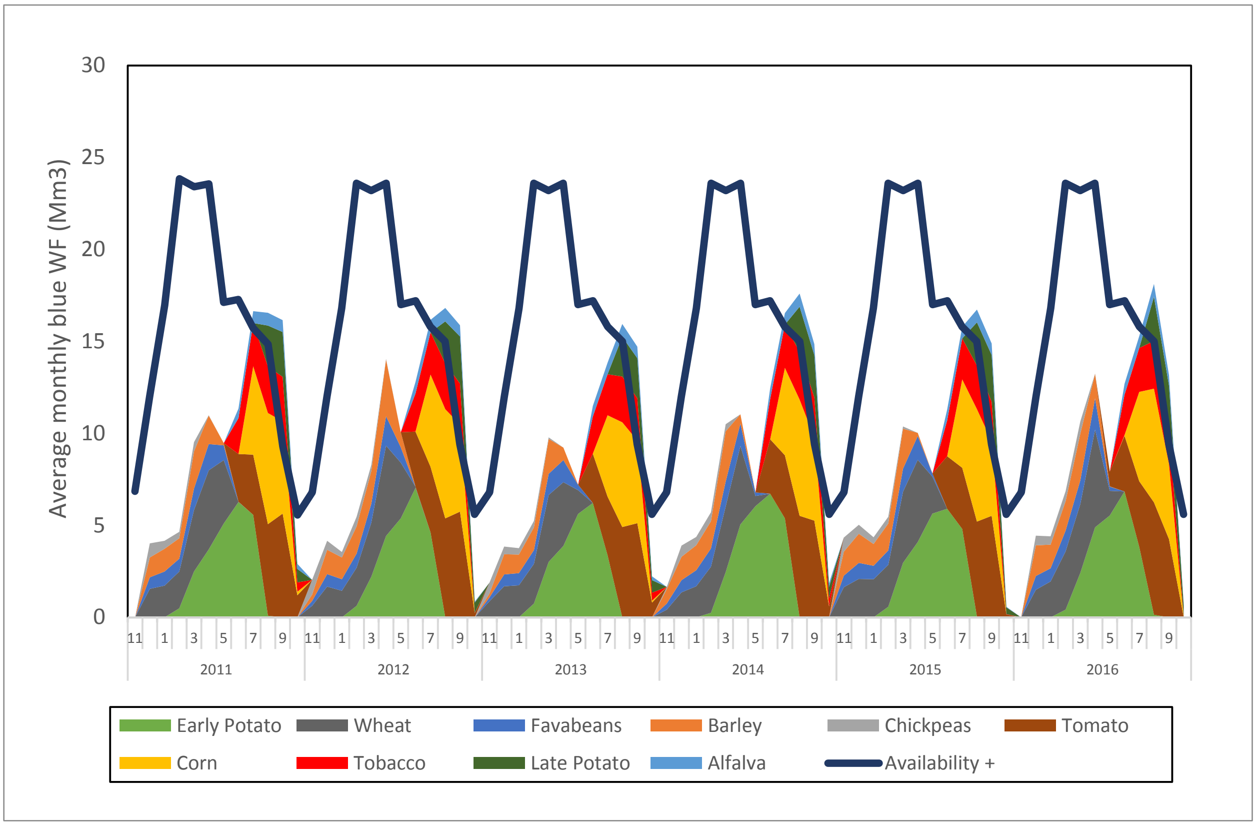
UNHCR, (2017) Vulnerability Assessment of Syrian Refugees in Lebanon: VASYR 2017, World Food Programme (WFP): Beirut., in: United Nations High Commissioner for Refugees (UNHCR), U.N.C.s.F.U.a.W.F.P.W. (Ed.). United Nations High Commissioner for Refugees (UNHCR), United Nations Children’s Fund (UNICEF) and World Food Programme (WFP), Rome, Italy.

USAID, (2014) Litani River Basin Management Support; Project completion report. United States Agency for International Development, Washington, USA.

Wang, Y.B., Wu, P.T., Engel, B.A., Sun, S.K. (2014) Application of water footprint combined with a unified virtual crop pattern to evaluate crop water productivity in grain production in China. Science of The Total Environment 497-498, 1-9.

Zhang, C., McBean, E.A., Huang, J. (2014) A Virtual Water Assessment Methodology for Cropping Pattern Investigation. Water Resources Management 28, 2331-2349.

Appendix



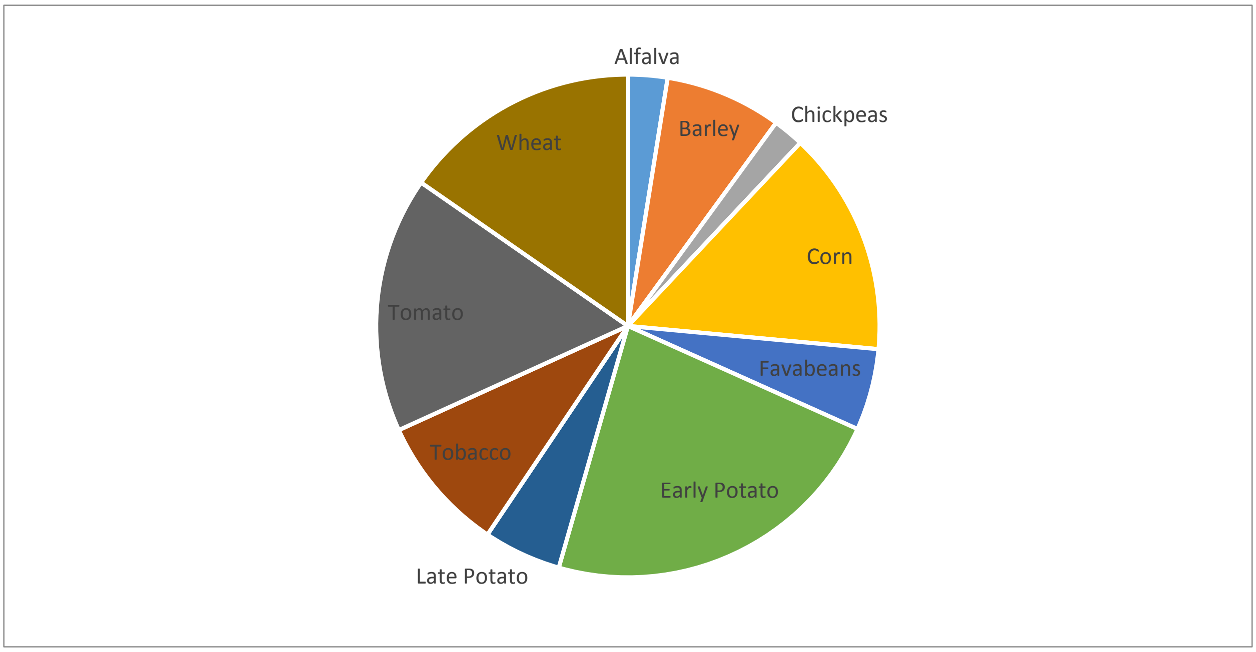


Figure A-1. Crop contribution in the blue water consumption of the ULB in current practice (Reference scenario) on a monthly basis (2011-2016)