

Article

Irrigation and Agricultural Opportunities: Evaluating Hemp (*Cannabis sativa* L.) Suitability and Productivity in Lebanon

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Abstract: Within the prevalent challenges posed by climate change and decreasing resources, this research underscores the importance of adopting sustainable agricultural practices combined with efficient water resource management. Employing comprehensive climate and soil suitability analyses, this research analyzed the capacity of hemp (*Cannabis sativa* L.) to adapt to Lebanon's heterogeneous environmental landscapes across two distinct growing seasons (autumn and spring). Both climate and edaphic suitability mapping were conducted to study hemp's suitability. AquaCrop v.7.1 was used to simulate seed yield, biomass production, irrigation needs and yield water productivity in the different agro-homogeneous zones of Lebanon for the two considered seasons. The findings revealed that approximately 30% and 19% of Lebanon's land exhibit suitability for hemp cultivation during the spring and autumn seasons, respectively. According to AquaCrop model simulations, under the prevailing climatic conditions, the predicted seed yield will range from 3.7 to 5.6 t ha⁻¹ under rainfed conditions and will reach 11.1 t ha⁻¹ for irrigated cultivation. Moreover, employing efficient irrigation techniques during the spring season showed a significant improvement in both yield and biomass of hemp. The enhancement was evident, with notable increases of 112.22% in yield and 96.43% in biomass compared to rainfed conditions. This research highlights the importance of identifying suitable regions within Lebanon capable of supporting hemp cultivation in a sustainable manner. Such research not only promises economic development but also aligns with broader global sustainability objectives.

Keywords: agro-homogeneous zone; suitability mapping; AquaCrop; water productivity



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1. Introduction

In the face of escalating challenges posed by climate change and the increasing scarcity of natural resources, there has been a growing emphasis on the adoption of bioeconomically sustainable practices in agriculture. This shift is particularly crucial when considering the effective use of water resources, a vital component of agricultural ecosystems. Researchers such as Chartzoulakis et al. [1] and Patle et al. [2] have underlined the crucial role of sustainable water management in agriculture. They advise enhancing water-use efficiency through the implementation of advanced irrigation technologies and adaptive measures. O'Neill and Dobrowolski [3] and Sapkota [4] have further emphasized the urgency of

improved water management strategies in response to a changing climate. These authors highlighted the importance of trans-disciplinary approaches and explored the potential of unconventional water sources, such as reclaimed or recycled water, in mitigating water scarcity in agriculture.

In this context, hemp (*Cannabis sativa* L.) is considered a promising crop for sustainable agriculture owing to its remarkable versatility and wide-ranging bioeconomic applications. The environmental consequences of hemp cultivation have drawn increased attention, with assessed impacts related to land cover change, water use, pesticide utilization, energy consumption, and air pollution [5,6]. Despite the recognition of these issues, the quasi-legal status of cannabis has posed a substantial obstacle to comprehensive research in this domain [7]. This legal ambiguity has resulted in a paucity of reliable data and a fragmented understanding of the environmental footprint of hemp cultivation.

Among the challenges posed by its ambiguous legal status, there is a pressing need to identify regions providing sustainable hemp production. Such a pursuit holds the potential to not only alleviate expenses for cultivators but also elevate the overall quality of hemp products and foster positive impacts on local economies [5]. This requires a thorough assessment of the environmental implications associated with hemp cultivation, a task complicated by the scarcity of data [6].

Lebanon prohibited the cultivation, sale, and consumption of hemp and hemp-related items for any reason until 22 April 2020 [8]. After decades of debate and controversy, the Lebanese parliament decided in April 2020 to legalize the cultivation, manufacturing, and sale of hemp for medical reasons [9]. In Lebanon, cultivation of hemp could constitute an opportunity for sustainable development while creating potential economic development. It could actively stimulate the Lebanese economy [10]. In this country, there are very few studies on hemp cultivation. For example, Sleiman et al. [11] and Al Khoury et al. [12] have studied the agronomic characteristics and the antioxidant effect of Lebanese hemp; however, there are still no studies on the potential suitability of this crop to grow and provide yields under the different agro-homogeneous zones of the country.

Within the ambit of this overarching framework, the primary objective of this study was to assess the suitability of various agro-homogeneous zones in Lebanon for hemp cultivation, taking into account two distinct growing seasons (autumn and spring). This investigation considered crucial factors such as crop yield, biomass production, irrigation needs, and water productivity. This study provided insights that can help with strategic decisions about hemp cultivation, promoting sustainable practices and optimizing its environmental impact. This research represents a significant step toward fostering a more informed and conscientious approach to hemp cultivation, aligning it with the broader global agenda of achieving sustainable agriculture and mitigating the challenges posed by a changing climate and dwindling natural resources.

2. Materials and Methods

2.1. Study Area

All regions of Lebanon were considered in this study. The areas of no interest, such as urban areas, forest cover, water bodies, etc. were all masked.

Lebanon is characterized by hot, dry summers and cool, moist winters. There are 360,000 hectares of arable agricultural lands in Lebanon. This comprises 35% of the country's surface area [13]. The greatest concentration of agricultural lands is located in the Bekaa Valley (42% of the total cultivated area), followed by Northern Lebanon (26%), Southern Lebanon (22%), and Mount Lebanon (9%). These lands grow a wide variety of crops. Thirty-one percent of total agricultural production are fruit trees, 23% are olives, 20% are cereals, 17% are vegetables, and the remaining nine percent are industrial crops, like tobacco, grape vineyards, and others [13]. In this country, the agricultural zones are organized according to the Agriculture Homogeneous Zoning (AHZ) method [14], as represented in Figure 1. The description of the different AHZs are provided in Table S1.



Figure 1. The Agricultural Homogeneous Zones of Lebanon.

2.2. Assessment of the Suitability of the Agro-homogeneous Zones of Lebanon for Hemp Growing

Both climate and edaphic suitability mapping were conducted to study hemp suitability by considering an index from 0 to 100 describing the degree of adaptability of a crop in each environment. This scale was then converted to standard land suitability classes (highly suitable, suitable, etc.) as provided in [15] and based on the agro-ecological zoning approach [16]. Agro-ecological requirements for individual crops were extracted from FAO EcoCrop [17] (Table S2) as provided in [18]. A Geographic Information System was used to process all of the needed mapping.

2.2.1. Climate Suitability

Monthly climate layers of temperature and rain at 1 km spatial resolution were downloaded from the WorldClim dataset [19]. The datasets correspond to weather averages (1970–2000) in geospatial formats allowing the performance of the suitability analysis at a national level. The downloaded layers were used to produce climate suitability maps

for two possible calendar year seasons: autumn (November to April) and spring (April to October).

The temperature and rain suitability indices were calculated using the following formulas, as reported in [15]. Particularly, the monthly temperature suitability index (T_{mi}) was first calculated as follows:

$$T_{mi} = \left\{ \begin{aligned} &0 \quad T_{ai} < T_{Amin} \quad \frac{T_{ai} - T_{Amin}}{T_{Omin} - T_{Amin}} \times 100 \quad T_{Amin} < T_{ai} < T_{Omin} \quad 100 \quad T_{Omin} < T_{ai} \\ &< T_{Omax} \quad \left(1 - \frac{T_{ai} - T_{Omax}}{T_{Amax} - T_{Omax}}\right) \times 100 \quad T_{Omax} < T_{ai} < T_{Amax} \quad 0 \quad T_{ai} > T_{Amax} \end{aligned} \right\} \quad (1)$$

where T_{ai} is the average monthly temperature for the location i , T_{Amin} and T_{Amax} are the marginal or absolute temperature averages for a species to survive, and T_{Omin} and T_{Omax} are the optimal minimum and maximum temperature averages for the species to grow and produce yield based on the FAO EcoCrop database.

Then, for each considered season, the seasonal temperature suitability for a crop was the minimum of all monthly indices that fall within the season s :

$$TS_{si} = \min(T_{m1i}, T_{m2i}, \dots, T_{mn_i}) \quad (2)$$

where TS_{si} is the total temperature suitability for season s at location i .

Finally, the rain suitability index was calculated by aggregating the monthly rain for each season using the following two formulas [15]:

$$R_{si} = \text{sum}(R_{m1i}, R_{m2i}, \dots, R_{mn_i}) \quad (3)$$

$$RS_{si} = \left\{ \begin{aligned} &0 \quad R_{si} < R_{Amin} \quad \frac{R_{si} - R_{Amin}}{R_{Omin} - R_{Amin}} \times 100 \quad R_{Amin} < R_{si} < R_{Omin} \quad 100 \quad R_{Omin} < R_{si} \\ &< R_{Omax} \quad \left(1 - \frac{R_{si} - R_{Omax}}{R_{Amax} - R_{Omax}}\right) \times 100 \quad R_{Omax} < R_{si} < R_{Amax} \quad 0 \quad R_{si} > R_{Amax} \end{aligned} \right\} \quad (4)$$

where R_{si} is the sum of rainfall (R_{mi}) for season s at location i and R_{Amin} , R_{Omin} , R_{Omax} , and R_{Amax} are the rainfall requirements for marginal and optimal conditions in millimetres/season based on data provided by the FAO EcoCrop database.

The climate suitability map obtained for each season corresponds to the average of the temperature and rain suitability indices layers.

2.2.2. Edaphic Suitability

Soil data were acquired from the SoilGrids global dataset, which provides gridded data based on a database of 150,000 soil profiles and physically based covariates including geomorphological data and global datasets of satellite images at 250 m spatial resolution [20]. Data on soil texture and pH were considered. Soil texture was defined using qualitative variables that are “light”, “medium”, and “heavy” as provided in the FAO EcoCrop database. This information was used to prespecify the soil texture in the form of % sand and % clay using known soil texture classifications [21]. The equation for deriving the texture index was as provided [15]:

$$\begin{aligned} TSTS_i &= \{100 \quad C_{ot} = \text{heavy} \text{ AND } SND_i < 65 \quad 100 \quad C_{ot} = \text{medium} \text{ AND } SND_i < 52 \text{ OR } CLY_i < 27 \quad 100 \quad C_{ot} \\ &= \text{light} \text{ AND } CLY_i < 15 \quad 25 \text{ else} \} \end{aligned} \quad (5)$$

where C_{ot} is the optimal soil texture required for a given crop. Soil texture was considered as a function of the SND_i and CLY_i variables, which are the relative presence of sand and clay particles, respectively.

A pH suitability index was calculated by defining optimal and suboptimal conditions for plant growth [15]:

$$pHS_i = \left\{ \begin{aligned} &0 \quad pH_i < pH_{Amin} \quad \frac{pH_i - pH_{Amin}}{pH_{Omin} - pH_{Amin}} \times 100 \quad pH_{Amin} < pH_i < pH_{Omin} \quad 100 \quad pH_{Omin} < pH_i \\ &< pH_{Omax} \quad \left(1 - \frac{pH_i - pH_{Omax}}{pH_{Amax} - pH_{Omax}}\right) \times 100 \quad pH_{Omax} < pH_i < pH_{Amax} \quad 0 \quad pH_i > pH_{Amax} \end{aligned} \right\} \quad (6)$$

The final edaphic suitability map was produced as the average of the soil texture and pH layers.

Finally, two hemp suitability maps were created by considering the average of the climate and edaphic suitability maps: one for autumn and another one for spring. Then, a Land Cover Land Use map for Lebanon for year 2020, extracted from the FAO-WAPOR portal [22], was used to mask the areas of no interest, such as urban areas, forest cover, and water bodies.

2.3. Simulations with AquaCrop

AquaCrop v.7.1 was used to simulate the hemp seed yield, biomass production, irrigation needs, and yield water productivity in the different agro-homogeneous zones of Lebanon for the two considered seasons. AquaCrop is a crop water productivity model developed by the Food and Agricultural Organization (FAO) that is able to simulate the response to water of herbaceous crops [23,24]. The model requires input data on the climate, crop, and soil conditions. In this study, the crop parameters used for hemp were the same as those calibrated and validated by other authors [18,25–31]. The crop parameters are provided in Table 1. Daily weather data from the ESA Copernicus AgERA5 database [32] were obtained for 10 years (2010–2019). It consisted of daily rainfall, temperature, and solar radiation data collected at 0.1 degree resolution and downloaded for each agro-homogeneous zone. Yield maps were generated using a Geographic Information System (GIS) by the ordinary kriging interpolation method based on the agro-homogeneous zones locations.

Table 1. AquaCrop input parameters for *Cannabis sativa* L.

Parameter	Description	Value
Tbase	Base temperature (°C)	1.5 ¹
Tupper	Cut-off temperature (°C)	40.0 ¹
CCx	Maximum canopy cover (%)	90 ¹
Zr min	Minimum rooting depth (m)	0.3
Canopy growth coefficient (CGC)	Increase in canopy cover (fraction soil cover per day)	0.1115
Canopy decline coefficient (CDC)	Decrease in canopy cover (fraction soil cover per day)	0.09615
Calendar days: from sowing to flowering		89
Calendar days: from sowing to emergence		10
Calendar days: from sowing to maximum rooting depth		60
Calendar days: from sowing to start of senescence		105
Calendar days: from sowing to maturity		150
Length of the flowering stage (days)		12
Build-up of harvest index (HI) starting at sowing		90
Length of HI build-up		15
Normalized water productivity (g m ^{−2})		15
HI (%)		18
Positive effect of HI as result of limited growth in vegetative period		Moderate
Positive effect of HI as result of water stress affecting leaf expansion		Moderate
Water stress during flowering (p-upper)		0.9
Negative effect on HI as a result of water stress inducing stomatal closure		Strong
Aeration stress		Sensitive
Plant population (plants ha ^{−1})		140,000

Note: ¹ Amaducci et al. [32].

3. Results

The overall suitability maps for hemp cultivation are presented in this part. In addition to the seasonal rain and reference evapotranspiration (ET_o), seed yield, biomass, normalized water productivity, and irrigation needs for the autumn and spring seasons in the different agro-homogeneous zones of Lebanon are shown using Aquacrop simulations.

3.1. Hemp Suitability Maps

The layers representing rainfall, temperature, and soil suitability are provided in Figures S1–S4 in the Supplementary Materials. During the autumn season, the climate predominantly favors hemp cultivation in terms of total seasonal rainfall, even if not in terms of temperature (except for some coastal areas and southern regions of the country as shown in Figure S2). Conversely, in the spring season, while total seasonal rainfall presents a limiting factor, temperature conditions are favorable across many parts of the country. Therefore, the viability of planting hemp in the spring depends largely on effective irrigation practices. The soil suitability for hemp cultivation ranges from suitable to highly suitable in numerous regions, primarily due to the prevalence of medium to friable soils in Lebanon, which are suitable for hemp growth.

The overall suitability maps for the cultivation of hemp in the autumn and spring seasons in Lebanon are presented in Figure 2.

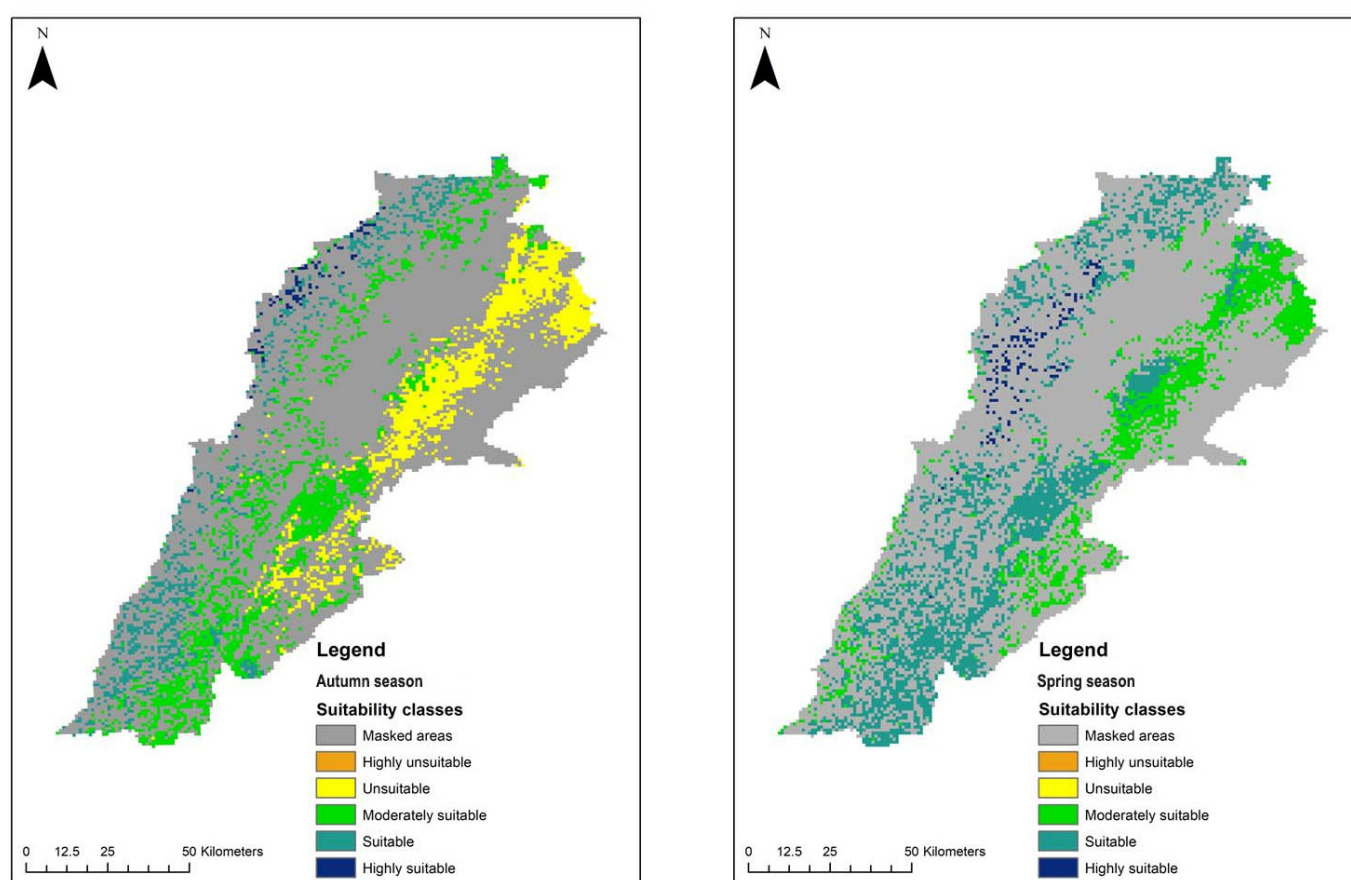


Figure 2. Overall suitability map for *Cannabis sativa* L. grown in autumn (on the left) and spring seasons (on the right) in Lebanon.

Tables 2 and 3 provide the percentage distribution of areas within the agro-homogeneous zones (AHZ) classified into different suitability classes for the autumn and spring seasons, respectively. According to this evaluation, approximately 30% of Lebanon's territory holds potential for hemp cultivation. In autumn, 1% of the total land is deemed highly suitable (suitability index > 80%), 5% is suitable (suitability index 60–80%), 13% is moderately suitable (40–60%), while the remaining 11% is considered permanently unsuitable for hemp cultivation. In spring, 1% of the total land is highly suitable, 18% is suitable, and 11% is moderately suitable. In certain regions such as the coastal plains of Lebanon, it may be possible to cultivate hemp across multiple seasons.

Table 2. The percentage distribution of areas with a potential for *Cannabis sativa* L. cultivation in the agro-homogeneous zones (AHZ) in relation to the different suitability classes for autumn.

Autumn Season			% Areas with Suitability Class						
Agro-Homogeneous Zones (AHZ)			Total Area (ha)	Areas of No Interest (%)	Highly Unsuitable	Unsuitable	Moderately Suitable	Suitable	Highly Suitable
Mohafaza	Code	Description							
North Lebanon	30	Olive zone in Tripoli	16,818	83	0	0	2	13	4
	31	Fruit trees zone of Danniyeh	29,191	85	0	0	11	3	0
	32	Olive zone in Batroun-Koura	32,860	81	0	0	3	9	8
	33	Mountainous zone of North Lebanon	35,588	91	0	0	8	1	0
	10	Coastal zone of Jbeil	19,577	83	0	0	4	9	4
Mount Lebanon	11	Mountainous zone of Northern Mount Lebanon	65,404	90	0	0	9	0	0
	12	Coastal zone of Northern Mount Lebanon	16,907	95	0	0	2	4	1
	13	Coastal zone of Central Mount Lebanon	24,085	80	0	0	6	11	1
	14	Mountainous Central Mount Lebanon	26,447	71	0	1	23	2	0
	15	Iqlim El Kharroub	15,207	81	0	0	4	13	0
	16	Mountainous zone of Chouf	27,942	69	0	0	27	3	0
South Lebanon	60	Plain of Saida	15,842	72	0	0	2	24	0
	61	Plateau of Saida	11,323	64	0	0	1	40	0
	62	Jezzine	23,609	64	0	0	28	9	0
	63	Plain of Sour	18,037	77	0	0	2	21	0
	64	Plateau of Sour	21,783	62	0	0	14	22	0
Nabatiye	70	Nabatiye	42,571	50	0	0	32	18	0
	71	Iqlim El Teffah	5755	58	0	0	31	4	0
	72	Marjeyoun/Hasbaya	35,895	59	0	2	30	7	0
	73	Bent Jbeil	23,663	43	0	0	51	2	0
Bekaa	50	Mountainous zone of Zahle	15,222	76	0	6	14	0	0
	51	Plain of Zahle	15,105	38	0	23	41	0	0
	52	Eastern watershed of Litani	18,198	69	0	20	12	0	0
	53	Western watershed of Litani	16,885	56	0	10	34	0	0
	54	Rachaya	51,226	69	0	20	9	0	0
	55	Plain of Litani	16,416	36	0	8	59	0	0
	56	Sohmor	6097	49	0	17	30	0	0
Baalbek El Hermel	40	Western watershed of Orontes	60,278	87	0	0	11	2	0
	41	Northern plain of Orontes	36,437	35	0	63	6	0	0
	42	Southern plain of Orontes	12,117	60	0	40	0	0	0
	43	Deir El Ahmar	18,633	76	0	14	10	0	0
	44	Eastern watershed of Orontes	37,821	73	0	26	0	0	0
	45	Baalbek	40,373	51	0	42	6	0	0
	46	Chaat and Younine	29,831	63	0	37	0	0	0
	47	Britel	25,352	91	0	8	0	0	0
	48	Bednayel	18,332	72	0	26	2	0	0

Table 2. Cont.

Autumn Season			% Areas with Suitability Class						
Agro-Homogeneous Zones (AHZ)			Total Area (ha)	Areas of No Interest (%)	Highly Unsuitable	Unsuitable	Moderately Suitable	Suitable	Highly Suitable
Mohafaza	Code	Description							
Aakkar	20	Plain of Aakkar and Minieh	13,821	83	0	0	1	11	6
	21	Plateau of Aakkar	23,256	69	0	0	4	25	0
	22	Fruit trees zone in Aakkar	21,608	71	0	0	25	4	0
	23	Qobayyat zone	18,524	64	0	3	28	4	0
All Lebanon			1,004,082	70	0	11	13	5	1

Table 3. The percentage distribution of areas with a potential for *Cannabis sativa* L. cultivation in the agro-homogeneous zone (AHZ) in relation to the different suitability classes for spring.

Spring Season			% Areas with Suitability Class						
Agro-Homogeneous Zones (AHZ)			Total Area (ha)	AHZ_Areas of No Interest (%)	Highly Unsuitable	Unsuitable	Moderately Suitable	Suitable	Highly Suitable
Mohafaza	Code	Description							
North Lebanon	30	Olive zone in Tripoli	16,818	83	0	0	2	14	1
	31	Fruit trees zone of Danniyeh	29,191	85	0	0	1	10	3
	32	Olive zone in Batroun-Koura	32,860	81	0	0	1	16	2
	33	Mountainous zone of North Lebanon	35,588	91	0	0	1	5	3
	10	Coastal zone of Jbeil	19,577	83	0	0	2	5	10
Mount Lebanon	11	Mountainous zone of Northern Mount Lebanon	65,404	90	0	0	1	4	5
	12	Coastal zone of Northern Mount Lebanon	16,907	95	0	0	2	2	1
	13	Coastal zone of Central Mount Lebanon	24,085	80	0	0	3	16	1
	14	Mountainous of Central Mount Lebanon	26,447	71	0	0	1	27	0
	15	Iqlim El Kharroub	15,207	81	0	0	5	14	0
	16	Mountainous zone of Chouf	27,942	69	0	0	1	30	0
	60	Plain of Saida	15,842	72	0	0	15	13	0
South Lebanon	61	Plateau of Saida	11,323	64	0	0	3	33	0
	62	Jezzine	23,609	64	0	0	0	36	0
	63	Plain of Sour	18,037	77	0	0	13	11	0
	64	Plateau of Sour	21,783	62	0	0	6	31	0
Nabatiye	70	Nabatiye	42,571	50	0	0	1	49	0
	71	Iqlim El Teffah	5755	58	0	0	1	40	1
	72	Marjeyoun/Hasbaya	35,895	59	0	0	3	38	0
	73	Bent Jbeil	23,663	43	0	0	1	56	0
Bekaa	50	Mountainous zone of Zahle	15,222	76	0	0	4	20	0
	51	Plain of Zahle	15,105	38	0	0	12	50	0
	52	Eastern watershed of Litani	18,198	69	0	0	19	12	0
	53	Western watershed of Litani	16,885	56	0	0	2	43	0
	54	Rachaya	51,226	69	0	0	28	3	0
	55	Plain of Litani	16,416	36	0	0	6	57	0
	56	Sohmor	6097	49	0	0	2	49	0

Table 3. Cont.

Spring Season			% Areas with Suitability Class						
Agro-Homogeneous Zones (AHZ)			Total Area (ha)	AHZ_Areas of No Interest (%)	Highly Unsuitable	Unsuitable	Moderately Suitable	Suitable	Highly Suitable
Mohafaza	Code	Description							
Baalbek El Hermel	40	Western watershed of Orontes	60,278	87	0	0	10	3	0
	41	Northern plain of Orontes	36,437	35	0	0	53	12	0
	42	Southern plain of Orontes	12,117	60	0	0	37	3	0
	43	Deir El Ahmar	18,633	76	0	0	7	17	0
	44	Eastern watershed of Orontes	37,821	73	0	0	27	0	0
	45	Baalbek	40,373	51	0	0	35	14	0
	46	Chaat and Younine	29,831	63	0	0	32	4	0
	47	Britel	25,352	91	0	0	9	0	0
	48	Bednayel	18,332	72	0	0	27	0	0
Aakkar	20	Plain of Aakkar and Minieh	13,821	83	0	0	1	16	0
	21	Plateau of Aakkar	23,256	69	0	0	0	31	0
	22	Fruit trees zone in Aakkar	21,608	71	0	0	4	25	0
	23	Qobayyat zone	18,524	64	0	0	3	33	0
All Lebanon			1,004,082	70	0	0	11	18	1

3.2. AquaCrop Simulations Results

The climate characteristics of the agro-homogeneous zones during the two hemp growing seasons (autumn and spring) are shown in Figure 3 and Table 4, respectively. The total rain for the autumn season fluctuated between a minimum of 82.2 mm and a maximum of 1312.3 mm, while the cumulative reference evapotranspiration (ET_o) was between 153.7 and 249.3 mm. For the spring season, the total rain was between 7.3 and 118.4 mm, while the ET_o ranged between 535.6 and 710.3 mm.

Table 4. Seed yield, biomass, normalized water productivity, and irrigation needs of *Cannabis sativa* L., and seasonal rain and ET_o for the autumn and spring seasons in Lebanon.

		Rainfed_Autumn Season	Rainfed_Spring Season	Irrigated_Spring Season
Seed yield (t ha ^{−1})	Minimum	0.0	0.5	1.7
	Maximum	2.0	1.2	2.3
	Average	0.3	0.9	2.0
	Standard deviation	0.6	0.1	0.1
Biomass (t ha ^{−1})	Minimum	0.1	5.0	9.4
	Maximum	11.1	6.8	13.0
	Average	3.7	5.6	11.0
	Standard deviation	4.0	0.5	0.7
WP (kg m ^{−2})	Minimum	0.0	0.2	0.3
	Maximum	1.1	0.5	0.5
	Average	0.1	0.4	0.4
	Standard deviation	0.3	0.1	0.0
Seasonal net irrigation amounts (mm)	Minimum	0.0	0.0	331.8
	Maximum	0.0	0.0	544.0
	Average	0.0	0.0	436.6
	Standard deviation	0.0	0.0	68.7

Table 4. Cont.

		Rainfed_Autumn Season	Rainfed_Spring Season	Irrigated_Spring Season
Seasonal rain (mm)	Minimum	82.2		7.3
	Maximum	1312.3		118.4
	Average	582.8		40.4
	Standard deviation	325.4		30.5
Seasonal Eto (mm)	Minimum	153.7		535.6
	Maximum	249.3		710.3
	Average	192.7		646.9
	Standard deviation	24.6		47.9

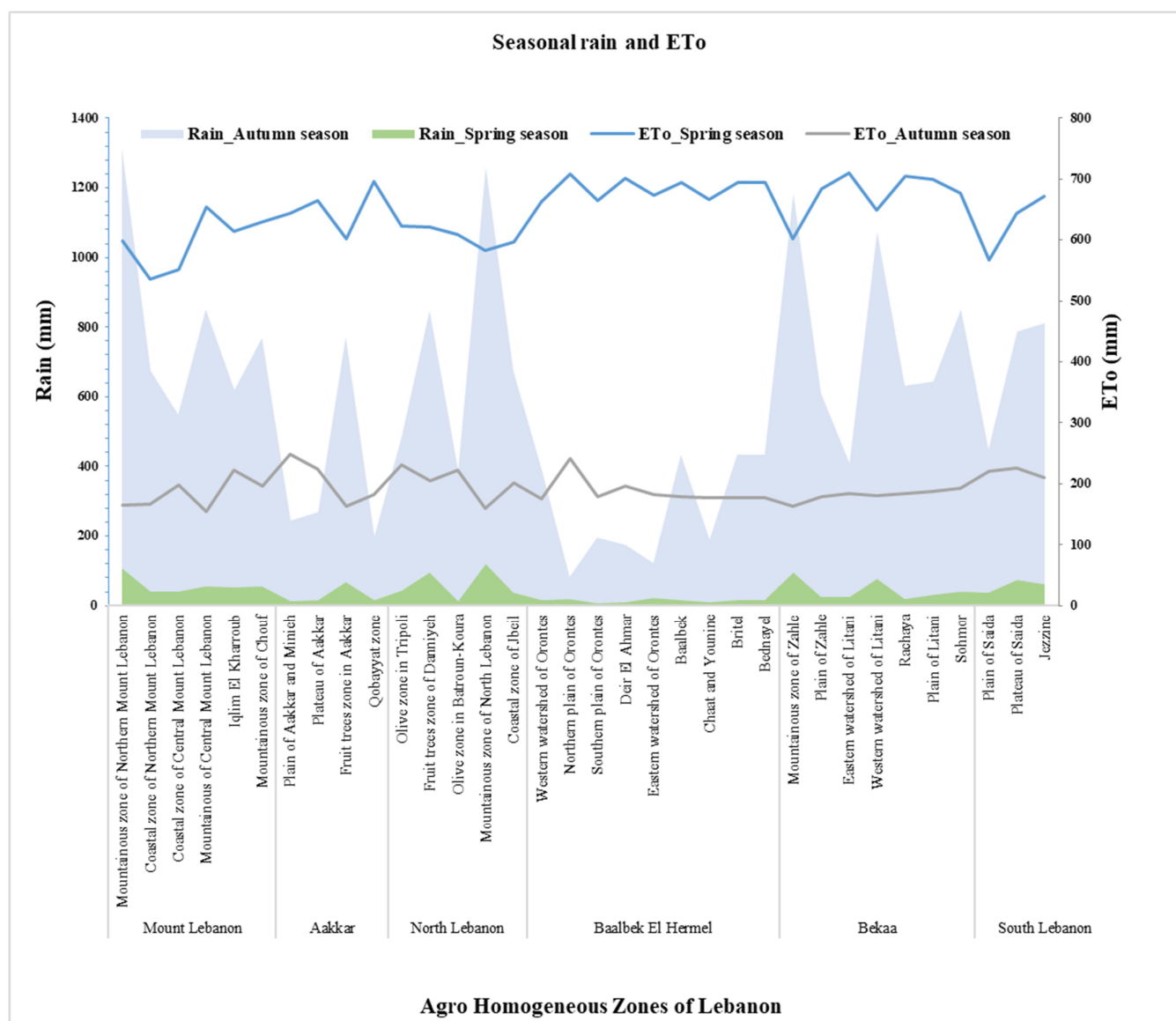


Figure 3. Seasonal rain and reference evapotranspiration (ETo) for autumn and spring in the different agro-homogeneous zones of Lebanon.

In the autumn season under rainfed hemp cultivation, the average biomass, seed yield, and normalized water productivity (WP) were $3.7 \pm 4.0 \text{ t ha}^{-1}$, $0.3 \pm 0.6 \text{ t ha}^{-1}$ and $0.1 \pm 0.3 \text{ kg m}^{-2}$, respectively (Table 4). In the spring season, the average biomass, yield, and WP under rainfed conditions were $5.6 \pm 0.5 \text{ t ha}^{-1}$, $0.9 \pm 0.1 \text{ t ha}^{-1}$ and $0.4 \pm 0.1 \text{ kg m}^{-2}$, respectively, while under irrigated conditions, the values were $11.0 \pm 0.7 \text{ t ha}^{-1}$, $2.0 \pm 0.1 \text{ t ha}^{-1}$ and $0.4 \pm 0.0 \text{ kg m}^{-2}$, respectively (Table 4). When hemp is grown under irrigated conditions in spring, it requires between 331.8 and 544 mm of seasonal net irrigation amounts (Table 4).

Figures 4–7 show, respectively, the Aquacrop simulated hemp seed yield, biomass, normalized water productivity and net irrigation amounts for the autumn and spring seasons in the different agro-homogeneous zones. Autumn is characterized by a lower seed yield than the rainfed and irrigated conditions of the spring season. Some AHZs, particularly those located in Mount Lebanon, such as the coastal zone of central Mount Lebanon and in South Lebanon, such as the Plain of Saïda, Plain of Sour, and Plateau of Sour are characterized by a higher seed yield than other AHZs $> 1.5 \text{ t ha}^{-1}$ (Figure 4).

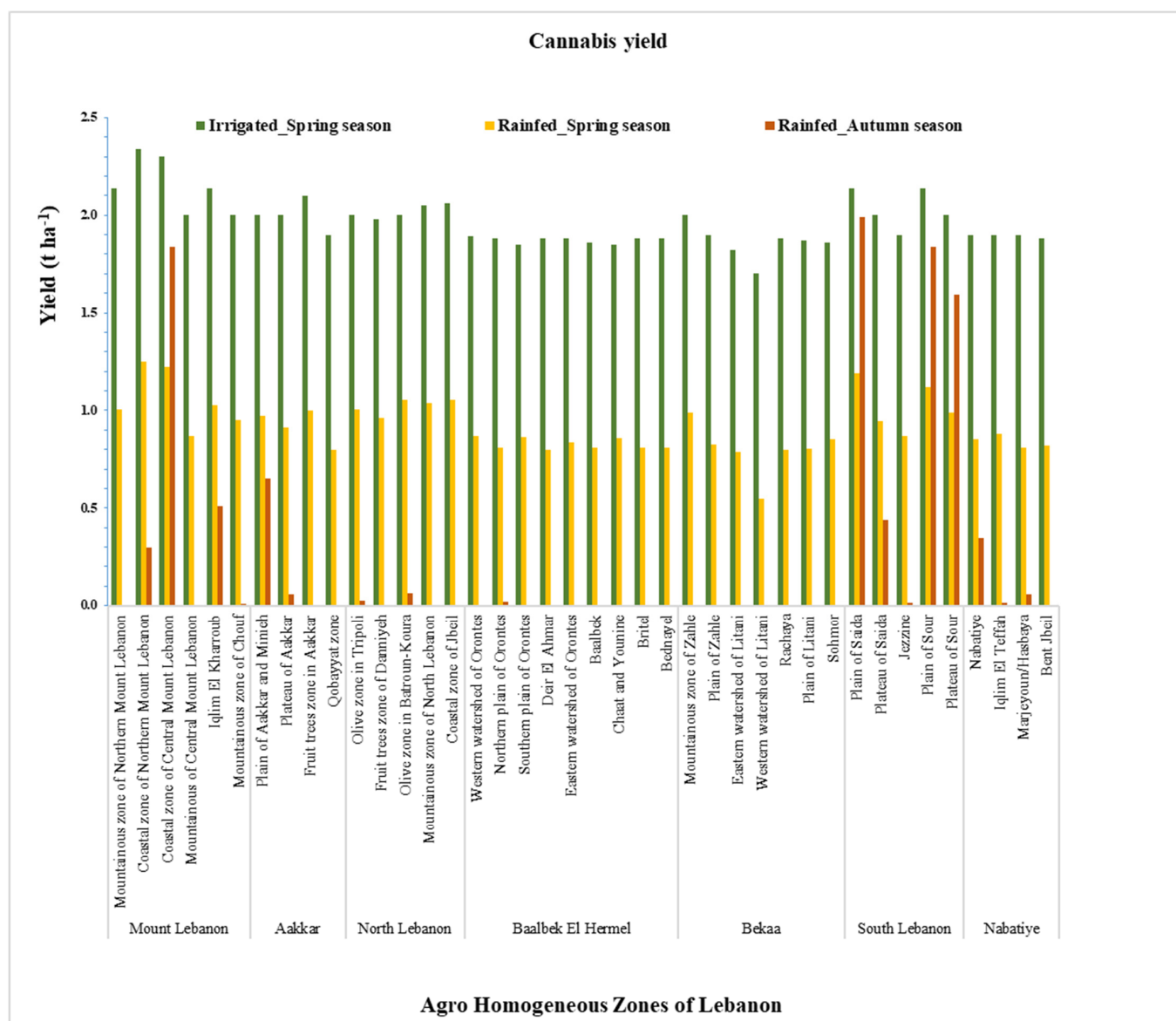


Figure 4. AquaCrop-simulated *Cannabis sativa* L. seed yield for autumn (rainfed) and spring (rainfed and irrigated) seasons in the different agro-homogeneous zones of Lebanon.

Autumn is characterized by a lower biomass than the rainfed and irrigated conditions of the spring season. Some AHZs, particularly those located in Mount Lebanon, such as the coastal zone of central Mount Lebanon and Iklm Elkharroub; in Akkar, the Plain of Akkar and Minieh; and in South Lebanon, such as the Plain of Saïda, Plateau of Saïda, Plain of Sour, and Plateau of Sour, are characterized by higher biomasses than the other AHZs $> 8 \text{ t ha}^{-1}$ (Figure 5).

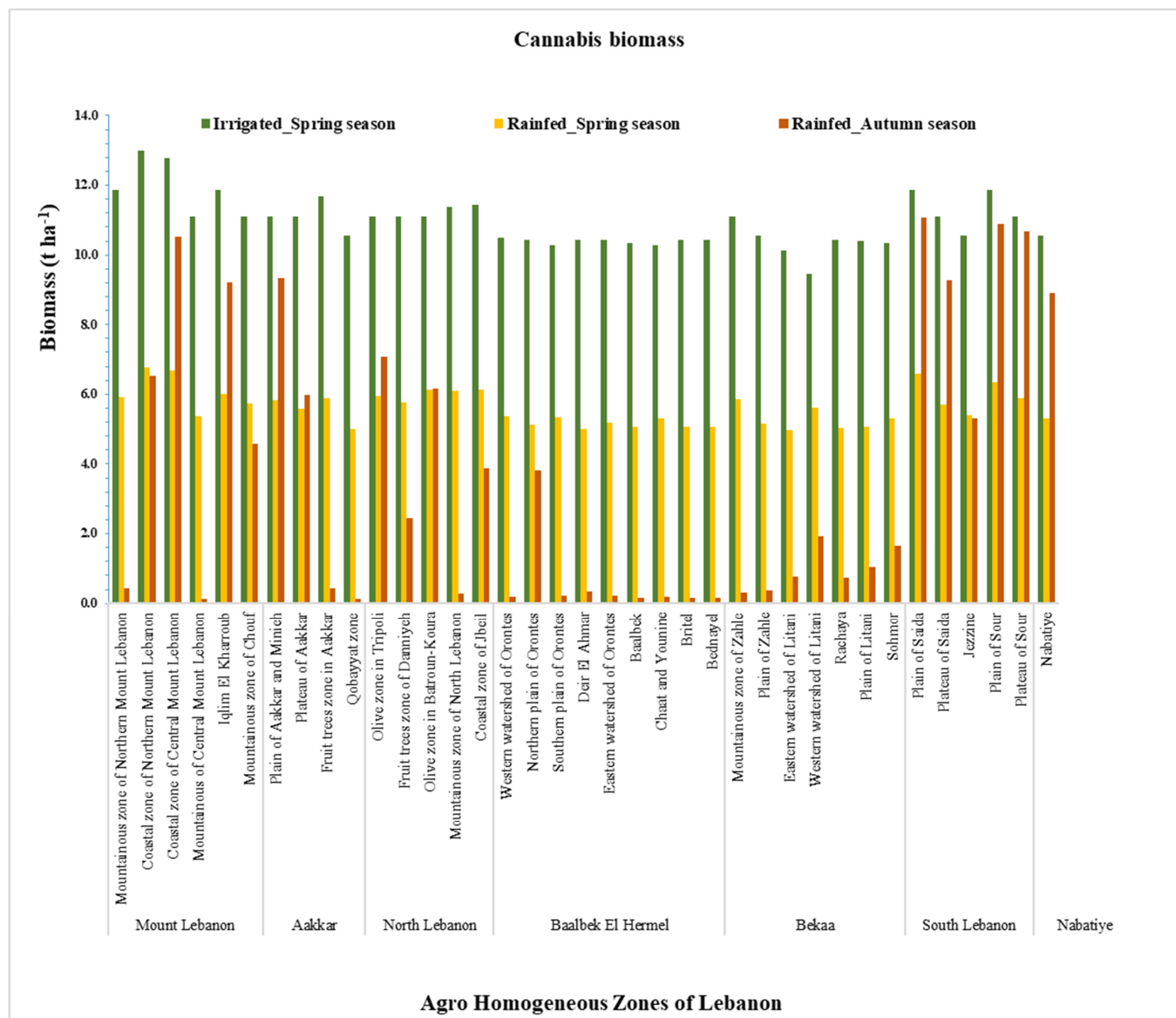


Figure 5. AquaCrop-simulated *Cannabis sativa* L. biomass for autumn (rainfed) and spring (rainfed and irrigated) seasons in the different agro-homogeneous zones of Lebanon.

Autumn is characterized by lower normalized water productivity than the rainfed and irrigated conditions of the spring season. Some AHZs, particularly those located in Mount Lebanon, such as the coastal zone of central Mount Lebanon; and in South Lebanon, such as the Plain of Saïda, Plain of Sour, and Plateau of Sour, are characterized by higher normalized water productivity than the other AHZs $> 0.8 \text{ kg m}^{-2}$ (Figure 6).

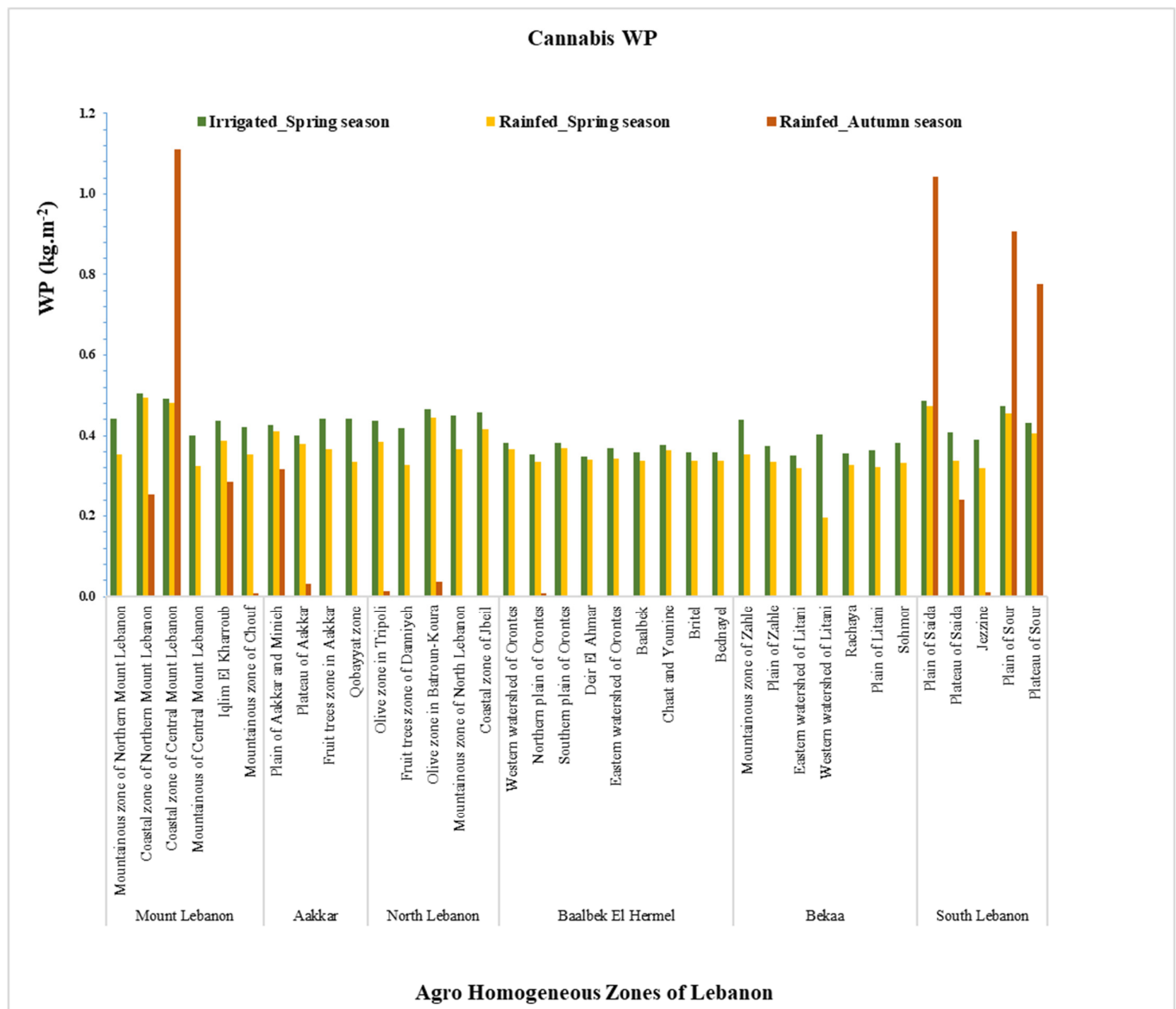


Figure 6. AquaCrop-simulated normalized *Cannabis sativa* L. water productivity (WP) for autumn (rainfed) and spring (rainfed and irrigated) seasons in the different agro-homogeneous zones of Lebanon.

Higher net irrigation amounts are recorded in some AHZs, particularly those located in Baalbek El Hermel and Bekaa (Figure 7). In general, the results showed that the autumn season is characterized by a lower biomass, yield and WP than the rainfed and irrigated conditions of the spring season. Potential yield maps showing the pattern of spatial distribution are given in Figure 8.

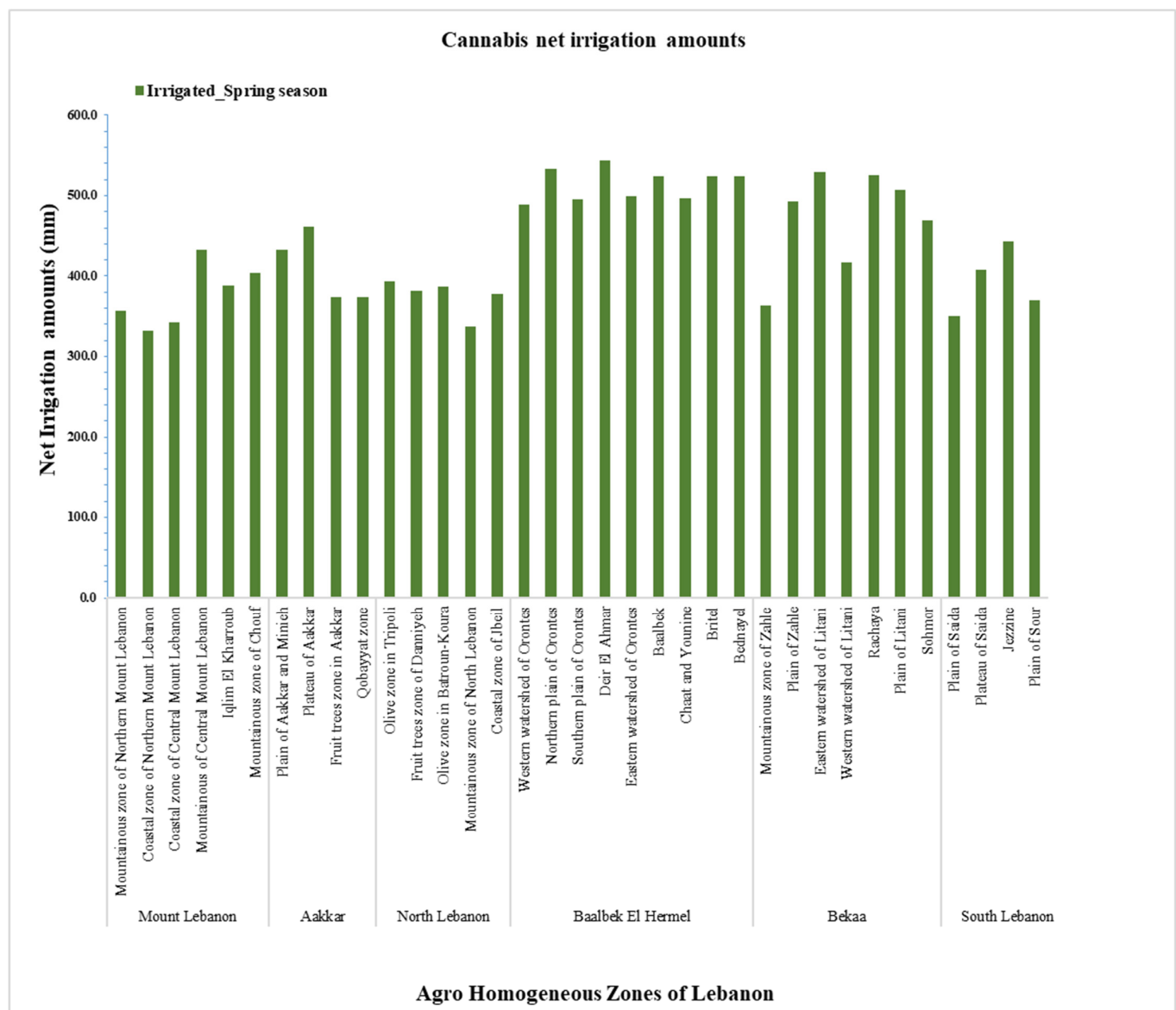


Figure 7. AquaCrop-simulated *Cannabis sativa* L. net irrigation amounts for spring season in the different agro-homogeneous zones of Lebanon.

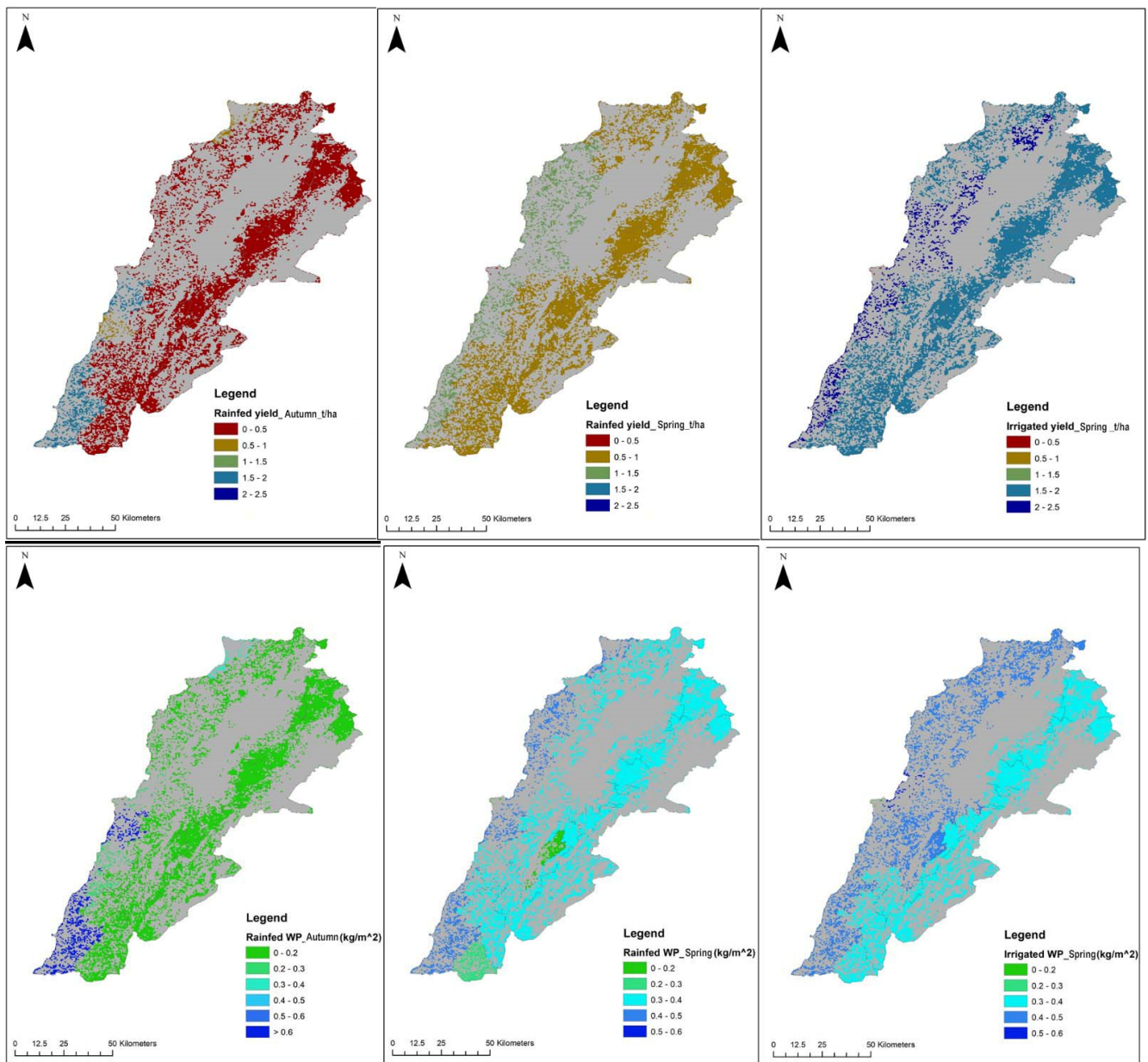


Figure 8. Maps of seed yield (**above**) and normalized water productivity (**below**) for autumn (rainfed) and spring (rainfed and irrigated) seasons.

4. Discussion

Hemp cultivation is feasible in nearly all regions of Lebanon when planted in spring. Areas exhibiting moderate suitability for spring planting are primarily concentrated in the Bekaa Valley (Figure 2), where rainfall levels fall below 600 mm. However, these areas could also become highly suitable for hemp cultivation with the implementation of appropriate irrigation practices. Additionally, only the coastal areas and some southern regions of Lebanon are suitable for hemp cultivation during the autumn season.

Autumn cultivation is characterized by a lower biomass, seed yield and WP than the rainfed and irrigated conditions of spring. However, it should be highlighted that some AHZs (mentioned above) are able to provide hemp productivity that is even higher than that of an irrigated spring season. In addition, those AHZs can provide two cultivation periods per year (Figures 4–8).

In Lebanon, the need to evaluate the suitability and productivity of hemp (*Cannabis sativa* L.) is becoming increasingly crucial due to the growing challenges posed by climate change and the limited availability of natural resources, particularly water.

Climate change is intensifying pressures on agriculture, and concerns about deforestation and other environmental and socioeconomic challenges associated with traditional crops are intensifying. In this context, suitability maps and other assessment tools are invaluable resources for farmers and policymakers, enabling informed decisions about hemp cultivation while considering its ecological and economic benefits. Recent research findings [11] indicate that Lebanon has favorable conditions for hemp cultivation, making it a promising agricultural option. However, challenges persist, particularly regarding land availability. Approximately 70% of the nation's land is unsuitable for hemp cultivation, with densely urbanized zones contributing significantly to this limitation.

According to Wimalasiri et al. [18], the adaptability of hemp to various soil types and climates, coupled with its moderate tolerance to salinity, positions it as a viable crop across diverse regions, including marginal areas with saline and alkali soils. Furthermore, the observed average hemp seed yields in Lebanon, ranging from 3.7 to 5.6 t ha⁻¹ under rainfed conditions and 11.07 t ha⁻¹ under irrigation, exceed those documented by FAO-STAT [33] for various countries spanning the period between 2000 and 2022, which ranged from 0.1 t (Romania) to 3.0 t ha⁻¹ (Australia). In rainfed Mediterranean environments, Gorchs et al. [34] reported relatively high hemp seed yields (0.60–1.43 t ha⁻¹) compared to European regions. The deep root system of hemp facilitates sufficient water uptake, allowing it to meet its water requirements even during prolonged dry spells without over-exploiting water resources, rendering it well-adapted to a drier, warmer, and more erratic climate [35].

This study demonstrated that the adoption of irrigation methods significantly enhanced both the yield and biomass of hemp, resulting in an increase of 112.22 and 96.43%, respectively, compared to rainfed conditions. In the Mediterranean context, hemp emerged as a more suitable option for the pulp paper industry compared to flax, demonstrating an average stem dry matter yield of 9.12 kg ha⁻¹ [36]. Salentijn et al. [37] highlighted the significant influence of hemp biomass yield and quality, which are shaped by both the genetic makeup of hemp cultivars and environmental factors such as temperature and photoperiod. According to Lisson et al. [38], the optimal photoperiod for hemp cultivation is 14 h, yet the actual photoperiod experienced in Lebanon varies depending on the season. During spring (April–May), Lebanon typically witnesses a photoperiod ranging from approximately 14 to 15 h of daylight, while shorter daylight hours are observed during winter (around November–December), with a photoperiod ranging from approximately 9 to 10 h of daylight.

Comparatively, Wise et al. [39] indicated that hemp requires 38% less crop water, with a 60% lower water footprint, 84% reduced crop irrigation requirement, and 91% lower irrigated water footprint than cotton, making it a water-efficient and sustainable choice for fiber production. Additionally, the existing literature suggests that hemp displays high responsiveness to fertilization and other agronomic practices [40–42]. Deng et al. [43] specifically emphasized the significant impact of planting density and fertilization on hemp fiber yield, particularly nitrogen application. Therefore, the integration of strategies such as fertilizer application and optimization of plant densities holds potential for enhancing hemp yields in Lebanon. However, further research is needed to comprehensively explore and validate these approaches.

The rising global demand for hemp products is rapidly transforming it into a pivotal component of the agricultural economy in many regions. Lebanon stands poised to seize upon this opportunity. Nevertheless, beyond the regulatory, legal, and cultural hurdles associated with hemp cultivation, it is imperative to identify the most suitable regions for its cultivation, assess its potential yields, and evaluate how its production could yield economic benefits for both producers and the broader national economy. Conducting these

preliminary analyses is crucial groundwork before initiating field studies, establishing supply chains, and implementing regulatory frameworks.

5. Conclusions

To facilitate decision-making regarding hemp cultivation in Lebanon, a comprehensive suitability assessment has been devised and effectively implemented at the national scale. With the potential legalization of hemp cultivation looming in Lebanon, there exists a propitious opportunity to capitalize on its favorable climate and promising yield potential. On average, approximately 30% and 19% of the country's land exhibits suitability for hemp cultivation during the April and November seasons, respectively. The projected seed yield under prevailing climatic conditions not only aligns with but also exceeds the global average, indicating Lebanon's potential to emerge as a formidable player in the international hemp market. Thus, by integrating suitability assessments with crop modeling, it can be deduced that hemp holds significant promise as an industrial crop in Lebanon. Nevertheless, conducting meticulous field experiments will be imperative to identify suitable hemp varieties, while substantial investment in research and development will be pivotal for optimizing cultivation practices.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w16131865/s1>, Figure S1: Rain suitability classes for hemp grown in November (left) and April (right); Figure S2: Temperature suitability classes for hemp grown in November (left) and April (right); Figure S3: Climate suitability classes for hemp grown in November (left) and April (right); Figure S4: Soil suitability classes for hemp grown in November (left) and April (right); Table S1: The different agro-homogeneous zones of Lebanon [14]; Table S2: General agro-ecological species requirements for hemp as provided by FAO-EcoCrop and taken from Wimalasiri et al. [18].

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