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Multi-Criteria Evaluation of Irrigated Agriculture Suitability to Achieve Food Security in an Arid Environment

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Abstract: This research aims at assessing land suitability for large-scale agriculture using multiple spatial datasets which include climate conditions, water potential, soil capabilities, topography and land management. The study case is in the Emirate of Abu Dhabi, in the UAE. The aridity of climate in the region requires accounting for non-renewable sources like desalination and treated sewage effluent (TSE) for an accurate and realistic assessment of irrigated agriculture suitability. All datasets were systematically aggregated using an analytical hierarchical process (AHP) in a GIS model. A hierarchal structure is built and pairwise comparisons matrices are used to calculate weights of the criteria. All spatial processes were integrated to model land suitability and different types of crops are considered in the analysis. Results show that jojoba and sorghum show the best capabilities to survive under the current conditions, followed by date palm, fruits and forage. Vegetables and cereals proved to be the least preferable options. Introducing desalinated water and TSE enhanced land suitability for irrigated agriculture. These findings have positive implications for national planning, the decision-making process of land alteration for agricultural use and addressing sustainable land management and food security issues.

Keywords: land suitability analysis; AHP-GIS modeling; irrigated agriculture; multi-criteria decision making; food security; sustainable; treated sewage effluent; United Arab Emirates

1. Introduction

In the United Arab Emirates, the share of the agricultural sector in the overall gross domestic production (GDP) was only 3.8% in 1999 [1] and declined to less than 1% in the year 2013 [2]. Despite its limited contribution to the GDP in the UAE, the agricultural sector used around 70% of the total water demand in the Emirate of Abu Dhabi in the year 2012 [3]. In the UAE, irrigation water is either from conventional water resources like groundwater and springs or from non-conventional water resources like desalination plants and treated wastewater facilities. The development of the agriculture sector in the UAE faces two main challenges. The first challenge is related to the prevailing arid atmospheric conditions which make that the region receives the very low amount of rainfall that is essential for the development and expansion of the agricultural sector. Second, the soil and land surface conditions in the region led to an overall low suitability of the land which also limited the potential agricultural sector and its productivity in the UAE. The latter is the focus of this study as it is important to investigate the spatial pattern of land suitability in the country and determine if it has been used to its full potential or not. The comparison of the determined land suitability maps to the current extent of lands used in farming in the UAE should indicate areas where future agriculture development should be done.

Lands that are suitable for irrigated agriculture represent only 6.81% of the total land area of UAE. Arable and permanent cropland represent 0.77% and 2.39% of land area respectively [4]. During the period of 2000–2009, the annual growth of arable and permanent croplands increased by 4.88% (654,000 ha) and 1.5% (1,939,000 ha) respectively, in comparison to 7.79% (420,900 ha) and 37.43% (640,000 ha) during the period of 1990–2000 [4] marking therefore a decline in the expansion of cropland in the country. Forest area represents 3.8% of the total land area in the UAE, with an annual growth of only 0.24% (3,122,000 ha) during 2000–2009. So, the limited expansion of land that is used for agriculture in the UAE has certainly made achieving food security in the country challenging. In fact, local agriculture production currently satisfies less than 10% of local needs [5].

On the other hand, a substantial increase in water desalination and non-conventional water resources development in the country has been observed in the last few years. Almost 1.7 billion cubic meters of desalinated water was pumped in 2011 which made the UAE the second largest producer of desalinated water in the world after Saudi Arabia. This amount accounts for 14% of the world's total output of desalinated water, which is a remarkably high proportion [6]. About AED 12 billion is being spent per year on water desalination, from about 70 major seawater desalination plants [6]. The government has initiated several programs to encourage the reuse of TSE in agriculture, forestry and urban design sectors. TSE is used in a controlled range of agricultural production in several piloting farms in the UAE [7]. However, it is being heavily used in forest plantations. In 2013, desalination and treated sewage effluent contribute about 35% to the total water demand [8].

So, in the UAE, on one hand, the agriculture sector is facing serious challenges related to the aridity of the climate and the low suitability of the land. On the other hand, the country is recording a significant increase of non-conventional water production which may help to boost productivity in the agriculture sector. It is essential to carefully analyze and aggregate all the available information to optimize the sustainable use of land and water and accurately determine its suitability. Proper management of the limited resources maximizes agricultural productivity and helps in achieving food security in the country. This is the main goal that we propose to pursue in this study through the determination of land suitability in the Emirate of Abu Dhabi that accounts among other for non-conventional water resources.

The assessment of land suitability for agriculture is a complex, multidisciplinary and multi-criteria process which entails land topography, climate, water resources available for irrigation, soil capabilities and current management practices including land use and land cover [9,10]. This complexity calls for the application of appropriate decision support tools, such as the multi-criteria decision making (MCDM). MCDM is one of the most widely used methods of overcoming the difficulties in defining relative weights of several criteria involved in decision-making on land suitability [11–13]. An integrated suitability assessment for land use planning and sustainable development purposes has been developed in the Emirate of Abu Dhabi [5] and used four soil related criteria namely salinity, depth, texture and moisture followed by sequential assessments of the topography and water availability criteria. An integrated Soil Information System in the United Arab Emirates (UAESIS) using multi-criteria decision-making approach was developed in 2014 to define land suitability for date palm production [14]. The study results show that 14.03% and 16.29% of total lands in the Emirate of Abu Dhabi are highly and moderately suitable for date palm plantation, respectively. However, non-conventional water resources were not used in [14].

There have been many MCDM methods used to assess land suitability like ordered weighted average [15,16], simple additive scoring [17], outranking methods [18], logic scoring of preference [19,20] and the analytical hierarchical processes (AHP) [21]. The latter has been largely used to solve complex decision-making processes which include multiple criteria, sub-criteria and alternatives [22]. AHP involves ranking relative criteria into a hierarchical structure, assessing the importance of these criteria per each level, comparing all alternatives for each criterion and determining an overall ranking of the alternatives [23]. Moreover, the determination of land suitability requires the integration of geospatial information from multiple sources among others on land cover, land use practices, soil type, soil nutrient content, pollution, weather condition, water resources and the technology used in agriculture. Such integration should be done in a geographic information system (GIS) [24] framework where diverse layers of information could be aggregated and processed to identify the most suitable location for agriculture for specific crops [25,26], coupling therefore AHP-GIS.

The AHP-GIS integrated method has been increasingly used in recent years as a powerful spatial decision support system in different fields; for land suitability assessment for agriculture [26,27], irrigated agriculture [21], eco-tourism purposes [28] and land-use suitability assessment [29]. In the AHP-GIS integrated method, assessing goal, criteria and alternatives need to be identified in relation to the purpose of the study. In selecting assessment criteria, attention should be paid to consider only those relevant to the decision-making process and contribute to the final goal. A spatial layer that includes all suitability classes with respect to the specific criterion in a specific location presents one evaluation criterion. The suitability classes then need to be rated and aggregated according to their relative importance based on the contribution of each criterion, to achieve the intended goal or objective.

This study addresses two original aspects. First, we combine in the context of an arid region a large number of agronomic and climatic factors into management, water resources and socio-economic factors, (16) criteria and (80) sub-criteria to define land suitability for seven of the Emirate's most critical crops as identified by the Government of the UAE in the national food security [30] and food diversification strategies [31]. Second, we introduce non-conventional water resources in the analysis, namely, desalinated water and treated sewage effluent as the main sources of water for irrigation for specific crops (non-edible and climate resilient crops) to ensure the sustainability of irrigated agriculture under current and future climate.

1.1. Study Area

The UAE is located on the eastern corner of the Arabian Peninsula to the north of the Sultanate of Oman and the Kingdom of Saudi Arabia. It is composed of seven coastal Emirates, six of which are located on the coast of the Arabian Gulf (they stretch over more than 650 km), while the Fujairah emirate lies on the Gulf of Oman stretching over ~90 km. The "83,600 km^2" total area of the UAE is mostly covered by sandy soils. The highest point in the UAE is Jebel Yibir at 1527 m, while the lowest point is the coastal area on the Arabian Gulf. The desert sand dunes dominate the UAE western and southern parts and merge into the Rub' Al Khali desert of Saudi Arabia as illustrated in Figure 1. The desert also includes two important oases—Al-Liwa Oasis (Mezaira) near the border with Saudi Arabia and Al-Buraymi Oasis shared with the Sultanate of Oman.

This study focuses on the Emirate of Abu Dhabi, the largest emirate in the UAE because of data availability constraints. The Emirate occupies more than 85% of the UAE's mainland area covering an area of over 67,000 km^2 [32]. The climate is extremely hot and humid in the Emirate mainly in summer. The average annual rainfall is estimated at 124 mm in the east coast, 131.9 mm in the mountain region, 107.7 mm in the gravel plain and 74.9 mm in the lowland desert [33]. The northeastern mountains receive the highest amount of 160 mm, while the southern desert receives less than 40 mm per year, with prevailing winds from North West. The evaporation rate is high, up to 2–3 m per year on average [34]. The mean daily air temperature ranges from 14 °C in winter to more than 45 °C in summer which is not suitable for many crops. The relative humidity can also be very high and may reach up to 100% in certain areas, especially near to the coast [35]. The study area is also affected by steep increasing trends of the number of dust events [36] which might have an adverse effect on agriculture activities. The relative humidity can also be very high and may reach up to 100% in certain areas, especially near to the coast [37].

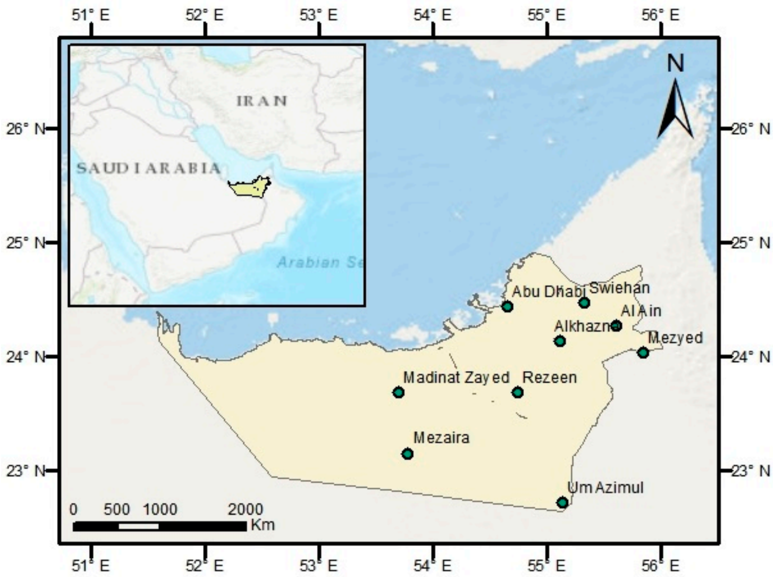

Figure 1. The study domain, Emirate of Abu Dhabi, UAE.

The study area has limited freshwater resources (only groundwater). Therefore, agriculture is heavily dependent on groundwater which has been depleted due to over-exploitation [38] and salt-water intrusion [39]. Estimates for 2011 indicate that groundwater reserves in the Emirate amount to 635.6 billion cubic meters (BCMs), out of which only 3% (19.1 BCMs) is fresh water [40]. The depth of groundwater ranges between 5 and 100 m [41]. However, the over-exploitation of groundwater throughout the years has led to a severe depletion of the reserve at a rate of 1.5 to 5 m per year. The current groundwater storage is insufficient for large-scale agricultural plantation.

Groundwater salinity is another critical issue in the Emirate as it ranges between 0 and 500 ppm and 125,000–160,000 ppm. Desalinated water is the main source of water for domestic use in the UAE. Treated wastewater, also widely known as TSE, is used in a controlled range of agricultural production in several farms in the UAE [42]. According to the UAE Ministry of Environment and Water each tree needs between 18 and 30 L of water per day [43]. The UAE treated around 450 MCM wastewater per year out of which only 60% is reused [44].

About 80 percent of the soil in the UAE is sandy soil with low organic matter [7] and therefore, as is, it is marginally suitable for agriculture activities. Soil classification in the UAE is based on the "Keys to Soil Taxonomy" that was developed by the International Center for Biosaline Agriculture in collaboration with the Environment Agency-Abu Dhabi (EAD) in 2013 [45]. The soil salinity in the Emirate is divided into four major classes with salinity values ranging between 0 and <2 dS/m EC for non-saline soil and equal to and greater than 40 dS/m EC for highly saline soil [46]. There are two soil orders in the Emirate—Aridisols and Entisols [47,48]—and six suborders, eight groups and 89 soil families [45,47,48]. The study area contains 14 different soil textures (clay, clay loam, coarse sand, coarse sandy loam, fine sand, fine sandy loam, loam, silty clay loam, loamy fine sand, loamy sand, sand, sandy clay, silty clay and silt). The soil in the study area is divided into four main sub-criteria in relation to soil moisture wet, humid, dry and very dry. Soil depth differs significantly among different soil types [49]. The study area is divided into five main soil depth categories; common hardpan, moderate probability, low probability, none or rare and not mapped areas. The land slope is not a critical factor in the UAE as more than 90% of the study area has a slope below 5.3% percentage. Land elevation ranges between −1 and 1132 m above sea-level.

1.2. Datasets Sources and Processing

Sixteen datasets are gathered and used in this study under five main categories, namely, climate, water resources, topography, soil capabilities and management data sets. Meteorological data for a 30-year period is used to create temperature and relative humidity layers using METAR data, while the precipitation layer is generated using the National Center for Meteorology (NCM) database for the years 2003 to 2015. Slope, elevation and aspect maps are derived from the UAE-ASTR-Digital Elevation Model [50] with 30-m resolution. Numerical data sets are converted to spatial layers to create the distance to desalination plants and wastewater treatment facilities. Desalination plants information were retrieved from the DesalData website (www.DesalData.com), while the treated sewage facilities database was provided by EAD. The Emirate of Abu Dhabi land-use map is generated from the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Data Base (www.eros.usgs.gov/land-cover). The spatially aggregated data for each year in the period 2001–2012 is used at $0.5° \times 0.5°$ resolution. Table 1 presents the description of the data sets used in this study and their sources.

Data collection and preparation in GIS is one of the fundamental steps in land suitability analysis. Different GIS techniques are used including interpolation, model building, reclassification, recalculation and weights overlay functions. All datasets including the numerical and spatial layers were converted into raster layers at a spatial resolution of 105 m, which is the coarsest resolution of the available spatial layers. Raster reclassification is used to reclassify all spatial layers into the five sub-criteria classes as integer raster representing different suitability levels. Then, all layers were projected or re-projected into Abu Dhabi Transverse Mercator using ArcGIS Spatial Analyst. The new spatial datasets were processed in ArcGIS. The produced layers are presented in Figure 2. Then, all layers were recalculated using the weights assigned to each sub-criterion based on the AHP analysis, before applying the Weighted Overlay function. The resulting weighted overlaid raster contains the five suitability classes.

The selection of the relevant criteria was based on the received feedback of local experts from The International Center for Biosaline Agriculture, Food and Agriculture Organization of the United Nations, EAD and the UAE Ministry of Climate Change and Environment. A comprehensive analysis of the literature [11,21] showed that similar regional and global studies have demonstrated the importance of using the following criteria: precipitation [10,19], temperature [19], relative humidity [51], groundwater salinity, groundwater table [52], soil texture [10,53], soil moisture [54], soil depth [10,53], soil salinity [52], aspect [19,23], slope [19], elevation [19,23], land use [53] and soil capabilities [19,23]. In this study, we are introducing the use of desalinated water and TSE for irrigation as a supplementary source–a significant omission from previous investigations. The sub-criteria of these main criteria are the different distances to the desalination plants and wastewater treatment facilities. Stations with private ownership or very small capacities are neglected from the study.

Table 1. Description of the datasets used in this study.

Main Categories	Attribute Criteria	Description	Source	Justification
Climate	Precipitation	Numerical data sets containing precipitation (2003–2015)	NCSM, 2017	Precipitation affects the growth and yield of plants and crops [55]. In an arid region, precipitation must be greater than 250 mm for profitable production of crops, without any supplementary irrigation [56]. Therefore, supplementary irrigation is crucial for agriculture in the UAE.
	Average Temperature	Numerical datasets containing hourly temperature observations	NOAA's NCEI (https://www.ncdc.noaa.gov/) [57].	[58].
	Relative Humidity	Numerical datasets containing hourly temperature observations	NOAA's NCEI (https://www.ncdc.noaa.gov/) [57].	Relative Humidity affects plants' growth, impacts plants' flowering, productivity and total yield [59]
Water Resources	Groundwater level	Spatial dataset containing groundwater levels	EAD, 2016	Groundwater level measured by the depth of the upper surface of the water table.
	Distance to Wastewater treatment plants	Spatial datasets containing the wastewater treatment plants names, locations, capacity and owners	EAD, 2016	The government has initiated several programs to encourage the reuse of treated wastewater in agriculture, forestry and urban design sectors
	Groundwater Salinity	Spatial dataset containing groundwater salinity categories	EAD, 2016	Groundwater salinity is one of the most critical water quality factors that affect plant growth and crops productivity. Water with high salinity means that less water is available to plants even if the soil is wet as plants capacity to absorb water decreases as salinity increases [60].
	Distance to desalination plants	Numerical datasets containing the desalination plans, locations, capacity, purpose and owners	The DesalData.com, through MIST subscription.	Data are obtained online for all plants across the UAE but only the main plants are taken onward for further analysis based on the purpose of desalination, owner and location. In addition to the name of the desalination plants, several other parameters are provided for each plant, including longitude, latitude, the capacity of water produced per day, owner and purpose of desalination and year of establishment.
Land Capability	Soil Salinity	Spatial datasets containing soil salinity	EAD, 2016	Soil salinity represents the accumulation of salts (soluble and readily dissolvable salts) in the soil [61]. It is one of the critical factors to consider in irrigated agriculture, mainly in arid and semi-arid regions [62].
	Soil texture	Numerical datasets containing soil texture at specific locations all over Abu Dhabi Emirate	EAD, 2016	Soil Texture affects soil ability to drain water, retain moisture, grow crops, be aerated and react to changes climate.
	Soil water content	Numerical datasets containing soil water content at specific locations all over Abu Dhabi Emirate	EAD, 2016	Evaporation has a directly proportional relationship with soil moisture content; it increases with increasing soil moisture [63]. Severe soil moisture deficits affect specific growth stages which affect plant growth and productivity [64].
	Soil Depth	Spatial datasets containing soil depth	EAD, 2016	Soil Depth is another critical criterion that defines land suitability for irrigated agriculture and it changes significantly among different soil types [49].

Table 1. *Cont.*

Main Categories	Attribute Criteria	Description	Source	Justification
Topography	Elevation	Derived from the DEM data (30 m resolution)	[65]	Elevation changes affect critical environmental factors like temperature thus affecting plants respiration and photosynthesis [66]. Land elevation also has a direct impact on the soil nitrogen and organic carbon content and thus has an indirect relationship with crop yields [67]
	Surface slope	Derived from the DEM data (30 m resolution)	[65]	The slope degree could be considered a restriction to land capability for irrigated agriculture [68] as it negatively restricts management and machinery applications such as irrigation, tillage and drainage [69] and determines the type of the irrigation system to be used and the flow rate, hence affecting crop yields and irrigation cost [68]. Slope also affects land productivity as high steep lands suffer from soil loss.
	Aspect	Derived from the DEM data (30 m resolution)	[68]	Land aspect is a driver in agricultural productivity, as plants need sun exposure at specific intervals in their lifespan in order to maintain some of their crucial processes. It also has significant effects on the soil quality [70].
Management	Land Use	Derived from MODIS	MODIS, 2016	The map is generated from the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Data Base. The spatially aggregated data for each year in the period 2001–2012 is used at $0.5^{\circ} \times 0.5^{\circ}$ resolution.
	Land suitability for agriculture	Abu Dhabi Emirate soil classification for irrigated agriculture suitability	[71]	The land suitability for irrigated agriculture is classified into five main categories ranging from most suitable to permanently unsuitable for irrigated agriculture based on eight different soil parameters.

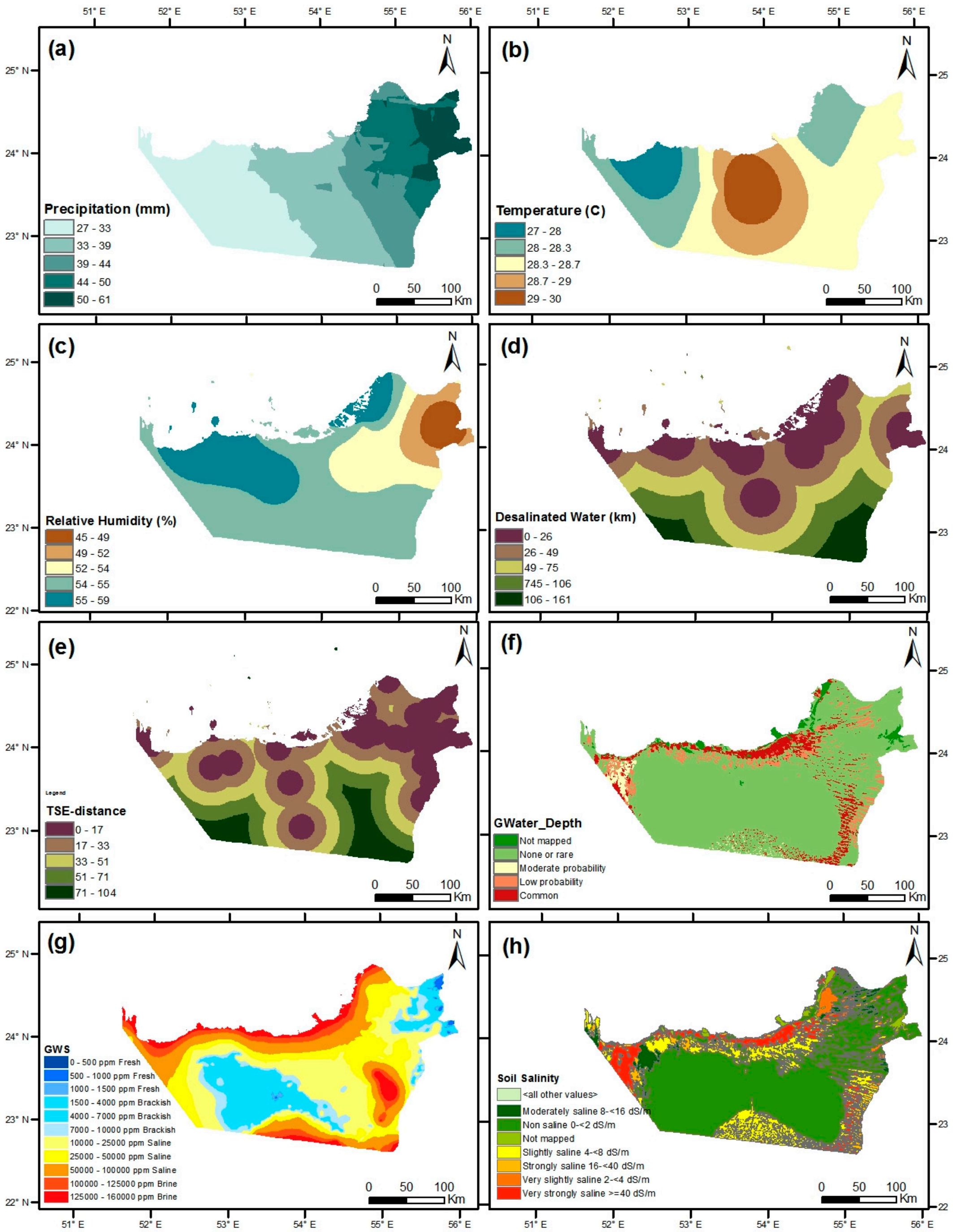

Figure 2. *Cont.*

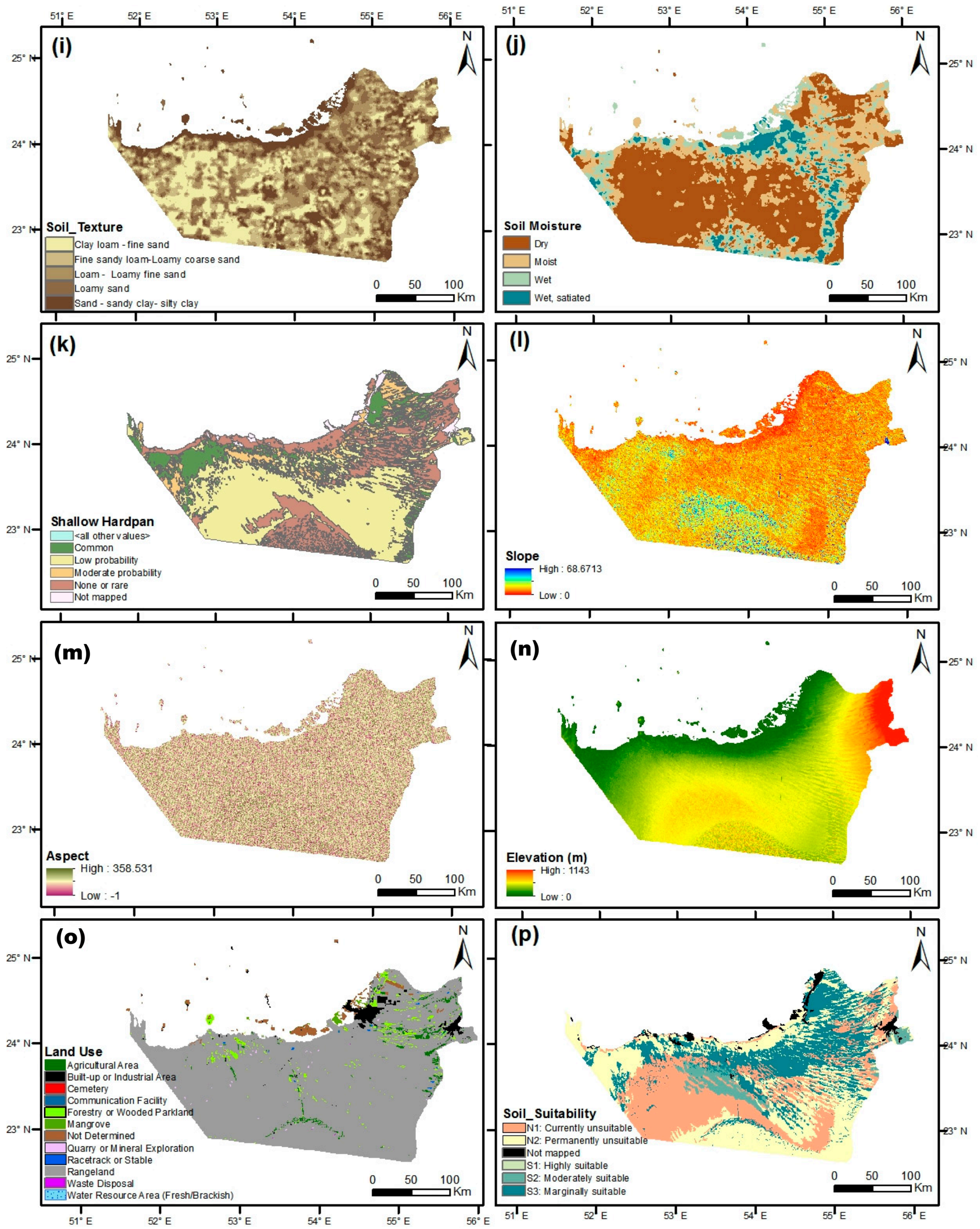

Figure 2. The sixteen selected criteria spatial coverage used to define land suitability for irrigated agriculture for the Emirate of Abu Dhabi: (**a**) precipitation; (**b**) temperature; (**c**) relative humidity; (**d**) distance to desalinated water; (**e**) distance to treated sewage effluent; (**f**) groundwater depth; (**g**) groundwater salinity; (**h**) soil salinity; (**i**) soil texture; (**j**) soil moisture; (**k**) soil depth; (**l**) slope; (**m**) aspect; (**n**) elevation; (**o**) land use; and (**p**) soil suitability for irrigated agriculture.

2. Methodology

2.1. Methods

The process of land suitability analysis for irrigated agriculture involves two main steps. First, a multi-criteria decision making using AHP is defined. It consists of defining land suitability classification, selection of evaluation criteria, selection of crops and criteria ranking and defining the hierarchical structure (AHP) and assessing the weights. Then, the second step consists of building a GIS model to process the collected geospatial and the predefined weights to produce suitability maps for specific crops. The produced maps are sensitive to selected weights and criteria. The development and deployment of the AHP-GIS model are introduced in the following sections.

The selected AHP-GIS technique has a number of positive advantages, such as the flexibility to adopt different criteria, AHP hieratical structures and ability to develop weighting scheme. Many MCDM techniques reviewed were best applied to less than 10 criteria. The AHP method is capable of integrating more elements, 16 criteria and 80 sub-criteria. The AHP pairwise matrix could also be redesigned based on stakeholders' preferences and requirements, yielding a different land suitability index for irrigated agriculture. Additionally, the outcome of this method could lead to the determination of lands in the Emirates that may fall under one of the three following categories: first, areas that are currently not suitable for irrigated agriculture but could be considered for agriculture use in the future; second, areas that are permanently unsuitable; and third, areas that are being used already or could be immediately used. The method could also be used to determined suitability levels under each category which was adopted in this study. Moreover, the method allows for the evaluation of different scenarios per crop by considering a different combination of influencing factors to demonstrate how suitability output map can vary as a result of different decision-making contexts. The implementation of the method is described in the following sections.

2.1.1. Multi-Criteria Decision Making (MCDM)/AHP

(a) Defining Land suitability classification. The commonly used land suitability classification approach is the "Framework for Land Evaluation" proposed by the Food and Agriculture Organization of the United Nations-FAO in the 1970s [72]. This classification is based on land characteristics mainly in relation to different crops and it categorizes land into five main classes as given in Table 2. They are stated as highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently unsuitable (N1) and permanently unsuitable (N2). The land suitability for irrigated agriculture in the Emirate is classified into five main categories ranging from most suitable to permanently unsuitable for irrigated agriculture based on eight different

(b) Selection of evaluation criteria. Based on literature review, expert opinion, data availability and accessibility a set of 16 criteria was selected.

Table 2. FAO's Land Suitability Classification and Definition [72].

Class	Description
Highly suitable (S1)	This soil is capable of producing sustained high yield. It is usually well-drained, deep, fine sandy-textured and has low soluble salts, gypsum content, calcium carbonate content, sodicity and neutral pH.
Moderately Suitable (S2)	This soil has a lower productive capacity than S1. It usually has a sandy texture, deep, well or excessively drained, slightly saline, non-sodic and has low gypsum content.
Marginally suitable (S3)	This soil is moderately deep, it has a sand to sandy load textures and is single grained or massive. It is typically slightly saline and has moderate gypsum content. It usually occurs in moderately steep gradient.
Currently unsuitable (N1)	This soil has high gypsum content, high steep gradients and high relief. It also has a shallow rooting depth with hardpans close to the surface.
Permanently unsuitable (N2)	This is a very shallow soil, associated with rock outcrops and on very steeply sloping land and a very high relief. It is usually very poorly drained, have the shallow depth to gypsum and strongly saline.

(c) Selection of crops and criteria ranking. Various food crops such as date palms, tomatoes, cucumbers and other vegetables and fruits are grown in the UAE [73]. Most of the agriculture in the UAE involves dates, as it is one of the top cultivators in the world with over 40 million date palm trees [74]. Vegetable production is the second largest category at over 71 thousand tons [32]. In this study, in addition to dates palm, vegetables and fruits, cereals are also selected since this is a staple food crop [75] and are mostly imported from other countries. Based on its adaptive capacity to harsh environmental conditions and due to its liquid wax and oil in its seeds, it is widely used in the industrial sector in biodiesel fuel, as engine lubrication and for pharmaceutical compounds, jojoba was selected to be used on experimental basis in order to analyze its impacts on future climate scenarios. Jojoba (Simmondsia Chinensis) is a member of the family Simmondsiaceae, genus Simmondsia [76]. The plant is very well adapted to the harsh desert environment and is capable of growing in very hot, very cold and very dry deserts. It can survive very low temperatures, down to −5 °C and very high, up to 50 °C. However, optimal growth requires a regular, if minimal irrigation. It is a shrub and typically grows to 1–2 m tall. The leaves have an oval shape, 2–4 cm long, usually thick, waxy and glaucous gray-green in color. It has small and greenish-yellow flowers, with 5–6 sepals and no petals. Jojoba blooms from March to May and is normally harvested by hand with an average yield of 3.5 tons/ha [77].

(d) Defining the threshold value per criteria per crop. After defining the selected criteria and the crops, the threshold values for evaluation criteria in each of the five suitability classes per crop are determined based on literature review as shown in Table 3. This table is used later to create the criteria maps per crop. Then, all criteria and sub-criteria are assessed and classified into five main categories as follows: very critical, critical, important, preferable and optional in order to define their relative importance per crop. The results of assessing and classifying all criteria per crop presented in Table 3 were used to define the analytical hierarchical structure subsequently.

(e) Defining the hierarchical structure and assessing the weights. In order to apply the AHP method the problem has to be structured hierarchically at all levels. According to Saaty [78], AHP constructs a rating scale associated with the priorities for the various items compared. This step includes four stages:

(i) Modeling Stage (constructing hierarchy): A hierarchical structure is built as a decomposition structure that includes main criteria, criteria and sub-criteria to be used to define land suitability. At the main criteria level, the decomposition process consists of defining categories of the analyzed compound item. In total, five main criteria are defined: climate, water resources, land capability, topography and management. Then, the decomposition continues to define the criteria under each one of these five main criteria. For example, the climate main criterion is decomposed into averages of rainfall, temperature and relative humidity. The aim of decomposing the main criteria into criteria and then to sub-criteria is to define those factors that are affecting land suitability which is quantifiable by a number of a specific value. For example, it is difficult to define a quantitative value or classify how the climate, in general, affects land suitability. However, when it is decomposed into rainfall, temperature and relative humidity, each of these criteria can be classified into sub-criteria that can be easily quantified to be used in subsequent evaluation steps presented in Table 3.

(ii) Prioritization Stage (standardization of criteria): this step entails defining the numerical representation of the relationships between two elements that share the same parent. It starts by comparing each pair of criteria and sub-criteria using Saaty's developed 9-point scale measurement, shown in Table 5, in order to express individual preferences [78]. This step eventually leads to the development of a square pairwise comparisons matrix, in which all elements are compared with themselves [79]. These comparisons allow independent evaluations of each factors' contribution [80], thus helping to simplify the decision-making process [81]. This requires comprehensive knowledge and literature review to provide the best judgment of the relative intensity of importance of one evaluation factor against another. The input for this step is the pairwise comparison matrix A, of n criteria, using Saaty's developed 9-point scale. It can be defined as follows:

$$A = [a_{ij}],\ i,j = 1, 2, 3, \ldots, n; \quad (1)$$

where A is the matrix with a_{ij} elements, i and j are the criteria or sub-criteria and $a_{ij} = W_i/W_j$ for all i and j. The developed matrix has the property of reciprocity (Table 6) and can be mathematically expressed as [82]:

$$a_{ij} = 1/a_{ji} \quad (2)$$

(iii) Assigning weights: defining of the criterion weights is a fundamental step in the MCDM/AHP process. The criterion weights are usually defined based on the overall goal of the study. The used AHP technique derives the weights by comparing their relative importance. Using the pairwise comparison matrix, the AHP calculates each criterion weights [83] using the Eigenvector corresponding to the largest eigenvalue of the matrix and then normalizing the sum of the components as shown in Equation (3):

$$\sum_{i=1}^{n} w_i = 1, \tag{3}$$

for each crop, three sets of pairwise matrices are formed as follows: 1 for the main criteria, 5 for the criteria and 16 for the sub-criteria. In total, 22 pairwise matrices are formed per crop. Based on these matrices, relative weights for main criteria, criteria and sub-criteria are derived.

In the resulting hierarchy structures (see Figure 3 for the date palm as an example), the goal to be achieved, which is defining the land suitability for irrigated agriculture, is placed on the top of the graph and then other aspects like criteria and sub-criteria, are placed in the lower levels based on their importance and level. This was done similar to Saaty, 1994 [79].

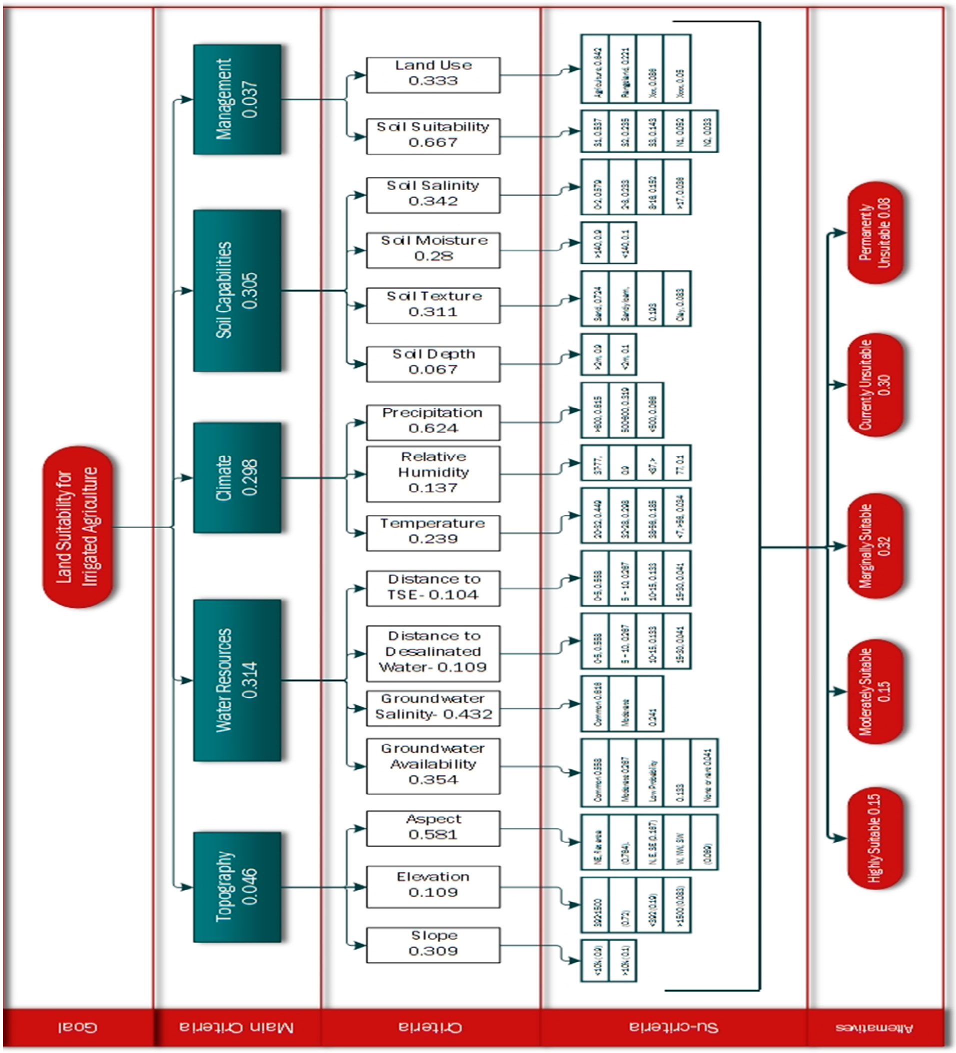

Figure 3. The resulting hierarchal structure showing the modeling procedure for irrigated agriculture areas for the date palm in Abu Dhabi Emirate, UAE.

Table 3. The selected sixteen criteria and sub-criteria thresholds per crop.

		Soil				Topography			Climate			Water Resources				Management		
Crop Type	**Suitability Index**	**Conductivity (Millimhos/cm at 25 C)**	**Soil Texture**	**Soil Depth/Hardpan (m)**	**Soil water content/Soil Moisture**	**Elevation**	**Surface slope%**	**Aspect**	**Precipitation (mm)**	**Temperature (C)**	**Relative Humidity (%)**	**Groundwater availability**	**Distance to TSE Facility (km)**	**Distance to Desalinated Water (km)**	**Groundwater Salinity (ppm)**	**Soil Capabilities**	**Land Use [1]**	**References**
Date Palm	S1	0–2	Sand	>2 m	>140 mm	−392 to 1500	<10%	NE	500–600	20–32	37–77	Common	0–10	0–10	<7630	S1	1	
	S2	2 to 4	Sandy loam	<2	<140 mm	<392		E	<500	32–38	<37	Moderate probability	10–20	10–20	7630–12,530	S2		
	S3	8 to 16	Clay			>1500		SE	<63	38–56	>77	Low probability	20–30	20–30	12,530–22,400	S3	2	[84,85] [84] [85]
	N1	>17					>10%			0-7		None or rare	>30	>30	>22,400	N1	3	
	N2									<0 or >56		Not mapped				N2	4	
Vegetable	S1	0.02–0.4	Loamy, loamy sand	0.6	>5%	2134	<0.1	NE	3600	15–20	<50	Common	0–10	0–10	<2380	S1	1	
	S2	0.4–0.6	LL, LT	0.4	<5%		0.1–1	E		20–30	50–60	Moderate probability	10–20	10–20	2380–3150	S2		
	S3	0.8–1.2	heavy clay	0.25			1.0–1.5	SE		70–15	60–90	Low probability	20–30	20–30	3150–4480	S3	2	[85] [86] [87] [88] [89]
	N1	1.2–3.2					>1.5	NW, SW		>40	>90	None or rare	>30	>30	>4480	N1	3	
	N2	>3.2								0		Not mapped				N2	4	
Fruits	S1	<1.5	coarse loam, loamy sand, find loam	>0.9	>2.5%	1066–1828	02–12.0%	NE	900–1000	15–20	<50	Common	0–10	0–10	<250	S1	1	
	S2	1.5–2.7	Sand to Clay	<0.9	<2.5%	100–1066	0–2%	E	<900	20–30	50–60	Moderate probability	10–20	10–20	250–750	S2		
	S3	2.7–5.5	Silt clay			1828–5000	12–18%	SE		<15–12.5 and >30	60–90	Low probability	20–30	20–30	750–3000	S3	2	[50] [89] [90] [84]
	N1	>5.5					18–30			<12.5	>90	None or rare	>30	>30	>3000	N1	3	
	N2						>30					Not mapped				N2	4	

Table 3. *Cont.*

		Soil				Topography			Climate			Water Resources				Management		
Crop Type	**Suitability Index**	**Conductivity (Millimhos/cm at 25 C)**	**Soil Texture**	**Soil Depth/Hardpan (m)**	**Soil water content/Soil Moisture**	**Elevation**	**Surface slope%**	**Aspect**	**Precipitation (mm)**	**Temperature (C)**	**Relative Humidity (%)**	**Groundwater availability**	**Distance to TSE Facility (km)**	**Distance to Desalinated Water (km)**	**Groundwater Salinity (ppm)**	**Soil Capabilities**	**Land Use [1]**	**References**
Cereal	S1	1.21–1.6	Sand	1–1.5	Good	2500–3000	<0.1	NE	600–800	15–20	50–90	Common	0–10	0–10	<4480	S1	1	[91] [91] [92] [93] [85]
	S2	1.6–6	Loam	1.5–2.5	5%	<2500	0.1–1	E	450–600	20–25	<50, >90	Moderate probability	10–20	10–20	4480–6100	S2		
	S3	>6	Clay				2.0–5.0	SE		10.0–15.0		Low probability	20–30	20–30	6100–8400	S3	2	
	N1							NW, SW		<10		None or rare	>30	>30	>8400	N1	3	
	N2											Not mapped				N2	4	
Sorghum	S1	1.21–1.6	Loamy	1–1.5	Good	<1500	0.1–0.5	NE	>150	25–35	30–50	Common	0–10	0–10	<1890	S1	1	[94] [85]
	S2	5.1–7.2		<1	5%	1500–1800	0.5–2.0	E	<150	25–15	<30, >50	Moderate probability	10–20	10–20	1890–2380	S2		
	S3	11	Very heavy clay				2.0–5.0 or <0.1	SE		25–37		Low probability	20–30	20–30	2380–5040	S3	2	
	N1	18						NW, SW		<10			>30	>30	>5040	N1	3	
	N2									>37		None or rare				N2	4	
Forage	S1	1.21–3.4	Sandy Loam, Loamy	1–2 m	5–10%	1200–4000	leveled	NE	800–1000	25	10.0–12	Common	0–10	0–10	<3990	S1	1	[95,96] [85] [97]
	S2	3.4–5.4	SL, S	>2		<1200	<0.1	E	<800	25–30 & 10–25	12.0–40	Moderate probability	10–20	10–20	3990–6300	S2		
	S3	5.4–8.8	Clay loam					SE		>30	40–60	Low probability	20–30	20–30	6300–9100	S3	2	
	N1	8.8–15.5						NW, SW					>30	>30	>9100	N1	3	
	N2	15.5		Shallow hardpan								None or rare				N2	4	

Table 3. *Cont.*

		Soil				Topography			Climate			Water Resources				Management		
Crop Type	Suitability Index	Conductivity (Millimhos/cm at 25 C)	Soil Texture	Soil Depth/Hardpan (m)	Soil water content/Soil Moisture	Elevation	Surface slope%	Aspect	Precipitation (mm)	Temperature (C)	Relative Humidity (%)	Groundwater availability	Distance to TSE Facility (km)	Distance to Desalinated Water (km)	Groundwater Salinity (ppm)	Soil Capabilities	Land Use [1]	References
Jojoba	S1		Sand, loamy sand	>2.0	>0.64%	0–1500	<5.0	NE	200–380	27–30	75–52	Common	0–10	0–10	<2000	S1	1	[98,99] [100] [101]
	S2		Heavy soil	0.9–1.0	<0.64%			E	76–200 and > 380	30–40		Moderate probability	10–20	10–20	2000–7000	S2	2	
	S3	6.0–10.0	Silt, clay, silty loam, sand					SE	<76	40–50		None or rare	20–30	20–30		S3	2	
	N1									<−1 up to −5			>30	>30		N1	3	
	N2									<−9		Not mapped				N2	4	

[1] Land use categories are: (1) Agricultural land; (2) Forestry and Rangeland; (3) Waste disposal, quarry and Stable; and (4) Built-up area, mangrove commercial and cemetery.

Table 4. Initial weights of sub-criteria per crop.

Crop	Conductivity (Millimhos/cm at 25 °C)	Soil Texture	Soil Depth	Soil Water Content	Elevation	Surface Slope	Aspect	Precipitation (mm)	Temperature (°C)	Relative Humidity (%)	Groundwater Table	Distance to TSE	Distance to Desalinated Water	Groundwater Salinity	Soil Suitability	Land Use
Date Palm	3	2	2	3	5	5	4	5	2	4	1	4	2	2	2	3
Vegetable	2	2	3	3	4	3	3	2	1	5	2	3	2	2	2	3
Fruits	1	2	2	4	4	3	3	3	2	5	3	5	2	2	2	3
Cereal	3	2	3	1	5	2	4	3	3	5	2	5	3	2	2	3
Sorghum	5	2	2	3	5	2	4	3	1	5	3	2	3	5	3	3
Forage	3	3	5	2	5	3	4	5	2	2	3	2	3	5	3	3
Jojoba	4	3	2	4	5	5	4	5	1	5	5	2	3	5	3	3

Legend: (1) Most critical; (2) Critical; (3) Important; (4) Preferable; and (5) Not critical.

Table 5. Saaty's Scale to assign numerical values to judgments made by comparing two elements with the smaller element used as the unit and the larger one assigned a value from this scale as a multiple of that unit.

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objectives
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity other another
7	Very strong or demonstrated importance	An activity is favored very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	A comparison is mandatory by choosing the smaller element as the unit to estimate the larger one as a multiple of that unit.
Rational	Rations arising from the scale	If consistency were to be forced by obtaining n numerical value to span the matrix
1.1–1.9	For tied activities	When elements are close and nearly indistinguishable; moderate is 1.3 and extreme is 1.9

To make the w unique, the matrix should be normalized to produce another matrix A′ (Table 6):

$$A' = [a'_{ij}],\ i,j = 1, 2, 3, \ldots, n; \tag{4}$$

where A′ is the normalized matrix of A and the a'_{ij} is defined as:

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}; \tag{5}$$

for all $i,j = 1, 2, 3, \ldots, n$. Then, the weights are computed using equation number 5 (Table 6):

$$w_i = \frac{\sum_{j=1}^{n} a'_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a'_{ij}} \tag{6}$$

Table 6. Assignment weights for the Palm Date main categories.

Main Categories	Soil Capability—SC	Climate—C	Water Resources—WR	Topography—T	Management—M	Sum	Soil Capability—SC	Climate—C	Water Resources—WR	Topography—T	Management —M	Sum	Priority	Rank
SC	1	1	1	6	9	18	0.3048	0.3039	0.3076	0.2857	0.32142	1.524	30.50%	2
C	1	1	1	6	8	17	0.3048	0.3039	0.3076	0.2857	0.28571	1.488	29.80%	3
WR	1	1	1	7	9	19	0.3048	0.3039	0.3076	0.3333	0.32142	1.571	31.40%	1
T	0.17	0.17	0.14	1	1	2.48	0.0518	0.0516	0.0430	0.0476	0.03571	0.23	4.60%	4
M	0.11	0.12	0.11	1	1	2.34	0.0335	0.0364	0.0338	0.0476	0.03571	0.187	3.80%	5

(iv) Matrix Consistency Check. It is critical to check the consistency of the matrices that are built. To do so, two figures should be calculated and checked. First, a consistency ratio [56] is calculated and used as an indicator of the degree of consistency or inconsistency. The largest eigenvalue of the matrix called (λ_{max}) is always greater than, or equal to, the number of rows or columns (n). The second method is to calculate the consistency index (CI) which measures the consistency of pairwise comparison and can be calculated and written as [102]:

$$CI = (\lambda_{max} - n)/(n - 1); \quad (7)$$

where n is the number of elements being compared in the matrix, λ_{max} is the largest eigenvalue of the matrix and CI is the consistency index. Then, the calculated CI is used to calculate the consistency ratio coefficient [56]. The calculated CR coefficient should be less than 10% which indicates the overall consistency of the pairwise comparison matrix [79].

$$CR = CI/RI; \quad (8)$$

where RI is the Random index developed by Saaty for different numbers of n as shown in Table 7. It provides the average of the resulting consistency index depending on the number of elements in the matrix [79]. If the calculated value of the CR is less than 10% (0.1), this means that the pairwise matrix has adequate consistency. If the CR value is greater than or equal to 10% then the AHP may not yield meaningful results and the pairwise matrix should be revised and changed to reduce the inconsistency below the 10% [79].

Table 7. The order of the matrix and the average RI [79].

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The consistency ratio for different pairwise matrices and the weights for all main criteria, criteria and sub-criteria calculated for the seven crops were all under 10% (See Table 8 for Date palm as an example), which means that the comparisons of land suitability criteria and sub-criteria were perfectly consistent.

2.1.2. GIS Data Processing

(a) Land suitability model builder. ArcGIS is used to build a land suitability model. The GIS Model Builder function is used to organize and integrate all spatial processes to model the land suitability. The 16 different layers were integrated into the GIS environment as information layers and overlaid to produce overall land suitability assessment for a particular crop. The suitability analysis for the different criteria weights was integrated within the GIS Model Builder. Using the weights calculated using the AHP method; the ArcGIS system links the suitability results to the different shapefiles of the same area by area's index. Each model operates in sixteen layers but with different weights per crop.

(b) Combining land suitability rating using a GIS Overlay Function. After the weights associated with the criteria are calculated and the maps of these criterion weights are generated, the ArcGIS Weighted Overlay function, which is an intersection of standardized and differently weighted layers, is used to generate the unified final land suitability maps [54]. The weights present and quantify the importance of the suitability criteria considered in relation to each other. The suitability scores assigned for the sub-criteria within each criteria layer were multiplied with the weights assigned for each criterion and main criterion to calculate the suitability index and generate the final suitability map.

The relative importance of the main criteria, criteria and sub-criteria derived using the pairwise comparison matrix, the composite weights—representing the land's suitability for the Irrigated Agriculture index (LSIAI)—are then derived via a sequence of multiplications of each main criterion weightings with each criterion and sub-criterion as presented in Table 8 for date palm (Equation (9)). The full names of Equation (9) abbreviations are presented in Table 9.

The LSIAI is defined as

$$\begin{aligned} \text{LSIAI} = & [\text{S}\ ((S_1\text{C}w_i\ .\ S_1\text{SC}w_i) + (S_2\text{C}w_i\ .\ S_2\text{SC}w_i) + (S_3\text{C}w_i\ .\ S_3\text{SC}w_i) + (S_4\text{C}w_i\ .\ S_4\text{SC}w_i))] \\ & +[\text{C}\ ((C_1\text{C}w_i\ .\ C_1\text{CC}w_i) + (C_2\text{C}w_i\ .\ C_2\text{CC}w_i) + (C_3\text{C}w_i\ .\ C_3\text{CC}w_i))] \\ & +[\text{W}((W_1\text{C}w_i\ .\ W_1\text{WC}w_i) + (W_2\text{C}w_i\ .\ W_2\text{WC}w_i) + (W_3\text{C}w_i\ .\ W_3\text{WC}w_i) \\ & +(W_4\text{C}w_i\ .\ W_4\text{WC}w_i))] + [\text{T}((T_1\text{C}w_i\ .\ T_1\text{CC}w_i) + (T_2\text{C}w_i.\ T_2\text{TC}w_i) + (T_3\text{C}w_i\ .\ T_3\text{TC}w_i))] \\ & +[\text{M}\ ((M_1\text{C}w_i\ .\ M_1\text{MC}w_i) + (M_2\text{C}w_i\ .\ M_2\text{MC}w_i))] \end{aligned} \tag{9}$$

Based on the resulted LSIAI, the produced maps were divided into five categories by using "natural interval ArcView" classification method according to five FAO classifications for irrigated agriculture. The seven generated combined suitability maps for the seven selected crops were overlaid with protected areas, urban centers and forestry maps. In this study and for all crops, built-up and industrial areas, mangrove, not determined land and communication facility areas are considered as unsuitable for irrigated agriculture, while other land-use classes vary according to the crop's type. These three layers were treated as unavailable land for irrigated agriculture even if the results show that the area is highly suitable for selected crops.

Table 8. The CRs and weights for different pairwise matrices for the date palm crop.

Goal	Main Criteria	Weight	CR	Criteria	Weight	CR	Sub-Criteria	Weight	Category	CR	Total Weight
Land Suitability for Irrigated Agriculture-LSIAI-date palm	Soil Capability	0.305	0.33	Soil Texture	0.311	2.50	Sand	0.724	S1	6.8	0.068631
							Sandy Loam	0.193	S2		0.018321
							Clay	0.083	S3		0.007819
				Soil Moisture, mm/m	0.28		>140	0.900	S1	0	0.076831
							<140	0.100	S2		0.008494
				Soil Salinity (dS/m)	0.342		0–2	0.579	S1	9.9	0.060302
							2–8	0.233	S2		0.024240
							8–16	0.152	S3		0.015878
							>17	0.036	N1		0.003798
				Soil Depth, m	0.067		>2 m	0.900	S2	0	0.018385
							<2 m	0.100	N1		0.002033
	Climate	0.298		Precipitation, mm per year	0.624	1.9	>600	0.615	S2	6.8	0.114212
							500–600	0.319	S1		0.059168
							<500	0.066	S3		0.012218
				Temperature, °C	0.239		20–32	0.449	S1	7.9	0.031957
							32–38	0.298	S2		0.021163
							38–56	0.185	N1		0.013172
							zero to 7	0.034	S3		0.002406
							>56	0.034	N2		0.002406
				Relative Humidity, %	0.137		37–77%	0.900	S1	0	0.036818
							<37, >77%	0.100	S2		0.004070
	Water Resources	0.314		Groundwater Availability	0.354	0.9	Common	0.558	S1	6.3	0.062180
							Moderate Probability	0.267	S2		0.029767
							Low Probability	0.133	S3		0.014804
							None or rare	0.041	N1		0.004610
				Groundwater Salinity (ppm)	0.432		<7630	0.616	S1	5.5	0.083714
							7630–12,530	0.241	S2		0.032737
							12,530–22,400	0.098	S3		0.013306
							>22,400	0.045	N1		0.006045
				Distance to Desalinated Water (m)	0.109		0–10,000	0.558	S1	6.3	0.019179
							10,000–20,000	0.267	S2		0.009182
							20,000–30,000	0.133	S3		0.004566
							>30,000	0.041	N1		0.001422
				Distance to TSE (m)	0.104		0–10,000	0.558	S1	6.3	0.018284
							10,000–20,000	0.267	S2		0.008753
							20,000–30,000	0.133	S3		0.004353
							>30,000	0.041	N1		0.001356

Table 8. *Cont.*

Goal	Main Criteria	Weight	CR	Criteria	Weight	CR	Sub-Criteria	Weight	Category	CR	Total Weight
	Topography	0.046		Aspect	0.581	0.4	NE, flat area	0.764	S1	6.8	0.020428
							N, E, SE,	0.167	S2		0.004456
							W, NW, SW	0.069	S3		0.001853
				Slope %	0.309		<10%	0.900	S1	0	0.012804
							<140 mm/m	0.100	S2		0.001416
				Elevation, m	0.109		392–1500	0.724	S1	6.8	0.003639
							<392	0.193	S2		0.000971
							>1500	0.083	S3		0.000415
	Management	0.037		Soil Suitability	0.667	0	Most Suitable	0.537	S1	8.8	0.013414
							Moderately Suitable	0.235	S2		0.005871
							Marginally Suitable	0.143	S3		0.003557
							Currently Unsuitable	0.052	N1		0.001293
							Unsuitable	0.033	N2		0.000823
				Land use	0.333		Agricultural Land	0.642	S1	5.2	0.008010
							Forestry and Rangeland	0.221	S2		0.002764
							Waste Disposal & Stable	0.086	S3		0.001078
							Buit-up Area, Mangrove, Commercial and Cemetery	0.050	N1		0.000627

Table 9. Main criteria, criteria, and sub-criteria used to calculate LSIAI in Equation (9).

Acronym	Full Name	Acronym	Full Name	Acronym	Acronym	Acronym	Full Name	Acronym	Full Name
S	Weight index of Soil capability main criteria	C	Weight index of Climate main criteria	W	Weight index of Water main criteria	T	Weight index of Topography main criteria	M	Weight index of Management main criteria
S_1Cw_i	Weight index of soil texture criteria	C_1Cw_i	Weight index of precipitation criteria	W_1Cw_i	Weight index of groundwater criteria	T_1Cw_i	Weight index of aspect criteria	M_1Cw_i	Weight index of soil suitability criteria
S_1SCw_i	Weight index of texture sub-criteria	C_1CCw_i	Weight index of precipitation sub-criteria	W_1WCw_i	Weight index of groundwater sub-criteria	T_1CCw_i	Weight index of aspect sub-criteria	M_1MCw_i	Weight index of soil suitability sub-criteria
S_2Cw_i	Weight index of soil moisture	C_2Cw_i	Weight index of temperature criteria	W_2Cw_i	Weight index of groundwater salinity criteria	T_2Cw_i	Weight index of slope criteria	M_2Cw_i	Weight index of land use criteria
S_2SCw_i	Weight index of moisture sub-criteria	C_2CCw_i	Weight index of temperature sub-criteria	W_2WCw_i	Weight index of groundwater salinity sub-criteria	T_2TCw_i	Weight index of slope sub-criteria	M_2MCw_i	Weight index of land use sub-criteria
S_3Cw_i	Weight index of soil salinity	C_3Cw_i	Weight index of relative humidity criteria	W_3Cw_i	Weight index of desalinated water availability criteria	T_3Cw_i	Weight index of elevation criteria		
S_3SCw_i	Weight index of salinity sub-criteria	C_3CCw_i	Weight index of relative humidity sub-criteria	W_3WCw_i	Weight index of desalinated water availability sub-criteria	T_3TCw_i	Weight index of elevation sub-criteria		
S_4Cw_i	Weight index of soil depth			W_4Cw_i	Weight index of TSE availability criteria				
S_4SCw_i	Weight index of depth sub-criteria			W_4WCw_i	Weight index of TSE availability sub-criteria				

3. Results and Discussions

3.1. Output Maps for Land Suitability for Irrigated Agriculture

The final suitability maps are presented in Figure 4. Results show that Jojoba and Sorghum are the most suitable crops for large-scale plantations in the Emirate with 25% and 18% of the total land are most suitable for these crops plantation, respectively. Followed by the Date Palm, Fruits and Forage with the percentage of the total land that is most suitable for these crops plantation was 15%, 16% and 14%, respectively. However, vegetables and cereals crops are the least preferable crops as the total area that is most suitable for these two categories is limited to 7% of the total area of the Emirate. Details of the percentages and total areas of different suitability categories per crop are summarized in Table 10.

Table 10. Percentage and areas of different land suitability categories per crop (area is in hectare).

Land Suitability Category	Date Palm		Vegetables		Fruits		Cereals		Sorghum		Forage		Jojoba	
	Area/Ha	%	Area/Ha	%	Area/Ha	%	Area/Ha	%	Area/Ha	%	Area/Ha	%	Area/Ha	%
S1	867,477	15	405,574	7	936,917	16	406,374	7	1,035,275	18	825,664	14	1,425,119	25
S2	867,477	15	732,286	13	2,246,343	39	1,162,680	20	1,198,128	21	2,035,884	36	3,212,172	56
S3	1,701,156	30	2,715,090	47	959,493	17	914,341	16	732,835	13	1,017,942	18	995,321	17
N1	1,825,082	32	1,239,253	22	451,526	8	2,223,767	39	2,024,022	35	1,402,498	25	22,621	0
N2	461,903	8	630,892	11	1,128,816	20	1,015,934	18	732,835	13	441,108	8	67,862	1

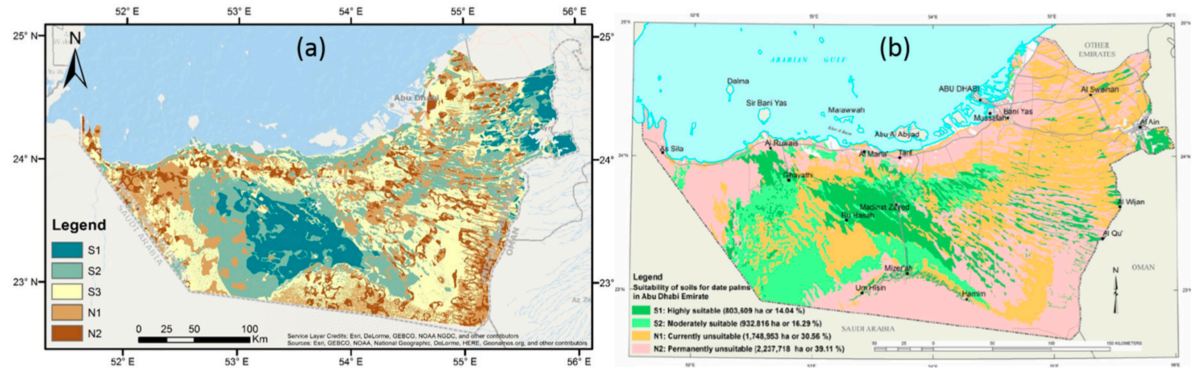

Figure 4. Land suitability maps: (**a**) obtained using AHP-GIS method and (**b**) prepared by the EAD, 2009.

3.1.1. Date Palm

Figure 4a shows the results of the land suitability assessment for Date Palm plantations based on the identified sixteen criteria and their sub-criteria. The main critical factors influencing date palm yield are the scope of irrigation by groundwater, groundwater salinity, soil texture, soil depth, rainfall and temperature. The areas close to Al-Ain city and near Liwa Oasis (Figure 1) are the most suitable for date palm plantations, because of groundwater availability and the suitability of the soil depth and texture in these areas. The coastal area is unsuitable due to high soil salinity and very limited scope of using fresh water for irrigation. Date palm survives in soil containing 3% soluble salts but will not grow if it goes above 6%. Date palm plantations depend on the sustainability of the water resources supply, the quality of the water available for irrigation and the distance of the water resources to the capable soil. The presence of desalination plants in different areas enhances the suitability of date palm plantations in different areas. Nevertheless, as the majority of desalination plants are coastal, those were counter-balanced by high soil salinity as indicated in the resulted suitability map.

To verify the outcome of the obtained date palm map (Figure 4a), a comparison with the similar map is needed. A study on the application of the UAE Soil Information System (UAESIS) to generate suitability maps for different purposes was conducted in 2014 [14] presented a suitability map for date palms in the Emirate (Figure 4b), using a multi-criteria decision making approach to integrate

8 criteria (bedrock depth, water table depth, surface salinity, subsurface salinity, gypsum, texture, slope and relief). A comparison between the geographic locations of the different categories generated by the UAE SIS and the Land Suitability Map generated by this study shows that the "highly suitable land" and the "moderately suitable lands for irrigated agriculture" are already being used for irrigated agriculture. According to the UAESIS study, it has been estimated that around 14% of the soil is highly suitable for date palms, while only 16.29% of the soil is moderately suitable, unsuitable soil represented 30.56% and the permanently unsuitable represented 39.11% of the soil. The comparison of the obtained extent of suitability classes to the one inferred from the official maps generated by EAD reveals a strong agreement as elucidated in Table 11. The main methodological differences between the two products are the number of categories while the percentages for the most suitable and moderately suitable classes are close to 0.96% and 1.29% difference and the number of criteria used. However, the use of non-conventional water resources in this study increased the suitability of land for date palm plantation in some areas that were considered unsuitable in the UAE SIS study. Hence, areas classified as marginally suitable in this study (around 30% of the total area) were completely absent in the UAESIS study.

Table 11. The distribution of the five categories of land suitability for date palm plantation scores Tor the EAD maps and this research map.

Land Suitability Category		AED Map [14]		This Study Map		Difference %
		Area	%	Area	%	
Most suitable	S1	803,609	14.04%	867,477	15%	0.9600%
Moderately suitable	S2	932,816	16.29%	867,477	15%	−1.2900%
Marginally suitable	S3	-	-	1,701,156	30%	30%
Not suitable	N1	1,748,952	30.56%	1,825,082	32%	1.4400%
Permanently not suitable	N2	2,237,718	39.11%	461,903	8%	−31.1100%

For further verification of the obtained suitability map, the current extent of farms and agriculture in the Emirate of Abu Dhabi was inferred using Worldview high-resolution imagery (Figure 5). The delineated farmed lands are in agreement with the extent provided by the Abu Dhabi Spatial Data Infrastructure Public Geospatial Portal. A total of around 4200 km^2 of farmed land was calculated distributed mainly in the western region around the Liwa Crescent and in Al-Ain and along the Abu Dhabi- Al-Ain road. Date palm trees are mainly distributed in the Liwa Crescent area which explains the significant overlap between the delineated agriculture and farms and suitability classes 1 and 2 of palm dates (Figure 5). One can also notice the existence of plantation on the Western side of the Liwa Crescent that does not match with the highly and moderately suitable lands. This could be attributed to possible errors in soil classification or the existence of other sources of water that are not accounted for in this study like deep-wells pumping. Nevertheless, the obtained extent of highly suitable (S1) and moderately suitable (S2) lands in the case of date palms stretch beyond their actual extent (Figure 5) which indicates a significant potential of expanding the present farmed land beyond their current limits when accounting for the non-conventional water resources. The use of the delineated lands to their full potential by expanding the plantation of date palms where highly and moderately suitable areas require a substantial investment in infrastructure, namely pipelines to channel the needed water for irrigation and roads to reach the identified lands. A feasibility study that should involve an economic analysis should be performed to prioritize the development of the identified highly and moderately suitable lands which stretches over 1,734,954 ha. If the required investments in infrastructure are made and assuming a yield of 7.18 tons/ha, the total production could reach 12,459,251 tons per season which are approximately 18 fold higher than the current production of 671,891 tons in 2016 [103].

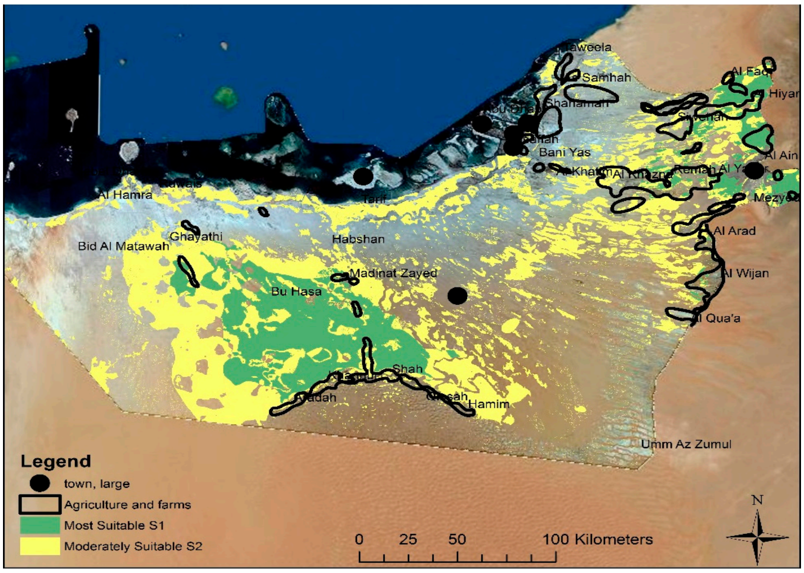

Figure 5. Comparison of the actual extent of agriculture and farms in the Emirate of Abu Dhabi to suitability classes 1 and 2 for date palms.

3.1.2. Suitability Maps for Other Crops in the Study Area

It is important to generate suitability maps for other crops although date palms are dominant in the UAE. However, in the absence of other studies addressing land suitability for other crops, it is not possible in this study to verify the outcomes of the AHP-GIS method in the case of other crops unlike the case of the palm dates addressed above. The developed maps are analyzed spatially with respect to the criteria and sub-criteria used to develop each of them, which addressed in the following sections.

The resulting maps show that only 7% of the total land is most suitable for vegetable plantation, while 13% of the area is moderately suitable and 47% are marginally suitable as shown in Figure 6a. Table 2 specifies the needed climate, topography, soil and water for vegetable plantation. For a vegetable, the temperature is a critical factor, in addition to soil salinity, soil texture, precipitation and the quantity and salinity of water available for irrigation. Vegetables bloom in loamy, loamy sand soil, with limited or no slope. They also require a moderate temperature, high precipitation >3600 mm and relative humidity less than 50%. Vegetables can tolerate up to 4480-ppm water salinity and less than 1.2 millimhos/cm at 25 °C soil salinity. The determination of vegetable suitability maps lacks most of the required data. Therefore, as shown in Figure 6a, only the areas presented by lowlands are moderately suitable, as it contains preferable soil texture and groundwater levels.

Fruits come up well on soils having low soil salinity, coarse loam, loamy sand and fine loam with a soil depth of 90 cm and more. Elevation should be between 1066 and 1828 m and land slope ranges between 2% and 12%. Fruits also cannot survive with high water salinity; they prefer a water salinity of <250 ppm but can stand up to 3000 ppm (see Table 2 for fruits requirements). The use of TSE and desalinated water was considered in fruit plantations, thus increasing the land suitability for irrigated agriculture. In the study area, the land in the central and eastern part of the Emirate is the most suitable for fruit plantations, with 16% of the total area most suitable, 39% moderately suitable and 17% marginally suitable as shown in Figure 6b.

Results show that lands in the Emirate do not favor cereal plantation, with only 7% of the total land most suitable, 20% moderately suitable and 16% marginally suitable. Limitations of drainage, climate, soil capabilities and water resources render lowlands in the central part of the Emirate highly to marginally suitable, with 39% of the land unsuitable and 18% permanently unsuitable as shown in Figure 6c. Soil moisture is an overriding factor for cereal plantation and production [104].

Cereal plantation is also affected by soil salinity, soil texture, soil depth, surface slope, elevation, the scope of water supply and water salinity [105].

For sorghum, factors affecting yields are rainfall, temperature, slope, soil salinity, soil depth and soil texture. If water is provided from desalination facility or TSE, as proposed in this study, around 18% of the total area is considered most suitable for sorghum plantation. These areas are located in the central and eastern parts of the Emirate. The possibility to use TSE for irrigation increases the total areas suitable or moderately suitable for sorghum plantation. Sorghum needs a little amount of water as low as 40–45 cm of precipitation during the growing season [106]. If treated sewage effluent provides this amount of water that would help to increase the total area suitable for irrigation (Figure 6d).

The possibility of using TSE for irrigation increased the total area suitable for forage plantation. Forage plantation can serve two purposes; it provides fodder, which would help the country in achieving its food security goals and increased green vegetation cover that provides a climate change mitigation mechanism. Around 14% of the total area is most suitable while 36% is moderately suitable and 18% is marginally suitable, as presented in Figure 6e. The 14% most suitable lands are mainly located in the eastern and central part of the Emirate. Soil moisture, temperature, soil salinity, relative humidity and quantity of TSE available for irrigation are the major factors influencing forage yield [107].

Jojoba grows in the soil of marginal fertility, needs little water, withstands salinity and does not seem to need fertilizers or other chemical treatment [108]. It prefers light, coarsely textured soil with good drainage and good water penetration and can withstand high soil salinity [109]. However, soil depth is a limiting factor. Due to these adaptation characteristics of the plant, more than 56% of the total land is classified as moderately suitable, 25% highly suitable and 17% marginally suitable, as presented in Figure 6f.

Considering desalinated water and the TSE as the two main water sources in the study area makes a large-scale plantation of this shrub viable and potentially feasible. The Emirate has more than 70 major desalination plants, many of which are seawater desalination plants that could be used to provide a sustainable and technically and economically feasible source of water for irrigation. Furthermore, the annual production of TSE is about 450 million cubic meters, which is about 7.2% of the total Emirate water production [44]. However, only 60% of the treated water is used in wetlands, landscaping and recreation areas as per the capacity of the distribution system after treatment [109]. The amount of TSE to irrigate food crops is around 27 million liters per day, which is used in 220 farms across the Emirate [110].

Another benefit of selecting this shrub could be the possibility of using its trimmed spare biomass to produce the necessary heat to run desalination plants, similar to the research on *Jatropha curcas* [111]. They estimated that it would take around 3 years before jatropha would provide enough spare biomass in the form of trimmings to produce the necessary energy to power the desalination plant. Therefore, large-scale plantations of Jojoba can be used for climate change mitigation mainly through carbon sequestration. In Oman, [111] reported that large-scale planting of jatropha can have major effects at regional scale as those effects are produced by subsidence caused by the Hadley circulation and the substantial horizontal moisture transport due to humid air advected from the south over the Arabian Sea, mainly in the summer. Several drought-resilient and salt tolerant trees (such as *Jatropha curcas*, *Moringa oleifera* and *Eucalyptus camaldulensis*), shrubs (such as *Simmondsia chinesis* and *Ricinus communis*) and reeds and grasses (such as *Arundo donax L* and *Miscanthus x giganteus*), have been reported to accumulate an above ground biomass between 5 and 25 tone dry mass per ha per year [112]. This is equivalent to 2.4–12 tons of carbon per ha per year [113].

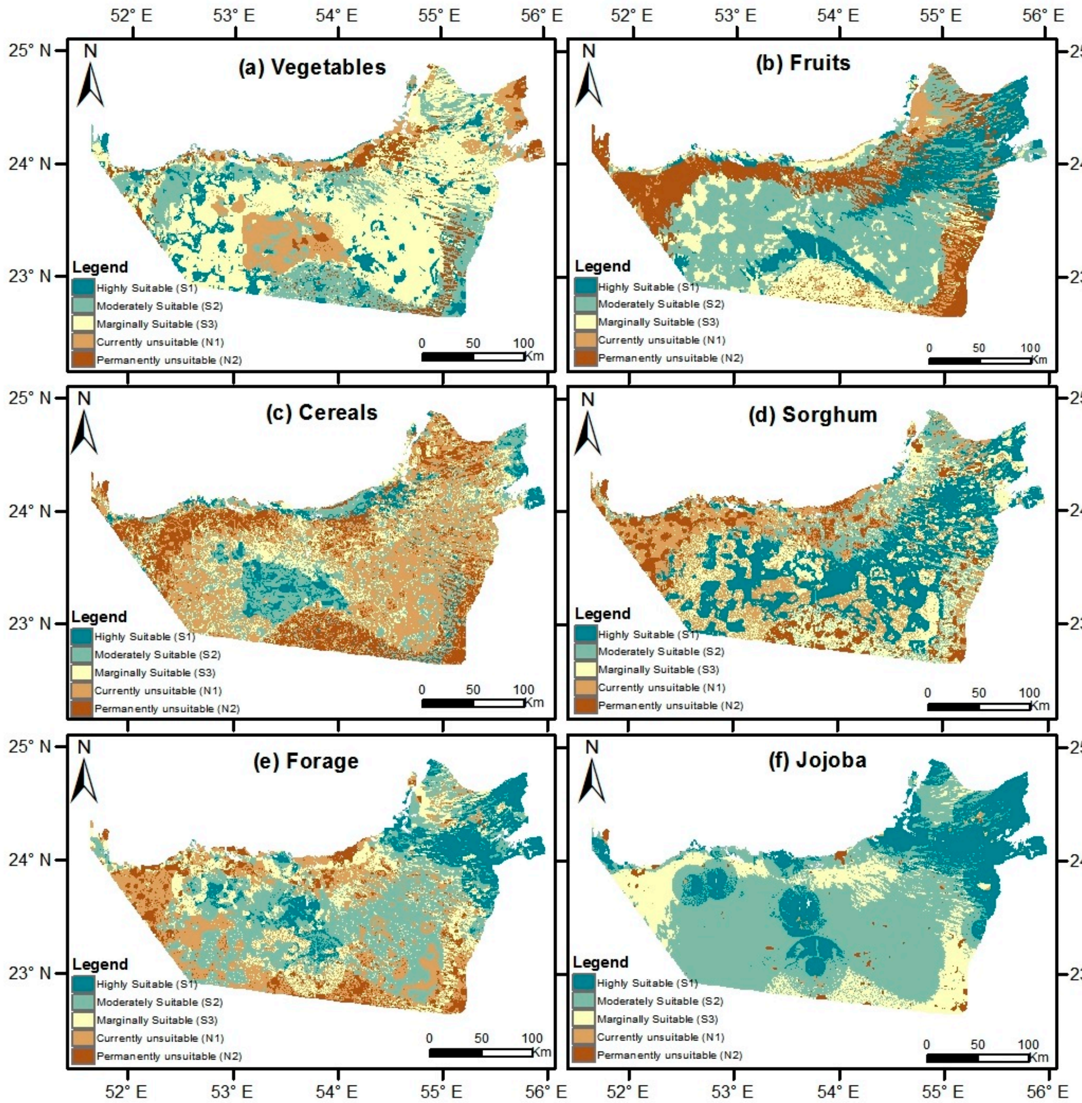

Figure 6. Land suitability for irrigated agriculture maps in the Emirate of Abu Dhabi per crop: (**a**) Vegetables; (**b**) Fruits; (**c**) Cereals; (**d**) Sorghum; (**e**) Forage; and (**f**) Jojoba.

3.2. Sensitivity Analysis of the AHP-GIS Technique

A sensitivity analysis of the AHP-GIS technique was conducted to determine the robustness and feasibility of its outcomes [114] and define the level of importance of each criterion to reduce the subjectivity of weights [115]. To perform the sensitivity analysis, the initial input weights assigned to selected criteria were changed. Changing the weights for one criterion, one at a time, without making any changes to all other criteria led to changes in the overall priorities of the alternatives which would allow for a comparability of the results. For this purpose, we considered all critical criteria to determine land suitability for date palm crop (rainfall, the scope of irrigation by groundwater, groundwater salinity, soil texture, soil depth and temperature). We analyzed the impact of increasing each criterion weight (to 20%), one at a time and calculate the changes in the total area per category.

Figure 7 presents the percentage area calculated of land suitability classes that were conducted to interpret the output of the sensitivity analysis for the different scenario. Results show that there is a change in the five categories of land suitability for Date Palm plantation. Increasing the weights of the six criteria, one-at-a-time, had a strong increasing or decreasing the effect of the suitability pattern in the study area, mainly on class (S1), the most suitable class and class (N1) as and (N2) as presented in Figure 8.

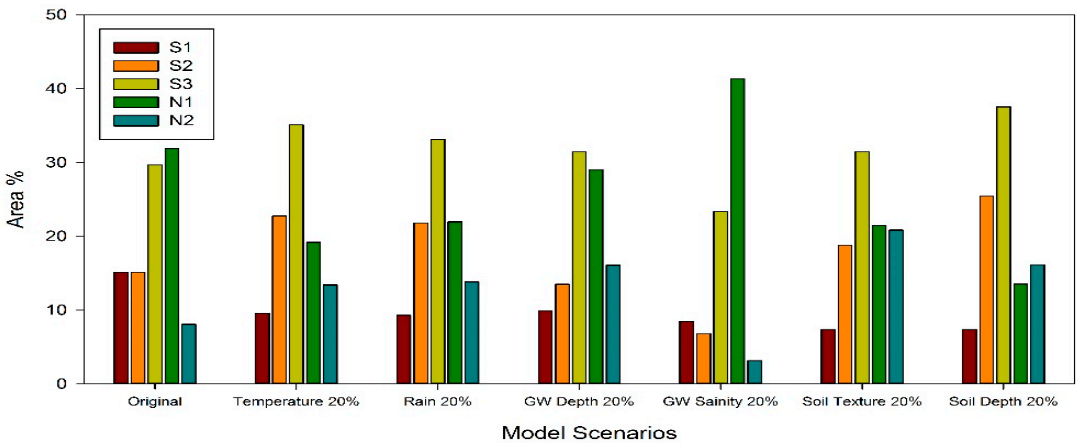

Figure 7. The area of land suitability classes for different scenarios.

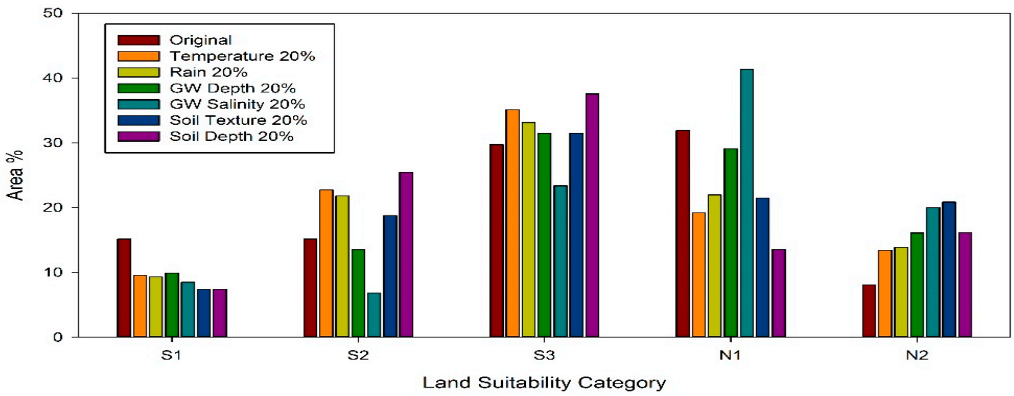

Figure 8. Changes in area percentages per land suitability categories under different scenarios.

The percentage area calculated for each criterion based on the results of variation of function are summarized in Table 12. One can observe how the suitability patterns changed with variations in the weighting schemes for the most critical criteria. Under the current climate conditions, food availability and stability is a major concern for the UAE [116,117]. With temperature increasing and precipitation and soil moisture decreasing in the Emirate of Abu Dhabi [118], freshwater availability for crop production which is already low will continue to decrease further in the future [119]. The sensitivity analysis shows that suitability patterns change with variations in the weighting schemes. Any increase in the temperature and decrease in precipitation will lead to decrease in soil moisture and groundwater availability and average irrigation requirements will increase [120]. Consequently, the assigned suitability category corresponding to the criteria thresholds will change and thus the weights leading to a decrease of areas with high and moderate suitability for irrigated agriculture. These findings will support national efforts in defining best ways to improve land suitability for irrigated agriculture. The UAE has initiated several programs to enhance rainfall with the aim of increasing water security through a combination of geoengineering and weather modifications techniques through the UAE Research Program for Rain Enhancement Science (https://www.uaerep.ae). If national efforts succeeded, weights of related criteria like soil moisture and rainfall availability will change, consequently and based on the above-discussion, the total area mostly or moderately suitable for irrigated agriculture will substantially increase.

Table 12. Percentage area calculated for each criterion based on the results of variation of function.

	Original	Temperature = 20%	Rain = 20%	Groundwater Depth = 20%	Groundwater Salinity = 20%	Soil Texture = 20%	Soil Depth = 20%
S1	15%	10%	9%	10%	8%	7%	7%
S2	15%	23%	22%	14%	7%	19%	25%
S3	30%	35%	33%	31%	23%	31%	38%
N1	32%	19%	22%	29%	41%	21%	14%
N2	8%	13%	14%	16%	20%	21%	16%

4. Conclusions

This study successfully implemented an integrated AHP-GIS model as an advanced and comprehensive MCDM approach to evaluate and define a land capability for irrigated agriculture suitability. The study was used to derive several AHP structures and suitability maps based on a significant number of criteria encompassing climate, water resources, topography, soil characteristics and land management. The inputs criteria were evaluated using AHP pairwise comparison matrix per crop. The highest capability weights, as presented in the resulted maps, were mostly found in areas of highly capable soils and in areas close to water resources (groundwater, desalination facilities and TSE). Moreover, comparisons of the date palm derived map and the Environment Agency-Abu Dhabi map indicated small disagreements, demonstrating the effectiveness of the AHP-GIS-based method.

Land in the central and eastern part of the Emirate has the highest capability weights (scores), confirming that current agricultural farms were developed on highly capable land. The selection of seven different crops provided a good indication of how suitability maps vary as a result of the different crop requirements, which are presented by different decision-making perspectives (AHP). For vegetables and cereals plantation, output maps indicate that areas of excellent suitability are limited and not exceeding 7% for each crop. Those suitable lands are close to agricultural zones, water resources and proper soil texture and moisture. Jojoba and sorghum output maps indicate the largest area of excellent suitability for those two crops productions, due to their ability to adapt to harsh environmental conditions and their limited need for continuous and excessive irrigation. When comparing all output maps, jojoba and sorghum present the most suitable crops, followed by date palm, fruits and forage and finally vegetable and cereals.

The inclusion of non-conventional water resources altered the classification of some areas making them suitable for irrigated agriculture. Consideration of defining a suitable area for large-scale plantation for specific crops that are tolerant to a harsh climate like jojoba is also incorporated.

Finally, this study is the first of its kind in the UAE to define a set of findings that will determine whether large-scale plantations are recommended for the UAE. It is the first study to identify the kind of crops that have the highest potential to adapt to the hot and dry weather without affecting the crop yield that ensures the sustainable use of the limited groundwater resources. According to the government's draft food diversification strategy (planned to be published soon), there is an urgent need to develop land suitability maps for irrigated agriculture in the UAE. This work corresponds directly to the requirements of the government of Abu Dhabi and provides a good evidence of the applicability of the AHP-GIS method to encompass a very large number of input criteria (16) and sub-criteria (80) in comparison with other commonly used multi-criteria methods. To our knowledge, this is the first paper to use AHP-GIS to cover 16 criteria, 80 sub-criteria and for seven crops.

Future work of this study is to cover other plants and Emirates. Additional plants such as *Jatropha*, *Sporobolus virginity* and *Distichlis spicate* should be considered in future research. Furthermore, a detailed analysis should be undertaken on the potential of these plants for carbon sequestration, energy production for desalination plants in remote areas and their contribution to evapotranspiration and large-scale climate processes. In addition, the focus should be on expanding the analysis to the rest of the UAE and the Arabian Peninsula and analyzing the impact of changes in climate conditions in the region on the suitability maps of different plantations, which should lead to a better understanding of the impact on food security and the sustainable use of natural resources in regional and local level.

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