A field survey suggests changes in oasis characteristics in the Kebili region of Southern Tunisia

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Abstract

Since their establishment, "traditional" oases have been known to be three-layered, while modern oases have been organized from their outset with one layer only of 'Deglet Nour' date palm cultivars. However, these definitions may no longer apply for Kebilian oases. A survey was therefore carried out on a random sample of 52 plots in Kebilian oases ("traditional" n=26 and "modern" n=26) to investigate the current situation. The data collected were analysed by the Pivot Tables method and a Chi-2 test of independence, and by a Multiple Component Analysis completed by an Ascending Hierarchical Classification analysis to characterise and classify each oasis type. Our results showed that "modern" oases have greater crop diversity than expected and can be organized in two or three-layer oases. In contrast, high crop diversity and the three vertical layers were found to be less frequent than expected in "traditional" oases. Our investigation found water availability in the oases, and irrigation frequency, to be the key factors of Kebilian oasis layout and typology changes. Agro-biodiversity losses could jeopardize the sustainability of the oasis system in "traditional" oases.

Keywords: *Survey, Traditional oasis, Modern oasis, Monoculture, Agro-biodiversity.*

1. Introduction

Oases are anthropized and cultivated medium-sized or small-sized spaces within vast dry climates, and even desert areas, near natural or artificial rivers. They are therefore found in most of the large dry regions of the world: around the Sahara, in the Maghreb as well as in the Sahel, in the Middle East, on the west coast of Latin America and in central Asia (Jouve, 2012; Yi *et al*., 2015; Zhao *et al*., 2010). In Tunisia, oases cover a total area of 54,000 ha divided into 4 governorates: Kebili, Tozeur, Gabes, and Gafsa, with Kebili having the largest area at 36,000 ha of oases (Ben Ahmed Zaag, 2017). Tunisian oases can be classed in 3

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different types according to their geographical location: (1) mountainous oases (6% of total oases, 5% of them in Gafsa), (2) coastal oases (17% of total oases with 13% in Gabes), and (3) continental or Saharan oases (67% in Kebili and 16% in Tozeur) (Ben Ahmed Zaag, 2017; MALE , 2016). Oases can also be classed as "traditional" or "modern" depending on their history, type of cropping system and governance. Overall, there are 267 oases in Tunisia divided into 126 "traditional" oases (53%) and 141 "modern" oases (47%) (CDCGE, 2017). Oases account for 9% of the total irrigated land in Tunisia, 0.8% of the country's agricultural land, and 30% of the irrigated tree area. (CDCGE, 2015).

"Traditional" oases have small-sized farms based on irrigated split-plots with a high density and varietal diversity of date palms and fruit trees (more than 200 trees per ha), and a high diversity of species typically organized in three vertical layers. "Traditional" oases place emphasis on self-consumption, with little openness to the socio-economic environment (Ben Ahmed Zaag, 2017; CDCGE, 2017). They are usually managed in agricultural development groups (GDA) involving hundreds of farmers. The GDA are usually the associations that are responsible for water irrigation distribution management in the oasis (Carpentier and Gana, 2017). In comparison, "modern" oases are larger in size, with a lower palm density (100 to 150 per ha), mainly based on monocultures of lucrative date cultivars (e.g. 'Deglet Nour') that are organized in a single vertical layer. "Modern" oases have dominant production relations of the wage type, and a direct way of asserting and opening up to input and product markets (Ben Ahmed Zaag, 2017; CDCGE, 2017). This dichotomy between "traditional" and "modern" is acknowledged and relevant. However, it is subject to disputes and disagreement between different authors. In both types of oases the water resource has the same origin, namely deep water tables from the Terminal Complex and Continental Intercalary (Ezzine *et al.*, 2016).

Since antiquity, date palms have existed in the Nefzaoua region (Southeastern Tunisia) (Héridote, 2003) and the Tunisian oases that initially developed around the natural water sources of southern Tunisia have turned into agricultural ecosystems enjoying great biodiversity, developing thanks to the specific know-how of the oasis population passed down from father to son (Zmerli and Bennouna, 2015). These oases are ecosystems that express the ingenuity of the local populations, who have managed to take advantage of the lower water possibilities offered by the natural environment to create spaces particularly rich in biodiversity and clearly distinct from the surrounding desert and steppe environment (CDCGE, 2017). The system of arranging crops in irrigation planks is very common in the Tunisian Saharan oases. On the ground, the cultivated and irrigated surface is delimited in planks (Battesti and Puig, 1999). Usually, lands in oases are occupied by date palms joined with Mediterranean fruit trees, vegetables and fodder crops for animal husbandry. During more than centuries of cultivation, several cultivars turned autochthone and participated in the enrichment of huge genetic and agronomic heritage that describes this system, distinguished by a single terroir (Peano *et al.*, 2021). These oases are the "traditional" ones and have developed systems for arboriculture, vegetables, forage, diversified and tiered crops, associated with small livestock. Alongside all their natural, cultural and heritage richness, Tunisian oases offer natural landscapes forming an ecotourism product of great value (Zmerli and Bennouna, 2015). In many oases and especially the "traditional" ones, there is strong fragmentation of the property explained by the division of lands between brothers after the death of the parent owner and which is usually created difficult social and relational approaches (Peano *et al.*, 2021). Nevertheless, the same authors added that it is very frequent that farmers are owners of many plots (2 or 3) that could not belong to the same GDA. Since the 1970s, newly created "modern oases", launched by large farms, have emerged based exclusively on the 'Deglet Nour' date palm, with well-aligned and regularly distributed palms, relying mostly on drilling for irrigation. This was the result of what was identified by Carpentier and Gana (2017) for the Tunisian oases, a process of de-territorialization that was related to the expansion of agribusiness, export-oriented intensive farming built on the model of patrimony valorization of oasis resources that participate to restore the diversified family farming systems. That was also included in strategies to enhance the incorporation of the Tunisian economy into global markets, especially along with the intensification of agricultural exports (Carpentier and Gana, 2017). This participated in the consolidation of the sector of large companies producing and exporting Deglet Nour dates (Carpentier and Gana, 2014). This change had created a strong transformation in the resource control operations leading to change in the sociospatial logic and the performance of these agricultural territories (Peano *et al.*, 2021), which are manifested in contrasting dynamics (Carpentier and Gana, 2014). In Kebili, there are 41 "traditional" oases (GDAs) and 71 "modern" oases (The World Bank, 2018) occupied by 3 million date palms ('Deglet Nour' and common cultivars) and accounting for almost 50% of the total date palms in Tunisia (CTD, 2021).

According to climate predictions, Kebili will be among the warmest regions in Tunisia by the end of the century and will lose almost all the chill accumulation (Benmoussa *et al.*, 2020) needed for the agricultural production of most fruit tree species. The soils of the Kebilian oases are also suffering from an increasing loss of fertility, which is exacerbated by saline irrigation water due to increased water table salinity (Ezzine *et al.*, 2016). Consequently, climate severity, along with the degradation of soil and water resources, combined with the repeated partitioning of cultivated plots, could threaten the development and agro-biodiversity of Kebilian oases. To our knowledge no studies have yet clarified the consequences for, and the evolution of, "traditional" and "modern" oases over time. To strengthen this evidence, we therefore undertook a field survey to investigate the actual situation in the "traditional" and "modern" oases of the Kebili governorate. Our study also set out to present a description and an updated typology of the diversity of the current oasis systems.

2. Methodology

2.1. *Study site and data collection*

During this study, a survey was carried out in September 2020 on a random sample of 52 plots equally distributed between "traditional" (n = 26) and "modern" (n = 26) oases owned by 38 farmers in the Kebili region located in Southeastern Tunisia. Several farmers exploit both a plot in the "traditional" oasis and another in the "modern" oasis, which is very common in the Kebili region. It should be noted that in our study, we reason at the plot scale, its characteristics, and its mode of governance. This is why we were interested in having more repetitions of plots rather than the farmers surveyed. Kebili region is characterized by severe climate conditions and belongs to the Saharan bioclimatic stage (MEAT, 1998), with annual rainfall ranging from 89 to 143 mm for 2008-2018 period (GDASD, 2020). Average monthly minimum temperatures varied between 4.6 and 24.7°C and average monthly maximum temperatures ranged between 17.1 and 39.2°C (National Institute of Meteorology, 2020). Sampling was focused on family farming and the plots were located in the different delegations of Kebili, such as Souk Al Ahad (Oum Somaa, Fatnassa), Faouar (Ghidma, Sabria), Douz Nord, Douz Sud (Nouaiel, Tarfaya), Kebili Nord (Tambar), Kebili Sud (Kelwemen and Blidette) and Rjim Maatoug (Figure S1, Supplementary material). The survey was used to collect data on the total cultivated land area, oasis type, and land ownership. We also collected data on agricultural practices and crops, including date palm cultivars, planting density, tree ages, number of layers, other species grown with date palms, irrigation water source, irrigation tools and irrigation frequency.

2.2. *Data analysis*

The data collected and the survey results were statistically analysed. The survey data and responses were analysed by the Pivot Table method, which is a grouped values table that assembles single items of a more complete table among one or more discrete categories and a relatively simple tool for data assessment using a derivable analysis of variable relationships (McKee, 2021).

This method therefore enables computing frequencies and percentages while crossing the variables. This was done using functions in two packages, "tidyverse" (version 1.3.0) (Wickham *et al.*, 2019) and "questionr" (version 0.7.4) (Barnier, 2020), included in the R programming environment (version 4.0.2) (R Development Core Team, 2020). We used a Pearson's Chi-squared (Chi-2) test to test the correlation between the studied variables. The Chi-2 test was also conducted using the R programming environment.

A Multiple Component Analysis (MCA) was also carried out to characterize each oasis type. This method is a factor analysis adapted to qualitative data that can be used to study relations between several qualitative variables. These variables were the oasis type, number of layers, cultivars, irrigation tools and water irrigation system. The age of the trees, the useful area, number of trees per hectare, the number of species and the number of date palm cultivars present in the plot were also used as additional quantitative variables. The MCA was completed by an Ascending Hierarchical Classification (AHC) analysis, which calculates indices of distances in ACM space and proposes plot clusters that share common properties. The Chi-2 test was also used to assess the link between the cluster variables and the categorical variables in the AHC. The results of the AHC were also expected to provide a statistical typology of the study plots. The MCA and AHC were performed using the R programming environment (version 4.0.2) (R Development Core Team, 2020) via functions of the two packages "FactoMineR" (version 2.4) (Husson *et al.*, 2020) and "Factoshiny" (version 2.3) (Vaissie *et al.*, 2020).

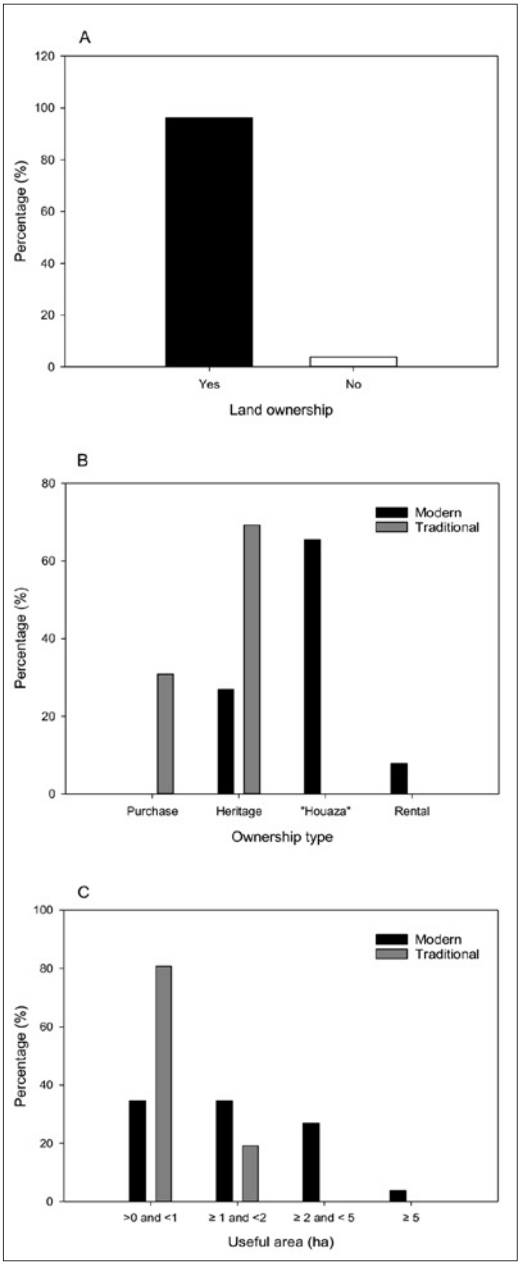
All these analyses enabled us to compare the two types of oases, determine their characteristics and classify the study plots.

3. Results

3.1. *Information about the land appropriation method*

Almost all the farmers claimed ownership of the land (96%) (Figure 1, A). However, the type of ownership differed, largely depending on the type of oasis. Almost 48.1% of farmers inherited their land, including 69.2% belonging to "traditional" oases and 26.9% to "modern" oases. Moreover, 32.7% of the farmers obtained the land by "Houaza", which mainly characterized 65.4% of the plots of "modern" oases (Figure 1, B). "Houaza" refers to lands

Figure 1 - Information about the land with A: Land ownership; B: Cross between oasis type and land ownership and C: Useful area.



in each village that are periodically voluntarily divided by the Steering Committee and allocated to each family or village. The farmers whose plots belong to the "modern" oases and are in the extensions had also bought land obtained initially by "Houaza". Furthermore, the farmers who obtained their land through "Houaza" declared ownership of their land and its acquisition by purchase. On the other hand, 15.4% of the farmers had bought their land and accounted for 30.8% of plots belonging to "traditional" oases (Figure 1, B).

A statistically significant association between cultivated area and the type of oasis was found (p-value of Chi-2= 0.002984). The plots belonging to "traditional" oases were the smallest, with 80.8% having an area of less than 1 ha (Figure 1, C). The plots that were part of "modern" oases had diverse areas and 65.4% of the plots had an area over 1 ha (Figure 1, C).

3.2. *Date palm cultivars, number of palms, and their age*

Whatever the oasis type, almost 51.9% of the plots were planted exclusively with 'Deglet Nour', and 48.1% of the plots were cultivated with 'Deglet Nour' and common cultivars (Figure 2, A). We chose to group cultivars other than 'Deglet Nour' in a single category called "common", because they are generally less well-known and less cultivated than 'Deglet Nour', and usually intended for self-consumption. Although the cultivated cultivars did not differ between the types of oases (p-value of Chi-2=0.09585> 0.05), the plots belonging to the "traditional" oases usually (61.5%) had both 'Deglet Nour' and a range of common cultivars (Figure 2, B). In contrast, 65.5% of the plots belonging to "modern" oases were exclusively planted with 'Deglet Nour' (Figure 2, B).

The most cultivated common cultivars in the "traditional" oases were found to be 'Rtob' (in 42% of plots), 'Alig' (in 38% of plots), and then 'Besser Helou' (in 15% of plots) (Table 1). Other cultivars also existed in these plots, but with lower occurrence (Table 1). In the plots of "modern" oases, the most frequent common cultivars were 'Alig' and 'Besser Helou' (both present in 15% of plots), but other cultivars were present at a lower frequency (Table 1).

The number of date palms was significantly associated with the type of oasis (p-value of Chi-2 <0.05). Over 50% of the plots belonging to "traditional" oases had 200 date palms. ha^{-1}. In contrast, most of the plots (88.5%) located in the "modern" oases had fewer than 200 date palms.ha^{-1} (Table 2).

The age of the date palms was significantly associated with the oasis type (p-value of Chi-2 <0.0001). In the plots of "traditional" oases, 73% of the date palms were over 40 years old. In contrast, in the plots of "modern" oases, 92% of the date palms were younger, between 8 and 40 years old (Table 2).

Figure 2 - Percentage of date palm cultivars grown in all the study plots (A) and "traditional" versus "modern" oasis plots (B).

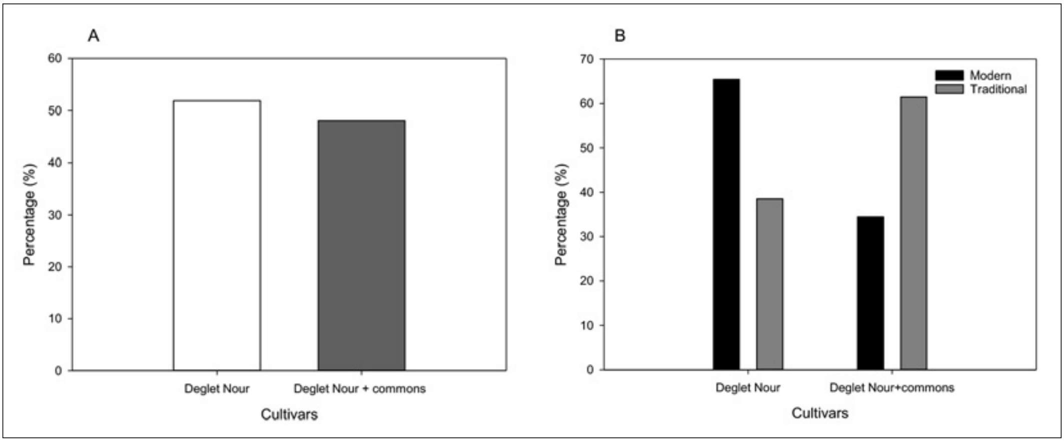


Table 1 - Common date palm cultivars grown with ‘Deglet Nour’ in each oasis type, the percentage of their occurrence and average cultivar number per plot.

Oasis type	*Common cultivars*	*Percentage of occurrence*	*Average cultivar number per plot*
“Traditional”	Rtob	42.31	2.3
	Alig	38.46	
	Besser Helou	15.39	
	Fazzeni	11.54	
	Ghars Souf	11.54	
	Horra	7.69	
	Galloul	3.85	
	Kenta	3.85	
	Kentich	3.85	
	Gosbi	3.85	
	Hammouri	3.85	
	Hissa	3.85	
	Ammari	3.85	
	Khalt	3.85	
	Choddakha	3.85	
“Modern”	Alig	15.38	1.8
	Besser Helou	15.38	
	Horra	7.69	
	Khalt	7.69	
	Rtob	7.69	
	Kenta	3.85	
	Gosbi	3.85	
	Arichti	3.85	
	Choddakha	3.85	
	Akhmet	3.85	
	Cheken	3.85	

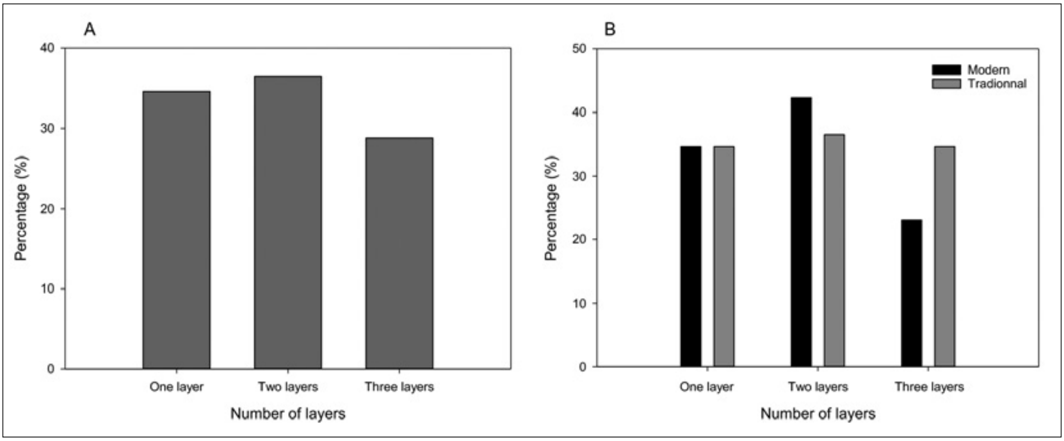
Table 2 - Number and age of date palms in all plots and those in “modern” and “traditional” oases.

	Number of date palms per ha				*Age of date palms*		
	>0 and <100	*≥100 and <200*	*≥200 and ≤300*	*≥300*	*Under 8 years*	*Between 8 and 40 years*	*Over 40 years*
“Modern”	15.4	73.1	11.5	0.0	7.7	92.3	0
“Traditional”	0.0	50.0	38.5	11.5	0	26.9	73.1
Total of all plots	7.7	61.5	25.0	5.8	3.8	59.6	36.5
Chi-2 p-value	0.007754				0.0000002603		

3.3. *Number of crop layers present in the plots*

Overall, 34.6% of the surveyed plots had only one vertical tree layer occupied by date palms, while 36.5% of these plots had two tree layers (Figure 3, A), frequently occupied by date palms and one or more fruit species. Only one of these plots was occupied by date palms and vegetable crops. Finally, 28.8% of these plots had the traditional three vertical layers (Figure 3, A) with date palms at the top, fruit tree species in-between, vegetable, and forage crops or cereals at ground level. The number of layers was not associated with the oasis type (Chi-2 p-value= 0.4822 > 0.05). The plots of the “tra-

Figure 3 - Percentage of layer numbers in all the study plots (A) and in "modern" versus "traditional" oasis plots (B).



ditional" oases had either one layer (34.6%), two layers (36.5%), or three layers (34.6%) (Figure 3, B). Similarly, plots of the "modern" oases mostly had two layers (42.3%), one layer (34.6%), and less frequently three layers (23.1%) (Figure 3, B).

According to the farmers' answers, in the plots of "traditional" oases pomegranate trees (54% of plots) and fig trees (35% of plots) were the most common fruit species, but there were also olives and grapevines in some of them (Table 3). The most common vegetable crops present in these plots were chard and onion (both present in 8% of plots) and some other vegetable crop species were also present (Table 3). Forage crops were generally alfalfa (15% of plots), oats (8% of plots), and triticale (4% of plots), along with barley, which was the main cereal grown in the "traditional" oases. Aromatic species were also found, such as mint and saffron (Table 3). In "modern" oasis plots, pomegranates, figs (43% of plots both) and olives (23% of plots) were also the most common fruit species, while grapevines and apple trees could be found in some of them (Table 3). Onion, potato, turnip and parsley were the most frequent vegetable crops in "modern" oasis plots, and alfalfa (19% of plots) and oats (11% of plots) were the most frequent forage crops. Barley was the main cereal grown in the "modern" oasis plots (11% of plots) (Table 3). In both oasis types, farmers claimed that barley was used sometimes as a forage crop. According to table 3, there was a wider choice of species grown in the "modern" oases compared to "traditional" oases, with an average of 3 species per plot versus 2 species, respectively. These findings revealed that there is a trend towards monocultures in "traditional" oases, as opposed to a trend towards a gain in agro-biodiversity in "modern" oases (organization in two and three layers).

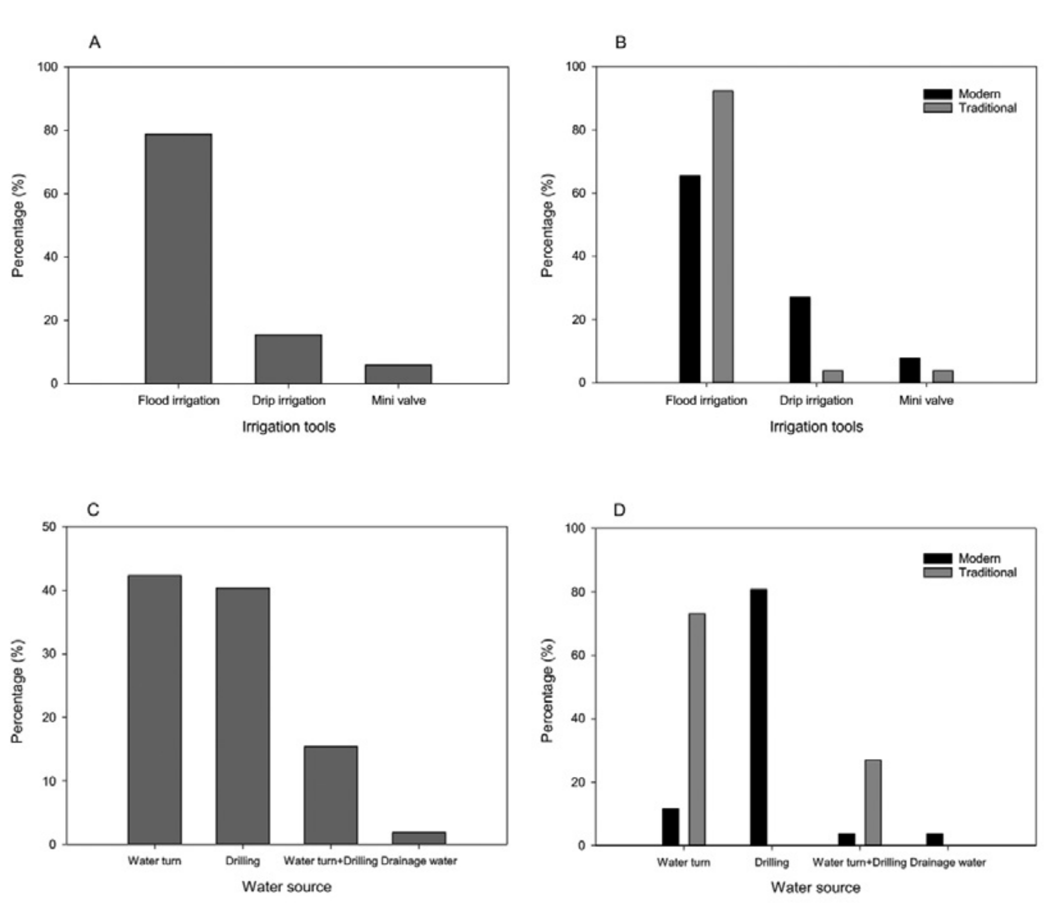
3.4. *Irrigation methods and water irrigation source*

The most widely used irrigation method proved to be flood irrigation (78.8%) (Figure 4, A). The irrigation method was found to be significantly associated with the type of oasis (p-value= 0.04908 <0.05). The plots of "traditional" oases were almost exclusively irrigated by flood irrigation (92%), while 26.9% of the plots in "modern" oases were irrigated by drip irrigation. The irrigation of the study plots was mainly provided either by a water turn system (42.3%), or by private drilling (40.4%). Both the water turn and private drilling systems irrigated only 15.4% of the plots. However, one of the farmers claimed to irrigate with drainage water (Figure 4, C). The source of water irrigation was highly significantly associated with the type of oasis (p-value of Chi-2= 0,00000002645<0.0001). Irrigation by water

Table 3 - Existing species other than date palms in the studied "traditional" versus "modern" oasis plots.

Oasis type	*Species type*	*Existing species*	*Percentage of occurrence (%)*	*Average number of species per plot*
"Traditional"	Fruit trees	Pomegranate	53.85	2.4
		Fig	34.62	
		Olive	23.08	
		Grapevine	23.08	
	Vegetables, cereals forage crops and aromatic plants	Alfalfa	15.38	
		Barely	15.38	
		Chard	7.69	
		Onion	7.69	
		Oats	7.69	
		Eggplant	3.85	
		Garlic	3.85	
		Pepper	3.85	
		Celery	3.85	
		Parsley	3.85	
		Fennel	3.85	
		Broad bean	3.85	
		Saffron	3.85	
		Triticale	3.85	
		Mint	3.85	
"Modern"	Fruit trees	Fig	43.20	3.1
		Pomegranate	43.20	
		Olive	23.10	
		Grapevine	7.69	
		Apple	7.69	
	Vegetables, cereals forage crops and aromatic plants	Onion	19.20	
		Alfalfa	19.20	
		Potato	11.54	
		Turnip	11.54	
		Parsley	11.54	
		Oats	11.54	
		Barley	11.54	
		Pepper	7.69	
		Garlic	7.69	
		Watermelon	7.69	
		Chard	7.69	
		Carrot	3.85	
		Radish	3.85	
		Broad bean	3.85	
		Sorghum	3.85	
		Corn	3.85	
		Rosemary	3.85	
		Mint	3.85	
		Pelargonium	3.85	
		Pennyroyal	3.85	

Figure 4 - Percentage of irrigation tools in all the study plots (A), irrigation tools in "traditional" versus "modern" oasis plots (B), irrigation water sources in all the study plots (C), and irrigation water sources in "traditional" versus "modern" oasis plots (D).



turn mainly characterized the plots of traditional oases, where the water source is public, i.e. 73.1% of cases, but there was still a significant number of "modern" oasis plots irrigating by water turn, with an agreement between farmers about private drilling, i.e. 15.4% of cases (Figure 4, D). Irrigation by drilling alone was found in the plots of "modern" oases (80.7%). In addition, the plots that were irrigated by both water turn and drilling amounted to 26.9% of those in the "traditional" oases where farmers had their borehole (Figure 4, D).

The time interval between turn irrigations ranged from 8 to 120 days, while drilling irrigation ranged from 3 to 22 days. More than 36% of farmers irrigated once a month, or could irrigate twice per month, and 17.3% could irrigate once a week (Table 4).

Table 4 - Irrigation frequency adopted by farmers in the study plots.

Irrigation frequency	*Percentage*
More than once a week	3.8
Once a week	17.3
Once a fortnight	36.5
Once a month	36.5
Less than once a month	7.7
Total	100

3.5. *Relation between irrigation, production factors, and oasis type*

The results showed that the number of layers did not only depend on the type of oasis, but also on the source of irrigation water (Table 5). Among the plots of "modern" oases using private drilling to irrigate, 33.3% had two layers and 20.8% had three layers. However, 33.3% of the plots in these oases equipped with drilling had a single layer (Table 5). Moreover, 33.3% of the "traditional" oasis plots with a single layer were irrigated within a water turn system from public drilling (GDA) (Table 5). In 25% of cases, the plots of "traditional" oases that were organized in two layers were irrigated by water turn (Table 5). Likewise, 20.8% of the plots of "traditional" oases organized in three layers relied on a water turn system to irrigate, but 17% were irrigated by water turn and private drilling (Table 5).

The result of the Chi-2 test showed that the irrigation frequency and the number of layers were not significantly associated together in either the "modern" or "traditional" oases (p-value> 0.05), while in "modern" oasis plots, when farmers irrigated more than once a week, 66.7% of the plots were organized in three layers (Figure 5, A). Of the plots irrigated once a week, 71.4% were organized in more than a single layer (Figure 5, A). Likewise, half of the

Figure 5 - Cross between irrigation frequency and number of layers for "modern" oasis plots (A) and "traditional" oasis plots (B).

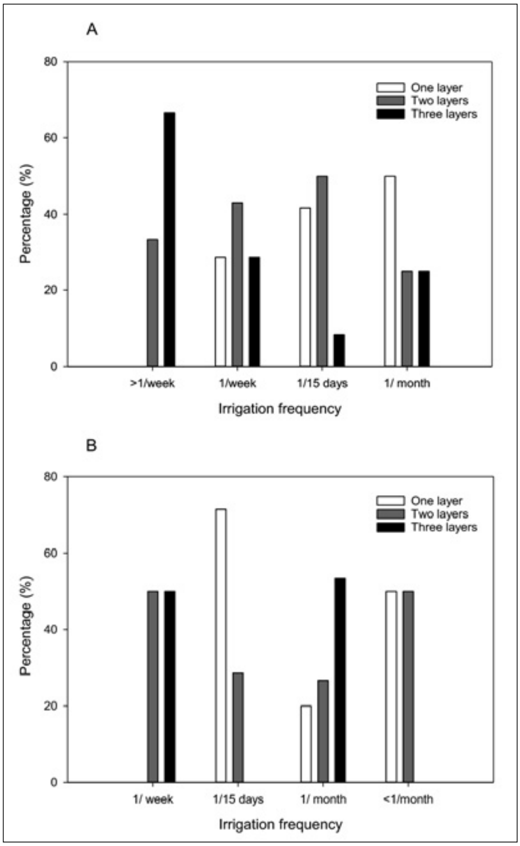


Table 5 - Relationship between oasis type, number of layers, and water irrigation.

Oasis type	*Number of layers*	*Water irrigation source*	*Percentage*
"Modern"	One layer	Drilling	33.3
"Modern"	One layer	Water turn	4.2
"Modern"	Three layers	Drainage water	4.2
"Modern"	Three layers	Drilling	20.8
"Modern"	Two layers	Drilling	33.3
"Modern"	Two layers	Water turn	8.7
"Modern"	Two layers	Water turn +Drilling	3.8
"Traditional"	One layer	Water turn	33.3
"Traditional"	One layer	Water turn + Drilling	4.2
"Traditional"	Three layers	Water turn	20.8
"Traditional"	Three layers	Water turn + Drilling	16.7
"Traditional"	Two layers	Water turn	25.0
"Traditional"	Two layers	Water turn + Drilling	8.3

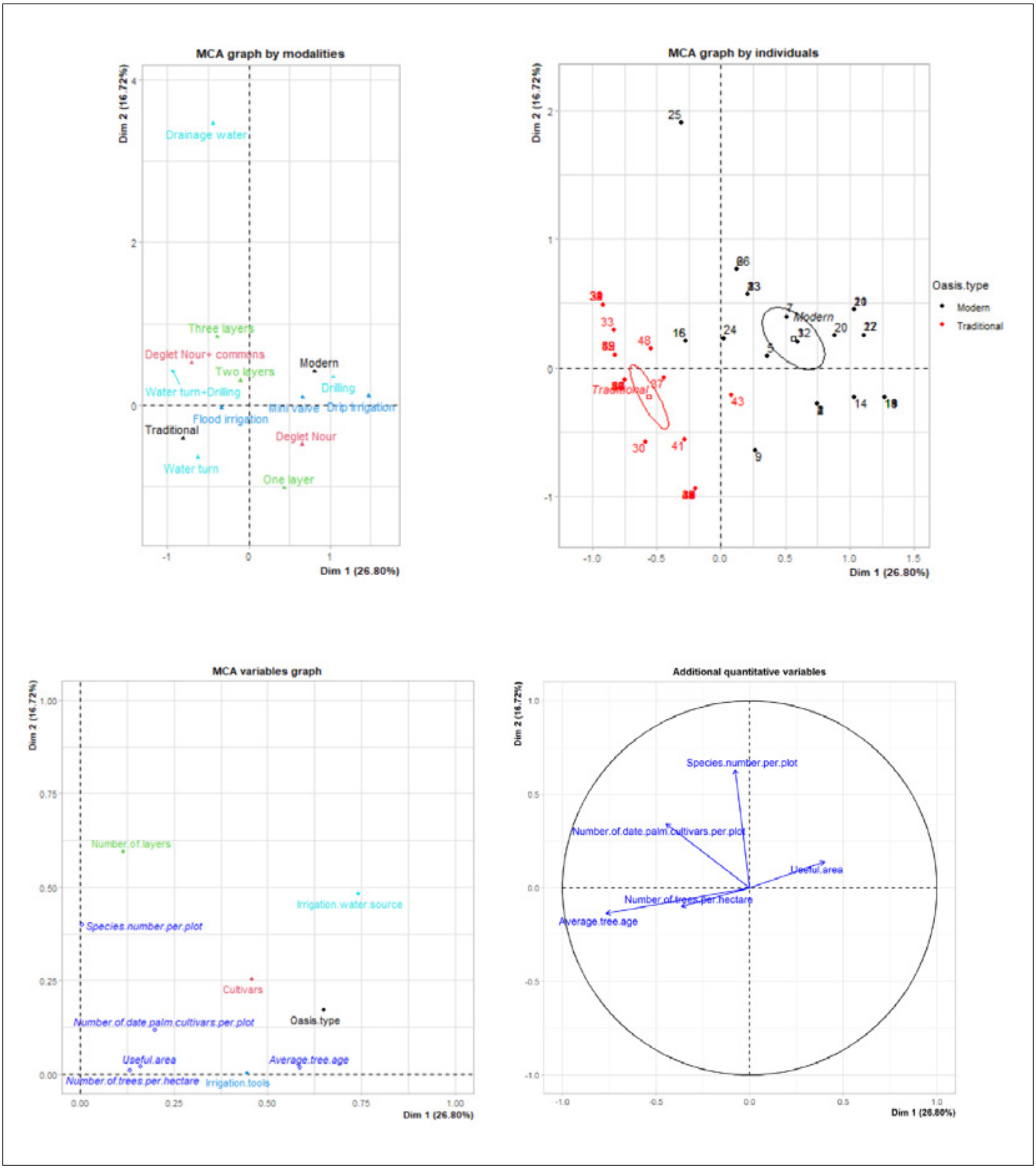
plots irrigated once a fortnight had two layers and 41.7% a single layer. Half of those irrigated once a month had only a single layer (Figure 5, A). For plots in "traditional" oases, when irrigation was practised once a week, the plots had several layers (50% two layers and 50% three layers), but when irrigation was provided once every two weeks, the plots had rather a single layer (71.4%), or two layers (28.6%) (Figure 5, B). Lastly, the plots irrigated less than once a month had either one or two layers (50% for each organization) (Figure 5, B).

Moreover, some of the interviewed farmers declared that they had become unable to grow fruit trees, vegetables and cereals in their "traditional" oases due to water scarcity, salinity and very long water turns, justifying the presence of only one layer. On the other hand, in these oases, some of the interviewed farmers declared also that only a small number of fruit trees remained in their plots due to a high mortality rate caused by warming and water scarcity. These findings indicate that the plots with a high irrigation frequency were more likely to be organized in more than a single layer. The "traditional" oasis plots were those with the lowest irrigation frequency mediated by a very long water turn. Thus, all these results indicate a loss of agro-biodiversity in the "traditional" oases, tending towards a monoculture due to a very long water turn. On the other hand, there is a gain in agro-biodiversity in "modern" oases which, overall, increasingly had two to three layers as soon as the farmers had private drilling in their plots for irrigation.

The results of the Multiple Component Analysis (MCA) seeking to compare "traditional" and "modern" oasis plot characteristics revealed that the number of layers and the irrigation water source were the discriminant factors, followed by the cultivars grown (Figure 6, Variables graph). The MCA also showed that drilling, drip irrigation, mini-valves, 'Deglet Nour', and the presence of two vertical tree layers characterized the "modern" oasis. In contrast, flood irrigation, 'Deglet Nour' and common cultivars, water turns and drilling, and three layers characterized the "traditional" oasis (Figure 6, MCA graph by modalities). The confidence ellipses around the barycentres are moderately small, and the subpopulations are quite separated. The ellipses do not overlap, which indicates that the subpopulations are significantly separated. (Figure 6, MCA graph by individuals). This indicates that the "traditional" oasis plots are significantly different from the "modern" oasis plots. These findings further strengthen all the results found. The plot useful area seemed to be discriminant for "modern" oases, while the number of trees per ha, average tree age, the species present and the number of date palm cultivars per plot were discriminant for "traditional" oases (Figure 6, Supplementary quantitative variables).

In addition, the results of the AHC carried out on individuals revealed 7 clusters (Supplementary material, Figure S2, A). The water irrigation source was the variable that best separated clusters joined to the average tree age and the number of date palm cultivars per plot variable and which were highly significantly correlated to the cluster variable (p-value <0.001 for all of them) (Table S1 and Table S2, Supplementary materials). The first cluster characterized plots that were irrigated by water turn, located in the "traditional" oases, organized in two layers and growing 'Deglet Nour' and common cultivars. This group was also characterized by high values for the variables "number of palm date cultivars per plot" and "average tree age" (Table S3 and Table S4, Supplementary materials). All plots in this cluster had a mean value of 49 years for the "average tree age" variable, while the mean value of all the categories was 35 years. The second cluster described plots irrigated by water turn and drilling and located in the "traditional" oases with a higher average tree age (Tables S3 and S5, Supplementary materials). All plots in this category had a mean value of 53 years for the "average tree age" variable. The third cluster included one plot that relied on drainage water for irrigation (Supplementary materials, Figure S2, B and Table S3). The fourth cluster corresponded to plots organized in one layer, irrigated by water turn, located in the "traditional" oases and cultivating only 'Deglet Nour' (Table S3, Supplementary materials). The fifth cluster was made

Figure 6 - Multiple Component Analysis (MCA) representing characteristics of "traditional" versus "modern" oasis plots.



up of plots irrigated by drilling using flood irrigation and located in the "modern" oases, with the lowest average tree age values (Table S4 and Table S5, Supplementary materials). Cluster 6 was characterized by a plot irrigated by mini-valves and by flood irrigation, and also by variables whose values did not differ significantly from the mean. (Table S4 and Table S5, Supplementary materials). Finally, the cluster 7 described plots irrigated by drip irrigation using drilling, cultivating 'Deglet Nour' and located in the "modern" oases. This group was characterized by higher useful area values (mean=2.6 ha) and lower average tree age values (mean=16.6 years) (Table S4 and S5, Supplementary materials).

4. Discussion

From our results, we were able to identify the typical plots of the "traditional" oases and the "modern" oases in the Kebili region. Indeed, the typical plots of traditional oases were owned by farmers who had inherited from their fathers. These plots, with a cultivated area of 1 ha or less, were most often occupied by 'Deglet Nour' and common date palm cultivars. The palms were over 40 years old and ranged in number from 100 to 200 per ha. The plots of "traditional" oases were organized equally into one, two and three layers. These plots were mainly irrigated by submersion and by water turn. As for the plots of the "modern" oases, they were obtained by "Haouza" and had cultivated areas of between 0 and 2 ha, including 100 to 200 trees per hectare and most often occupied by the "Deglet Nour" cultivar. The trees were between 8 and 40 years old and the plots were usually organized in two layers and were irrigated by submersion.

Our analysis showed significant differences in characteristics between the "traditional" and the "modern" oases. "Modern" oasis plots that were acknowledged in the past to be organized in only one layer have become increasingly organized in two and three layers. In these plots, we also found common date palm cultivars, yet "modern" oases were assumed previously to be exclusively planted with 'Deglet Nour'. On the other hand, "traditional" oasis plots that were assumed in the past to be organized in three layers, were found to be tending towards monocultures (35% of plots with one layer only). When first established, "modern" oases were maintained by large companies, and also by locals. Afterwards, locals who had plots in the traditional oases started to have more and more plots in their extensions. This was because traditional oasis lands are often inherited and divided between several sons, thus creating a significant fragmentation reducing their profitability, associated with a lack of irrigation water, salination and soil fertility loss. Furthermore, having a plot in an oasis is considered a symbol of life, part of the heritage, traditions, and cultural heritage of Kebilians and is a source of pride and income. Moreover, many farmers in Kebili use their plots for self-consumption, especially for fruits, vegetables, and cereals. They therefore reproduce what existed in "traditional" oases. Hence, this could be one reason for the appearance of many layers in "modern" oases. Our results also revealed that the "traditional" oasis plots were occupied by almost 2 species, on average, while those in the "modern" oases were planted with more than 3 species, on average. There are therefore agro-biodiversity losses in "traditional" oases versus a gain in agro-biodiversity for "modern" oases. This all suggests that our findings reveal dynamics in progress in Kebilian oases, and the data we present correspond to a "photo" of their current situation.

Our analysis also revealed that water availability, and mainly the water irrigation source, are key factors for the agro-biodiversity of "traditional" versus "modern" oases in the Kebili region, and one of the main reasons for the diversity in the typology and characteristics of Kebilian oases. In addition, most "modern" oasis plots are mainly irrigated by drilling, allowing frequent irrigation, whilst in "traditional" oasis plots, irrigation is mainly based on the water turn system. The water turn has an average of 30-45 days, with sometimes 60 to 120 days. Elbekkay *et al.* (2016) had already found that the frequency of irrigation in the governorate of Kebili was about one irrigation per month in 66% of oases. They also found that only 24% of oases in Kebili could irrigate twice a month. Indeed, the high irrigation frequency was likely to allow farmers to organize their plots in more than a single layer. The level of cultivated agro-biodiversity is therefore related to water availability and irrigation frequency. Most farmers in "modern" oases are equipped with private drilling and some of them have solar energy for electricity (not affordable for all farmers due to its high cost), which allows them to irrigate frequently and have multiple cropping choices apart from the date palm. Besides, in Algeria, the exploitation of the underground water resources of the Terminal Complex and the Continental Intercalary, thanks to drilling technologies borrowed from the hydrocarbons sector, has made it possible to broaden the possibilities of diversifying agricultural, plant and animal production. In addition to the date palm, an emblematic crop of the Saharan regions of Algeria, cereals, forage crops, vegetables on fields or in greenhouses, fruit growing, olive trees, industrial crops and aromatic crops with various farms activities (dairy cattle, small ruminants and/or aviculture) have been developed (Benmihoub *et al.*, 2021). On the other hand, in "traditional" oases, with very long water turn periods, trees and plants lack water for several days. This was found to be aggravated by increasing salinization, soil degradation, and fertility loss, along with drainage problems, bearing in mind that irrigation water in the Kebili governorate is already saline. In 1999, Kebilian water table salinity was between 3.4 and 9.7g/l and the Douz water table salinity was between 4 and 11.5 g / l (DRE, 1999) in Ezzine *et al.*, 2016. Soil salinization is common in oases located in the aridest regions, where irrigation water is loaded with salts and where evapotranspiration is high. In the oases of southern Morocco, soil salinization, sometimes very spectacular, has proven to be more a consequence of the decline of the oases than a cause of this decline (Jouve, 2012). Salinity is involved in the degradation of soil structure and in physical and hydraulic properties, due to sodium and sodicity phenomena (Ghadiri *et al.*, 2004) and consequently soil fertility loss. This is already encouraged by the nature of the soils in the Kebili region, which is generally shallow sandy aeolian with a gypsum crust, and soils that are very poor in organic matter. This therefore jeopardizes the cultivation of many vegetables and fruit trees (such as many stone and pome species) in "traditional" oases due to severe conditions. In most "traditional" oases, we found the existence of only a few pomegranate, fig and olive trees, and farmers had noted high mortality, low vigour, and low yields. With gaps of 60 days or more between irrigation operations, even date palms, which are known to be drought-tolerant, could not resist and suffered from water stress, leading to mortality.

Moreover, the presence of more than a single layer was mostly found in "traditional" oasis plots that combined irrigation water sources (with water turn and drilling), mainly near to extensions, or with very short water turns and where vegetables could also be grown.

Agro-biodiversity plays a key role in a sustainable food supply on an environmental and nutritional scale (Dawson *et al.*, 2019). An oasis is reputed to be an agroforestry system. Crop diversity and the multiple tree layers in such an agroforestry system confer a favourable microclimate and buffer climate changes, and may also decrease water consumption. Therefore, preserving agro-biodiversity and the vertical structure in "traditional" oases is becoming more crucial than ever. Trees in "traditional" oases are already old. Older date palms become very tall, making access to the date palm wreath no longer possible for farmers. In this case, farmers will no longer climb to pollinate them, cover the fruit bunches, and treat against diseases and pests. As a result, ageing of the date palms could, in this case, greatly reduce their potential production and thereby jeopardize their sustainability in "traditional" oases and make them fragile and more vulnerable to pests and diseases that already exist and to those that could increase in the future due to global warming and climate change. The rehabilitation and rejuvenation of "traditional" oases is thus becoming crucial.

However, if the conditions become even more severe, including water scarcity, we will end up with endangered "traditional" oases, particularly with low rainfall and the depletion of water in aquifers. The governorate of Kebili already draws almost all its water requirements from groundwater and particularly from deep aquifers. This region is also characterized by two groups of water tables: oasis and alluvial water tables and two types of deep-water tables, the Terminal Complex and the Continental Intercalary (Ezzine *et al.*, 2016). These aquifers and tables are unfortunately fossil and non-renewable water.

Moreover, apart from the physicochemical characteristics of the soils, irrigation water in the oases, along with the irrigation practices of farmers and climatic conditions, and the speed with which production factors, i.e. soil and water, are being exploited, lie at the root of the decline in soil fertility, especially in the old oases. Soil remediation practices in these areas to counteract the harmful effects should therefore offer some respite.

As the "traditional" oasis has always had historical value in the Kebili region, solutions must be found. The priority should be given to making water more available. This could be made possible by shortening the interval between irrigations and by irrigating more frequently but with a shorter irrigation time when water turn is used. For instance, farmers should plan irrigation based on actual plant or tree requirements, not only time, and should also allow for salt leaching. Water saving techniques and collection basins to optimize the amount of water allowed and avoid wasting it, especially during flood irrigation, could be potential solutions. The groundwater governance system, in its formal and informal components, is one of the key factors in the sustainability and robustness of farming methods such as that adopted in the oasis system, i.e. their adaptation and maintenance skills (Daoudi and Lejars, 2016).

Efforts should also be made to improve soil fertility damaged by salinization and structural destruction. Providing relevant organic matter could be greatly beneficial for improving soil fertility. Organic matter acts on both the chemical and physical properties of soil, such as the structure, moisture-holding capacity, diversity, the activity of beneficial and damaging organisms, nutrient accessibility, and the general health of the soil (Bot and Benites, 2005; Ferreras *et al.*, 2006). Organic matter can be supplied via manure from animal waste, especially since most Kebilian oases have animal husbandry, or by compost such as oasis waste and palms. Sand amendment could also be helpful for regenerating soil structure and improving fertility. This practice is increasingly being implemented by farmers and should be encouraged. Farmers should therefore be informed and guided to help them save their wealth.

It seems that the problems found not only characterize the Tunisian oases but also the Algerians. Indeed, Benmihoub *et al.* (2021) have identified that among the main ecological issues of Algerian oasis agroecosystems: the lack of water linked to the drying up of wells and the delay in the construction of boreholes; the scarcity of arable land limited to depressions as well as the risk of land loss due to erosion and silting phenomena; the decrease in soil fertility due to the low organic matter content; varietal losses, date palm in particular, due to the selection of varieties with high commercial value; low agricultural yields; loss of crops due to climatic hazards.

Farmers should be strongly encouraged to grow local cultivars, given their adaptation to local conditions and their lower water requirements. Our investigation revealed that common cultivars were certainly less frequent in the "modern" oasis plots than in the "traditional" oasis plots, but the presence of these cultivars in this oasis type, where water is often more available, will participate in some way to ensuring their sustainability, as common cultivars are threatened with disappearance in favour of the 'Deglet Nour' cultivar, which is the most widely grown and which is intended mainly for export. The organization of a sector and value chains around common dates and their by-products, and ensuring their marketing channels, will encourage farmers to plant them more.

During our survey, we found that the notion of "modern" and "traditional" oases does not exist among the oasis inhabitants of Kebili and they often speak of "old oases" and "new oases" (a reference to the extensions), which further strengthens the ambiguity of the terms and the disagreement between authors in defining a clear and applicable typology for the oases.

5. Conclusions

In the Kebili region, our survey results revealed that the availability of water, and mainly the frequency of irrigation, are the factors that determine the cropping mode and lead to differences between "traditional" and "modern" oases. Our findings suggest an increasing trend towards monocultures for "traditional" oases, due to water scarcity caused by a very long water turn and soil degradation, with only "traditional" oases with drilling or a short water turn remaining with three layers. In contrast, "modern" oases, usually perceived as very simple, can also have two or three layers enabled by water drilling and frequent irrigation. It seems that "traditional" oases are under severe threat of disappearance due to low water availability, causing mortality not only in fruit trees and vegetable crops, but also in date palms.

This situation could become more severe due to climate change, particularly the increase in temperatures that causes a lack of chill for fruit species and greater water demand due to an increase in evapotranspiration, hence greater water requirements.

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Appendix - Supplementary materials

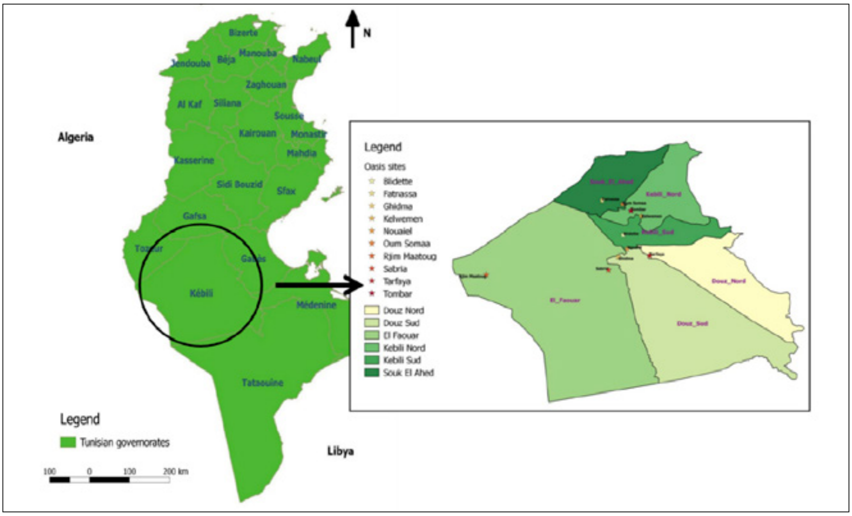

Figure S1 - Geographical locations of the studied oases (Qgis software version 3.4.6).

Figure S2 - Ascending Hierarchical Classification for the different study plots with A: Hierarchical tree, B: Factor map and C Hierarchical tree on the factorial map.

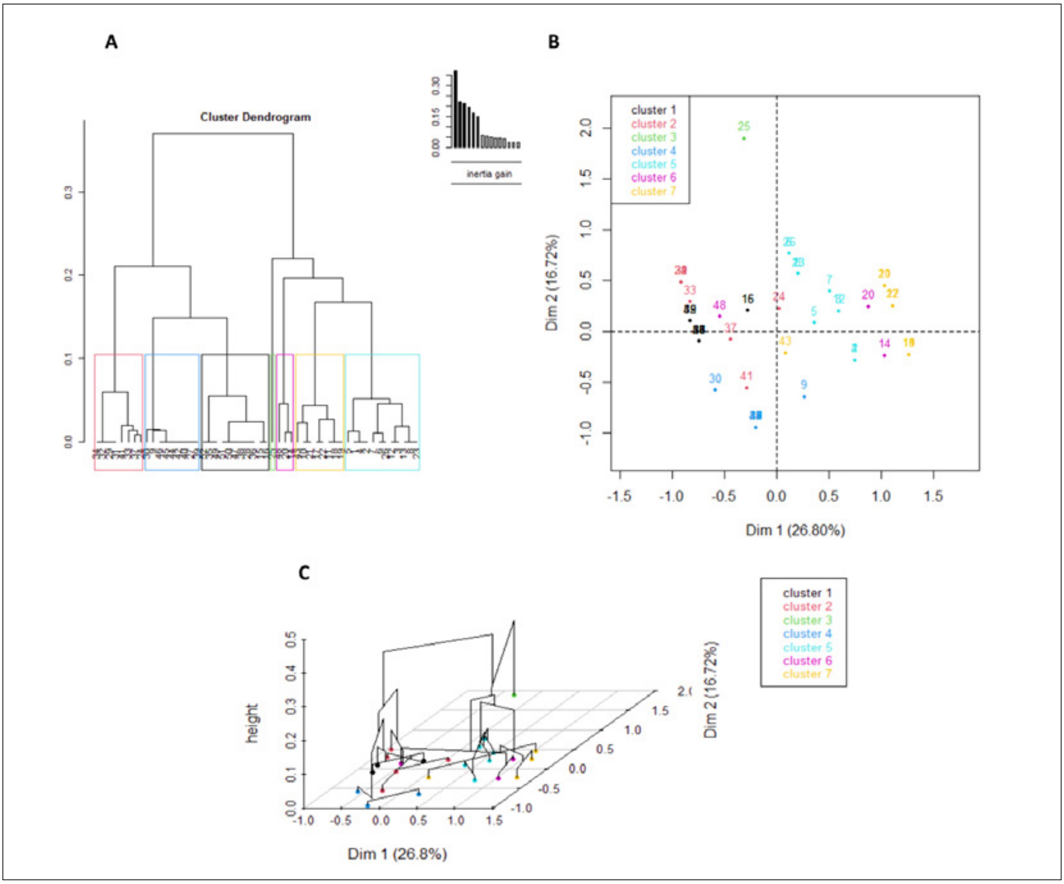

Table S1 - Link between the cluster variable and the categorical variables (chi-square test).

Variables	*p-value*	*Df*
Water irrigation source	$1.429\ e^{-22}$	18
Water irrigation tools	$9.130\ e^{-17}$	12
Oasis type	$1.473\ e^{-05}$	6
Cultivars	$2.009\ e^{-04}$	6
Number of layers	$2.514\ e^{-03}$	12

Table S2 - Link between the cluster variable and the quantitative variables.

Variables	*Eta2*	*p-value*
Average tree age	0.452	$8.796\ e^{-05}$
Number of date palm cultivars per plot	0.266	$2.425\ e^{-02}$

Table S3 - Description of clusters 1, 2, 3 and 4 by the category.

Clusters	*Variable categories*	*Cla/Mod (%)*	*Mod/Cla (%)*	*Global (%)*	*p-value*	*v.test*
Cluster 1	Irrigation water source = Water turn	50.0	100.0	42.3	$1.168\ e^{-05}$	4.383
	Cultivars = Deglet Nour +commons	44.0	100.0	48.1	$7.379\ e^{-05}$	3.963
	Number of layers = Two	42.1	72.7	36.5	$8.545\ e^{-03}$	2.629
	Oasis type = Traditional	34.6	81.8	50.0	$2.164\ e^{-02}$	2.297
	Oasis type = Modern	7.7	18.2	50.0	$2.164\ e^{-02}$	-2.297
	Number of layers = One	0.0	0.0	34.6	$4.736\ e^{-03}$	-2.824
	Irrigation water source = Drilling	0.0	0.0	40.4	$1.401\ e^{-03}$	-3.194
	Cultivars = Deglet Nour	0.0	0.0	51.9	$7.379\ e^{-03}$	-3.963
Cluster 2	Irrigation water source = Water turn + Drilling	100.0	100.0	15.4	$1.328\ e^{-09}$	6.064
	Oasis type = Traditional	26.9	87.5	50.0	$2.688\ e^{-02}$	2.213
	Oasis type = Modern	3.8	12.5	50.0	$2.688\ e^{-02}$	-2.213
	Irrigation tools =Drilling	0.0	0.0	40.4	$1.048\ e^{-02}$	-2.559
	Irrigation tools = Water turn	0.0	0.0	42.3	$7.777\ e^{-03}$	-2.661
Cluster 3	Irrigation tools = Drainage water	100	100	1.923	0.0192	2.341
Cluster 4	Number of layers = One	50.0	100.0	34.6	$1.321\ e^{-05}$	4.356
	Irrigation water source = Water turn	40.9	100.0	42.3	$1.352\ e^{-04}$	3.817
	Oasis type = Traditional	30.8	88. 9	50.0	$1.274\ e^{-02}$	2.491
	Cultivars = Deglet Nour	29.6	88. 9	51.9	$1.763\ e^{-02}$	2.373
	Number of layers = Three	0.0	0.0	28.8	$3.381\ e^{-02}$	-2.122
	Cultivars = Deglet Nour+ commons	4.0	11.1	48.1	$1.763\ e^{-02}$	-2.373
	Oasis type = Modern	3.8	11.1	50.0	$1.274\ e^{-02}$	-2.491
	Number of layers = Two	0.0	0.0	36.5	$1.048\ e^{-02}$	-2.559
	Irrigation water source = Drilling	0.0	0.0	40.4	$5.480\ e^{-03}$	-2.777

Mod/Cla indicates within-cluster distribution; Cla/Mod indicates across-cluster distribution. v.test is the value of the statistical test to determine the significance of the group description and should be > 1.96. The p-value should be < 0.05; The sign of the v.test indicates if the mean of the cluster is under or over-expressed for the category, i.e. if the value is positive, there is over-representation of the considered modality, if it is negative, under-representation.

Table S4 - Description of cluster 5, 6 and 7 by category.

Clusters	*Variable category*	*Cla/Mod (%)*	*Mod/Cla (%)*	*Global (%)*	*p-value*	*v.test*
Cluster 5	Irrigation water source = Drilling	57.1	100.0	40.4	1.424 e^{-06}	4.822
	Oasis type = Modern	46.1	100.0	50.0	4.679 e^{-05}	4.071
	Irrigation tools = Flood irrigation	29.3	100.0	78.8	3.827 e^{-02}	2.072
	Water irrigation source = Water turn	0.0	0.0	42.3	4.191 e^{-02}	-3.528
	Oasis type = Traditional	0.0	0.0	50.0	4.679 e^{-05}	-4.071
Cluster 6	Irrigation tools = Mini valve	100	100	5.8	4.525 e^{-05}	4.079
	Irrigation tools = Flood irrigation	0	0	78.8	7.467 e^{-03}	-2.675
Cluster 7	Irrigation tools = Drip irrigation	100.0	100.0	15.4	1.329 e^{-09}	6.064
	Cultivars = Deglet Nour	29.6	100.0	51.9	2.950 e^{-03}	2.973
	Irrigation water source = Drilling	33.3	87.5	40.4	5.331 e^{-03}	2.786
	Oasis type = Modern	26.9	87.5	50.0	2.688 e^{-02}	2.213
	Oasis type = Traditional	3.8	12.5	50.0	2.688 e^{-02}	-2.213
	Cultivars = Deglet Nour+ commons	0.0	0.0	48.1	2.950 e^{-03}	-2.973
	Irrigation tools = Flood irrigation	0.0	0.0	78.8	2.192 e^{-07}	-5.182

Mod/Cla indicates within-cluster distribution; Cla/Mod indicates across-cluster distribution. v.test is the value of the statistical test used to determine the significance of the group description and should be > 1.96. The p-value should be < 0.05; The sign of the v.test indicates if the mean of the cluster is under or over-expressed for the category, i.e. if the value is positive, there is over-representation of the considered modality, if it is negative, under-representation.

Table S5 - Description of each cluster by quantitative variables.

Clusters	*Variable categories*	*v.test*	*Mean in category*	*Overall mean*	*SD in category*	*Overall SD*	*p-value*
Cluster 1	Number of date palm cultivars per plot	2.833	3.273	2.058	1.354	1.586	0.00460
	Average tree age	2.528	49.454	35.115	17.645	20.979	0.01146
Cluster 2	Average tree age	2.578	52.875	35.115	17.330	20.979	0.00994
Cluster 3	Null	Null	Null	Null	Null	Null	Null
Cluster 4	Species number per plot	-2.656	0	2.769	0	3.4060	0.00790
Cluster 5	Average tree age	-2.461	21.917	35.115	9.500	20.979	0.01386
Cluster 6	Null	Null	Null	Null	Null	Null	Null
Cluster 7	Useful area	2.623	2.635	1.276	3.004	1.578	0.00871
	Number of date palm cultivars per plot	-2.030	1.000	2.058	0.000	1.586	0.04230
	Average tree age	-2.683	16.625	35.115	14.317	20.979	0.00728

SD: standard deviation.