Oasis extension trajectories in Kebili territory, southern Tunisia: drivers of development and actors' discourse

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Abstract

Since the 1970s, the Kebili region in Southern Tunisia has undergone important landscape transformations due to the rapid expansion of date palm plantations based on illicit boreholes tapping the underlying deep aquifers. These private initiatives, called "extensions", have developed on collective unfarmed areas outside historical oases. These landscape transformations have taken place in heterogeneous and complex trajectories and have raised sustainability concerns of groundwater resources. To address this concern, local actors need to build a joint vision of on-going landscape transformations. The objective of the present study is: (I) to analyse the trajectories of the landscape change, (II) to give an overview of the socio-economic and the environmental drivers, and (III) to better understand local actors' perception of on-going changes taking place in the oasis extensions. The study builds on spatial analysis, on surveys and participatory workshops with actors of the Kebili region. The rapid development of oases extensions was triggered by economic factors that led to the development of innovative techniques to access water, land, and energy. Extensions were first created on lands in proximity of ancient oases before spreading to other areas. These extensions can be described as spontaneous, where farmers exploit new lands outside ancient oases. With the support of local councils in charge of land management, other extensions were initiated on lands located far from ancient oases. While the rapid development of these extensions led to improved date palm production, it was also the source of increased groundwater consumption. Actors have identified the overexploitation of groundwater resources as the main threat to the sustainability of the Kebili region, but there has been no discussion on how to respond to this concern. The current study highlights the need for a contextualized analysis of the heterogeneous trajectories of date palm extensions in order to inform sustainable natural resource management frameworks.

Keywords: *Landscape changes, Groundwater management, Palm Date, Sustainability.*

1. Introduction

Landscape constitutes an arena in which entities, including humans, interact according to rules (physical, biological, and social) that determine their relationships (Sayer *et al.*, 2013). Land use changes are spatial patterns, observed at the scale of the landscape, that impact nu-

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merous biophysical processes such as water and soil degradation, contaminant fluxes and agricultural production as well as their sustainability (Jackson *et al.*, 2007; Wohlfahrt *et al.*, 2010). Developing more sustainable land use systems that satisfy growing demands while avoiding negative environmental and social outcomes is one of the main challenges mankind will face in the coming decades (Foley *et al.*, 2011). Characterizing the drivers of land use changes and actors' discourse is a prerequisite for (1) exploring and simulating plausible land use scenarios, and (2) quantifying the subsequent ecosystem services and disservices (Benoît *et al.*, 2012; Rizzo *et al.*, 2013).

A substantive body of literature suggests that land use change results from the collective impact of individuals' decisions that depends on a range of factors which operate and interact at different spatial and temporal scales (Rizzo *et al.*, 2013). Other studies considered top-down drivers of change such as policies, trade, migration and the community-based responses (Lambin and Meyfroidt, 2011; Novotny *et al.*, 2021). Baynes *et al.* (2015) show the role of communities in landscape planning and conservation, pointing to the relevance of dual governance systems by governments as well as communities. At regional and larger scales, most of the landscape transformation is attributed to agricultural and urban expansion (Lambin and Meyfroidt, 2011). Actors' goal-oriented perspectives can affect the degree to which land use changes will follow either a pathway towards natural resource conservation or depletion and degradation (Sayer *et al.*, 2013). To enhance community agency in natural resource conservation, community and governmental goals need to be carefully aligned to allow communities to effectively manage their natural resources (Novotny *et al.*, 2021). Numerous studies have also shown that similar water or land use changes at the local level can have different drivers and consequences in different contexts or at different scales of analysis (Foley *et al.*, 2011; Mekki *et al.*, 2013; Amichi *et al.*, 2020).

The oasian landscape in the Maghreb has undergone rapid changes in response to a combined effect of environmental, socio-economic and institutional drivers accelerated by access to water and land resources for the development of irrigated agricultural areas. Irrigation in the oases was traditionally based on groundwater. The availability of new drilling techniques enabled to trigger "pioneering fronts" where previously uncultivated land shifted to intensive irrigation farming (Hamamouche *et al.*, 2018). In Algeria, the government supported this development to promote a wide range of value chains (Daoudi and Lejars, 2016; Amichi *et al.*, 2020; Benmihoub *et al.*, 2021). In Morocco, as part of the Green Morocco Plan, some farms obtained support to develop palm groves (Raiskila, 2015). Public policies thus fully acknowledge these newly farmed areas.

In the Kebili region in Southern Tunisia, date palm production has boomed since the 1990s as part of this boom in groundwater use. The government supported the development of groundwater use infrastructures to revitalize ancient oases and to develop a few modern oases (Côte, 2002; Mekki *et al.*, 2013). The government, however, had no clear plans for the future of palm grove areas in the Kebili region (Brochier-Puig, 2004). Still, farmers were not allowed to drill individual boreholes on their own outside traditional oases to limit the use of the aquifers. Despite this lack of vision, palm grove developments took place, especially from the 2000s onwards, in areas locally referred to as "extensions". In 2020, the production of dates in these extensions represented approximately 85% of the date production in the region and 80.7% of national date production (CRDA, 2020). Collectively, these extensions are currently the largest illicit agricultural area based on groundwater use in Tunisia. The Regional Office for Agricultural Development (CRDA after its French acronym) considers the situation to be increasingly untenable. However, there has been to date little discussion about the desired pathway of development for these areas, which have remained largely outside the scope of public policies.

There have been several investigations on agricultural dynamics in the newly farmed areas of the Kebili region. Illicit extensions across the region were identified in the 1990s (Bisson, 1991) and several studies analysed the initial steps of

the development of palm grove extensions in the early 2000s (e.g. Kadri and Van Erst, 2002). These factors jointly enabled the expansion of the pioneering front, but also led to a nascent crisis of the rapid depletion of aquifers. More broadly, building a transversal, dynamic and spatialized vision of the landscape is essential in order to reduce the gap between public actions and responses to local problems. There are currently, however, no studies of the overall dynamics of the extensions of the entire region. Moreover, other characteristics of oasian landscapes that need to be taken into account are also less perceptible such as aquifer characteristics, land tenure status, interdependencies between actors, rules for the management of infrastructure or access to common resources, or delineations of the territory of farms.

Building such a vision requires to consider various topics, including the explanation of components that characterize the management territory (e.g., socioeconomic, environmental, spatial planning), the identification of the co-evolution of actors and the dynamics of access to land and water trajectories for exploring possible strategies (e.g., strategies of extensions), as well as the determinants of types of extensions. There is a need for a dynamic analysis that considers water and land as indicators of landscape transformation. Taking into account past and present dynamics allows the localization of the changes and differentiation of the types of evolution in progress in order to identify the scales and the nature of future interventions. Understanding these dynamics also enables the delineation of possible future patterns of change of local territories: anticipating possible negative impacts on resources; identifying the potential evolution of oasian landscapes in different contexts; identifying potential conflicts between actors and suitable responses to change their practices and adopt collective strategies to mitigate these conflicts (Casanova and Helle, 2012).

Landscape approaches have been able to find ways to reconcile biodiversity conservation with human development targets (Reed *et al.*, 2017, Angelstam *et al.*, 2019a). They have also proposed means for improved governance towards increased sustainability (Angelstam *et al.*, 2019a, 2019b). This is particularly important for tackling groundwater governance issues in collaboration with stakeholders. This article aims to analyze the key drivers and the spatio-temporal dynamics behind the advance of the palm grove extensions of the Kebili region using a landscape approach. The article first analyses how the new oases were developed and the drivers of their development as well as examine their effects on groundwater resources. Second, it investigates the way local actors assess the drivers and the impacts of these extensions and the current (fragile and very limited) attempts to build a framework to integrate them in the ambit of public management. These elements can provide much-needed information about available opportunities and threats and contribute to the dialogue about possible future pathways toward the sustainable development of the Kebili region.

2. Methods

2.1. *Case study*

The study area belongs to the Kebili Governorate (22,500 km^2) located in the southwest of Tunisia (Figure 1). The climate regime is arid with less than 150 mm of annual precipitation, which occurs during the winter season. Agricultural systems are mainly based on palm grove oases and livestock. The old oases as well as the new ones created by the government are locally referred to as “public irrigated areas” and are managed by water users’ associations. Inside these areas, farmers have access to a collective irrigation network.

Three classes of farms in public irrigated areas were reported by the CRDA (2018). Small-scale farms (less than 0.5 ha) represent 12% of the irrigated area, medium-scale farms (between 0,5 ha and 5 ha) 86% and large-scale farms (between 5 and 35 ha) 2%.

The Kebili region draws almost all its water needs from two confined groundwater aquifers: the Intercalary Continental (IC) and the Terminal Complex (TC). Intensive exploitation of the groundwater began in the Kebili region in the mid-1970s. The depth of the Terminal Complex

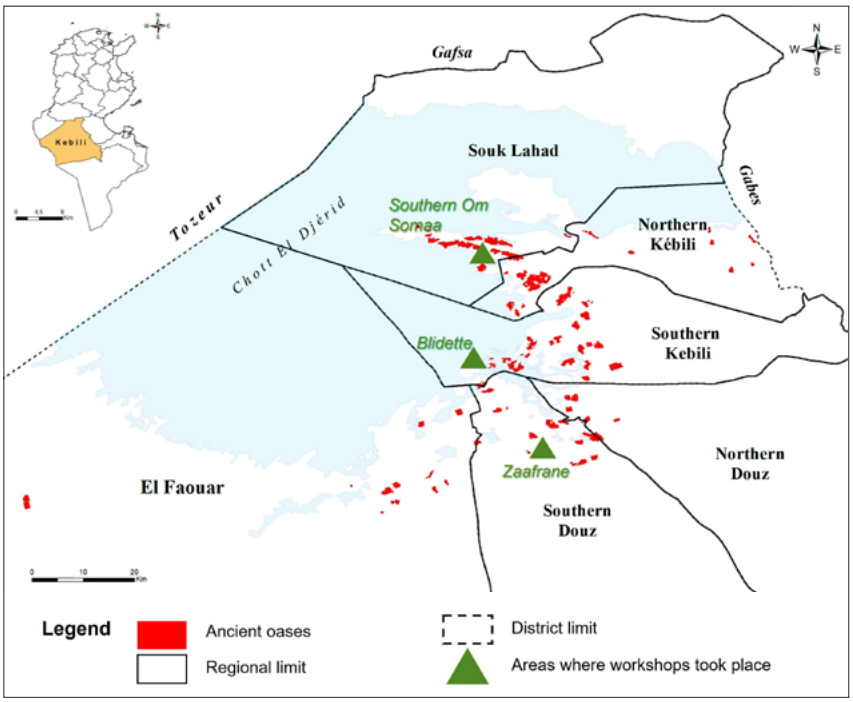


Figure 1 - Kebili region and selected areas for workshops.

aquifer varies between 100 and 400 m. The depth of the Intercalary Continental aquifer varies between several tens of meters to more than 1000 m.

Two regional programs that focused on the use of groundwater resources were also implemented during the last decades: the PDES (French acronym for Southern Water Planning Program) and the APIOS (French acronym for Improving Oases Irrigated Areas a Tunisian). The PDES programme aimed to increase water abstraction and irrigated areas, while also improving hydro-agricultural infrastructures for soil preservation and to optimize water use. The APIOS programme addressed the preservation of water resources through 1) the modernization of distribution and drainage infrastructures, and 2) the strengthening of institutional structures (Ghazouani *et al.*, 2009).

In the Kebili region, management councils managed collectively owned land in rural areas. These councils were composed by representatives of each tribe at the community scale. At the district level, other management councils were composed of representatives from each local council and at the governorate scale level, they were composed of representatives of each district. The status of these management councils was in 2022 being reviewed by the government and they had not been renewed since 2021.

2.2. *Analytical framework: landscape approach*

The landscape approach was developed in response to increasing societal concerns about environment and development tradeoffs (Sayer *et al.*, 2013). We aimed to understand the integration and feedback between social, economic and environmental components of complex systems, and to apprehend the types of change underway, the way in which changes occur and the opportunities presented. Thus, we placed the landscape and its dynamics at the center of the analysis (Casanova and Helle, 2012; Niedertscheider *et al.*, 2014). Sayer *et al.* (2013) identified ten principles to support the implementation of a landscape approach and guide the process of decision-making in landscape contexts. These principles emphasized that paying attention to agricultural and environmental priorities will require stakeholder involvement and a people-centered approach at various landscape scales. This

framework has been used to assess the sustainability and to design improved agricultural systems, taking into account tradeoff and synergies among the drivers (Sayer *et al.*, 2013).

It is important to consider the diversity of actors within a territory and identify the diversity of strategies, actions and interactions (e.g. cooperation/conflicts between these actors) that influence territorial resources. This leads us to conceptualize the oasian landscape as a complex system in which humans and nature are intricately linked and in continuous interaction (Baynes *et al.*, 2015). Taking into account both land use change patterns and the drivers underlying it opens up opportunities to improve methodologies for developing prospective approaches at territorial levels (Casanova and Helle, 2012). Institutional stakeholders have considerable expectations with regard to such methodologies.

Within the Kebili oasian agrosystems, we opted for the following structure: connect anthropogenic processes and drivers of land use change with the uses of natural resources (groundwater), actors' discourse and policies (Figure 2). The main drivers included socioeconomic dimensions (e.g., market constraints, technological developments), which drive the trajectories of the farm extension and extension area at the territory scale. We considered the way land use changes impacted groundwater resources (e.g. salinization and the lowering of the piezometric level). The response mechanisms were characterized in terms of public policies and individual adaptation strategies.

2.3. *Data collection and analysis*

The first phase of the study started in 2019 and aimed to diagnosis the prevailing situation in the region. Data on the development of extension areas was collected from various public offices: Kebili CRDA and its local offices, an Interprofessional Group for Date production and marketing, the Direction of Water and Soil Conservation, and the Office for the Development of the South.

Between November 2019 and August 2020, individual semi-structured interviews were conducted in the field with 36 farmers and completed with collective semi-structured interviews with 7 farmers. All interviewed farmers have plots both in the traditional oasis and within the extensions. Fifteen semi-structured interviews were completed with CRDA officers and technicians from agricultural organisations (the Agricultural Investment Promotion Agency-APIA and the Agricultural Land Agency-AFA). Interviewees were asked to describe: (I) the dynamics of their area (history of their farms, the perceived changes, and the driving factors); (II) constraints on land, energy and water resources and their adaptation strategies to face these constraints; and (III) the future scenarios and potential future development of extensions.

Between March and July 2021, the authors organized a workshop with 19 representatives of the local offices of the Ministry of Agriculture, followed by three workshops with 36

Figure 2 - Analytical framework based on a landscape approach.

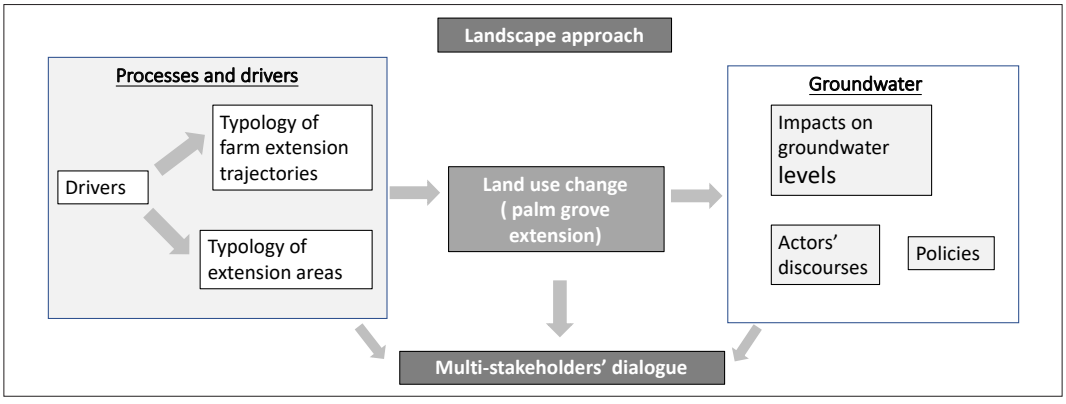
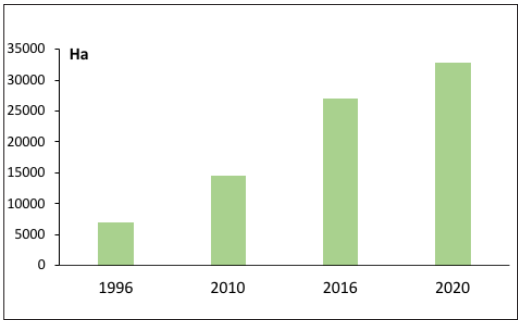


Figure 3 - Evolution of oasis extension area in Kebili region from 1996 to 2020.



Source: Kassah, 1996; CRDA Kebili reports from 2010 to 2020.

farmers from three zones as illustrated in Figure 1: Om Somaa South (Souk Lahad district), Blidette (Southern Kebili district) and Zaafrane (Southern Douz district). The workshops aimed to complement interviews, in order to delimitate extensions and uncover factors that could explain their evolution. Participants were invited to describe the agrarian dynamics in their area for the past 40 years and to identify factors that could explain changes that had occurred. The interviews and workshop discussions were recorded and transcribed.

Issues of data availability and quality are a concern of any long-term land-system change assessment (Erb *et al.*, 2009) including those in an oasis territory. Because of the illicit status of extensions, public data defining the boundaries of oasis extensions did not exist. Therefore, we opted for manual digitisation of contours based on satellite images (Sentinel-2 and Google Earth) from 1984 to 2020.

Moreover, long-term measurements (1960-2020) of piezometric levels of TC and IC aquifers were obtained from Kebili CRDA. This office regularly measured manually groundwater levels in boreholes installed in official irrigated areas and not in illegal extensions. The resulting database was however mostly fragmentary.

Through our interviews with the administration staff and farmers, we tried to trace the history of government interventions, including attempted interventions, in the hopes of finding solutions to the rapid development of extensions occurring today. Analysis of satellite data and interviews of actors allowed the identification of different types of extension trajectories. To better understand the trajectories, a sample of fields covering 1247 ha in the study area was mapped. The field contours were manually digitalised based on satellite images and the mapping was supported by interviews. A total of 1061 polygons, corresponding to irrigated plots, were digitalised. Data on irrigation pumping systems (electric, fuel energy, photovoltaic) were obtained for a sample of legal and illegal 640 plots (CRDA inventory, 2018).

3. Results

3.1. *Diverse and rapid dynamics*

3.1.1. *Growth in planted areas*

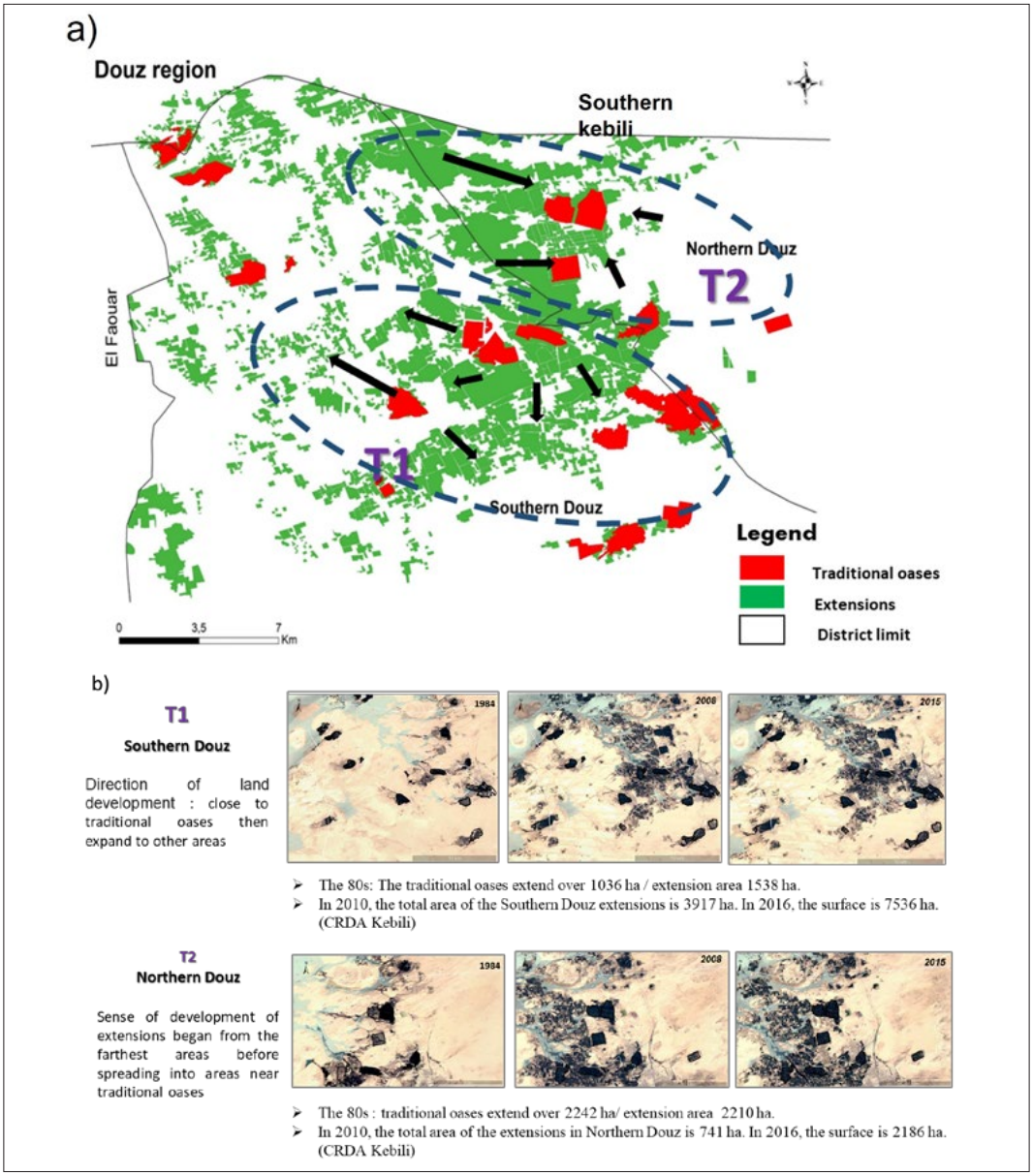
The first oasis survey carried out by the Ministry of Agriculture in 1976 revealed that the total area of date palm oases in Kebili was around 5,240 ha. As private extensions were not recognized by the administration, they were not counted until the end of the 1990s. The results of the survey conducted by the Ministry of Agriculture between 1994 and 1996 and reported by Kassah (1996) showed that the area of the extensions reached 7,000 ha by then. The speed of development of extensions, as well as their geographical dispersion, made it difficult to accurately measure their actual spatial extent and boundaries. The censuses of oases carried out by the administration since 2008 have led to a more precise assessment of the extension areas. Figure 3 shows the evolution of extension areas based on Kebili CRDA (2010 and 2016), and our estimate for 2020 (32,700 ha).

The annual average rate of increase over the three periods 1996-2010, 2010-2016 and 2016-2020, is 540 ha/year, 2073 ha/year and 1434 ha/year, respectively. The speed of development is characterized by an acceleration phase from 2010-2016 and a deceleration phase from 2016-2020. In comparison with extensions, the pace of development of legal oases is rather low and stable. Legal oases covered around 8,315 ha in 1996 and did not exceed 10,485 ha in 2018.

3.1.2. *Two types of trajectories*

Each extension was created gradually and according to very different rhythms from one extension to another. Interviewed farmers and CRDA staff members identified two trajectories (Figure 4a and Figure 4b). In the trajectory T1, extensions were created first on lands near ancient oases before spreading to more distant areas. Generally, farmers developed these "out-spreading" extensions without the involvement of management councils. In some cases, the management council intervened to divide collec-

Figure 4 - a) The two identified trajectories; b) The spatio-temporal evolution of extensions in Southern Douz and Northern Douz districts (1984-2020).



Realized by the authors based on satellite images (Sentinel-2 and Google Earth), surveys and workshops with actors of Kebili region.

tive land between the inhabitants of the region (and between farmers and non-farmers).

In the trajectory T2, extensions were created first on lands located far away from the ancient oases. This trajectory can be labelled as "initiated in the outskirts" and is mainly triggered by the management councils. In order to assert their authority on area located within their jurisdiction (usually located far from traditional oases), the management council asked members of the tribes represented in the council to start farming in this area. The management council can attribute a land allocation title, but not a title of individual property. This land allocation title can be sold or inherited. Entrepreneurs can have a land allocation title directly from the management council, or by buying and grouping several neighbouring plots. In this trajectory T2, extensions thus began from the boundaries of the sector managed by a council and then expanded later to the centre of this sector. Figure 4b illustrates examples of these trajectories in Southern Douz district and Northern Douz district.

For each trajectory, Table 1 presents the number and the size of the plots according to the sampled farm group and the irrigation pumping system in the Southern and Northern Douz districts. Field interviewed enabled us to confirm that, in extensions, limits of plots also correspond to limits of farms. Small-scale (less than 0.5 ha) plots are located mostly near ancient oases, whether they were installed in the first phase of extension creation (T1) or more recently (T2). Solar irrigation systems are quasi-absent in these areas, due to limited financial means or limited available space. Interviews with actors showed that farmers of plots close to ancient oases in T1 trajectory are also holders of plots inside the ancient oases, whereas farmers of plots close to ancient oases in T2 trajectory are inhabitants of the region who were not previously farmers from ancient oases.

Past extensions by "agricultural entrepreneurs" in T2 trajectory were of medium (between 0.5 ha and 5 ha) and small size. In T1 trajectory, large (between 5 ha and 35 ha) farms

Table 1 - Number of farms and their area by trajectory type, farm group and irrigation pumping system.

		Extensions close to ancient oases		*Extensions far the ancient oases*	
		Area	*Plot*	*Plot*	*Area*
"Outspreading" T1 trajectory	*Plot group*				
	Total	144	113 ha	158	757 ha
	Small	41%	16%	0%	0%
	Medium	59%	84%	56%	33%
	Large	0%	0%	44%	67%
	Irrigation Pumping System				
	Total	41	n.a.	363	n.a.
	Electric/fuel	83%	n.a.	58%	n.a.
	Solar	17%	n.a.	42%	n.a.
"Initiated in the outskirts" T2 trajectory	*Plot group*				
	Total	664	274 ha	95	103 ha
	Small	80%	59%	22%	7%
	Medium	20%	41%	78%	93%
	Large	0%	0%	0%	0%
	Irrigation Pumping System				
	Total	57	n.a.	35	n.a.
	Electric/fuel	93%	n.a.	74%	n.a.
	Solar	7%	n.a.	26%	n.a.

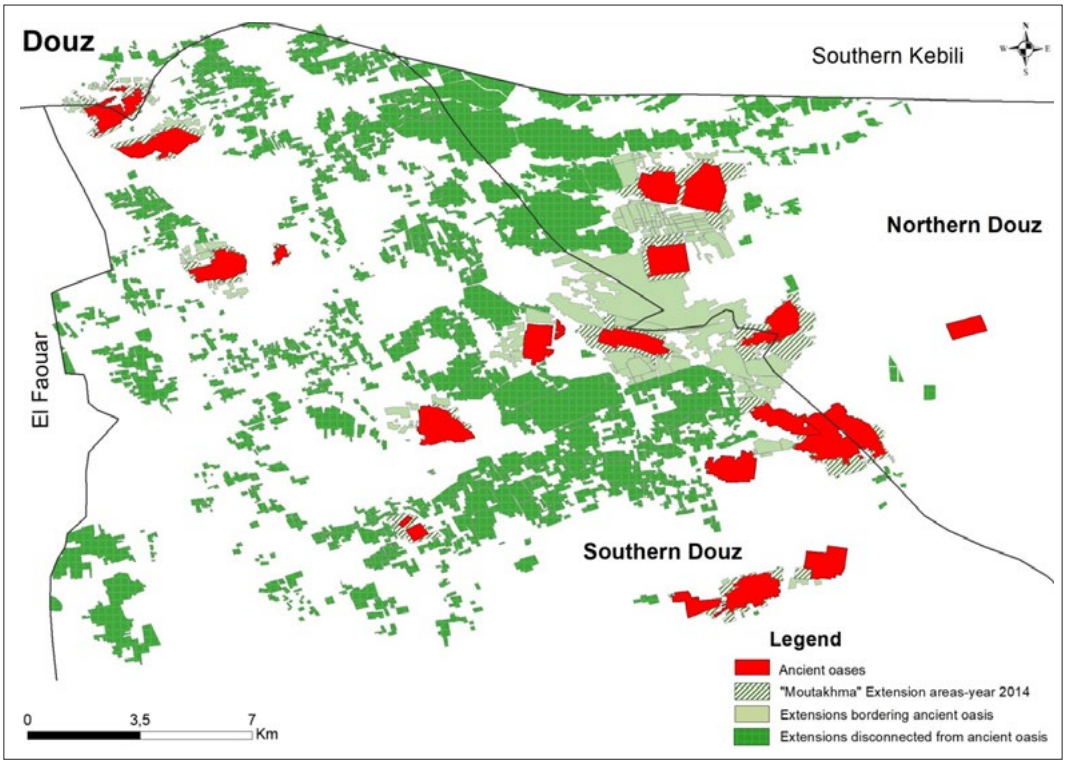
were developed only recently in extensions located far from ancient oases. These recent farms are also those with the higher rate of use of solar energy. Our surveys with local actors revealed that entrepreneurs from outside the region on the whole operated large-scale farms.

The areas for potential future development of extensions were identified based on interviews with the administration officers. The physical barriers to extension development could be dunes, *chotts* (shallow saline lakes), urban extensions or touristic areas. In the Northern Douz district, opportunities to develop new extensions currently appear very limited. In contrast, in the Southern Douz district, there are still spaces available for planting between the oases of Zaafrane, Nouaiel and Klibia. Farmers from the Zaafrane extensions in the Douz region and who participated in the workshops, mentioned that they expected a future increase in illegal extensions and new drilling technologies to exploit deeper aquifers, which would ensure the viability of farms.

3.1.3. *Typology of extensions*

In extensions, most palm groves are recent and Deglet Noor is the dominant variety. Through mapping and field investigation, we classified extensions according to their position relative to legal oases. There are three classes of extensions as illustrated in Figure 5: (I) Extensions bordering ancient oases, i.e. the *mutakhma*, which are partially acknowledged by Kebili CRDA. Any extension in the periphery of ancient oases that is not traversed by a road, a river or a drain is considered as a *mutakhma*; (II) Extensions bordering ancient oases, but which are not interconnected and are considered illicit by Kebili CRDA; and (III) Extensions disconnected from ancient oases and considered illicit by Kebili CRDA. In the Northern and Southern Douz districts, the total area of extensions in 2020 covered 10,387 ha. The *mutakhma* extensions covered 751 ha (7.23%), bordering extensions covered 1,645 ha (15.83%) and disconnected extensions 7,991 ha (76.93%).

Figure 5. Typology of illicit extensions in Northern and Southern Douz districts.



The *mutakhma* extensions are considered as a continuity of ancient oases. Most farmers farming these extensions are small-scale family farmers who also own other plots in the ancient oases. They irrigated from illicit boreholes (individually and, many times, collectively) and also have access to the collective irrigation network of ancient oases. Other types of extensions do not have access to collective irrigation networks.

3.2. *Factors that triggered the pioneering front*

According to the actors interviewed and participants in the workshops, agricultural systems in Kebili region changed significantly during the 1970-2020 period in relation with profound technical, socio-economic transformations and public policies. The development of illicit extensions depended primarily on the availability of groundwater resources. By the end of the 1970s, various push and pull factors led to a movement to private oases extensions outside of the traditional perimeter.

There were four important factors that were identified. First, farming in ancient oases became less profitable due to land fragmentation and a decrease of land fertility because of the loss of biodiversity. Moreover, there were water deficits in traditional oases, and pumped water flows had been decreasing. In particular, artesian wells, which were numerous in the area, had all dried out by the early 2000s. Second, market liberalisation of the date palm sector led to an increase of the price of Deglet Noor dates.

Third, in some ancient oases, various public projects drilled boreholes to tap deep aquifers so as to increase water flows in collective networks. Farmers created extensions on the periphery of traditional oases (in areas called *mutakhma*) and built canals in order to use water from collective irrigation networks. These extensions were then included in the distribution water turns managed by water user associations. Farms located at the periphery of ancient oases drilled surface wells to make use of this new source. The relatively high salinity of the shallow aquifer was compensated by frequent and abundant irrigation.

And fourth, farmers developed innovative ways of accessing water, land, and energy. In the mid-1980s, low-cost drilling techniques became easily available in the Kebili region. Illegal boreholes were drilled in the new extensions created in the periphery of old oases. Farmers operated using diesel pumps. In lands in proximity to urban areas, farmers also operated electric pumps illegally. There were also public subsidies for building cold warehouses for the conservation of Deglet Noor dates inside and outside ancient oases. Owners of cold warehouses took advantage of their legal access to electricity to provide energy to boreholes located in extension areas. Later, from 2014 onwards, farmers started using solar power, especially in areas located far from urban areas. The increasing number of solar panels used for irrigation can be explained by I) the increasing costs of fuel and electricity, and II) the increasing number of solar panel companies and the growing competition between them, which led for instance some of these companies to offer payment facilities to farmers). According to interviewed actors, costs of installation of solar panels decreased by almost 50% between 2015 and 2020. The size of these solar installations varied greatly. Our spatial survey shows the intensified use of solar panels in the Douz region, particularly in the Southern Douz district area. In total, 2358 solar panels were detected in the Kebili region, of which 1083 were located in the Southern Douz district and 281 in the Northern Douz district.

Interviewed administration representatives acknowledged the limitations of ancient oases. They underlined the inefficient management of collective irrigation networks and the lack of maintenance of networks created by farmers in the *mutakhma* extensions. Both problems induced a decrease in the frequency of the delivery water turns. They also reported that, with the exception of 500 ha of new oases created by the PDES, only a few oases had been developed by the administration. A manager commented that: “sometimes we regret not having created new irrigated oases in collective lands; at least they could have been irrigated from collective and public wells and we would have avoided all these illicit drillings.” Moreover, they under-

lined the role of immigrants from other regions of Tunisia in extension development (the Kebili region has the second highest immigration rate in Tunisia), especially as they provide capital to invest in these extensions. Administration representatives also stressed the role of the 2011 Revolution. Before the revolution, Kebili CRDA had better control over illegal borehole drilling and had more legitimacy to act. In 2011, thousands of boreholes were created, and the CRDA was unable to intervene. A staff member mentioned that "In some places, the CRDA felt obliged to give permission to access electrical energy even if it had doubts about the intentions of the farmers [in terms of creating new palm groves outside official areas]. The CRDA has thus played a role in accelerating the development of extensions and illegal drillings."

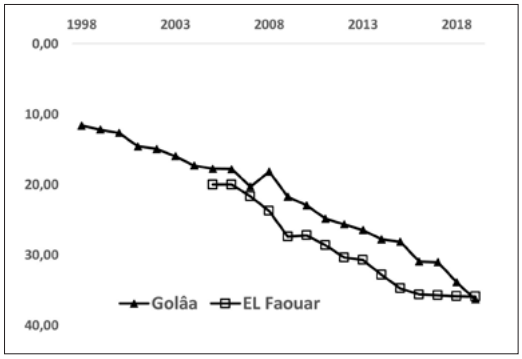
3.3. *A shared concern: the future of water resources*

3.3.1. *Intense groundwater use and its consequences*

The rapid development of extensions based on illicit wells led to improved date palm production, but it has also accelerated the degradation of natural resources. According to interviewed actors, boreholes are operated non-stop during certain periods of the year, leading to a rapid decrease of water table levels. Available estimates suggest the number of illicit boreholes in extensions increased from several dozen in the 1970s to 1,500 in the 1990s, 3,500 in 2010 (Gharbi, 2010) and to 9,678 in 2017 (CRDA, 2018). Concomitantly, a strong decline in piezometric levels was observed in several locations (Figure 6). The linkage between the growth of extensions and the decrease in Terminal Complex aquifer levels is also highly likely. In the Southern Douz district, the larger the area of oasis extension (eg, Golâa area), the greater is the decrease in the aquifer level. A decrease in the piezometric levels of 24.70 m has also been observed at Smida oasis between 1991 and 2020 (average of 1.18 m decreases per year).

Moreover, salinization of soil and waterlogging stemmed (I) from shallow saline water tables due to excessive irrigation with saline water from deep fossil aquifers and (II) from deficiencies in artificial drainage due to channel clogging by sand and roots (Ben Aïssa, 2006). Interviewed Kebili CRDA managers linked the degradation of groundwater quality and the decreasing levels of groundwater to the increasing amount of pumped water.

Figure 6 - Evolution of piezometric levels of Terminal Complex aquifer in two locations.



Source: CRDA Kebili, 1998-2018.

3.3.2. *Actors' discourse about causal relationship between extension development and overexploitation of groundwater resources*

Interviewed CRDA staff members underlined that the main threat to sustainability of agriculture in Kebili region was decreasing water resources. They put forward that throughout the 1980s, farmers exploited unused water from collective irrigation networks in the evenings to irrigate small extension plots located in the vicinity of ancient oases. From the 2000s, water started to become scarce and the impacts of these "nearby" extensions on ancient oases were clearly perceptible. They led to reduced water resource availability within these oases. The intense exploitation of deep aquifer has also resulted in an increase of groundwater levels in shallow aquifers, which has caused drainage problems.

Interviewed farmers also linked the extension dynamics with the degradation of water resources and identified this to be the main threat to sustainability. Farmers from Om Somâa extension, mentioned that: "[due to extensions close to the ancient oasis] the water turn can reach 20 days"

and that in the extension area "the salinity of the shallow water table has become very high in the last 5 years and exceeds 5 g/l." Farmers from the Blidette extension highlighted the effect of photovoltaic panels that were installed on the aquifer in 2015. Farmers rarely stopped pumps connected to these panels, which has led to increased use of groundwater. As one farmer mentioned: "If we had been authorised to equip our boreholes with electricity, we could have avoided the current situation of development of solar irrigation systems leading to a more intensified use of groundwater resources."

Farmers were pessimistic about the future of oases if current trends remain unchanged. They expressed their interest in designing innovative governance arrangements to ensure sustainable water use. However, the intervention of public policies in extension areas was perceived as both a threat and an opportunity. Deepening the boreholes, or searching for other lands were the main strategies that farmers identified to cope with decreasing levels of water resources.

3.4. *Limited attempts to manage palm grove extensions*

At the end of the 1980s, after the intervention of the Nefzaoua and APIOS projects, the administration formally integrated certain groups of extensions that were in continuity with the ancient oases into the water turn of collective networks, as in the Nefzaoua area (Ghazouani, 2009). However, a continuous decline in administrative surveillance and control of illegal drilling, as well as applying sanctions was reported by Kassah (1996). The decline of government control was attributed to the difficulty of monitoring a process that affected the whole region, to strong social pressures, and to the lack of alternative solutions in the region. It was only in 2008 that the administration began researching tangible solutions.

A visit by a government delegation in the Kebili region in 2017 led to an initiative to legalise *mutakhma* extensions. At the time, private farms inside the *moutakhma* extensions covering around 3750 ha were legalised and were provided subsidies. These subsidies were mainly water saving (drip irrigation; basins) and soil protection (the sandy amendment) equipment. However, subsidies to *moutakhma* extensions were later put on hold due to a lack of a legal basis for this new initiative. In 2018, Kebili CRDA announced a plan to provide subsidies to all other extensions, but this was later also put on hold.

Discussions to find solutions that would allow the provision of subsidies to any type of extension were still ongoing in 2022. To find legal solutions for extensions, discussions involved the Ministry of Agriculture, the Agricultural Investment Promotion Agency (APIA) and the Agricultural Land Agency (AFA). In July 2021, in cooperation with the AFA, a new attempt was made to legalise extensions by creating irrigated public areas. This decision will be applied in the first stage to the *mutakhma* areas.

In 2021, the production of Deglet Noor dates in the Kebili region, which is mainly cultivated in the extensions, was included in the national production of dates in Tunisia. However, the administration still did not recognize these private areas, which has led to various consequences. The first is a lack of strategies to improve irrigation water use. Apart from the *mutakhma* extensions, farmers within other type of extensions do not have access to either water saving or soil protection subsidies. Farmers created drainage networks without any idea about their real effectiveness. Negotiation mechanisms between farmers and the administration has yet to be put into place to reduce the volumes of water pumped by farmers, to stop the continuous movement of extensions or to deal with the problems of hydromorphy and salinisation of the soil in these areas.

The second consequence is land tenure insecurity. The illegal status of the extensions is not due to unauthorized access to the land, but rather to the unauthorized access to water resources. This paradoxical situation results in a blockage when it comes to the security of land holdings. Even though farmers benefit from a land allocation title issued by a management council, they cannot get a title of individual property. The situation becomes more problematic when the palm groves created become productive. Farmers cannot access public subsidies, they cannot get loans from banks nor can they benefit from public extension services.

4. *Discussion*

4.1. *Various dynamics toward one crop*

Most of the "push and pull" factors that led to the development of extensions in Kebili have been identified in other studies that focused on the development of agricultural economies based on the use of groundwater in North Africa since the 1990s (Faysse *et al.*, 2011). These factors particularly include drilling technologies that are available locally and financially accessible, water scarcity in existing irrigation schemes, and opportunities of remunerative markets for agricultural products (Fofack *et al.*, 2015; Kuper *et al.*, 2016). Other factors have also emerged as playing a key role in extension development, such as solar energy, which is currently available locally and financially accessible. The trajectory of the development of extensions has differed in the North African countries. Compared to Morocco, Tunisia's land regulation has accelerated the privatisation of collective land in a manner that has created opportunities for small landowners to invest in agriculture (Houdret *et al.*, 2017). However, private ownership of land in a fragile environment has had very serious consequences, causing uncertainty about the future of these developments and a decrease in investors' ability to face such insecurity (Bensâad, 2011).

At the national level, the Kebili region is a pioneering demonstration zone for agricultural expansion based on illicit boreholes. The current debate within research as well as in wider public arenas now often put forward environmental and sustainability issues including groundwater overexploitation, soil hydromorphy, salinity, and biodiversity loss. However, few academic studies have considered the main drivers and the different spatial expansion dynamics in Kebili region. Therefore, the region might be considered as a benchmark to initiate societal dialogues and national debates concerning water and land public policies, which could lead to more efficient and sustainable uses of these natural resources.

For the past 30 years, the diversity of farmers' origin and of processes for farmers to get access to land, has contrasted with the focus on one specific crop and variety, i.e. Deglet Noor dates. This dynamic was on the whole initiated by small and medium-sized farms. Yet, extensions created in 2020 are not the same as 30 years ago: larger plots are planted by medium-sized farms and large investors in locations far from legal oases; and solar energy enables easy access – for the moment – to water.

4.2. *Towards comprehensive and innovative policies*

In Morocco and Algeria, the government actively promoted the development of agriculture based on groundwater use to develop southern regions. By contrast, in Tunisia, the government chose to consider these activities as illegal, but at the same time chose not to act to limit the extension of groundwater-based agriculture – a stand that is quite common in many regions located in the centre or in the North of these countries (Fofack *et al.*, 2015). The difficulty for the state to take initiative is even higher in the Kebili region because palm date production was considered important for the development of the region and a much-welcome opportunity for exports. The financial and human resource deficits in Tunisian CRDAs and the crisis of legitimacy of the administration have also been accentuated since the 2011 Tunisian revolution.

This has led to the prevailing situation of tolerance, which is not officially acknowledged, i.e., what Brochier-Puig (2004) described as "the hidden face of the public policy." Since extensions are deemed illegal, extension development is also "hidden" from public policies, and it has taken several years for the administration to acknowledge their presence and to measure the phenomenon of extensions (Bisson, 1991). Moreover, the supervision of the piezometric and salinity levels, carried out by Kebili CRDA, mainly concerns the water points located inside the legal oases.

Initiatives to render these extensions legal have been limited to legalising a small part of the extension areas (the *mutakhma*), but do not consider the issue of water use. Thus, the legalisation initiative promoted by the Tunisian administration is not built on a strategic vision to support sustainable development of the region. Moreover, lack of initiatives to address the problem has led to anar-

chical creation of extensions, as well as to some "lock-ins" and the impossibility to tap new opportunities. Some farmers who were interviewed in extensions declared their interest to connect to the public electric network. This is the case for farmers using fuel (which is expensive and requires maintenance). Incentives for farmers that have installed solar panels are lower, but are still present. For these farmers, connecting to the public electrical grid could allow them to irrigate by night, but also to sell solar energy when they do not need it. This would provide incentives for them to stop pumping when not needed and would also contribute to national energy production. However, the lack of initiatives to address the "extension problem" triggered farmers that used fuel to shift to solar energy (thus decreasing their interest to access electricity) and made it impossible to tap the potential benefits of connecting existing solar panels to the national electric grid.

In India, Mantri *et al.* (2020) presented the benefits of grid-connected water pumping systems. Farmers connect their solar irrigation pumps to the grid to sell surplus electricity, gaining an additional source of income and a greater economic return on solar investments. However, they showed that the off-grid solar system improved power supply reliability, but it also led to further over-extraction of groundwater as there were no incentives for farmers to limit the amount of water pumped. In Tunisia, the potential benefits to connect existing solar panels to the electrical grid have not yet been tapped, because of technical issues (panels are scattered) and because of the lack of initiatives taken by the public electricity company to support such connexions.

The failure of public policies devoted to regulating the use of water resources from deep fossil aquifers highlights both the lack of consideration for individual initiatives when establishing such policies and the long-term uncertainties when implementing them (Mekki *et al.*, 2013). From this perspective, the Kebili oasian socio-agrosystem constitutes a case in which farmers' practices are driven by various factors (cultural perceptions of access to land and water resources, demography, and technological development), with subsequent changes in the actors' behaviours that mitigate public actions.

This double situation of over-pumping beyond authorised limits and illegal deepening into deep aquifer layers makes the monitoring of real abstracted volumes difficult and puts into question the values presented by the Ministry as official abstracted volumes (Elloumi, 2016). As a revealing anecdote, the announcement by the Ministry in 2011 that all wells in Kairouan, including illegal ones, would qualify for connection to the grid resulted in 12,000 requests to the public electricity company (Molle and Closas, 2017), however, there are only an estimated 8,000 to 9,000 wells for the entire area. Based on this, the Ministry's estimates of boreholes in Tunisia (5,111 according to data from 2005) are clearly inaccurate, and so is the estimated amount of water withdrawn from them (Elloumi, 2016).

4.3. *Opportunities for multi-stakeholder dialogue*

The above-mentioned legalisation of extensions could be a welcome – and rare – opportunity for the government and the farmers to come together to discuss more sustainable agricultural dynamics of extensions. Various options could be considered, for instance, which could include initiatives towards more efficient water use, a limitation of planted areas, in exchange for the legalisation of the area. Other options for a more sustainable future trajectory for the region could also encompass developing activities outside irrigated agriculture (Shah, 2009). Exploring initiatives to render these extensions legal and implementing actions toward sustainable use of groundwater resources will require initiating active communication and dialogue between Kebili CRDA and farmers.

Our research in this paper is based on a trans-disciplinary approach so as to prepare a dialogue between stakeholders. Such dialogue is a central component of any landscape approach, both in theoretical and operational terms (Sayer *et al.*, 2013). A dialogue was initiated by a research team (to whom the authors belong), involving Kebili CRDA and three farmers' groups in Kebili since 2020, as part of the Massire research project. Such a dialogue was launched putting forward that both CRDA staff members

and farmers participating in the workshops considered decreasing water resources is the main risk for the sustainability of agriculture in Kebili region in the future. The means of intervention that are available to the administration to control and regulate groundwater abstraction are obviously the most difficult challenge. Sharing experiences or 'success stories' from other countries or the case of Bsissi in Gabes Governorate in Tunisia (Frija *et al.*, 2016), could be put on the table as proposals for discussion.

5. Conclusion

The study showed the land use change dynamics and the driving forces behind it in the region that had most likely seen the highest growth in the illegal irrigation sector in Tunisia in the past decades. To our knowledge, this study provides the first regional-scale assessment of the oases extensions trajectories in the Kebili region in Southern Tunisia. The rapid development of extensions based on illicit wells led to improved date palm production, but it has also accelerated the degradation of water resources.

The landscape approach, which considers together challenges of space and scale, enabled to understand complexities of the oasis extension dynamics linked to local, regional and national contexts. Workshops hold with farmers located in extensions and with public governance actors enabled to build a shared vision of land use changes, of the drivers of these changes, and of prevailing and possible futures consequences on groundwater resource and on the sustainability of the agriculture in Kebili region. This knowledge can provide a basis for discussion between farmers located in the extensions and Kebili CRDA, to identify actions toward sustainable use of groundwater resources.

Multi-stakeholder dialogue will also have to face the complexity of existing dynamics (e.g. various types of extensions, drivers of change of various natures, difficulties in measuring the volume of water pumped by farmers and lack of a calibrated model of groundwater resources). In addition, this dialogue will need to address challenges relative to the specific institutional setting, and in particular the administration will need to acknowledge that farmers in extensions are de facto stakeholders that need to be involved in the discussion. Third, stakeholders would greatly benefit from examples of groundwater governance elsewhere, however, the specific characteristics of the Kebili region landscape dynamics would most likely require the development of solutions specific to the region. Innovative methods must be developed to address these interrelated challenges in order to find ways to improve agriculture and water management of traditional oases and to ensure the sustainability of extensions.

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References

Amichi F., Bouarfa S., Kuper M., Caron P., 2020. From oasis archipelago to pioneering eldorado in Algeria's sahara. *Irrigation and Drainage*, 69(S1): 168-176.

Angelstam P., Munoz-Rojas J., Pinto-Correia T., 2019a. Landscape concepts and approaches foster learning about ecosystem services. *Landscape Ecology*, 34(7): 1445-1460. https://doi.org/10.1007/s10980-019-00866-z.

Angelstam P., Manton M., Elbakidze M., Sijtsma F., Adamescu M., Avni N., Beja P., Bezak P., Zyablikova I., Cruz F., Bretagnolle V., Díaz-Delgado R., Ens B., Fedoriak M., Flaim G., Gingrich S., Lavi-Neeman M., Medinets S., Melecis V., Muñoz-Rojas J., Schäckermann J., Stocker-Kiss A., Setälä H., Stryamets N., Taka M., Tallec G., Tappeiner U., Törnblom J., Yamelynets T., 2019b. LTSER platforms as a place-based transdisciplinary research infrastructure: learning landscape approach through evaluation. *Landscape Ecology* 34(7): 1461-1484. https://doi.org/10.1007/s10980-018-0737-6.

Baynes J., Herbohn J., Smith C., Fischer R. Baray D., 2015. Key factors which influence the success of community forestry in developing countries. *Global Environmental Change*, 35: 226-238.

Ben Aïssa I., 2006. *Evaluation de la performance d'un réseau de drainage enterré au sein d'une oasis modernisée du sud tunisien : Cas de l'oasis de Fatnassa Nord à Kébili (Tunisie)*. Mémoire de Master Recherche "Eau et Environnement", AgroM-UM2, Montpellier, 119 pp.

Benmihoub A., Akli S., Benabid N., 2021. Enjeux, pratiques et contraintes pour une mise en valeur agroécologique des terres au Sahara. Cas d'un périmètre péri-oasien dans la Vallée du M'Zab (Algérie). *New Medit*, 20(2): 79-96. https://doi.org/10.30682/nm2102f.

Benoît M., Rizzo D., Marraccini E., Moonen A.C., Galli M., Lardon S., Rapey H., Thenail C., Bonari E., 2012. Landscape agronomy: a new field for addressing agricultural landscape dynamics. *Landscape Ecology*, 27(10): 1385-1394.

Bensâad A., 2011. Les conseils de gestion des terres collectives en Tunisie entre mauvaise gouvernance et marginalisation. *Options Méditerranéennes : Série B. Etudes et Recherches*, 66: 73-84.

Bisson J., 1991. Un front pionnier au Sahara tunisien : le Nefzaoua [Nefzawa: a pioneering front in Tunisian Sahara]. *Bulletin de l'Association de géographes français*, 68: 299-309.

Brochier-Puig J., 2004. Société locale et Etat face aux limites de la ressource eau (Nefzaoua, Sud-Ouest tunisien). In: Picouet M., Sghaier M., Genin D., Abaab A., Guillaume H., Elloumi M. (eds.), *Environnement et sociétés rurales en mutation : approches alternatives*. Paris: IRD, pp. 307-321.

Casanova L., Helle C., 2012. Ce que les dynamiques foncières révèlent du devenir des territoires : éléments de prospective du sud-est français. *L'Espace geographique*, 41: 111-127.

Côte M., 2002. Des oasis aux zones de mise en valeur : l'étonnant renouveau de l'agriculture saharienne. *Méditerranée*, 99: 5-14.

CRDA-Kebili, 1998-2018. *Excel data base. Piezometric levels of Terminal Complex aquifer* (in French).

CRDA-Kebili, 2010-2020. *Annual Technical Reports. Regional planning Commission for Agricultural Development, Kebili, Tunisia* (in French).

Daoudi A., Lejars C., 2016. De l'agriculture oasienne à l'agriculture saharienne dans la région des Ziban en Algérie. Acteurs du dynamisme et facteurs d'incertitude. *New Medit*, 15(2): 45-52.

Elloumi M., 2016. *La gouvernance des eaux souterraines en Tunisie*. IWMI Project Report No. 7, "Groundwater governance in the Arab World". Colombo: International Water Management Institute. Supported by United States Agency for International Development (USAID).

Erb K.H., Krausmann F., Gaube V., Gingrich S., Bondeau A., Fischer-Kowalski M., Haberl H., 2009. Analyzing the global human appropriation of net primary production-processes, trajectories, implications. An introduction. *Ecological Economics*, 69: 250-259.

Faysse N., Hartani T., Frija A., Tazekrit I., Zairi C., Challouf A., 2011. *Usage agricole des eaux souterraines et initiatives de gestion au Maghreb : Défis et opportunités pour un usage durable des aquifères*. Note Economique de la Banque Africaine de Développement, Tunis, Tunisie.

Fofack R., Kuper M., Petit P., 2015. Hybridation des règles d'accès à l'eau souterraine dans le Saiss (Maroc) : entre anarchie et Léviathan ? *Études rurales*, 2: 127-150. https://doi.org/10.4000/etudesrurales.10427.

Foley J., Ramankutty N., Brauman K. *et al*., 2011. Solutions for a cultivated planet. *Nature*, 478: 337-342. https://doi.org/10.1038/nature10452.

Frija I., Frija A., Marlet S., Leghrissi H., Faysse N., 2016. Gestion de l'usage d'une nappe par un groupement d'agriculteurs : l'expérience de Bsissi Oued El Akarit en Tunisie. *Alternatives Rurales*, 4. https://alternatives-rurales.org/wp-content/uploads/Numero4/AltRur4ExpBsissiGestionAquifereTunisieLectEcr.pdf.

Gharbi N., 2010. Hydraulic infrastructures and improvement of water management in southern oases. In: Marlet S., Mekki I. (eds.), *Proceedings of the SIRMA Workshop "Natural Resources Management and Sustainable Development of Nefzawa Oasian Systems"*. Douz, Tunisie, Cirad, 5 pp. (in French).

Ghazouani W., 2009. *De l'identification des contraintes environnementales à l'évaluation des performances agronomiques dans un système irrigué collectif : cas de l'oasis de Fatnassa (Nefzaoua, sud tunisien)*. Doctoral dissertation, Doctorat en Sciences de l'eau, Institut des Sciences et Industries du Vivant et de l'Environnement, AgrParisTech, Montpellier.

Ghazouani W., Marlet S., Mekki I., Vidal A., 2009. Farmers' perceptions and engineers' approach in a community-managed irrigation scheme. A case study from an oasis of the Nefzawa (South of Tunisia). *Irrigation and Drainage*, 58(S3): S285-S296. https://doi.org/10.1002/ird.528.

Hamamouche M.F., Kuper M., Amichi H., Lejars C.,

Ghodbani T., 2018. New reading of Saharan agricultural transformation: Continuities of ancient oases and their extensions (Algeria). *World Development*, 107: 210-223.

Houdret A., Zakaria K., Bossenbroeck L., 2017. A new rural social contract for the Maghreb? The political economy of access to water, land and rural development. *Middle East Law and Governance*, 9: 20-42.

Jackson L.E., Pascual U., Hodgkin T., 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agriculture, Ecosystems & Environment*, 121(3): 196-210.

Kadri A., Van Ranst E., 2002. Contraintes de la production oasienne et stratégies pour un développement durable. Cas des oasis de Nefzaoua (Sud tunisien). *Science et changements planétaires / Sécheresse*, 13(1): 5-12.

Kassab A., 1980. Problems in Tunisian oases. *Rural studies in Tunisia*, Tunis Faculty of Letter and Human Sciences, second series: Geography, VI, pp. 391-412 (in French).

Kassah A., 1996. *Les oasis tunisiennes : aménagement hydro-agricole et développement en zone aride*. Tunis: Secrétariat d'Etat à la Recherche Scientifique et à la technologie, Université des lettres, des arts et des sciences humaines (Tunis 4), Centre d'Etudes et de Recherches Economiques et Sociales (Cahier du Ceres, série géographique 13).

Kuper M., Faysse N., Hammani A., Hartani T., Marlet S., Hamamouche F. *et al*., 2016. Liberation or Anarchy? The Janus nature of groundwater use on North Africa's new irrigation frontiers. In: Jakeman A.J., Barreteau O., Hunt R.J., Rinaudo J.D., Ross A. (eds.), *Integrated Groundwater Management: Concepts, Approaches and Challenges*. Cham: Springer, pp. 583-615.

Lambin E.F., Meyfroidt P., 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, 108(9): 3465-3472.

Mantri S.R., Kasibhatla R.C., Chennapragada V.K.B., 2020. Grid-connected vs. off-grid solar water pumping systems for agriculture in India: a comparative study. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. DOI: 10.1080/15567036.2020.1745957.

Mekki I., Jacob F., Marlet S., Ghazouani W., 2013. Management of groundwater resources in relation to oasis sustainability: The case of the Nefzawa region in Tunisia. *Journal of Environmental Management*, 121: 142-151.

Molle F., Closas A., 2017. *Groundwater Governance: A Synthesis*. IWMI Project Report No. 6, "Groundwater governance in the Arab World". Colombo: International Water Management Institute. Supported by United States Agency for International Development (USAID).

Niedertscheider M., Kuemmerle T., Müller D., Erb K.H., 2014. Exploring the effects of drastic institutional and socio-economic changes on land system dynamics in Germany between 1883 and 2007. *Global Environmental Change*, 28: 98-108.

Novotny I.P., Fuentes-Ponce M.H., Tittonell P., Lopez-Ridaura S., Rossing W.A.H., 2021. Back to the people: The role of community-based responses in shaping landscape trajectories in Oaxaca, Mexico. *Land Use Policy*, 100: 104912.

Poussin J.C., Imache A., Beji R., Le Grusse P., Benmihoub A., 2008. Exploring regional irrigation water demand using typologies of farms and production units: an example from Tunisia. *Agricultural Water Management*, 95: 973-983.

Raiskila R.A., 2015. *Between rights and drought: socio-political perspectives of water scarcity in a Moroccan oasis*. Master's thesis, University of Helsinki. http://urn.fi/URN:NBN:fi-fe2017112251687.

Reed J., Van Vianen J., Barlow J., Sunderland T., 2017. Have integrated landscape approaches reconciled societal and environmental issues in the tropics? *Land Use Policy*, 63: 481-492. https://doi.org/10.1016/j.landusepol.2017.02.021.

Rizzo D., Marraccini E., Lardon S., Rapey H., Debolini M., Benoît M., Thenail C., 2013. Farming systems designing landscapes: land management units at the interface between agronomy and geography. *Danish Journal of Geography*, 113(2): 71-86.

Sayer J., Sunderland T., Ghazoul J., Pfund J-L., Sheil D., Meijaard E., Venter M., Boedhihartono A-K., Day M., Garcia C., van Oosten C., Buck L-E., 2013. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *PNAS*, 110(21): 8349-8356. www.pnas.org/cgi/doi/10.1073/pnas.1210595110.

Shah T., 2009. *Taming the anarchy: groundwater governance in South Asia*. Washington, DC: Resources for the Future; Colombo, Sri Lanka: IWMI - International Water Management Institute, 310 pp.

Wohlfahrt J., Colin F., Assaghir Z., Bockstaller C., 2010. Assessing the impact of spatial arrangement of agricultural practices on pesticide runoff in small catchments: Combining hydrological modeling and supervised learning. *Ecological Indicators*, 10(4): 826-839.