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Climate footprint in arid Tunisia: cropping systems, crop pattern and crop water productivity

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ABSTRACT

Tunisia is recognized as vulnerable to climate change impact, ranked 64th out of 187 countries in the 2022 ND-GAIN Index. With less than 150 mm mean annual rainfall, irrigation becomes essential in arid regions. Additional water supply was estimated between 2970 and 9730 m^3/ha. Crop water productivity (CWP) was high in mulberry and pomegranate (CWP > 1.5 kg/m3), while low values were recorded in species like pistachio, olives and date palm (CWP ≤ 0.5 kg/m3). In palm groves, appropriate water management systems could save until 620 m^3/ha by a 10% increase in CWP. For olive tree, CWP can be amplified by creation of medium- to high-density orchards, reducing tree spacing within the row. Warm temperatures during the chilling period of dormancy led to the limitation of suitable land for pome fruits' growing and accentuating alternate bearing in some nut crops. Scion/rootstock combinations are under test for better growth and yield performances. The national strategy should focus on cultivating crops with low chill needs and reduced water consumption. Biodiversity *in-situ* should be enhanced to promote sustainability and resilience of fruit cropping systems in dry lands.

KEYWORDS Adaptation, Alternative fruit crops, Biodiversity extinction, Mediterranean climate, Sustainable Development Goals (SDGs).

INTRODUCTION

Tunisia is facing increased challenges linked to agricultural adaptive capacity and to food security. Extreme weather events, such as drought and high temperature, are the major climatic constraints affecting crop yields and ecosystem balance. Several emerging pests and diseases have been declared present since 2012: *Erwinia amylovora* in pear, *Citrus tristeza virus* (CTV) in citrus, and cochineal *Dactylopius opuntiae* in prickly pear leading to progressive loss of ground and diversity within fruit crops. The arid regions of Tunisia, characterized by limited water resources, face significant challenges in sustaining agricultural productivity [1]. With over 70% of its land belonging to the arid and semi-arid, the country has its agricultural development drive closely linked to meteorological and climatic hazards [2]. Assessment of climate footprint in conjunction with cropping systems and water use efficiency becomes thus critical for regional food security and environmental sustainability [3]. This study focuses on analyzing the environmental impact of various agricultural practices, including diverse cropping patterns and irrigation management strategies under water shortage situation in arid Tunisia. Such investigations are crucial for developing sustainable agricultural models that can mitigate the impacts of climate change, especially given that semi-arid regions globally are projected to experience increased aridity and more frequent droughts [4]. Therefore, understanding the complex interplay between climate change, crop patterns and agricultural water use in such vulnerable ecosystem is essential for informing effective adaptation and mitigation strategies [5, 6]. Moreover, rising global temperatures and altered precipitation patterns are exacerbating water scarcity, placing immense pressure on agricultural systems to produce more with less, especially in low-latitude regions where adverse impacts are most pronounced [7]. This situation necessitates a comprehensive evaluation of crop water productivity and the overall climate footprint of agricultural activities to identify resilient crops associated to efficient farming systems [8].

Specifically, the effectiveness of carbon farming practices in Mediterranean agricultural systems, such as those found in Tunisia, is often challenged by unstable soil carbon storage due to low organic matter, intensive land use, and arid climatic conditions [9, 10]. Arable lands from arid regions are gradually losing from their potential to produce foodstuffs [11]. Climatic hazards are also expected to impoverish dietary diversity and food balance, especially in rural communities where resources are less available [12].

The design of a new fruit mapping system adapted to global changes in Tunisia supports the implementation of the United Nations Sustainable Development Goals (SDGs), in particular SDG2, SDG12, SDG13, and SDG15 [13]. Fruit crops re-mapping will help increase food production from decreasing land and water allocations and boost adaptation actions against extremes and sudden climate events among smallholder farmers and rural communities whose main horticultural activities predominately rely on olive cultivation and olive oil production.

SETTING AND STUDY DESIGN

Climate data (ET_0, precipitation, annual water requirements) were calculated using CROPWAT 8.0 and CLIMWAT for CROPWAT 8.0 for Windows OS with reference to the Penman-Monteith formula. Climate key trends were established based on data provided by FAO [14] and the World Bank Climate Change Portal for Development Practitioners and Policy Makers [15] with short- and long-term data previsions.

Crop water productivity (CWP), defined as the ratio of crop yield (kg/m^2) over water consumed (m^3/m^2), is designed to measure the net benefits from agricultural systems relative to the volume of water consumed [16].

(1) CWP (kg/m^3) = Crop yield (kg/ha) / Crop water use (m^3/ha)

The yield for each crop was collected from DGPA data sources for the time period 2010–2023 [17]. Crop water use or crop evapotranspiration (ET_c) was calculated using CROPWAT 8.0. The three parameters: ET_0, Kc and WUE (water use efficiency) were considered as the following:

$$(2)\ ET_c = Kc \times ET_0/WUE$$

CWP, known as the 'crop per drop' concept, can be increased by two main ways: (1) by increasing the yield of crops without using more water, or (2) by reducing water while maintaining or increasing yields [16]. CWP is one of the most used indicators to evaluate the performance of irrigated perimeters [18].

RESULTS

1. CLIMATE BASELINE AND TRENDS

Despite being the smallest country in North Africa, Tunisia comprises five climate zones. The country is largely influenced by the Atlas Mountains and Mediterranean Sea. It experiences precipitation gradients, one from north to south, with decreasing precipitation, and the other west to east, with increasing gradient. The Atlas Mountains are the dominant force in Tunisian's northern areas, which is characterized by a typical Mediterranean climate with hot summer (June to September) and precipitation occurring in the winter (November to February). In the arid and semi-arid regions of the center and south, drought is frequent, while the coastal region experiences relatively frequent flooding [19]. Long term projections estimated a rise in mean annual temperature from +1.5°C to +1.9°C by 2050 (Fig. 1). A net decrease in cold spells and the duration of wet periods is currently observed concomitant with an increase in frequency and intensity of drought and heat waves.

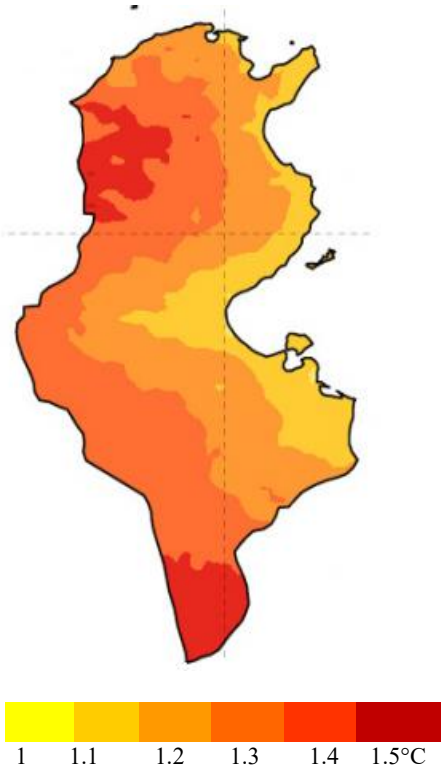


Fig. 1 Weather forecasts on the future climate trend in Tunisia (2021-2050) [19]

Examination of the figure 2 shows a net tendency to warming since 2010 with an increase in physical parameters (min, max and means temperatures). Since 2020, the temperature rise reached alarming value of 2.54°C in 2021 with discernible impact on fauna and flora throughout the country.

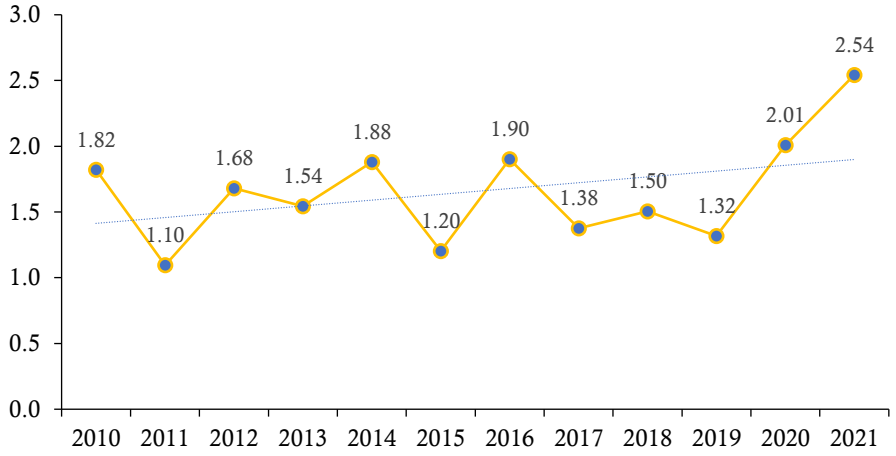


Fig. 2 Temperature (°C) rise in Tunisia from 2010 to 2021 [15]

The trendline of rainfall evolution during the last twenty years showed a drastic moving toward a situation of drought and water scarcity. From 2002 to 2022, the mean annual rainfall decreased in a rather outstanding way (Fig. 3). Water scarcity and droughts have become usual facts in most regions.

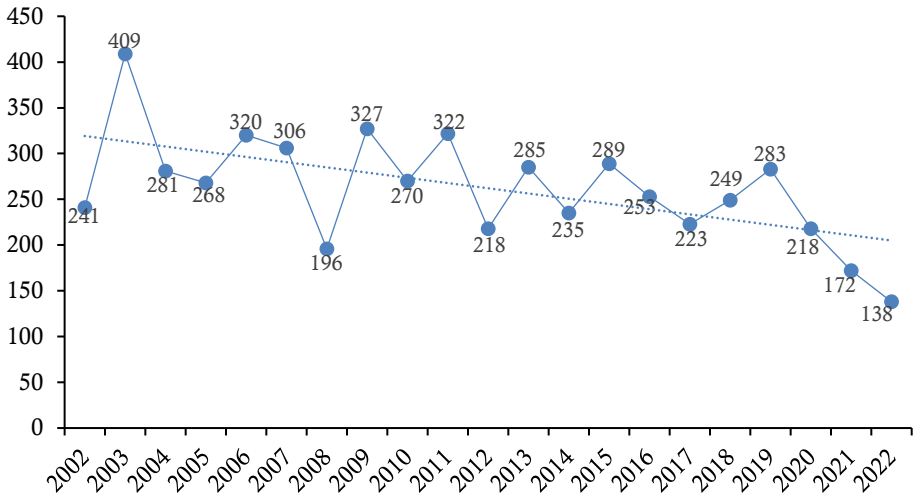


Fig. 3 Annual rainfall (mm) in Tunisia during the time-period 2002-2022

Precipitation in Tunisia is highly fluctuating (Fig. 3). Precipitation was observed to have decreased approximately 3% over the past 30 years. Stronger precipitation events resulting in flash flooding in recent years have also been observed [15]. Tunisia receives on average 36 billion m^3 of annual precipitation while mobilizable water potential is estimated to 4.8 billion m^3 which correspond to only 13.3% [20].

Other indicators of climate change hazards concern the scaling up and relocation of bioclimatic stages with extension of the Saharan and arid stages upwards, which means increasing desertification, and regression of the humid stage in the north [18, 21]. The decrease in precipitation is expected to continue with projections indicating longer and more frequent dry spells [15]. In a narrow scale, assessment of the vulnerability to climate change highlight the following: a decrease in the water balance with a decline in the rainfall distribution index; an increase in evapotranspiration impacting mainly the arid zones; a

153 shortening in the vegetative growth period; a decrease in the number of frosty days which
154 hinds the cold needs of fruit trees and results in an early invasion of harmful pests [18].
155
156 2. CROP WATER PRODUCTIVITY
157 Annual water requirements of the main fruit crops growing in arid Tunisia expected a range
158 values from 435 mm (pomegranate) to 1111 mm (loquat). With a mean annual rainfall of 138
159 mm, additional water supply by irrigation is needed and was estimated to a maximum of 1614
160 mm (Table 1).

161 **Table 1** Annual water requirements, crop yields and crop water productivity (CWP) for fruit crops to
162 recommend in arid lands of Tunisia. For areas harvested, the data relates to the 2023 crop season

Crop	Area harvested (ha)	Yield (ton/ha)	Annual water requirement (mm)	Irrigation water requirement (mm)	CWP (kg/m^3)
Almond	225,453	1.45	604	466	0.24
Pistachio	30,600	0.15	1093	955	0.01
Figs	11,350	1.90	523	385	0.36
Pomegranate	13,000	7.17	435	297	1.65
Carobs	395	2.06	1091	953	0.19
Mulberry	255	11.01	604	466	1.82
Apricot	8,153	4.08	541	403	0.75
Prickly pear	117,771	5.00	482	344	1.04
Loquat	436	6.07	1111	973	0.55
Olives	1606,909	0.66	1071	933	0.06
Dates	63,224	4.16	1703	1614	0.24

163
164 Crop water productivity varied from 0.01 to 1.82 kg/m^3 (Table 1). Variance was observed
165 between the different crops: the highest values were observed in mulberry and pomegranate,
166 while the lowest values were recorded in pistachio, olives and date palm. Low CWP in olives
167 (0.06 kg/m^3) is explained by the low density of olive trees (17 trees/ha) cultivated under arid

conditions of the center and the south. In the case of date palm, the situation is different. The low CWP (0.24 kg/m^3) is mainly due to extensive water consumption of date palm oases in the south with absence of adequate water management systems. Channel irrigation system is still used in most palm groves.

3. CROP PATTERN: ALTERNATIVE FRUIT CROPS

Arid and semi-arid lands of Tunisia are at 69% covered by olive tree while common fruit crops and date palms represent 28% and 3% respectively (Fig. 4). Olives are suitable for water-less cultivation with no additional irrigation for most of the season [21]. Irrigated orchards cover more than 228 thousand hectares (~10% of total fruit crop areas) and are mainly concentrated in the north where water resources are clean and available. Such results highlight the critical role of irrigation, particularly in regions where reliable water sources are essential for nurturing fruit tree growth and maximizing agricultural output [21]. Some non-native and introduced varieties of pear demonstrated low capacity of adaptation to changing climate and are predisposed to extinction [22]. In contrast to foreign cultivars, local pears are naturally adapted to warmer climate, and many local varieties are resilient to various forms of climate related stresses. Geographical options for pome fruits (apple, pear and quince) are becoming limited. Climate change is shifting the habitat range of pome trees and some pear and apple crop areas previously used to be productive will not be so in the next few years.

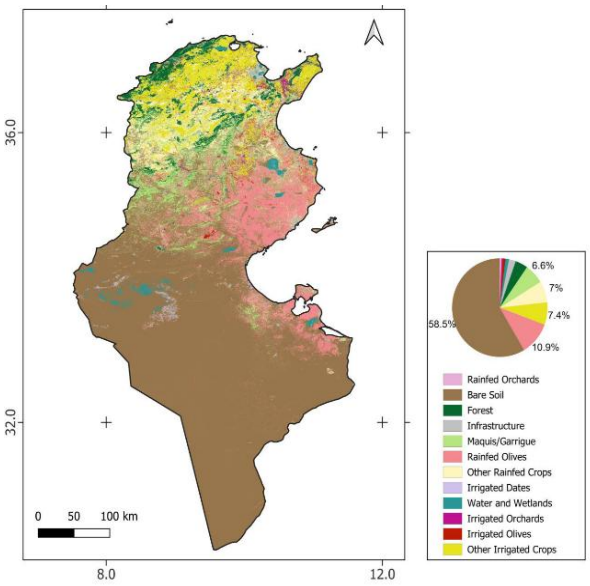


Fig. 4 Land cover map of Tunisia with a chart showing the proportional cover of each class of crop [21]

Almond and pistachio trees are extremely drought tolerant. Without irrigation, cultivation of such species remains not profitable. Almond trees make good use of frequent small amounts of water. Temperatures during the chilling period were the dominant determinant of quality of bloom. High temperatures during this period become more frequent leading to delayed and abnormal bloom subsequently less productivity, alternate bearing and poor quality of the fruit [23, 24].

Fig and pomegranate are drought hardy crops suited to arid and semi-arid environments where the use of marginal water for irrigation is possible. However, long periods of high temperatures can cause plant dieback. The introduction of indigenous fruit crops like mulberry, carob and prickly pear could boost mitigation against negative impacts of increasing temperatures in arid lands. Prickly pear, a typical plant of dry lands, has a CAM pathway adapted to minimize water loss and photorespiration. With the large infestation by *Dactylopius opuntiae* reported first in 2021, an official strategy of control has been deployed for pest eradication and to prevent its dissemination in clean areas. The selection of new resistant/tolerant clones has been initiated to cope with this serious threat. Date palm occupies

the south areas of Tunisia. Over 50% of dates are cultivated in the south-east, exemplifying the crop's suitability for cultivation in arid and semi-arid climates. Date palm varieties in Tunisia are known to be water intensive and are often located within the oases where water availability is ensured [21].

The selection of adapted plant material was established basing on geographical plant distribution, growth potential and yields, evapotranspiration (ETc) and water use efficiency (WUE) to keep cropping systems sustainably profitable under arid conditions of Tunisia.

DISCUSSION

Which crops should be favored? In terms of water allocation by irrigation, fruit growers should focus on cultivating crops with low water consumption and high added value. This orientation allows to particularly reduce over-exploitation or degradation of internal resources [20]. Water productivity has become a central concept in thinking about water management and agricultural development. The extrapolation of the present study demonstrates that an increase of 10% in CWP could save a minimum of 0.62 million liters of water per hectare in the case of date palms. With the actual context of water scarcity and lack in water resources this can be considered important. In the case of olive tree, extended in over 1.6 million hectares [17], the total water savings can reach 1,727 billion liters, i.e. 2-fold the capacity of the largest dam of Tunisia (*Sidi Salem* dam). In conclusion, the potential for saving water is high when appropriate water management is undertaken.

High temperatures during dry seasons became an issue in fruit development and ripening [25]. For example, retarded maturation of pistachios for some late varieties cultivated in the north of Tunisia exposed fruits to seasonal and heavy rains of September with consequence delaying harvesting operation and reducing quality of the product: about 5% of the total harvest was lost in 2020. Fig tree, known to be resilient fruit crop in arid Tunisia, becomes

more sensitive to biotic and abiotic stresses [26]. The recent regain of interest in fig cultivation was accompanied by the development of protected crop cultivation on the soil and off-soil. Protected cultivation of fig is proposed as adaptive solution to overcome temperature extremes and related emerging pests. Appropriate plant material should be selected to ensure sustainability of such orientation [26].

For sustainable fruit production, national strategies and breeding programs are now focused on the use of adapted and yield-efficient cultivars with low chill requirements and the selection of vigorous and resilient rootstocks. An apple breeding program was started in 1985 at the INRAT (National Institute for Agricultural Research, Tunisia) over collaboration with INRA Angers (France). The principal objective was to address the rising bio-climate challenges and to promote adaptability and sustainability of national apple production. The breeding program led to a final selection of 3 new apple genotypes with low chilling needs, high storability and good quality of the fruit [27]. In the same framework, a national public/private project is currently being undertaken by INRAT to select new pistachio rootstocks that are drought tolerant, salt tolerant, and/or resistant to fungus diseases. Moreover, the growth and yield performance of scion/rootstock combinations are also being assessed [28]. Transposing of new orchards to more favorable bioclimatic conditions and the extension of irrigated/partial root irrigated orchards are other alternatives to maintain regular production and nut quality [23, 24]. Recent works, carried out at the INRAT in collaboration with the profession, resulted to the selection of two almond genotypes and their pollinators to produce controlled almond progenies. Thus, new rootstocks will be commercialized in future for renewing old plantations and creating new orchards with good adaptation to poor soils and harsh environments [29].

Sustainable agricultural practices involve several approaches. The most important approach is cropping diversification [30]. It allows farmers conserve the resource base and boosts land-

use efficiency. Crop diversification promotes crop diversity by multiple cropping, relay cropping or inter-cropping with the goal of improving productivity, sustainability, and supply of ecological systems. In the south of Tunisia, most of the oases are designed in a dynamic multi-crop combination. Association of date palms with pomegranate tree and Medicago (fodder) make a specific agro-ecosystem resilient which contributes to stability and profitability of local farm holdings. Another example of resilient biodiversity is seen in the association of common crops like olive with under-utilized fruit crops typical of arid lands such as mulberry and carob. The carob tree, with large evergreen leaves, is of capital importance for rural populations who find in the tree: food for themselves and their livestock, wood for heating and cooking, and additional income from the sale of carobs. Carob beans and kernels are useful for a variety of purposes including food, fodder, and as source of industrial products such as gums, sugar, and alcohol. The tree, adapted to a wide variety of soils, could also be used for shade and erosion control. Mulberry (*Morus* spp.) is a tree with a strong ecological tolerance. It shows high growth capacities under arid conditions. The plant diversity is confirmed in Tunisia with a large distribution in the central and the southern regions. With CWP = 1.82 kg/m^3 (Table 1), mulberry remains highly rewarding and proposes promising opportunities for food industry and processing. The fruit, rich in vitamins, flavonoids, anthocyanins and phenolic acids, can be used for medicinal and therapeutic purposes and the leaves are potentially used for silk production [31].

CONCLUSION

Prospective strategies for adapting agriculture to climate change have been undertaken in Tunisia. The challenge is to move from crisis management (floods, unpredictable successive droughts) to risk management linked to global climate change (anticipatory adaptation actions).

Selection of the appropriate plant material (scions and rootstocks) for the suitable environment is the starting of an adapting strategy to face weather extremes. Innovative farming practices using new technologies and climate-resilient crops can help mitigation to changing climate. Digital agriculture combined with precision agriculture based on real-time remote monitoring and early warning system is recommended to prevent the impact of climate change. Sustainable water management ensures efficient water usage and reduces pressure on water resources used for irrigation. The water supply management policy focused on water mobilization should continue to be a national priority with a transition towards the implementation of water-saving programs. It consists of valuing the water used in agriculture in favor of crops with high added value.

AUTHOR CONTRIBUTION

All authors contributed to the design of this work, each in its own field. Conceptualization, planning, data processing and analysis and writing of the article were carried out by M. Trad. Data resources, statistics, paper revision and editing were performed by A. Lachkar, A. Chelli and S. Mselmi. The final layout of the paper was approved by all authors.

DATA AVAILABILITY

Data supporting Fig. 4 are publicly available in this record: https://doi.org/10.4060/cc9442en [21]. Supplemental data will be made available on request.

DISCLOSURE STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

COMPETING INTEREST

There are no competing interests to declare relevant to the content of this article.

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