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The effect of climate change and drought on Aleppo pine (*Pinus halepensis* Mill.) forests in the Geopark M'Goun, High Atlas of Morocco

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ABSTRACT

Climate change in Morocco has intensified drought conditions, increased temperatures, and reduced precipitation, significantly affecting vegetation dynamics. In the High Atlas, particularly within the M'Goun Geopark, an unprecedented dieback of Aleppo pine (Pinus halepensis Mill.) has been observed. This study aims to quantify this decline and identify its main climatic drivers.Climatic variability was assessed using TX90 and TN90 (extreme temperature days), P10mm, Tmin, Tmax, mean temperatures, the Standardized Precipitation Index (SPI), the Emberger quotient (Q2), and the De Martonne aridity index. Aleppo pine cover changes were analyzed using supervised classification of Sentinel-2 imagery (10 m) via Google Earth Engine, and evapotranspiration was used as an indicator of plant water stress.Results show a significant increase in temperature-related indices, with an overall rise of approximately 1°C between 1960 and 2020. Precipitation decreased by 77.14 mm, with increased interannual variability confirmed by SPI. Q2 and De Martonne indices indicate a shift from sub-humid to predominantly semi-arid conditions. Aleppo pine forests lost 22 km² (≈40%) between 2015 and 2022. Vegetation decline is strongly correlated with temperature, while precipitation shows no significant relationship in August. Evapotranspiration also decreased markedly, indicating increasing water stress.These results highlight climate change as the main driver of Aleppo pine dieback, emphasizing the need for urgent conservation strategies.

Keywords: *Climate change, Aleppo pine, Temperatures, Precipitation, Morocco.*

1. Introduction

Droughts are a prevalent weather-related natural hazard affecting environment across nearly all climate zones, differing in their frequency, severity, and duration [1][4]. Climate change has become increasingly severe, threatening ecosystem stability and, in particular, biodiversity[5]. The effect of climate change on vegetation is expected due to changes in the temperature, rainfall [6]. Climate change is accelerating [7] under the influence of natural and anthropogenic factors [8]. In addition, the natural, social and climate systems havestrong interactions with human-induced climate change [9]. These changes in climate have severe and major negative consequences, especially on our societies and environment [10]. Among the countries of North Africa, it is likely that Morocco will face the strongest effects of climate change [11]. There are two major climatic zones in Morocco the Northern regions (north of the High Atlas) with temperate and rainy climate and the Southern regions (south of the High Atlas), which have a semi-arid to desert climate with irregular rainfall [12].

Furthermore, climate variability has profoundly impacted a wide range of macroecological processes [13]. Decreases in precipitation, increasing aridity and higher temperatures, coupled with pressures of population growth and rapid urbanization is increasing Morocco's vulnerability [14]. Indeed, the worst in 30 years, reduced cereal yields by 70 % and projections suggest will slow economic growth [15]. in part contributing to a deceleration in economic growth of 1.7 %[12]. Deforestation, rising temperatures, drought, fire and other ecological disturbances are reducing forest [16]. The manifestations of climate change, such as a decrease in annual precipitation and an increase in temperatures impacted forests [17]. Most of Morocco's forests have become degraded including *Pinus halepensis* [18]. Aleppo pine is found mainly in North Africa and Spain [19]. Aleppo pine (*Pinus halepensis* Mill.) is a widespread tree species whose natural range is limited to the Mediterranean basin[20]. In Morocco, it covers an area of65,000 hectares, spread over the Mediterraneanslope of the Rif, the central Middle Atlas, and some valleys of the High Atlas [21].

Because of its plasticity, it has been extensively used as a reforestation species to restore degraded areas [22].Correlation analysis revealed an increased negative relation with maximum temperature in April, June, and July, supporting the adverse effect of global warming on P. halepensis growth[23]. Tramblay et al. demonstrate that the climate change simulations indicate a decrease in extreme precipitation, -12% in average for the projection period 2070-2099 and a great variabilityprojection period 2020-2050 in Morocco [24], similar study took place in High Atlas of Morocco and revealed decreasing annual precipitationby 10–14% [25].

Several indices have been developed to assess and describe the climate and climate change; for example, bioclimatic levels [26], described by Emberger 1931 and vegetation levels, that describe the vegetation type according to climate features; these indices have been developed to spatially delineate bioclimatic zones and to explain the geographic distribution of vegetation through the combination of various climatic factors [27]. Along with TX90, TN90 and P10mm. Significant temperature increases lead to increased evapotranspiration, which may negatively affect vegetation growth, while the change of precipitation distribution pattern may lead to different degrees of vegetation degradation or increase in different areas [28][30], in addition, Many of the studies into the response of plant life to climate change seem to suggest that most plants will be more stressed[31]. Techniques of vegetation mapping and assessment are various, among them the supervised classification. Supervised classification is the process of assigning a class value to a set of grid cells [32].This technique involves using training data to classify different classes in the raster image.

Our objectives are;firstly, assess the Aleppo pine dieback in the High Atlas Geopark Mgoun reserve, secondly evaluate the main drivers of the pine degradation.

2. Methodology

2.1. Study area

The study took place inside the Geopark M'goun in Azilal province, situated in central Morocco and in the Central High Atlas. The area of the Geopark, illustrated in Figure 1 and recognized by UNESCO in 2014, is 5700 km2. The area present a highly biodiverse geological substrate, accounting for limestone, clays, dolomites, marls, volcanic rocks, detrital formations and others '[33]. Furthermore the region receive precipitations between 500 and 700m in average '[34], presenting a Mediterranean like climate featured by rainy winter and dry summer [33] [35].

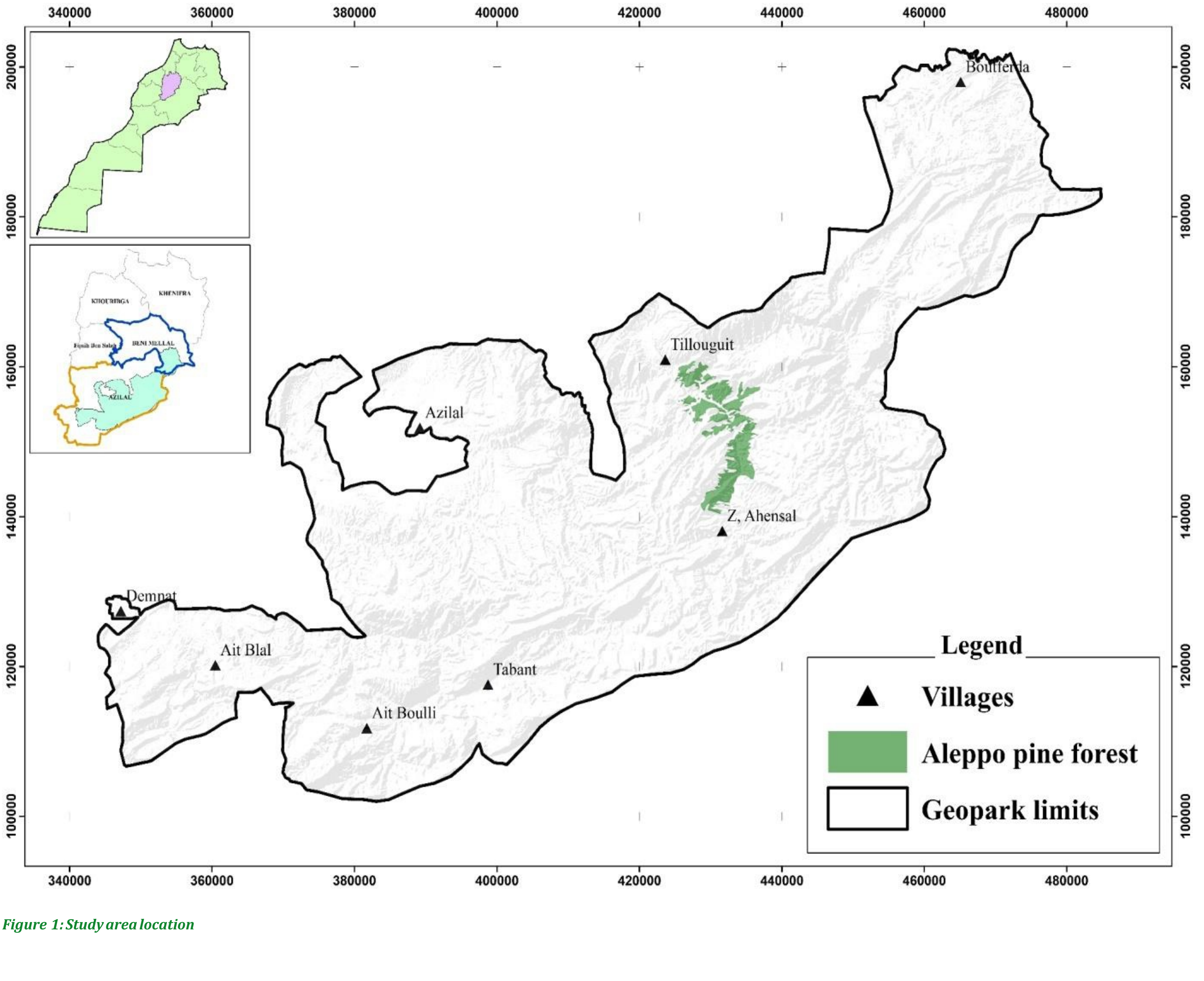


Figure 1: Study area location

The Aleppo pine in the geopark M'goun are largely affected by the wood production during the Frensh colonization and after independence, as a result the Moroccan authority have announced this region asReserve, concurrently the area has classified as SIBE (Area of biological and ecological significance) of Tamga, and ZIP Tamga (Area of importance for plants of Tamga). The Tamga region contains 366 (or 436, considering the taxa from Belghazi's work) species distributed among 62 (or 64) families, constituting 10% of Moroccan plant richness [36]. Belghazi in 2000 has proved that the Aleppo pine forest (*Pinus halepensis*Miller) in Tamga (Western High Atlas of Morocco), nestled in the valley of the Oued Ahansal, is characterized by remarkable production compared to the usual performance of this species [37]. However, during the last years an unprecedented massive dieback of pine trees is located in the area as revealed by images in figure 2.

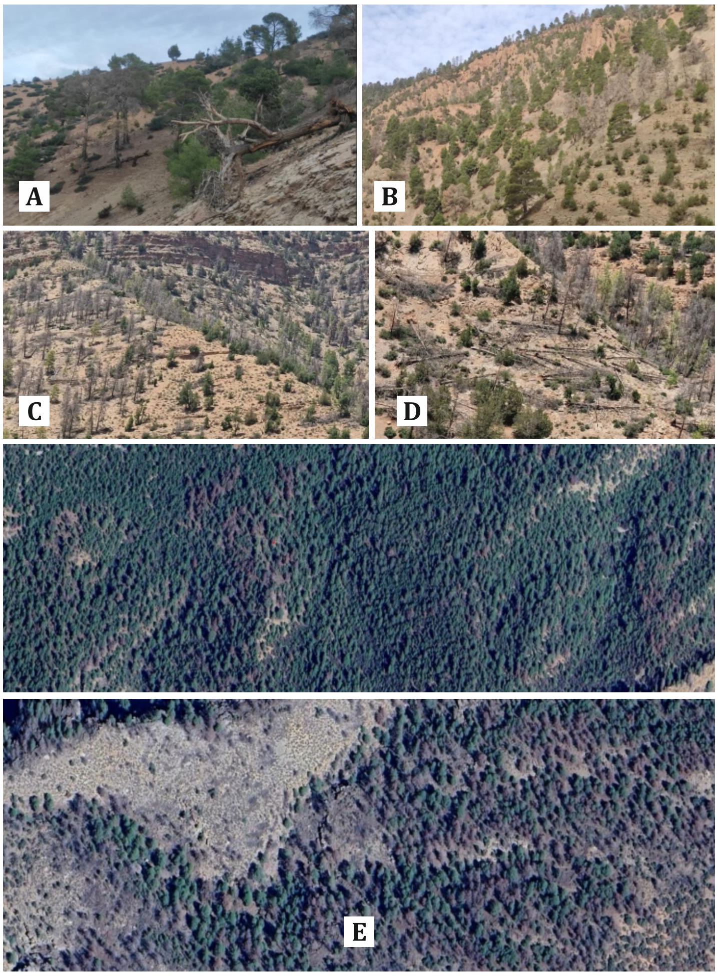


Figure 2: (A, B, C, D, E), The dieback aspects in the study area

2.2. Climate change indices

Three indices have been selected to assessclimate change in the study area; TX90° for the days where the temperature is higher to 90th percentile, TN90° wheretemperature is higher to 90th percentile and days where precipitation are higher to 10 mm [38], [39].

2.3. SPI

Monthly precipitation data from the Tilouguite station (1980–2019), located in the Aleppo pine forest and provided by the Hydraulic Basin Agency of Oum Er-Rbia 2022, were used to calculate the SPI.

The resulting values were interpreted according to the standard SPI classification, allowing the identification of dry and wet periods, as well as their spatio-temporal variability, and enabling the assessment of their potential impacts on forest ecosystems.

2.4. Emberger bioclimatic index

Among the bioclimatic indices traditionally used in North Africa and elsewhere in the Mediterranean [40], his index takes into account annual precipitation, the average maximum temperature of the warmest month (M in °C), and the average minimum temperature of the coldest month (m in °C). Afterward, temperatures are transformed into Kelvin by adding 273[41]:

$$Q_2 = \frac{1000P}{\frac{(M-m)(M+m)}{2}} = \frac{2000P}{M^2 - m^2}$$

Q2 : Quotient bioclimatic indices
P : Annual precipitation (mm)
M : Maximum temperature of the warmest month (K)
m : Minimum temperature of the coldest month (K)
The Q2 facilitates the characterization of distinct bioclimatic zones, and the minimum temperature during the coldest month aids in defining climatic variations[40]. The selected bioclimatic zones include the Saharan zone, arid zone, semi-arid zone, sub-humid zone, humid zone, and per-humid zone[42].

2.5. De Martonne aridity index

Among the climatic indices commonly used to characterize aridity in Mediterranean and semi-arid regions, the De Martonne aridity index is widely applied due to its simplicity and effectiveness in integrating both precipitation and temperature [43][44]. This index is based on annual precipitation and mean annual temperature, allowing the evaluation of climatic dryness.

The De Martonne aridity index (I) is calculated as follows:

$$I = \frac{P}{T + 10}$$

2.6. Aleppo pine assessment

Firstly, the Aleppo pine forest in the area is delineated using Google Earth imagery, as Aleppo pines have specific visual characteristics compared to the surrounding forests of holm oak and Juniperus phoenicea. Then, supervised classification is employed to analyze Aleppo pine density over time. The Google Earth Engine is utilized for this supervised classification (SC), followed by an assessment of the Aleppo pine area for the study period. The area of Aleppo pine is estimated based on vegetation classes and bare soils. Evapotranspiration is considered as it reflects plant adaptability to climatic conditions, particularly their response to water and thermal stress. It's important to note that the Tamga Aleppo pine forest is protected, with grazing restrictions and prohibitions on pine cutting, which are relatively controlled by local authorities, and the month of August was selected to avoid the effect of herbaceous plants, as these plants degenerate during the late summer and autumn seasons.

SC is based on using suitable algorithms to label the pixels in an image as representing particular ground cover types, or classes [45], some of these algorithms areSupport Vector Machine (SVM), Spectral Angle Mapper (SAM), Maximum Likelihood Classification (MLC), Artificial Neural Network (ANN) and Random Forest Classifier (RFC) [46]. During this study the Support Vector Machine (SVM) is utilized as it' the most efficient [46][49].

2.7. Statistical analysis

The correlation coefficient is implemented to evaluate the Aleppo pine forest interaction with climate patterns to determine the factors that drive its evolution. Since the vegetation cover evolution is a complex set where large scale of scales the PCA is used to assess the multidimensional evolution of these forests.

2.8. Data sources

The climate data used in the current study, including (Tmin, Tmax, and precipitation), were downloaded from World Clim (https://www.worldclim.org). SPI calculations were based on monthly precipitation data from the Tilouguite station (1980–2019), provided by the Hydraulic Basin Agency of Oum Er-Rbia,2022. ArcMap was used for data processing, while R software was applied for statistical analysis. These datasets cover climate information for all land surfaces and are interpolated using advanced methods. They have proven useful for various studies on climate change [50][51], Additionally, MODIS evapotranspiration data were obtained from https://lpdaac.usgs.gov/products/mod16a2v061/.

3. Results:

3.1. Climate change Indices

The days where the minimal and maximal temperatures pass the limit of 90th quantile increase considerably for the study period, indeed, for the maximum temperatures, TX90 has increased respectively from 27.49 in 1984 to 46.11 in 2020 and from 28.8 to 45.5 for minimum temperatures TN90 (figures3 and 4).

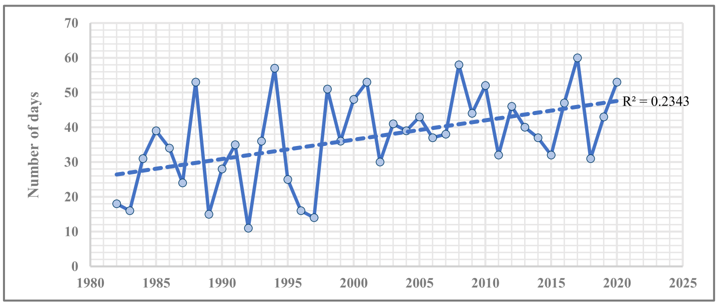


Figure 3: The TX90° variation in the chosen four stations in the Geopark M'goun

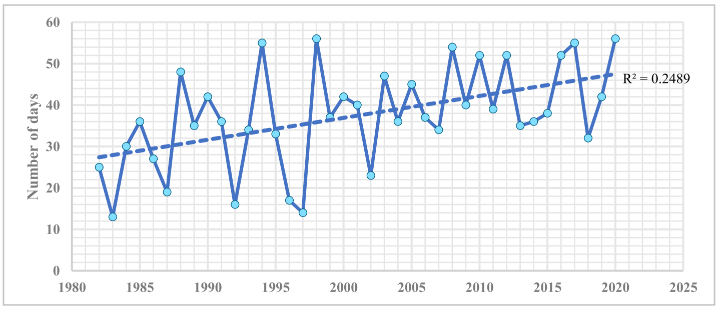


Figure 4: The TN90° variation in the chosen four stations in the Geopark M'goun

The number of the days where are irregular across the study period and un the study area, presenting an important spatiotemporal variation (Figure 5)

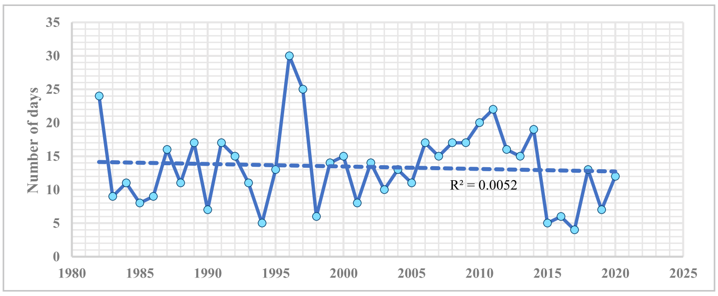


Figure 5: The variation of the number of days where precipitations exceed 10mm

3.2. Temperatures variation

The average temperatures fluctuations, revealed by figure 5, vary in the study area between 12 during in 1992 and 15°C in 2005. The linear regression demonstrates the rise of Average temperatures by 1°C during the study period (figure 6). Furthermore,Tmin and Tmaxare progressively increasing during last decade (Figure 7).

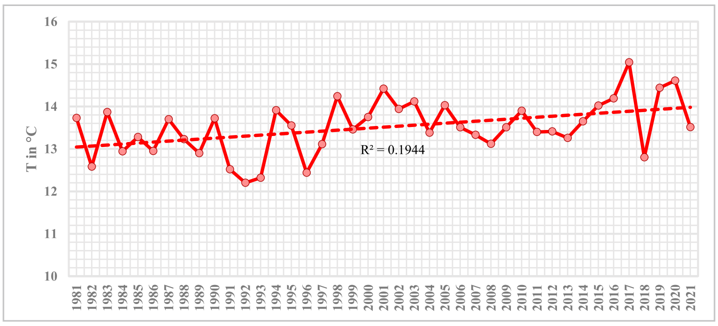


Figure 6: The annual average temperatures variation in the study area between 1980 and 2021

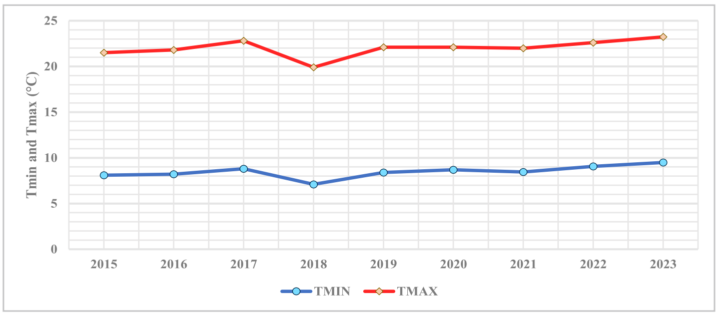


Figure 7: The minimum and maximum temperatures fluctuations in the study area for the las decade

3.3. Precipitations

The precipitations oscillate in the study area between 168.67 mm during in 1981 and 903.35 in 1996. The linear regression demonstrates the rise decrease of precipitation by an average of 77.14 mm between 1960 and 2019, as shown by figure 8.

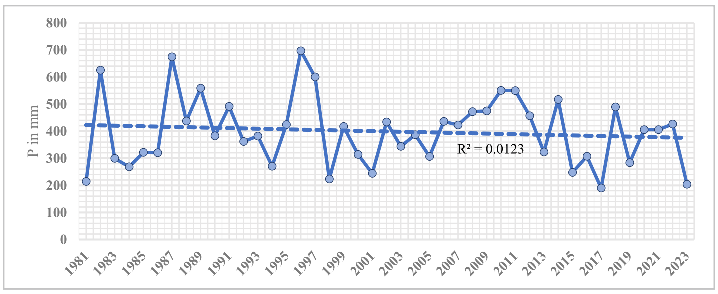


Figure 8:The annual average precipitation fluctuations between 1980 and 2021

3.4. SPI (Standardized Precipitation Index)

The SPI (Standardized Precipitation Index) graph for the Tilouguite station (1980–2019) shows strong interannual variability in rainfall, with alternating wet and dry periods. Several pronounced drought episodes are evident, particularly in the mid-1980s, the early and late 1990s, as well as between 2007–2010, and again in 2013 and 2016. In contrast, some years are characterized by very wet conditions, such as 1990, 2003–2004, and 2017 (Figure 9).

Overall, there is no clear linear trend, but there is an apparent increase in the frequency of dry episodes in recent decades.

For the Aleppo pine forests of the geopark, this rainfall variability leads to repeated water stress, which can affect growth, regeneration, and increase ecosystem vulnerability, despite the species' adaptation to semi-arid conditions.

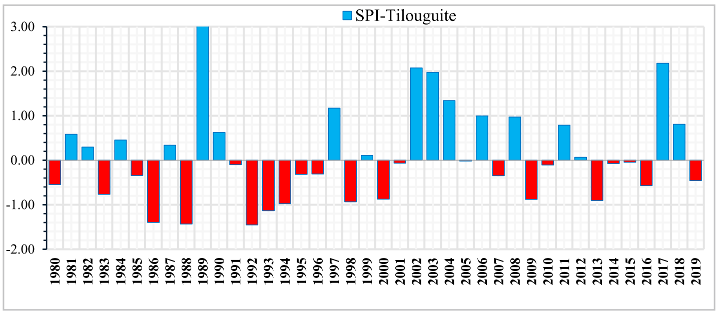


Figure 9: SPI of the Tilouguite station

3.5. The evapotranspiration

The evapotranspiration tends to decrease during the 2015-2023 period (figure 10).

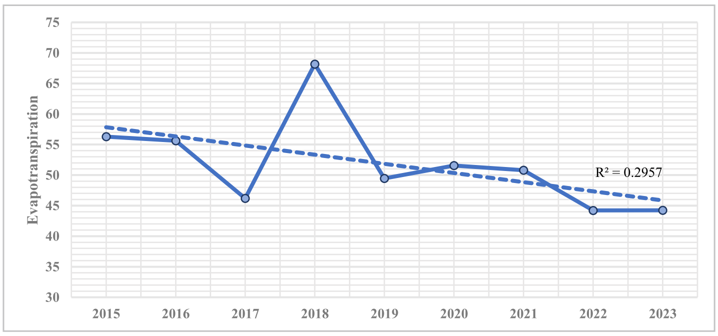
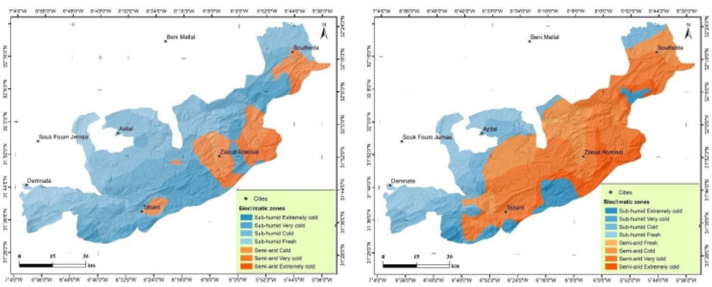


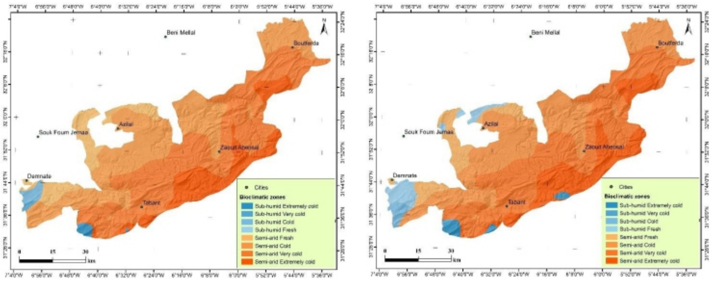
Figure 10: The evapotranspiration availability in the Aleppo pine forests between 2015 and 2023

3.6. Bioclimates variation

The maps figure 11 reveal that climate became more and more semi-arid. The most part of the geopark in the 60s decade are sub-humid, however the subsequent decades the semi-arid takes over as revealed by map C and D.



A B

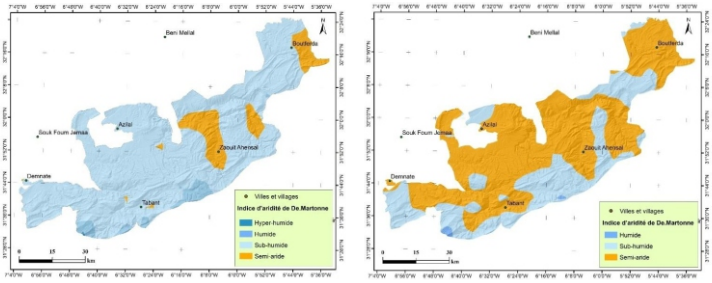


C D

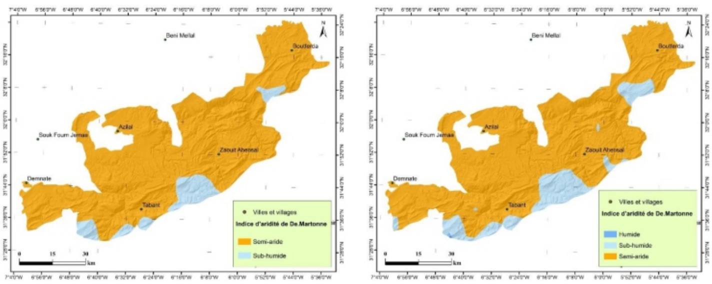
Figure 9:The bioclimates levels fluctuations between 1960 and 2020:A) between 1960-1969, B) 1970-1979, C) 2000-2009, D) 2010-2019

3.7. De Martonne aridity index

The maps figure 12 highlights a progressive shift towards semi-arid conditions. While sub-humid climates dominated the geopark during the 1960s, semi-arid conditions gradually expanded in the following decades, becoming predominant in the most recent periods (maps C and D).



A B



C D

Figure 12: Spatial distribution of the De Martonne aridity indexbetween 1960 and 2020:A) between 1960-1969, B) 1970-1979, C) 2000-2009, D) 2010-2019

3.8. Aleppo pine fluctuations

The Aleppo pine forests is largely devasted in the Tamga reserve, the supervised classification revealed that the pine forest have lost 22 Km^2, shrinking from 54,1 (2016) to 31 Km2 in 2022 (figure 13), the maps illustrated in figure 12 confirm these fluctuations. The SC accuracies are (table 1):

Table 1: the supervised classification accuracy

Year	Accuracies
2015	0.97
2016	1
2017	0.98
2018	0.95
2019	0.98
2020	0.96
2021	0.96
2022	0.97
2023	0.98

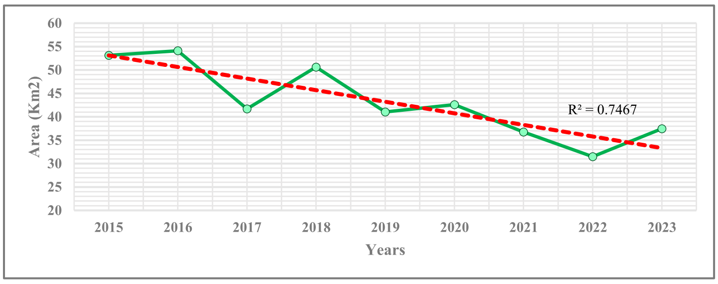


Figure 13: Aleppo pine area fluctuations between 2016 and 2023

Figure 10: The spatial evolution of the Aleppo pine forests in the study area: A) 2015, B)2018, C) 2020, and D) 2023

The correlation test indicates a substantial association between vegetation cover and increasing temperatures, particularly highlighted by the strong correlation observed between pine cover and both Tmin and Tmax as table 2.

Table 2: The correlation between pine forests area and key climate parameters that influence their development is significant

	Vegetation	Pa	ET	TMIN	TMAX
Vegetation	1	ns	0,76	-0,71	-0,64
ET	0,76	0,76	1	-0,96	-0,97

ns: not significant

The correlation test is generally confirmed by the CPA plot. Indeed, the majority of the variation is explained by PC1 (91.3%) and PC2 (8.1%). The cos 2 plot also confirms the representativeness of the test. Furthermore, vegetation cover and temperatures are strongly correlated with PC1, indicating a strong interaction between them, unlike precipitation (Figure 15).

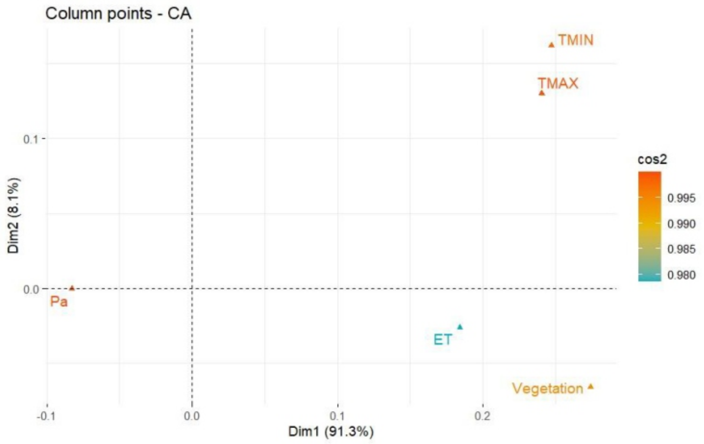


Figure 11: The CPA plot of interaction between vegetation cover and other climate variables

Discussion

The change indices revealed a profound climate change and variability in the study area. The days where the maximum temperatures exceed the 90th quantile has considerably increased, showing an increase 21 day in 60 years 22 days in 60 years for TN90. Regards the P10mm index it's generally variable, its variation during the study period reveals that the number of days where the precipitations rate exceeds 10mm decreased during last years. In addition, the trend of temperatures tend to increase as the maximum temperatures rises and minimal temperatures and between 1991-2020 the average temperatures rhas risen by 1°C. in fact, the mean annual temperature for Morocco is 18.05°C, with average monthly temperatures ranging between 9.4°C and 26°C. Mean annual precipitation is 301.6 mm [14]. Youssef et al. have proved that the minimum and maximum temperatures have been risen by +1.7 and +1.4 respectively in the some villages in the study area 1984 and 2020 [52][53]. Future climate trends in Morocco include rising temperatures of 1 to 1.5 C by 2050, as Morocco is experiencing an increase in temperature [54] and Morocco warmed by approximately 1.1 °C between 1984 and 2016 [55]. Generally the average global warming over the entire territory is about to change and estimated around 1 °C [54][57].

In the other hand, The regression of spatial precipitations distribution show significant decrease in the study area decrease by -77 mm, the precipitation in the area are characterized by its complexity, in the High Atlas of Moroccobetween 1984 and 2021 [52] [60]. In average precipitation reduced by 10 % and 20 % across the country, and 30 % decrease for the Saharan region by 2100 [12]. In addition, the average annual amount of precipitation reached a decrease of around 15% in the period 1971–2000 compared to the national precipitation levels of 1961–1990 '[59]. Furthermore, the decrease represents approximately 25% of total rainfall in the rainy season in the northwest of the country '[59] [61]. On the basis of 1961–1990 records, climate predictions point to a 4–6°C warming and a 20–60% reduction in rainfall towards the end of the century in Morocco [62].

In the context of climate change, the results of the De Martonne aridity index highlight a clear spatio-temporal pattern of increasing aridification. The analysis shows a gradual transition from a subhumid climate in the 1960s to predominantly semi-arid conditions in recent decades.

Subhumid areas, initially extensive, have progressively declined, becoming limited and fragmented, mainly in high-altitude zones, while semi-arid conditions have expanded and now dominate almost the entire geopark. This evolution reflects the intensification of water deficit driven by the combined effect of decreasing precipitation and rising temperatures, consistent with trends observed in Mediterranean regions [43][44] [63].

These findings are reinforced by the Q2 bioclimatic index, which highlights a modification in the ecological functioning of the regional climate. The decrease in Q2 values confirms a shift toward more arid conditions, with high values being associated with humid climates and low values with arid climates [42][64]. Thus, while the De Martonne index illustrates the spatial redistribution of aridity, the Q2 pluviothermal quotient helps characterize the transition between bioclimatic stages.

This convergence between climatic indices confirms a robust trend toward the aridification of the Mediterranean climate in the studied region, consistent with regional observations in Morocco and North Africa [54] [58] [65]. Such an evolution is likely to have major impacts on ecosystem functioning, particularly on Aleppo pine forests, which are highly sensitive to water stress and variations in the water balance [66][69].

During droughts, low water availabilities induce stomatal closure to prevent transpiration, leading to reductions in evapotranspiration (ET), yet drought-associated meteorological lead to ET increase [70].The change in terrestrial ET during droughts is influenced by supply, energy, demand, and vegetation activities. However, significant uncertainties persist due to discrepancies among various ET products and simulations [71], lack or reduction of evapotranspiration indicates drought [72], the reduction of the ET during lasts years indicate the stress inside the High Atlas Aleppo pine forests. Indeed the behavior of ET under drought is complicated, The studies in US, Europe, and SE Asia found that negative water deficit values were prevalent in arid and semiarid zones, while positive values were observed in subhumid and humid zones [73], which confirm the current study fundings as the region occurs in semi-arid region.

In the other hand, the temperature shows strong dependence on Aleppo pine area decrease (fluctuations), confirmed by the strong correlation between pine cover andTmin and Tmax, indeed, the images (figure 15) show that this degradation and continuous diminution of vegetation area is driven by mortality (dieback). Between 2015 and 2023 the pine forest in the Tamga reserve have lost 20 Km^2 due to the dieback. The same results are confirmed in High Atlas, as dry and hot years drive growth decline of *Pinus halepensis* at its southern range limit in the Moroccan High Atlas Mountains [23]. Temperature and rainfall may constrain growth during certain periods [74], The climate warming should thus produce significant effects on the short-term on forest productivity [75], *Pinus halepensis* shows sensitivity to drought, resulting in an increased response magnitude to pre-, during and post-drought conditions [76].In addition, radial growth of Aleppo pine was mainly controlled by soil water availability during the growing season, and differed by crown class [77]. It's important to note that the performance of Aleppo pine forest has been strongly related to water balances and the disturbance regime in Mediterranean conditions [78] [79]. Furthermore, the precipitations play small role in vegetation trend as the low correlation is proven between two parameters. The CPA test confirms this result as the vegetation trends are correlated with the rises in temperatures.

Drought intensity reduced tree growth resistance but hardly affected its resilience [76]. *Pinus halepensis* exhibited higher growth rate and drought tolerance, as well as higher resilience and resistance[80], yet the current study revealed that the Aleppo pin main mortality dieback are climate resulting stress.

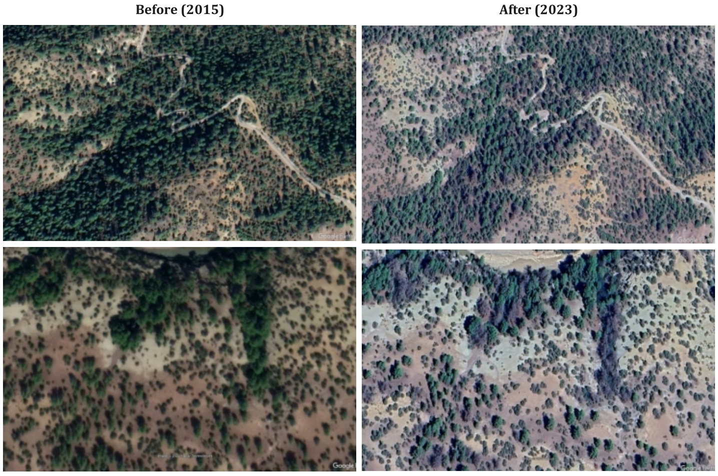


Figure 12: The comparison of the Aleppo pine cover in 2015 and 2023

The dieback and climate due degradation are not the only factors that threaten Aleppo pine in Morocco, indeed this plant is under danger of wildfires outbreak, as a result of the pine needles accumulation [19]. The Aleppo pine has undergone significant degradation due to anthropogenic overexploitation[81], the main anthropic pressure in Morocco are cutting of trees and overgrazing [52][82]. In addition, the Aleppo pine is not the only impacted plant as well, to Aleppo pine, *Quercus suber, Q. ilex*, and *Q. pyrenaïca, Pinus pinaster*, thuja (*Callitris articulara*) have gone profound changes in Oued Lahdar in the northern Morocco reducing their area form 94.3% in 1984 before deteriorating to 54.3% in 2017 due to drought [83].

The region is considered a reserve for the protection of this plant and its inherent richness. Consequently, strict conservation measures must be intensified. However, climate-induced degradation is highly difficult to control and mitigate, as it is driven by greenhouse gas emissions. Therefore, policies should be implemented to reduce greenhouse gas emissions, promote sustainable land use practices, and protect critical habitats from further anthropogenic stressors.

Conclusion

Morocco's ecosystems are facing a critical situation, with continuous degradation of vegetation cover attributed largely to climate change and human activities. Factors such as grazing, expansion of agricultural lands, and deforestation for timber and charcoal have exacerbated this degradation, leading to a pronounced danger of deforestation in recent years. Current studies highlight the impact of Aleppo pine dieback on forest ecosystems in the Mediterranean climate of High Atlas, with climate patterns identified as a key driver. Despite protective measures in place and controlled human activities in the studied region the vegetation undergoes major threats due to rising temperatures and drought. However, the precise mechanisms by which climate influences these forests remain elusive. This study serves as both a warning of the severe mortality observed in the Moroccan High Atlas and a call to action for detailed investigations into the phenomenon.

By uncovering the underlying causes and effects of dieback, we can better understand and address the degradation of Morocco's precious ecosystems and the mediterranean climate as well.

Authors contribution

Material preparation, data collection, and analysis were performed by Outourakhte Aboubakre, Youssef Gharnit, MoujaneAbdelazize, Abdelali Boulliand Khalid El Haddany. The first draft of the manuscript was written by Outourakhte Aboubakre. Supervision and guidance: Abdelali Boulli and Aziz Hasib. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declaration of competing interest

We affirm that there is no conflict of interest associated with this publication. We declare that this manuscript is original, has not published before and is not currently being considered for publication elsewhere.

References

1. J. Zhou et al., "Choice of potential evapotranspiration formulas influences drought assessment: A case study in China," *Atmos. Res.*, vol. 242, p. 104979, 2020, doi: https://doi.org/10.1016/j.atmosres.2020.104979.
2. J. Sheffield, E. F. Wood, and M. L. Roderick, "Little change in global drought over the past 60 years," *Nature*, vol. 491, no. 7424, pp. 435–438, 2012, doi: 10.1038/nature11575.
3. R. C. Deo and M. Şahin, "Application of the Artificial Neural Network model for prediction of monthly Standardized Precipitation and Evapotranspiration Index using hydrometeorological parameters and climate indices in eastern Australia," *Atmos. Res.*, vol. 161–162, pp. 65–81, 2015, doi: https://doi.org/10.1016/j.atmosres.2015.03.018.
4. R. C. Deo, O. Kisi, and V. P. Singh, "Drought forecasting in eastern Australia using multivariate adaptive regression spline, least square support vector machine and M5Tree model," *Atmos. Res.*, vol. 184, pp. 149–175, 2017, doi: https://doi.org/10.1016/j.atmosres.2016.10.004.
5. G.-Q. Sun et al., "Impacts of climate change on vegetation pattern: Mathematical modeling and data analysis," *Phys. Life Rev.*, vol. 43, pp. 239–270, 2022, doi: https://doi.org/10.1016/j.plrev.2022.09.005.
6. M. Ali, "Effects of Climate Change on Vegetation BT - Climate Change Impacts on Plant Biomass Growth," M. Ali, Ed., Dordrecht: Springer Netherlands, 2013, pp. 29–49. doi: 10.1007/978-94-007-5370-9_4.
7. H. Heshmati, "Impact of Climate Change on Life," 2020. doi: 10.5772/intechopen.94538.
8. V. Yakovlev and G. Belyaev, "Global climate change, its consequences and ways to solve the problem," *E3S Web Conf.*, vol. 390, Jun. 2023, doi: 10.1051/e3sconf/202339004007.
9. H.-O. Pörtner et al., Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2022. doi: 10.1017/9781009325844.
10. O. Adedeji, R. Okocha, and O. Olatoye, "Global Climate Change," *J. Geosci. Environ. Prot.*, vol. 02, pp. 114–122, Jan. 2014, doi: 10.4236/gep.2014.22016.
11. J. Schilling, K. P. Freier, E. Hertig, and J. Scheffran, "Climate change, vulnerability and adaptation in North Africa with focus on Morocco," *Agric. Ecosyst. Environ.*, vol. 156, pp. 12–26, 2012, doi: https://doi.org/10.1016/j.agee.2012.04.021.
12. United Nations Development Programme, "National Adaptation Plans in focus: Lessons from Morocco," NAP-GSP, 2018.
13. R. M. Beyer, M. Krapp, and A. Manica, "High-resolution terrestrial climate, bioclimate and vegetation for the last 120,000 years," *Sci. Data*, vol. 7, no. 1, p. 236, 2020, doi: 10.1038/s41597-020-0552-1.
14. The World Bank Group, Climate Risk Profile: Morocco. 1818 H Street NW, Washington, DC 20433: World Bank Group, 2021.
15. United States Agency International Development, "Climate change risk profile: Morocco," USAID, no. December 2016, pp. 1–5, 2016.
16. H. D. Safford and V. R. Vallejo, "Chapter 12 - Ecosystem management and ecological restoration in the Anthropocene: integrating global change, soils, and disturbance in boreal and Mediterranean forests," in *Global Change and Forest Soils*, vol. 36, M. Busse, C. P. Giardina, D. M. Morris, and D. S. B. T.-D. in S. S. Page-Dumroese, Eds., Elsevier, 2019, pp. 259–308. doi: https://doi.org/10.1016/B978-0-444-63998-1.00012-4.
17. L. Zahra and D. Thami, "Impact of urban dynamics and climate change on forest areas the Maamora forest in the city of Kenitra, Morocco," *Multidiscip. Sci. J.*, vol. 6, no. 7, p. 2024123, 2024.
18. A. Benabid, "Forest degradation in Morocco," in *The North African Environment at Risk*, Routledge, 2019, pp. 175–190.
19. R. Mahmoud et al., "The Needles of Aleppo Pine from the Province of Taza-Morocco – A Biomaterial of Great Potential," *J. Ecol. Eng.*, vol. 24, no. 1, pp. 41–50, 2023, doi: 10.12911/22998993/156008.
20. K. Mechergui, S. Naghmouchi, M. S. Alsubeie, W. Jaouadi, and Y. Ammari, "Biomass, radial growth and regeneration capacity of Aleppo pine, and its possible use as rootstock in arid and degraded areas," *iForest - Biogeosciences For.*, vol. 15, no. 3, pp. 213–219, 2022, doi: 10.3832/ifor3954-015.
21. D. Simón, S. Gass, C. Palet, and A. Cristóbal, "Disposal of wooden wastes used as heavy metal adsorbents as components of building bricks," *J. Build. Eng.*, vol. 40, p. 102371, 2021.
22. W. Jaouadi, S. Naghmouchi, and M. Alsubeie, "Should the silviculture of Aleppo pine (*Pinus halepensis* Mill.) stands in northern Africa be oriented towards wood or seed and cone production? Diagnosis and current potentiality," *iForest - Biogeosciences For.*, vol. 12, no. 3, p. 297, 2019.
23. J. Vieira, C. Nabais, and F. Campelo, "Dry and hot years drive growth decline of *Pinus halepensis* at its southern range limit in the Moroccan High Atlas Mountains," *Trees*, vol. 36, Jun. 2022, doi: 10.1007/s00468-022-02314-z.
24. Y. Tramblay, W. Badi, F. Driouech, S. El Adlouni, L. Neppel, and E. Servat, "Climate change impacts on extreme precipitation in Morocco," *Glob. Planet. Change*, vol. 82–83, pp. 104–114, 2012, doi: https://doi.org/10.1016/j.gloplacha.2011.12.002.
25. V. Simonneaux, A. Cheggour, C. Deschamps, F. Mouillot, O. Cerdan, and Y. Le Bissonnais, "Land use and climate change effects on soil erosion in a semi-arid mountainous watershed (High Atlas, Morocco)," *J. Arid Environ.*, vol. 122, pp. 64–75, 2015, doi: https://doi.org/10.1016/j.jaridenv.2015.06.002.
26. P. T. Nastos, I. D. Polychroni, J. Kapsomenakis, S. Solomos, and C. S. Zerefos, "Bioclimatic Change Impacts on Tourist Destinations in the Mediterranean, by Means of the Assessment of Human Thermal Perception," *Environmental Sciences Proceedings*, vol. 26, no. 1, 2023, doi: 10.3390/environsciproc2023026196.

27. R. G. Gavilán, "The use of climatic parameters and indices in vegetation distribution. A case study in the Spanish Sistema Central," *Int. J. Biometeorol.*, vol. 50, no. 2, pp. 111–120, Nov. 2005, doi: 10.1007/s00484-005-0271-5.
28. X. Liu et al., "Water use strategies of *Robinia pseudoacacia* and *Quercus acutissima* vary among seasons and planting methods," *Plant Soil*, vol. 483, no. 1, pp. 199–207, 2023.
29. S. Yang et al., "Vegetation coverage changes driven by a combination of climate change and human activities in Ethiopia, 2003–2018," *Ecol. Inform.*, vol. 71, p. 101776, 2022.
30. T. Yin et al., "Impacts of climate change and human activities on vegetation coverage variation in mountainous and hilly areas in Central South of Shandong Province based on tree-ring," *Front. Plant Sci.*, vol. 14, 2023.
31. R. Cho, "How climate change will affect plants," Columbia Clim. Sch. State Planet, 2022.
32. K. Merry, P. Bettinger, M. Crosby, and K. Boston, "8 - Geographic data processing—raster data," K. Merry, P. Bettinger, M. Crosby, and K. B. T.-G. I. S. S. for F. and N. R. M. Boston, Eds., Elsevier, 2023, pp. 231–267. doi: https://doi.org/10.1016/B978-0-323-90519-0.00009-1.
33. Y. Gharnit, A. Outourakht, A. Boulli, and A. Hassib, "Biodiversity, autecology and status of aromatic and medicinal plants in Geopark M'Goun (Morocco)," *Ann. Di Bot.*, vol. 13, 2023.
34. A. N. Taïbi, M. El Hannani, Y. El Khalki, and A. Ballouche, "Les parcs agroforestiers d'Azilal (Maroc): une construction paysagère pluri-séculaire et toujours vivante," *J. Alp. Res. Rev. géographie Alp.*, no. 107–3, 2019.
35. J. Ionesco and T. Mateez, CLIMATOLOGIE, BIOCLIMATOLOGIE ET PHYTOGEOGRAPHIE DU MAROC, 1st ed. Rabat: Centre National de Documentation, 1964.
36. M. I. Tattou and M. Fennane, "PROJET DE GESTION DES AIRES PROTEGEES : SIBE TAMGA," Proj. Gest. des aires protégées (GEF – TF 023494 – MOR), pp. 1–46, 2016.
37. B. Belghazi, M. Ezzahiri, and F. Romane, "La productivité des peuplements naturels de pin d'Alep dans la forêt de Tamga (Haut Atlas marocain)," *Forêt méditerranéenne*, vol. 21, no. 4, p. 530, 2000.
38. D. S. Ragatoa, K. O. Ogunjobi, N. A. B. Klutse, A. A. Okhimamhe, and J. O. Eichie, "A change comparison of heat wave aspects in climatic zones of Nigeria," *Environ. Earth Sci.*, vol. 78, no. 4, p. 111, 2019, doi: 10.1007/s12665-019-8112-8.
39. L. V Alexander, "Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond," *Weather Clim. Extrem.*, vol. 11, pp. 4–16, 2016, doi: https://doi.org/10.1016/j.wace.2015.10.007.
40. P. Daget, "Le bioclimat mediterraneen: Caracteres generaux, modes de caracterisation," *Vegetatio*, vol. 34, no. 1, pp. 1–20, 1977, doi: 10.1007/BF00119883.
41. N. Mokhtari, R. Mrabet, P. Lebailly, and L. Bock, "Spatialisation des bioclimats , de l ' aridité et des étages de végétation du Maroc," *Rev. Marocaine des Sci. Agron. Vétérinaires*, vol. 2, pp. 50–66, 2014.
42. P. Quézel and M. Barbero, "Definition and characterization of Mediterranean-type ecosystems," *Ecol. Mediterr.*, vol. 8, no. 1, pp. 15–29, 1982, doi: 10.3406/ecmed.1982.1929.
43. E. de Martonne, "Une nouvelle function climatologique: L'indice d'aridité," *Meteorologie*, vol. 2, pp. 449–459, 1926.
44. Programme des Nations Unies pour l'environnement, World atlas of desertification. Arnold, 1997.
45. J. Richards, Remote sensing Digital Image Analysis. Kensington NSW 2033, Australia ISBN: Centre for Remote Sensing, and School of Electrical Engineering and Computer Science, 1986.
46. R. Almalki, M. Khaki, P. M. Saco, and J. F. Rodriguez, "Monitoring and Mapping Vegetation Cover Changes in Arid and Semi-Arid Areas Using Remote Sensing Technology: A Review," *Remote Sensing*, vol. 14, no. 20, 2022, doi: 10.3390/rs14205143.
47. M. Elhag and S. Boteva, "Mediterranean Land Use and Land Cover Classification Assessment Using High Spatial Resolution Data," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 44, no. 4, p. 42032, 2016, doi: 10.1088/1755-1315/44/4/042032.
48. F. Y. Osisanwo, J. E. T. Akinsola, O. Awodele, J. O. Hinmikaiye, O. Olakanmi, and J. Akinjobi, "Supervised machine learning algorithms: classification and comparison," *Int. J. Comput. Trends Technol.*, vol. 48, no. 3, pp. 128–138, 2017.
49. V. Jakkula, "Tutorial on support vector machine (svm)," Sch. EECS, Washingt. State Univ., vol. 37, no. 2.5, p. 3, 2006.
50. B. B. Osejo, T. B. Vargas, and J. A. Martinez, "Spatial distribution of precipitation and evapotranspiration estimates from Worldclim and Chelsa datasets: Improving long-term water balance at the watershed-scale in the Urabá region of Colombia," *Int. J. Sustain. Dev. Plan.*, vol. 14, no. 2, pp. 105–117, 2019.
51. M. Khaydarov and L. Gerlitz, "Climate variability and change over Uzbekistan-an analysis based on high resolution CHELSA data," *Cent. Asian J. Water Res.*, vol. 5, no. 2, pp. 1–19, 2019.
52. G. Youssef, M. Abdelaziz, O. Aboubakre, A. Hasib, and A. Boulli, "Impact of climate and demographic changes on the vegetation of the M'goun Geopark UNESCO of Morocco (1984-2021)," *Investig. Geográficas*, no. 81, pp. 225–243, 2024.
53. A. Outourakhte, Y. Gharnit, A. Moujane, K. El Haddany, A. Hasib, and A. Boulli, "The floristic composition and phytoecological characterization of plant communities in the M'Goun Geopark, High Atlas, Morocco," *Ecologies*, vol. 6, no. 2, p. 29, 2025.
54. K. Khomsi, G. Mahe, Y. Tramblay, M. Sinan, and M. Snoussi, "Regional impacts of global change: seasonal trends in extreme rainfall, run-off and temperature in two contrasting regions of Morocco," *Nat. Hazards Earth Syst. Sci.*, vol. 16, no. 5, pp. 1079–1090, 2016.
55. F. Driouech, K. ElRhaz, W. Moufouma-Okia, K. Arjdal, and S. Balhane, "Assessing future changes of climate extreme events in the CORDEX-MENA region using regional climate model ALADIN-climate," *Earth Syst. Environ.*, vol. 4, no. 3, pp. 477–492, 2020.
56. L. Bouchaou, T. Tagma, S. Boutaleb, M. Hssaisoune, and Z. E. A. El Morjani, "Climate change and its impacts on groundwater resources in Morocco: the case of the Souss-Massa basin," *Clim. Chang. Eff. Groundw. Resour. a Glob. Synth. Find. Recomm.*, vol. 129, 2011.
57. K. Born, M. Christoph, A. H. Fink, P. Knippertz, H. Paeth, and P. Speth, "Moroccan climate in the present and future: combined view from observational data and regional climate scenarios," *Clim. Chang. Water Resour. Middle East North Africa*, pp. 29–45, 2008.
58. F. Driouech, "Distribution des précipitations hivernales sur le Maroc dans le cadre d'un changement climatique: descente d'échelle et incertitudes," 2010.
59. L. Van Praag and L. Ou-Salah, "Environmental Change and Migration in Morocco: What Has Been Done So Far?" in *Migration and Environmental Change in Morocco: In Search for Linkages Between Migration Aspirations and (Perceived) Environmental Changes*, L. Van Praag, L. Ou-Salah, E. Hut, and C. Zickgraf, Eds., Cham: Springer International Publishing, 2021, pp. 35–59. doi: 10.1007/978-3-030-61390-7_3.
60. J. Schilling, E. Hertig, Y. Tramblay, and J. Scheffran, "Climate change vulnerability, water resources and social implications in North Africa," *Reg. Environ. Chang.*, vol. 20, pp. 1–12, 2020.
61. M. Benassi, "Drought and climate change in Morocco. Analysis of precipitation field and water supply," *Options méditerranéennes*, vol. 80, pp. 83–87, 2008.
62. M.-D. Jihad, "Climate Change and Rural Development in the Middle Atlas Mountains and Fringe Areas (Morocco)," *Rev. géographie Alp.*, vol. 104, Jul. 2016, doi: 10.4000/rga.3465.

63. N. Bella, “Spatial and temporal analysis of aridity trends using the De Martonne Index: A GIS-based study of the Timgad Basin, Algeria,” *Innovative Technologies in Social Science*, vol. 4, no. 44, pp. 0–11, 2024, doi: 10.31435/ijitss.4(44).2024.3067.
64. P. Daget, “Le bioclimat méditerranéen: analyse des formes climatiques par le système d'Emberger,” *Vegetatio*, vol. 34, no. 2, pp. 87–103, 1977.
65. A. Agoumi and A. Debbarh, “Ressources en eau et bassins versants du Maroc: 50 ans de développement (1955-2005),” 50 ans développement Hum. au Maroc, Perspect. 2025. Rapp. thématiques, pp. 13–62, 2006.
66. S. M. Vicente-Serrano, T. Lasanta, and C. Gracia, “Aridification determines changes in forest growth in *Pinus halepensis* forests under semiarid Mediterranean climate conditions,” *Agric. For. Meteorol.*, vol. 150, no. 4, pp. 614–628, 2010.
67. A. Gazol, J. Oliva, C. Valeriano, M. Colangelo, and J. J. Camarero, “Mixed pine forests in a hotter and drier world: The great resilience to drought of Aleppo pine benefits it over other coexisting pine species,” *Front. For. Glob. Chang.*, vol. 5, p. 899425, 2022.
68. A. Gazol, M. Ribas, E. Gutiérrez, and J. J. Camarero, “Aleppo pine forests from across Spain show drought-induced growth decline and partial recovery,” *Agric. For. Meteorol.*, vol. 232, pp. 186–194, 2017.
69. C. Valeriano, A. Gazol, M. Colangelo, and J. J. Camarero, “Drought drives growth and mortality rates in three pine species under Mediterranean conditions,” *Forests*, vol. 12, no. 12, p. 1700, 2021.
70. M. Zhao, G. Aa, Y. Liu, and A. Konings, “Evapotranspiration frequently increases during droughts,” in *EGU General Assembly Conference Abstracts*, 2022, pp. EGU22-6904. doi: 10.5194/egusphere-egu22-6904.
71. Q.-L. He, J.-L. Xiao, and W.-Y. Shi, “Responses of Terrestrial Evapotranspiration to Extreme Drought: A Review,” *Water*, vol. 14, no. 23, 2022. doi: 10.3390/w14233847.
72. X. Zhan et al., “Remote Sensing of Evapotranspiration for Global Drought Monitoring,” in *Global Drought and Flood*, Geophysical Monograph Series, 2021, pp. 29–46. doi: https://doi.org/10.1002/9781119427339.ch2.
73. M.-J. Um et al., “Impacts of potential evapotranspiration on drought phenomena in different regions and climate zones,” *Sci. Total Environ.*, vol. 703, p. 135590, Feb. 2020, doi: 10.1016/j.scitotenv.2019.135590.
74. S. Sabaté, C. A. Gracia, and A. Sánchez, “Likely effects of climate change on growth of *Quercus ilex*, *Pinus halepensis*, *Pinus pinaster*, *Pinus sylvestris* and *Fagus sylvatica* forests in the Mediterranean region,” *For. Ecol. Manage.*, vol. 162, no. 1, pp. 23–37, 2002, doi: https://doi.org/10.1016/S0378-1127(02)00048-8.
75. M. Vennetier, B. Vila, E. Y. Liang, F. Guibal, A. Thabeet, and C. Gadbin-Henry, “Impact of climate change on pine forest productivity and on the shift of a bioclimatic limit in a Mediterranean area,” *Options Méditerranéennes, Série A*, vol. 75, pp. 189–197, 2007.
76. L. Veuillen et al., “Pre- and post-drought conditions drive resilience of *Pinus halepensis* across its distribution range,” *Agric. For. Meteorol.*, vol. 339, p. 109577, 2023, doi: https://doi.org/10.1016/j.agrformet.2023.109577.
77. J. Olivar, S. Bogino, C. Rathgeber, V. Bonnesoeur, and F. Bravo, “Thinning has a positive effect on growth dynamics and growth–climate relationships in Aleppo pine (*Pinus halepensis*) trees of different crown classes,” *Ann. For. Sci.*, vol. 71, no. 3, pp. 395–404, 2014, doi: 10.1007/s13595-013-0348-y.
78. E. Chirino, A. Bonet, J. Bellot, and J. R. Sánchez, “Effects of 30-year-old Aleppo pine plantations on runoff, soil erosion, and plant diversity in a semi-arid landscape in south eastern Spain,” *CATENA*, vol. 65, no. 1, pp. 19–29, 2006, doi: https://doi.org/10.1016/j.catena.2005.09.003.
79. M. A. Zavala, J. M. Espelta, and J. Retana, “Constraints and trade-offs in Mediterranean plant communities: the case of holm oak-Aleppo pine forests,” *Bot. Rev.*, vol. 66, pp. 119–149, 2000.
80. J. Jevšenak and J. Saražin, “*Pinus halepensis* is more drought tolerant and more resistant to extreme events than *Pinus nigra* at a sub-Mediterranean flysch site,” *Trees*, vol. 37, no. 4, pp. 1281–1286, 2023, doi: 10.1007/s00468-023-02413-5.
81. N. Wahid, H. Jouidre, M. S. Lamhamedi, A. Z. El Abidine, and A. Boulli, “Évaluation de la structure et de la variabilité génétiques des populations naturelles du pin d'Alep (*Pinus halepensis* Mill.) au Maroc à l'aide de marqueurs isoenzymatiques,” *Acta Bot. Gall.*, vol. 157, no. 3, pp. 419–431, Jan. 2010, doi: 10.1080/12538078.2010.10516219.
82. A. Moujane, A. Outourakhte, Y. Gharnit, A. Boulli, and A. Ouhammou, “Geographical distribution of the Thuriferous juniper (*Juniperus thurifera* L.) and the influencing factors in the Atlas Mountains of Azilal (Central Morocco),” *Geol. Ecol. Landscapes*, vol. 00, no. 00, pp. 1–12, 2023, doi: 10.1080/24749508.2023.2203281.
83. H. Khalis, A. Sadiki, F. Jawhari, H. Mesrar, and E. Azab, “Effects of Climate Change on Vegetation Cover in the Oued,” *Plants*, vol. 10, no. 1624, pp. 1–16, 2021.