



Spatio-temporal analysis of North African forest cover dynamics using time series of vegetation indices – case of the Maamora forest (Morocco)

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North African forest areas play several roles and functions and represent a heritage of great economic and ecological importance. As a result of global changes, that act independently or synergistically, these areas are currently undergoing a pronounced degradation and their productivity is decreasing due to several factors. This work aims to characterize spatio-temporal dynamics of vegetation within the Maamora forest. This forest is considered as the most extensive cork oak woodland in the world and is divided, from west to east, into five cantons A, B, C, D and E. The data, extracted between 2000–2021 from MODIS NDVI/EVI images of 250 m, were analyzed using statistical parameters with the Pettitt homogeneity and the Mann-Kendall trend tests, with their seasonal and spatial components, in order to better consider the vegetation distribution of this forest. Results show a clear temporal and spatial (inter-canton) variability of vegetation intensity, unrelated to the continental gradient. In fact, recorded mean values in cantons C and E are significantly higher than those of cantons B and D respectively. This is confirmed by both regressive and progressive trends, which were identified respectively from the months of March 2012 and October 2008, in the data series of cantons B and E successively. Spatially, the regressive dynamic remains generalized and affects more than 26.7% of the Maamora's total area with extreme rates (46.1% and 14.0%) recorded respectively by the two aforementioned cantons. Similarly, all the stand types in canton B show the highest regressive rates, especially the cork oak regeneration strata (75.4%) and the bare lands (86.1%), which may explain the positive tendencies identified by the related series during the fall season. However, the cantons C and E record the lowest rates, respectively, for natural stands of cork oak and artificial plantations. These results highlight also the absence of a causal relationship between the contrasting vegetation dynamics of the Maamora and the climatic conditions, expressed here by the continental gradient. However, they do highlight the effects of other factors, particularly those of a technical nature.

Keywords: cork oak; cover trend; degradation; spatial variability.

Introduction

Climate change and global warming are an accepted scientific truth and political reality on the international scene (Allan, 2021). They are associated with observed changes in a variety of other climate parameters, including precipitation patterns and extreme climate events (Coumou et al., 2013; Stocker et al., 2013; Lehmann et al., 2015). Global average surface temperature has increased by about 1.1 °C since the beginning of the industrial revolution, and the nine years from 2013 to 2021 are among the ten warmest years on record.

More than just one of the world's largest reservoirs of biodiversity (Mayers et al., 2000), the Mediterranean basin has long been identified as one of the most sensitive regions to climate change on a global scale (Rogers & Vladimir, 2013). These changes may act, along with other pressures of anthropogenic origin particularly in the form of overexploitation, pollution, habitat destruction, either independently or synergistically, to form a different Mediterranean than the one we know today (Stocker et al., 2013; Moukrim et al., 2018, 2020, 2022). All the physico-chemical modifications induced by climate change lead to a disruption of the ecosystems' biological components (Allan, 2021). As a result, their conservation is a complex problem due to the heterogeneity of situations and the multiple uses and anthropic pressures practiced by the various cultural

entities of the Mediterranean for millennia (Quézel & Médail, 2003; Aafi et al., 2005; Rifai et al., 2018; Elmalki et al., 2022).

The cork oak, an endemic species of the Mediterranean-Atlantic domain of the Mediterranean basin (Myers et al., 2000; Fennane & Ibn Tattou, 2012), bears witness to these global changes over long periods of time, with a sharp reduction in its range (Aafi et al., 2005). Morocco ranks fourth in the world for cork oak cover while the cork oak stands of the Maamora continue to form nowadays the most extensive forest of this species in the world with an area of about 70,000 ha. They originally covered an area that exceeded 300,000 hectares (Natividade, 1956). Currently, this forest of 132,000 ha, is also made up of other artificial stands based on eucalyptus, acacia and pine and contains a lot of bare land (Aafi et al., 2005; Laaribya, 2006).

This clear regression of the surface area of the subterranean forest, coupled with a disturbance in the specific composition and a reduction in the number of floristic species (Aafi et al., 2005), are the corollary of an abusive exploitation, and of a poorly adapted management of this heritage. One should not forget the effects of climate change, even if the cork oak is among the most plastic species, both in terms of temperature and rainfall (Emberger, 1939; Achhal et al., 1979; Benabid, 1982). The fate of this emblematic forest will be highly dependent on future climate and the severity of predicted impacts is closely related to the magnitude of climate

change (Benabou et al., 2022a). In order to monitor the state of vegetation and detect changes in space and time caused by human and natural disturbances, we used free earth observation data. For this purpose, numerous vegetation indices have been constructed and used for decades (Bannari et al., 1995). These indices have a wide range of applications including the monitoring of the vegetation spatio-temporal dynamics, especially since the relationship between vegetation indices and vegetation cover structure is well established. In this work, two of the best-tested indices were used, namely the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) and the Enhanced Vegetation Index (EVI) (Huete et al., 2002), taking into account the influence of other parameters such as soil and atmosphere.

In this context, this work proposes to analyze, for the period 2000–2021, the spatial and temporal dynamics of the forest cover of this emblematic forest, verifying whether they identify in a significant way possible trends and/or breaks in homogeneity. This analysis takes advantage of the possibilities offered by earth observation and the availability of satellite imagery related to the two vegetation indices NDVI and EVI. It attempts to follow the dynamics of the forest cover, by analyzing the hypothesis of some causal relationship between the climatic conditions translated in

particular by the gradient of continentality and the changes observed in the forest cover of the Maamora.

Material and methods

Study area. The Maamora forest is located in northwestern Morocco on the edge of the Atlantic Ocean. It is framed in a rectangle about 30 km wide and 60 km long, between meridians 6°20' and 6°45' W, and parallels 34° and 34°20' N (Fig. 1). It is divided, by five rivers, into 5 cantons called, from West to East, A, B, C, D and E. It covers an area of nearly 132,000 ha (Benabou et al., 2022a).

The Maamora is located in a coastal subhumid bioclimate with warm winters in its western part comprising Canton A and the western part of Canton B, and in a semi-arid bioclimate with temperate winters in its central and eastern part (Benabid, 1982). It benefits from ecological compensations in the form of relatively high and constant atmospheric humidity, which decreases from West to East. The annual rainfall recorded from October to May, marks the same spatial variability, oscillating from 450 to 600 mm according to the same gradient of continentality (Achhal et al., 1979; Aafi et al., 2005; Mokhtari et al., 2014).

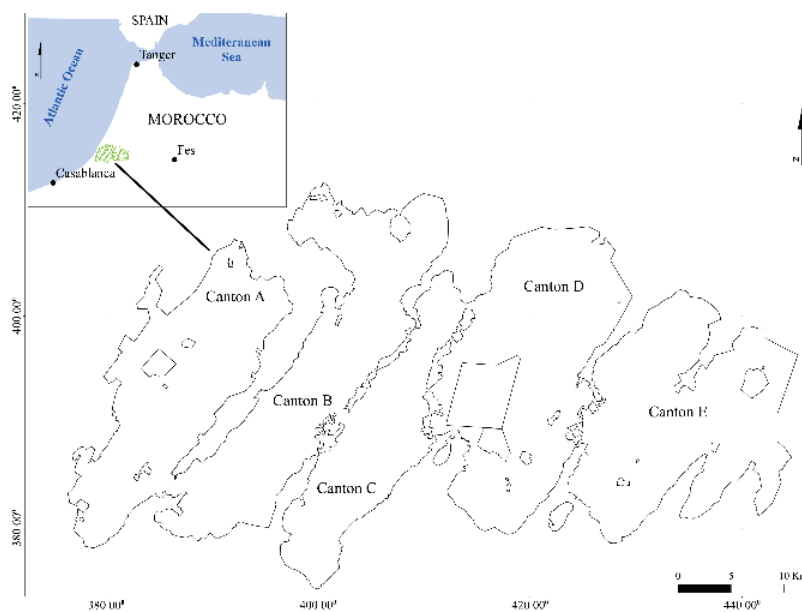


Fig. 1. Study area localization

The average monthly temperatures are in the range of 12 °C (January) to 25 °C (July–August), and the average maximum of the hottest month is 37 °C and the average minimum of the coldest month is 5 °C. The cork oak thrives in mild temperatures from 13 to 18 °C and suffers when temperatures fall below –9 °C, if these last more than 3 days (Aafi et al., 2005). The dry season, as defined by the umbrothermal method of Bagnouls and Gaussen, is more accentuated in the eastern part than in the western portion of the Maamora. It generally begins in late April/early May and extends until October (Achhal et al., 1979; Benabid, 1982; Aafi et al., 2005).

The Maamora forest topography is generally flat with altitudes not exceeding 300 m. The slope is slightly exposed to the North, which fa-

vours a flow from South to North. The soils of the Maamora are constituted almost entirely by a layer of beige and red sands of siliceous type, with depth of 50 cm to more than 4 m and with contents of clay and silt variable. This layer rests on a compact red clay formation of the Quaternary, whose thickness also varies from 1 to more than 10 meters. The differentiation between the different soil types of the Maamora is based essentially on three criteria: (i) the thickness of the sands covering the clay, (ii) the nature of the sands, and (iii) the more or less abrupt transition from sands to clay at depth (Lepoutre, 1965). The five cantons of the Maamora forest are made up of natural stands of cork oak (69 500 ha), artificial stands (eucalyptus (43 000 ha), acacia (2 700 ha) and pine (9 800 ha) in mosaic, matorral (450 ha) and bare land (5 700 ha).

Table 1
Spatial distribution of forest stands in the Maamora

Cantons	Cork oak						Hardwoods		Pine	Mat	OT	Bare land	Total, ha
	Qs1	Qs2	Qs3	Qs4	Rg Qs	Qs M	Euc	Aca					
A	13 910	2 982	753	210	3 222	256	789	755	879	265	202	953	25 177
B	9 171	3 180	1 705	164	5 817	214	4 087	1 180	2 125	7	94	1 568	29 312
C	2 366	2 654	3 521	153	1 723	829	4 339	320	1 222	4	10	356	17 498
D	3 788	3 171	2 002	319	670	2 648	13 580	178	1 966	42	25	1 052	29 374
E	966	1 130	441	20	1 244	362	20 185	282	3 620	195	176	1 761	30 382
Total, ha	30 200	13 117	8 422	866	12 677	4 310	42 979	2 716	9 812	445	508	5 691	131 742

Note: Qs (*Quercus suber*); 1 to 4 (dense, medium dense, sparse and clear density classes); Rg (regeneration); Euc (*Eucalyptus*); Aca (*Acacia*); M (Mixed); Mat (Matorral); OT (Other stand types).

This forest is considered to be the most extensive lowland cork forest in the world (Natividade, 1956), although its area has shrunk to about 70 000 ha nowadays. This cork oak forest decreases in extent as one moves away from the ocean (Canton A) towards the interior (Canton E), going from more than 21 000 to about 4 000 ha. Conversely, artificial stands increase in extent along the same continental gradient, from less than 2 500 ha (Canton A) to over 24 000 ha at Canton E.

Recommended approach. The data used for the realization of this study are mainly the two vegetation indices NDVI (Rouse et al., 1973) and EVI (Huete et al., 2002), covering the five cantons of the Maamora forest during the period 2000–2021. They were extracted from MODIS/Terra (Moderate-Resolution Imaging Spectroradiometer) Global MOD13Q1 satellite images, provided every 16 days with a spatial resolution of 250 m (Didan, 2015).

These two vegetation indices are considered dimensionless. Their value, ranging from -1 to $+1$, measures the green intensity of a given area, indicating its vegetation mass, as well as its health status or growth vigour. The EVI use is primarily intended to correct for inaccuracies in the NDVI, including variations in solar incidence angle, atmospheric conditions such as distortions in light reflected from particles in the air, as well as land cover signals below the vegetation (Meneses-Tovar, 2011).

The trend analysis of the time series of these vegetation indices was performed based on the following non-parametric tests, including: (i) Pettitt (1979) homogeneity test; (ii) the Mann-Kendall test proposed by Mann (1945) and Kendall (1975), coupled with the Sen (1968) method for calculating the linear regressions' slopes; (iii) the seasonal Kendall test as improved by Hirsch et al. (1982) takes into account the seasonal character of the observations; and (iv) the spatial Mann-Kendall test applied to the time series of satellite images of the two vegetation indices NDVI and EVI (Abdi et al., 2019).

The two Mann-Kendall tests as well as the Pettitt homogeneity test allow one to detect respectively trends that are not necessarily linear, and a break in the mean in a series by identifying, if necessary, a single break year. They are said to be statistically significant when their p-value is lower than the significance threshold set at 5%. Data processing and analysis were conducted using several packages of the statistical software R, the cartographic software ArcGis 10.6 (ESRI, USA, 2018).

Results

Spatial and temporal distribution of NDVI and EVI. Spatial variability of the time series average values for the two vegetation indices NDVI and EVI is illustrated in Figure 2, with a distinction between the five cantons of the Maamora forest, the subject of the present study.

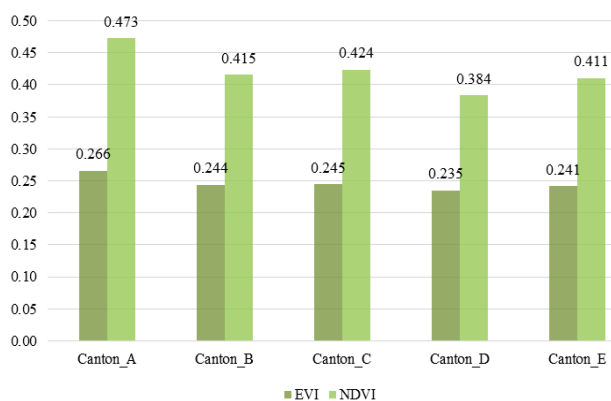


Fig. 2. Average vegetation index values per Maamora Canton

These results highlight the fact that the average values of the two vegetation indices decreases as one moves away from Canton A towards cantons C, D and E located in the eastern parts of the Maamora. Nevertheless, Canton B, most of which is classified in the western zone, shows similar or lower EVI and NDVI values (0.244 and 0.415) than those recorded by Canton C (0.245 and 0.424). The same observation occurs between Canton D and E with EVI and NDVI values increasing from 0.235 to 0.241 and from 0.384 to 0.411 respectively. The drop in the va-

lues of the two vegetation indices of Canton B is revealed from the year 2010. Their increase can be identified from the year 2008 for the cantons C and E, whose vegetation indices from the year 2012 significantly exceed those of the Canton B.

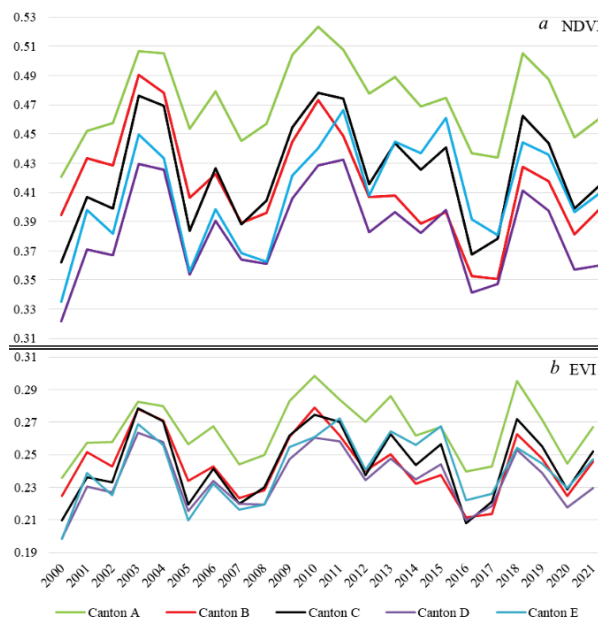


Fig. 3. Annual variability of vegetation indices by Maamora Canton: a – NDVI; b – EVI

Test of homogeneity break of the time series. The results of Pettitt's homogeneity break test applied to the time series of monthly means of the two studied vegetation indices are presented in Table 2.

Table 2

Results of the Pettitt test applied to the series of monthly means

Canton	EVI			NDVI		
	K	t	p-value (bilateral)	K	t	p-value (bilateral)
Canton A	2756	Oct.-08	0.263	2526	Sept.-02	0.421
Canton B	4236	May-13	0.007*	5768	Mar.-12	<0.0001*
Canton C	2630	Oct.-08	0.350	2304	Oct.-02	0.600
Canton D	2808	Jun.-15	0.258	2646	May-15	0.336
Canton E	5020	Nov.-08	0.001*	4746	Oct.-08	0.002*

Note: * (P-value < 0.05).

The results show that two vegetation indices NDVI and EVI characterize a very significant break in homogeneity at the level of the Canton E, respectively during the months of October and November of the year 2008. Similarly, at the level of Canton B, the NDVI time series characterizes a highly significant break with a p-value lower than 0.0001 reported during the month of March 2012.

Figure 4 allows us to determine the trajectories of these breaks detected in the three time series above, based on the averages of the NDVI and EVI values for the two periods “before” and “after” the identified break dates. Thus, a positive trend is observed at the scale of Canton E for both NDVI and EVI, with averages ranging from 0.387 to 0.426 and from 0.230 to 0.249 respectively. On the other hand, the series for Canton B showed a negative trend with a mean ranging from 0.435 to 0.391 and from 0.251 to 0.233 successively, while noting that the related EVI series did not show a statistically significant break (Table 2).

Concerning the series of annual averages of the two studied vegetation indices, the applied test's results are summarized in Table 3. The latter shows significant breaks for the EVI series of Canton A and the NDVI series of Canton B with p-values of 0.04 and 0.02 respectively.

The break identified during 2012 for the NDVI series of Canton B is consistent with the results plotted in Table 2 and Figure 4. The one characterized by the EVI series of Canton A is produced during the year 2013. These two breaks, as analyzing the data reported in Figure 5, draw a regressive trend, with average values between the two periods of the break

years, having decreased from 0.55 to 0.47 and from 0.31 to 0.27, respectively for the two series of cantons A and B.

Mann Kendall trend test. The results of the Mann Kendall test applied to the series of monthly means of the EVI and NDVI vegetation indices are summarized in Table 4. They show that the only significant trends are identified at the scale of cantons B and E.

A positive evolution is described by the NDVI time series of Canton E, with a Kendall's tau value of about 0.091. On the other hand, the two series of Canton B show rather regressive trends, with values of Kendall's p-value and tau ranging from 0.02 to less than 0.0001 and from -0.097 to -0.163 respectively for EVI and NDVI. These contrasting dynamics are confirmed by the Sen's slope values, as presented in Figure 6.

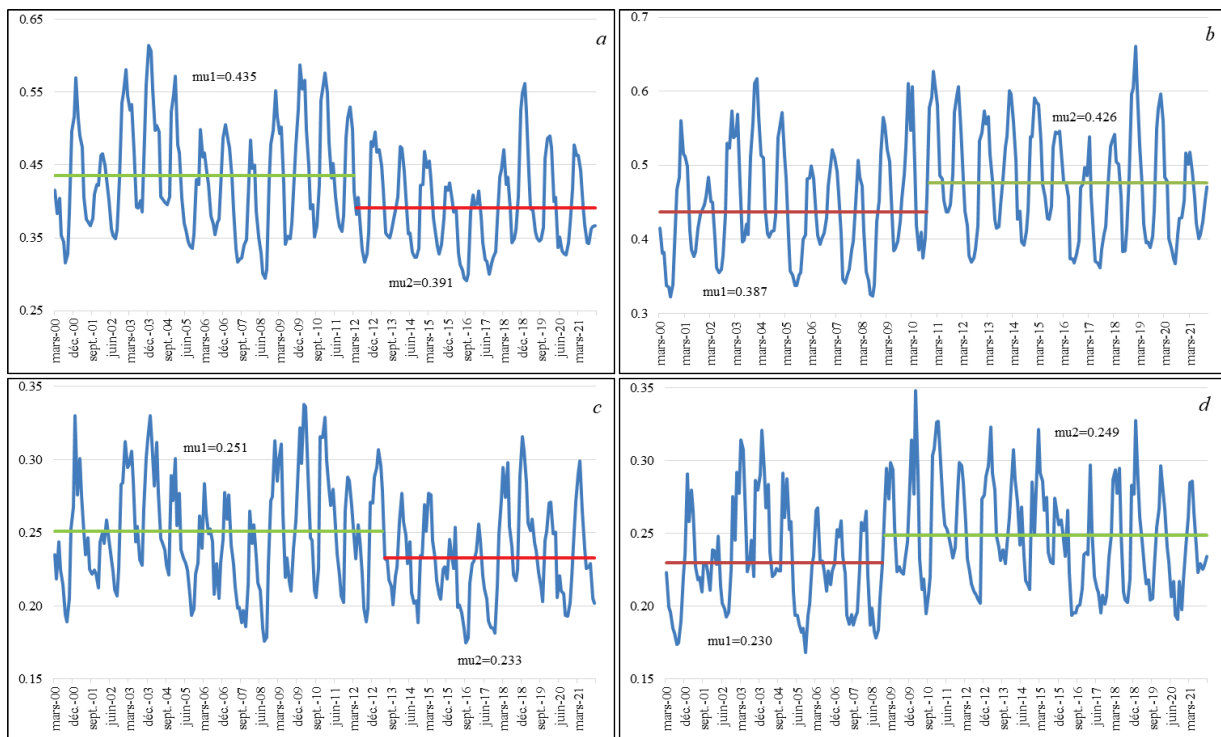


Fig. 4. Results of Pettitt test applied to the series of monthly averages of NDVI (*a* – Canton B, *b* – Canton E) and EVI (*c* – Canton B, *d* – Canton E)

Table 3

Results of the Pettitt test applied to the series of annual means of the EVI and NDVI vegetation indices

Index	Cantons	A	B	C	D	E
EVI	p-value	0.04*	0.06	0.48	0.60	1.00
	estimate	2013	2013	2013	2012	2013
NDVI	p-value	0.22	0.02*	0.74	0.60	0.43
	estimate	2013	2012	2012	2012	2009

Note: * p-value < 0.05.

Table 4

Results of the Mann-Kendall test applied to the series of monthly means of the EVI and NDVI indices

Cantons	EVI					NDVI				
	A	B	C	D	E	A	B	C	D	E
Tau	0.002	-0.097	0.007	-0.016	0.073	-0.003	-0.163	-0.003	-0.023	0.091
p-value	0.956	0.020*	0.869	-0.706	0.078	0.937	<0.0001*	0.936	0.583	0.028*

Note: * p-value < 0.05.

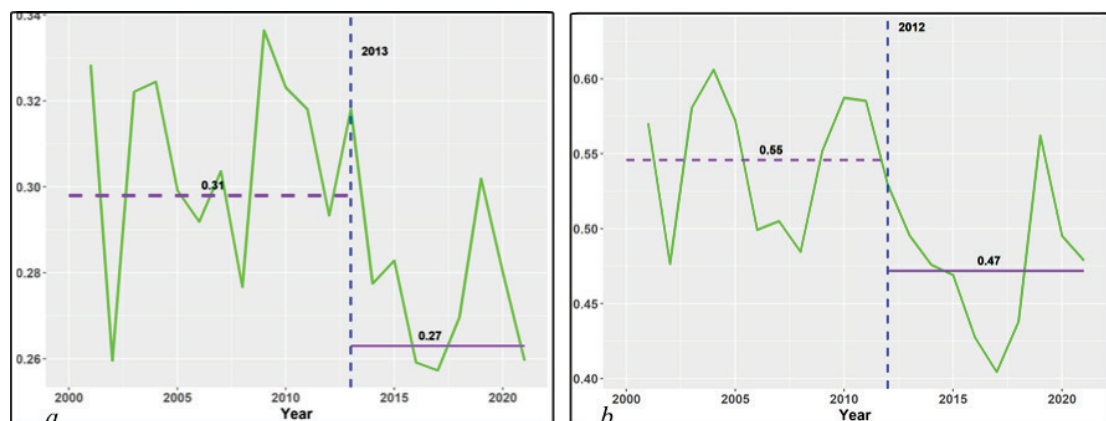


Fig. 5. Results of Pettitt's test applied to the annual means of EVI for Canton A (*a*) and NDVI for Canton B (*b*)

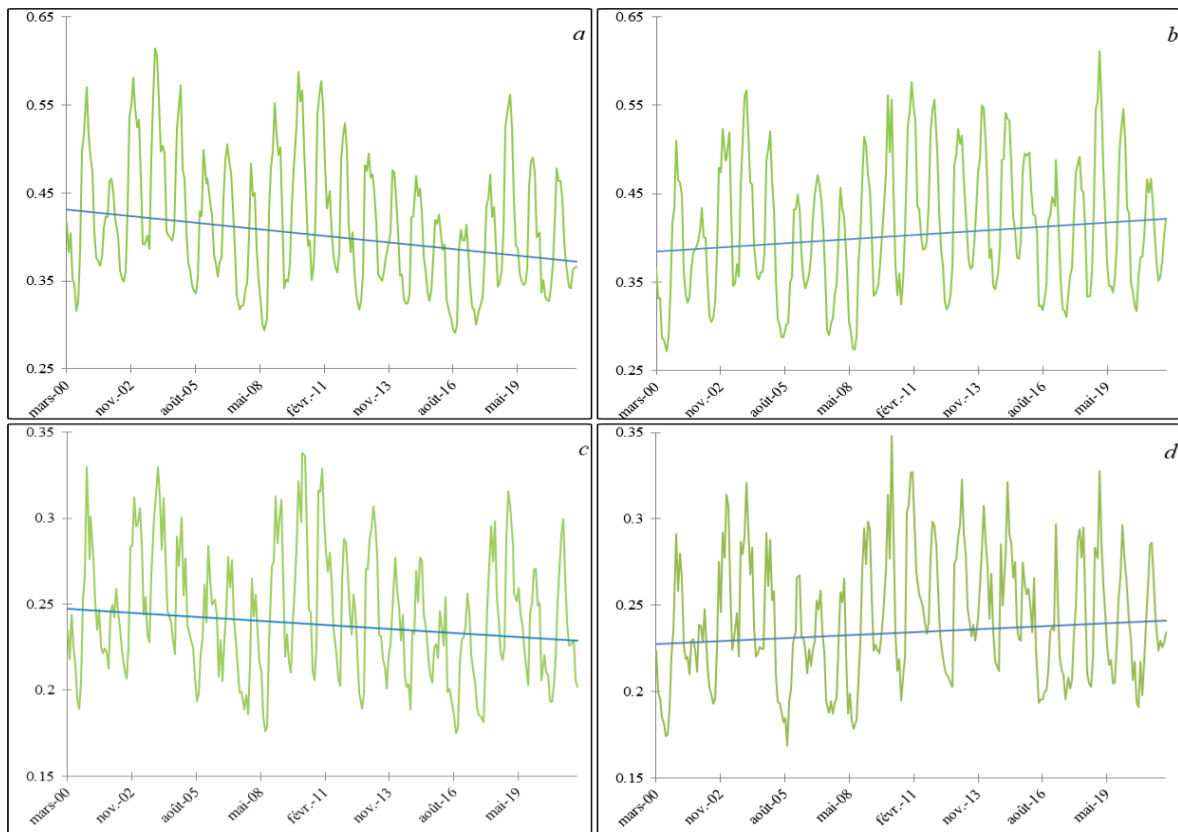


Fig. 6. Results of the Mann-Kendall test and Sen's slope for NDVI (a – Canton B, b – Canton E) and EVI (c – Canton B, d – Canton E)

Seasonal Kendall trend test. The results of the Mann Kendall test with seasonality are summarized in Figure 7.

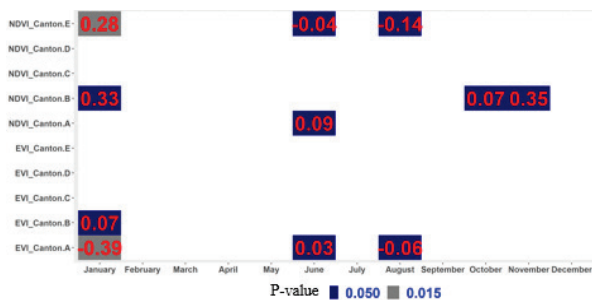


Fig. 7. Results of the Seasonal Mann-Kendall Test (tau) showing series with significant trend (for different p-values)

The figure shows some series composed of monthly averages with significant trends, mainly in cantons A and B for both indices, in addition

to Canton E for the NDVI index alone. These trends are characterized by the time series corresponding to the months of January, June and August, with p-values ranging between 0.015 and 0.05.

In addition, it is important to point out that only the NDVI series of Canton B shows a trend during the autumn season in the months of October and November. Concerning the nature of the detected trends, and based on Kendall's tau values displayed in Figure 7, it appears that they are negative for the case of the EVI series of the Canton A for the months of January and August, as well as for the NDVI series of the Canton E for the months of June and August. On the other hand, the other identified trends are rather positive.

Spatial Mann Kendall trend test. Results of the spatial Mann-Kendall trend test applied to the time series of EVI and NDVI satellite images are presented in Figures 8 and 9 respectively. They map forest areas where regressive trends are identified, based on negative values of Kendall's tau. These maps were generated, proposing a categorization of the test's significance levels, with p-values intervals at the thresholds of 0.001, 0.01, 0.05.

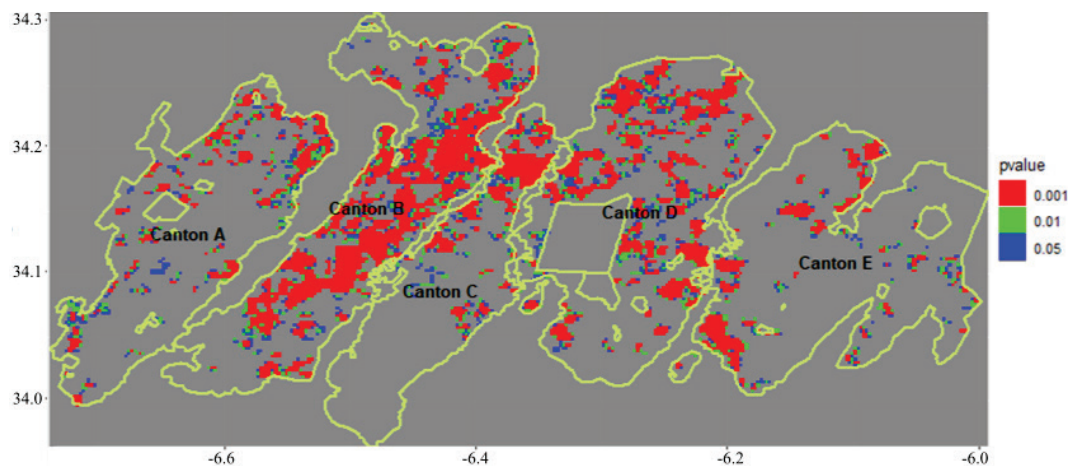


Fig. 8. Spatialization map of forest areas showing a regressive trend by the EVI

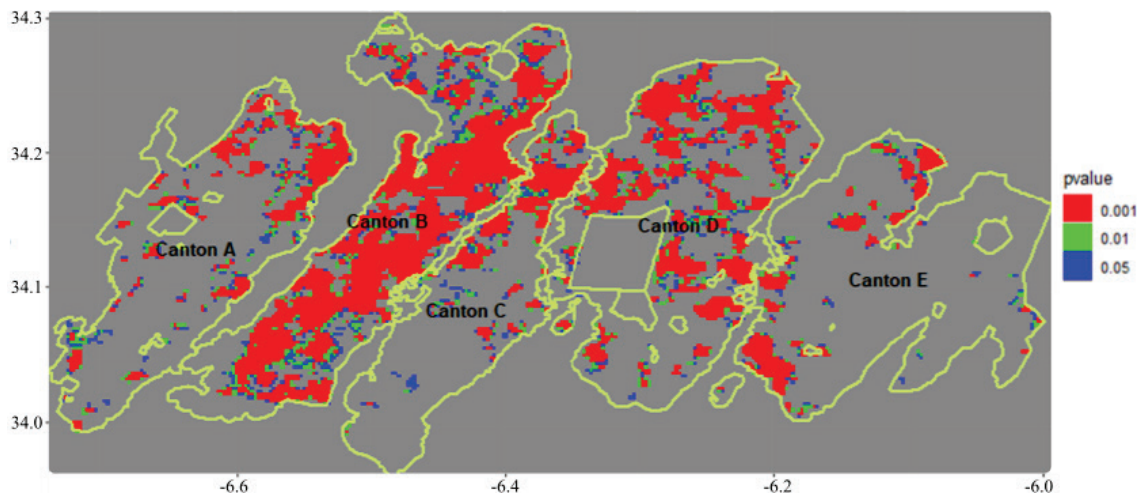


Fig. 9. Spatialization map of areas showing a regressive trend by NDVI

Analysis results of these maps are summarized by index in Table 5, by calculating the frequency of obtained p-values at both the scale of each canton and that of the entire Maamora forest. They show that Canton B recorded the highest regression rate, in the range of 46.1–63.2% of the area, followed by Canton D, then cantons A and C recording the same rates oscillating between 20.3 and 23.4%. Canton E had the lowest rate of regression between 13.2 and 14%. At the scale of the entire Maamora

forest, regression ranged from 26.7% to 32.5% of its area, depending on the reference vegetation index. To better refine the analysis of the identified regressive trends, through a consideration of the diversity of forest stands in the Maamora forest, as well as their heterogeneous structures, the areas of regression zones were quantified by vegetation strata, based on the stand types' map made in the management study of this forest. This analysis results are summarized, with respect to the main strata, in Table 6.

Table 5
Seasonal Mann Kendall test results by Canton (%)

Indices	p-value	Canton A	Canton B	Canton C	Canton D	Canton E	Whole forest
EVI	0.001	11.1	35.0	14.1	21.4	8.8	19.0
	0.01	4.2	5.5	3.2	5.2	2.5	3.8
	0.05	5.0	5.6	3.6	5.5	2.6	3.9
	total, %	20.3	46.1	20.9	32.1	14.0	26.7
NDVI	0.001	15.3	50.6	16.1	28.6	9.2	25.0
	0.01	4.0	6.5	3.0	5.2	1.7	3.8
	0.05	4.1	6.1	4.1	4.4	2.3	3.8
	total, %	23.4	63.2	23.2	38.2	13.2	32.5
Forest area, ha		25 177	29 312	17 498	29 373	30 382	131 742

Table 6
Spatial Mann Kendall test results by stand type (%)

Index	p-value	Qs1	Qs2	Qs3	Qs4	Qs in M	Rg Qs	Bare land	Euc	Aca	Pine	Mat
EVI	0.001	10.2	14.0	9.4	10.4	15.0	33.3	36.6	20.6	43.4	15.5	12.2
	0.01	3.4	4.4	4.2	5.5	6.4	5.2	3.4	4.1	6.2	2.5	2.4
	0.05	4.2	5.5	4.0	8.9	8.3	3.9	2.7	3.7	5.7	2.6	2.4
	total, %	17.8	23.9	17.6	24.8	29.6	42.5	42.8	28.5	55.3	20.6	17.1
	sup, ha	5 376	3 131	1 486	214	1 277	5 381	2 433	12 228	1 501	2 019	27
NDVI	0.001	19.2	22.0	15.2	14.4	25.4	44.4	38.8	24.5	50.2	16.4	12.2
	0.01	4.5	5.7	4.4	4.0	8.0	5.7	3.3	3.1	4.6	1.2	9.8
	0.05	4.9	5.1	4.7	3.5	7.6	4.1	2.8	3.3	4.1	1.3	0.0
	total, %	28.6	32.7	24.3	21.8	41.0	54.2	44.9	30.9	58.9	19.0	22.0
	sup, ha	8 643	4 294	2 046	189	1 765	6 870	2 553	13 259	1 598	1 862	35
Area, ha		30 200	13 117	8 422	866	4 310	12 677	5 691	42 979	2 716	9 812	445

Note: Qs (*Quercus suber*); 1 to 4 (dense, medium dense, sparse and clear density classes); Rg (regeneration); Euc (Eucalyptus); M (Mixed); Aca (Acacia); Mat (Matorral).

The analysis of Table 6 shows that regressive dynamics affect all stand types without exception, with rates exceeding 17% of their respective areas. The highest rates, of more than 42% of the respective strata areas, are found in the stands of cork oak from regeneration and acacia, in addition to bare land. Concerning the cork oak stands, the regressive dynamics is observed on 24% to 34% of their area according to the EVI and NDVI respectively.

This analysis was further investigated by looking for possible relationships that could be established between the regressive trends identified by stand type in relation to the continental gradient. To this end, Table 7 details in a cross-tabulated manner the areas of forest zones showing a regressive trend at the scale of each of the five Maamora cantons and by cover type. This cross analysis shows that the main stand types in Canton B show the highest rates of regression, with the exception of mixed cork

oak strata or acacia plantations where these exponential rates are shared with Cantons C and D. The regression at the level of bare lands beats its maximum by exceeding the threshold of 82% of their area. As for the lowest rates, they are mainly observed in cantons C and E respectively for natural stands of cork oak and artificial plantations.

Discussion

Spatial analysis of the vegetation indices (NDVI and EVI) time series at the scale of the five cantons of the Maamora forest, based on some parameters of the descriptive statistics, showed that Canton A has the highest corresponding average values (0.266 and 0.473), which reflects its forestry importance based mainly on dense stands of cork oak (Aafi et al., 2005). Being covered only by natural stands of medium densities (as in

Canton D), Canton C occupies the second rank in terms of vegetation intensity by (0.245 and 0.424), while Canton B (0.244 and 0.415) in ranked 3rd, despite the fact that it is located mostly in the western part of the Maamora, which is covered by dense stands of cork oak. This reversal of rank is also recorded between cantons D and E (Fig. 2). They show respective values from 0.235 to 0.241 and from 0.384 to 0.411 respectively for EVI and NDVI, considering that Canton E, far from oceanic influences, has a very low area and density of cork oak, substituted by exotic

species based mainly on eucalyptus (Table 1). The characteristics of this spatial heterogeneity were confirmed by the results of the interannual variability analysis of these two vegetation indices (Fig. 3). It revealed the triggering of contrasting trajectories of forest cover dynamics at the level of each of the Maamora cantons. Thus, and while a drop in vegetation intensity can be observed from the year of 2010 at the level of Canton B, a positive evolution is emerging, from the year 2012, at the scale of Cantons C and E.

Table 7
Results of the seasonal Mann Kendall test by stand type and Canton (%)

Canton	Indices	Qs1	Qs2	Qs3	Qs4	Qs M	Rg Qs	Euc.	Aca	Pine	Bare land	%
A	EVI	13.5	23.6	34.1	23.5	21.8	32.2	15.6	48.9	11.9	20.7	19.4
	NDVI	15.6	29.1	37.1	15.7	23.6	43.1	15.0	47.8	11.3	21.1	22.6
B	EVI	24.3	39.4	38.0	55.0	25.5	57.5	61.2	65.8	52.3	81.9	45.5
	NDVI	50.6	58.6	56.8	65.0	42.6	75.4	73.1	72.4	54.1	86.1	63.0
C	EVI	7.4	6.5	5.3	13.2	40.1	23.7	36.4	68.9	23.7	55.4	20.5
	NDVI	11.4	7.0	8.2	13.2	44.4	24.0	39.6	74.3	23.0	60.8	22.8
D	EVI	27.5	28.2	18.4	14.0	28.6	39.5	39.4	59.0	12.5	26.1	31.9
	NDVI	37.3	34.1	23.1	7.5	43.2	48.2	44.9	62.4	14.4	33.0	38.5
E	EVI	4.7	9.6	5.9	50.0	20.7	26.2	13.3	10.8	7.4	27.3	13.5
	NDVI	16.4	26.3	10.8	25.0	27.6	29.0	11.6	12.3	1.3	24.8	12.8

These initial findings were confirmed, at the level of cantons B and E, by the concordant results from the application of more than one statistical test on the time series concerning at least one vegetation index. Thus, the Canton B has demonstrated, in a very to highly significant way, a regressive dynamic and this, from the month of March 2012, is based mainly on the NDVI index times series (Table 2 and 3; Fig. 4, 5 and 6), in addition to that of the EVI annual averages (Table 3; Fig. 5). In contrast, the forest cover of Canton E characterized, from the months of October/November 2008, a progressive dynamic, as shown by the data in Tables 2 and 4 and figures 4 and 6 for the two vegetation studied indices.

Moreover, it must be noted that Canton A has exhibited, in turn, a regressive trend, which is identified from the year 2013 (Table 3; Fig. 5). This makes it possible to identify, on the basis of these contrasting trajectories of the dynamics in forest cover, a form of inversion in the gradient of continentality. This is often put forward in an attempt to explain the forest cover distribution within this emblematic forest area, as well as its evolution (Aafi et al., 2005). Similarly, it is well demonstrated that the degradation process has affected, with varying intensities, the two cantons B and A, considered as areas conducive to cork oak, benefiting from a subhumid bioclimate and sea spray from the Atlantic Ocean (Aafi et al., 2005; Lahssini et al., 2015; Laarbya et al., 2021). However, this process cannot be circumscribed only within these two cantons, without spreading in a continuous manner to all the other Maamora Forest territories.

In fact, the mapping of this regressive dynamic, by means of the spatial Mann Kendall test, showed that 26.7% to 32.5% of the total area of the Maamora forest is subject to this trend, with a very clear variability among the cantons. Thus, it affected 46.1% to 63.2% of Canton B, 32.1–38.2% of Canton D, 20.3–23.4% of cantons A and C, and less than 14.0% of the Canton E area (Table 5 and Fig. 8, 9).

In relation to the forest stand typology, the highest regressive rates (over 30% to 40% for EVI and NDVI respectively) are observed mainly in the cork oak regeneration strata, as well as in the bare lands (Table 6). These two stand types are strongly represented in Canton B, where the highest regressive rates were found, representing more than 57% of their respective areas (Table 7). The other types of artificial stands reveal in majority the same finding at the level of this Canton. Such situation is mainly in relation to their conversion programs for the recovery of cork oak and to the application of silvicultural treatments prescribed by the dedicated management plan.

The relative predominance of these two strata at the level of this Canton could explain the progressive trend identified, during the fall season, based on the seasonal Mann Kendall test's results (Fig. 7). It may be related to the two-month delay in the resumption of the NDVI sinusoidal cycle, which was delayed until November, due to the effects of the drought period extension until October and the worsening of its intensity.

The regressive dynamics of the forest cover, mainly at the level of cork oak-based strata, can be explained by the failures encountered in the

realization of regeneration and reconstitution programs of these stands. Indeed, some works have highlighted the main determining factors and have noted the difficulty of its regeneration (Belghazi et al., 2001; Belghazi et al., 2011; Lahssini et al., 2015; Laarbya et al., 2021), of which some authors have even stipulated that, in some areas of the Maamora, this species is currently at its ecological limit (Laarbya, 2006; Lahssini et al., 2015).

On another aspect, the obtained results did not mark in an explicit way a causal relationship between the contrasting dynamics of the vegetation cover (NDVI, EVI) and the climatic factors, referring to the gradient of continentality. This points to the combined effect of several factors, both biotic and abiotic, affecting the forest environment of the Maamora, including cork oak regeneration techniques, management patterns of regenerated plots (Lahssini et al., 2015), issues related to genetic variability (Varela et al., 2014) and the choice of species made for reforestation and restoration of forest stands in the study area (Zine El Abidine et al., 2020).

Additionally, the anthropic pressures, largely exceeding the production possibilities of this forest space, marked sometimes by aged and decaying stands (Aafi et al., 2005; Laarbya et al., 2014) compromise in the long run their undeniable contribution to the provision of ecosystem services and to the socio-economic development of local territories (Aafi et al., 2005; Benabou et al., 2022b). In this sense, this area is in urgent need of conservation measures, which will entail close consultation and involvement of the local population (Moukrim et al., 2019).

Conclusion

The Maamora forest represents a natural heritage that is characterized by a great ecological diversity that gives it an important role in safeguarding natural resources. However, this once flourishing area, which provides a wide range of ecological, environmental and socio-economic services, is witnessing a regeneration potential deterioration and an increasing degradation process.

The spatio-temporal dynamics' analysis of the vegetation cover within the Maamora forest, based on the NDVI and EVI vegetation indices, highlights the extent of the degradation process, which has increased over 26.7% of its total area, with a concentration in Canton B (over 46.1% of its area). At the same time, it reveals a contrasting dynamic in Canton E, composed mainly of artificial plantations, notably based on eucalyptus, which have been established without major difficulties.

These changes call for an in-depth reflection on the regeneration and restoration techniques of cork oak stands in the Maamora, taking into consideration the different components of the forest ecosystems as a socio-ecological unit. Similarly, a monitoring and surveillance system of the spatio-temporal dynamics of forest cover is to be established, taking advantage of data from satellite images made available online via many specialized platforms.

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