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Spatial patterns of environmental degradation and demographic changes in the Mediterranean fringes

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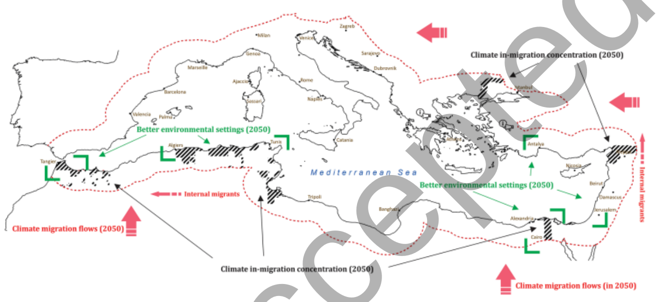
Abstract

Environmental and climatic factors contribute to the range of causes of increased socioecological conflicts, especially in the transcontinental transition areas. However, knowledge of the precise extent and patterns of environmental change driving social and migratory mutations in these areas is still quite limited. This article shows that the Mediterranean transition fringe will undergo climatic-environmental degradation except from four scattered areas of abundance which are likely to be more affected by human activity by 2050. Through an integral socioecological approach, it was found that long droughts are likely to alternate with sporadic intense storms with an impact on the loss of biodiversity, degradation of biocultural heritage, and reduction of ecosystem services. Forced migration trends towards areas of abundance have been identified according to particularly stressful divergent flows at European borders (Turkey and Morocco). The need for increased international cooperation and cross-cultural exchange is foreseen to identify and address common challenges.

Graphical Abstract



Keywords Migration; Climate; Environment; Change; Google Earth Engine

Introduction

The human behavioural mutations driven by climate-environmental change are barely perceived due to the slow pace of the partial transformations which progress gently like clouds. However, even though the phenomenon seems static, it is very active when viewed from another angle and at an appropriate scale. Unfortunately, the limited perception and commitment of some governments and media result in an underestimation of the magnitudes of change. This causes a legitimacy deficit among public opinion and lack of recognition of the phenomenon as one of the major challenges in the near future (Berrang-Ford et al., 2019; Carmichael and Brulle, 2017).

Consequently, this will negatively affect funding programs of hazard reduction and social mitigation and thus we would be wasting valuable time without trying to remedy it or, at least, avoid the worst.

Though it is recognized that climatic and environmental perturbances create varying degrees of stress leading to direct or indirect economic impacts (e.g., large-scale migration), their causality to armed conflict is not certain, except when other fundamental factors (physical, geopolitical and intrastate) have been compromised (Feitelson and Tubi, 2017). Throughout history, climate change has stirred social, environmental, economic, and political upheavals in the Mediterranean, so much so, that it is claimed that Rome fell due to environmental stress under a combination of pandemics and climate change (Harper, 2017). Much earlier, the sequential collapse of the Mediterranean civilizations in the Late Bronze Age is likely due to the effects of an abrupt climate change-driven famine and causal linkage with the 'Sea Peoples' invasions, region-wide warfare, and politico-economic breakdown, in whose wake new societies and ideologies were created (Kaniewski et al., 2013).

Environmental and climatic factors are often added to the set of causes that push many people to move far from their homeland. These displacements refer to situations in which the decision-making power of people is very limited and the forced displacement is the result, at least partially, of a natural disaster (Kolmannskog, 2012). In this contexts, women, people with fewer economic resources and those who suffer discrimination are the first to suffer these forced movements (GreenPeace and CEAR, 2021). For instance, internal displacement in 2020 reached a record of 40.5 million new cases in 149 countries and territories, of which 75% (30.4 million) were linked to meteorological, climatic and geophysical events (IDMC, 2020). By 2050, the global worst-case scenario predicts that the 140 million mark could be crossed (Clement et al., 2021).

According to different studies, the scenarios of future climate change and environmental stress that will affect internal displacement will apparently transform Turkey and North African countries into new immigration poles due to increasing migratory flows from sub-Saharan Africa to the whole Mediterranean (de Haas, 2011). The coastal fringe will be under greater stress, not only because it is a natural barrier to the flow of migrants into Europe but also because of its role as a transitory geo-confluence space. From the natural perspective, it is expected a climatic transition affected by geographical factors from the coastal areas to the interior, and from a sociological perspective, the projection is from a space open to multicultural encounters and exchanges towards a more reserved one (Bolle, 2003; Davis, 2015; Goffredo and Dubinsky, 2013); a set of characteristics that make this zone a fringe of socio-environmental transition.

With this in mind, this study explores the conditions of this transition fringe to assess future drivers of environmental stress and migration. Its extent generates an issue of visibility and scale of representation that was overcome by considering a buffer of 250 km. Consequently, the total area is 2.2 million km^2 which includes areas of 24 countries in Africa, Asia, and Europe. It is a land of history, trade, a hotspot of biodiversity, culture, heritage and tourism, located at the intersection of two major landmasses - Eurasia and Africa, the largest of the world's five Mediterranean-climate regions, and one of the largest archipelagos in the world (Agency, 2006; Médail and Quézel, 1999; Murray et al., 2019).

To address the processes of interactions between social structures and environmental systems that lead to these migratory crises, socioecology is the most integral, multidisciplinary, and productive approach (Fischer-Kowalski and Haberl, 2007). Indeed, it is only through the integrated study of coupled social-natural systems that we can understand dynamic human-environmental interactions and begin to manage them for sustainable goals (Fitzhugh et al., 2019).

To this purpose, we have studied the recent evolution (up to the last 40 years) of the fundamental environmental factors - NDVI, rainfall, land surface temperature, total and potential evapotranspiration, and wet and dry spells - and their projection by 2050, with application of trend tests (Mann-Kendall test and Sen's slope) and looking for statistical spatial-temporal anomalies. On the other hand, we have studied demographic trends in relation to the evolution of population density and its future projection, land use, and we focused particularly on estimates of climate-environmental migrations by 2050 extracted from the Global Migration Data Portal. Finally, we have analysed the findings of the 'Anna Lindh Intercultural Trends Survey', which is based on a large sociodemographic sample of Euro-Mediterranean people interviewed over time, that studies the transformations of Mediterranean societies, mutual perceptions, their behaviours, and values with a focus on intercultural interactions.

Material and methods

1. Environmental assessment

To study the environmental factors, a wide range of 17,999 satellite images from nine different collections were processed through copious and, sometimes, long codes on Google Earth Engine (Fig. 1, Table 1). The latter is a powerful and transversal open tool to assess climate change anomalies and their relationship with multiple anthropogenic and environmental factors (Jamali et al., 2022).

The landcover map is a composite of land use/land cover (LULC) predictions for 10 classes throughout the year to generate a representative snapshot of 2020. It is derived by Esri (Environmental Systems Research Institute) from ESA Sentinel-2 imagery at 10 m resolution (Karra et al., 2021).

The Gridded Population of World Version 4 (GPWv4), Revision 11 (CIESIN, 2018) was used to calculate the human population of the study area for the years 2000, 2005, 2010, 2015, and 2020 on approximately 1 km grid cells and to model the population density for 2020.

The changing population used the 'WorldPop Global Project Population Data' dataset at 92.77 m resolution (www.worldpop.org). We created a time band (in milliseconds) and we applied a linear regression between 2000 and 2100 (we thus created 101 annual images). The result of 2100 was then subtracted from 2020 to estimate the total change.

The assessment of the pixel-based NDVI (Normalized Difference Vegetation Index) average for 2020 was based on a dataset of 23 'MOD13Q1.006 Terra Vegetation Indices 16-Day' images (Didan, 2014) with a spatial resolution of 250 m over the 20-year period from 2000-02-18 to 2020-12-31.Subsequently, we determined the accumulation of NDVI anomalies over the last nine years through the 'MYD13A1.006 Aqua Vegetation Indices 16-Day' dataset (Didan, 2015) with a resolution of 500 m (441 images). We defined the reference conditions from the first 10 years of data (2002-2012) then we calculated the average at the pixel scale. Afterwards, this last was subtracted from each of the images in the data collection (from 2013-01-01 to 2021-07-31) and an iteration was applied over the calculated anomaly images to create a collection of cumulative anomalies over time.

Land Surface Temperature (LST) was assessed using a dataset 'MOD11A2.006 Terra Land Surface Temperature and Emissivity 8-Day' at a resolution of 1 km over a period of 20 years (2001-2020) (Didan, 2015). The data collection (919 images) was filtered according to LST-Day and LST-Night separately then we applied a conversion to Celsius. The median at the pixel scale was calculated for each of the day and night collections and then the average was deduced. Admittedly, it is better to use the median when dealing with outliers (extreme values at the end) or a large data set, as it allows a better representation of the centre point and is not distorted by outliers.

For spells of precipitation, we used a dataset of 363 images from the 'CHIRPS Daily: Climate Hazards Group InfraRed Precipitation with Station Data (Version 2.0 Final)' collection (Funk et al., 2015) at a resolution of 5.56 km over a 40-year period (1981-2020). First, the maximum dry spell (MDS) was assessed on a daily scale for pixels with precipitation below the threshold (5 mm considered here as the topline of significant dry days). We created a first image on which we applied the iteration function to calculate the counters accumulation. Second, the average dry spell was calculated by averaging the annual maximum value at the pixel scale. Finally, the maximum wet spell was calculated according to the same logic of the MDS but by exploring the values above the threshold (10 mm considered here as the baseline of days of significant precipitations).

The latest data collection (14,822 daily images) was used to assess the long-term annual average and the spatial-temporal precipitation trend. In the last case, we executed a Sen's slope trend algorithm at the pixel scale and tested it later based on the Mann-Kendall statistical test ($\alpha \leq 0.05$ and $Z = 1.96$).

The daily downscaled precipitation projections used 365 images from the 'NEX-GDDP: NASA Earth Exchange Global Daily Downscaled Climate Projections' collection (Thrasher et al., 2012) at a resolution of 27.83 km between 2050-01-01 and 2050-12-31. The collection was filtered by parameter (precipitation) and by date, and the pixel-based annual value was calculated by sum of all daily values.

For total (ET) and potential evapotranspiration (PET), the 'MOD16A2.006 Terra Net Evapotranspiration 8-Day' collection(Running et al., 2017) at 500 m resolution (919 images) was used for the period 2001-2020. The collection was filtered separately according to the desired parameter (ET and PET). We then calculated for each parameter the annual sum at the pixel scale, and we deduced the average over the whole period.

2. Social analysis

In parallel to the environmental assessment, the rates of migration (general meaning) according to the statistics of the Global Migration Data Portal (www.migrationdataportal.org) were analysed by country and then grouped into five sub-regions (North Africa, Middle East, South-eastern Europe, Western Balkans, and Southern, Western, and Central Europe) to discern the links and possible preferential directions of movement. Our attention was focused on four indicators which reveal the evolution of migration in the Mediterranean, namely: i) the international migrant stock as a percentage of the total population in 2020, ii) the international emigrants in relation to the population in 2020, iii) the difference in the share of migrants in the total population between 2000 and 2020, and iv) the net migration rates between 2015 and 2020.

Lastly, the findings of the 'Anna Lindh Intercultural Trends Survey 2020'(ALF, 2021) were analysed. The study is based on a public opinion polling exercise carried out in eight European countries and five countries bordering the Southern and Eastern shore of the Mediterranean. For the last edition of the Survey carried out in 2020, in total 13,264 persons were approached according to Computer Assisted Telephone Interviewing between March and October 2020, with a pause in-between to account for the pandemic lockdown. Respondents were asked about a range of topics but we were attentive to some key indicators, namely: the perception of common characteristics of the Mediterranean and level of interest in relation to news and information about people from other parts of the region (way of life and food, cultural heritage and history, hospitality, resistance to change, instability and conflicts, and migration), the level and barriers to cross-cultural encounters (different languages, sociocultural constraints, visa and travel difficulties, economic barriers, religion, and historical tensions), and the perception about cultural and religious diversity and expected gains from the Euro-Med cooperation (economic growth and development, environmental sustainability, fair response to refugee situation, and recognition of cultural diversity).

Results

We analysed 17,999 satellite images from nine different collections to assess the current situation of the Mediterranean transition zone, to spatialize recent trends in key ecological indicators, and to estimate their future projections. Our study responds to an increased need for a detailed evaluation of the environmental and climatic drivers of movement strategies under forced migration regimes and their potential impacts on spatiotemporal dynamics, especially in areas of large transient influence such as the Mediterranean fringe. Thus, we compared the aforementioned ecological indicators to social parameters extracted from recent social findings of high standards data collections according to an integrated socioecological approach.

1. Contrasted indicators and spatial links

With regard to land use/land cover (Fig. 2.a), we observe an evident contrast between the northern and southern Mediterranean shores, and between the centre and the outskirts. Indeed, the density of vegetation cover is higher in the North as compared to the South, which is dominated by scattered shrubs and bare land, except in the Nile Delta and the western shores of the Maghreb.

The shrubland is quite extensive on the southern shore from the Moroccan oriental coast to the Nile Delta, except from the Algerian-Tunisian coasts. It is also abundant in the East and in areas on the northern shore as in Andalusia, Turkey and the Adriatic eastern countries. In the South, the shrubs are mostly scattered and contiguous to bare land.

In the North as in the South, there is a significant influx of built areas towards the coasts (Wolff et al., 2020). However, these areas tend to expand where vegetation cover is abundant while they concentrate where it is scarce or absent. For instance, the built-up is mainly concentrated in the South Centre around Tripoli and Benghazi. As a result, we notice that the built-up is reduced to a few small towns where there is shrubland. In contrast, we do not observe built-up on bare ground.

The above-mentioned LULC contrast is confirmed by the average NDVI map (Fig. 2.b). Thus, the South and the East show spatially extensive low values, giving evidence of sparse or no vegetation cover. The latter is dense (values greater than 0.5) exclusively in four scattered areas of abundance which are from East to West: The Tangier peninsula, the coast between Algiers and Tunis, the Nile Delta, and the coast between Jerusalem and Antalya. On the Spanish side, the density gradually decreases south of Barcelona to give rise to a sparse vegetation cover to the South and East of Valencia.

The spatialization of the average annual rainfall (Fig. 2.c) follows the same pattern observed, with higher values in the North (more than 1,000mm in the Adriatic zone) against a progressive scarcity towards the southern centre (less than 100 and 200 mm in Egypt and Libya respectively). It should be noted that the higher density of the vegetation cover is correlated with the abundance of rainfall, except in the Nile Delta where the vegetation is maintained thanks to the contributions of this great river.

Likewise, the annual average temperatures (Fig. 2.d) are milder in the North (less than 15°C) then they gradually increase towards the East and the West to reach maximums in the South between Tunis and Aleppo (more than 20°C). Libya and Egypt record very hot annual average temperatures which in some places exceed 30°C.

With these observations in mind, it is normal for the total annual evapotranspiration (Fig. 1.e) to be greater in places of abundant precipitation and vegetation cover, namely in the North, and in the four areas of the South mentioned above. On the contrary, the potential evapotranspiration (Fig. 2.f) highlights a stressful water demand towards the East, West, and South. As a result, southern Spain and Turkey, and western Greece bear higher PET values (above 1,750kg/m^2/8 days). With regard to the four areas of abundance in the South, the most affected are the Nile Delta (in particular Cairo where the annual average of PET exceeds 2,000kg/m^2/8 days) and Jerusalem-Antalya. Obviously, the white areas to the South have values of 0 ET and PET due to the absence or non-significant existence of vegetation or water bodies.

A particularly important element we have studied is the average of rainy days (a day is considered significantly wet when the rainfall exceeds 10 mm and dry when it is less than 5 mm (Kostopoulou and Jones, 2005; Martin-Vide and Lopez-Bustins, 2006; Salhi et al., 2019)). Admittedly, a rainy sequence of several days will sustain the water needs and create an important useful reserve while a long dry sequence will increase the needs and consume the reserves. In this sense, the annual average dry spell map (Fig. 2.g) shows that the dry sequences are short in the North (less than 10 consecutive days), and they stretch slowly (less than 30 days) from the South of Valencia to Tunis, and from the South of Istanbul to Beirut. These dry sequences are spreading more and more from the South of Tunis to Cairo where they exceed 120 days/year on average, which means that these areas have larger dry spells than the ordinary Mediterranean summer period.

Therefore, it is not strange to observe a good spatial connection between population density and climate-environmental conditions. Thus, it is clear that the best conditions favour the growth of dense agglomerations, while the deficit in the South correspond to repulsive zones which expel the population to the East and the West (Fig. 2.h). The Nile delta is a special case where the densest (over 1,000 inhabitants/km^2) and extensive agglomeration, favoured by a dense vegetation cover and abundant water supplies from the Nile, is thwarted by a very dry and hot climate. With this in mind, after the complete filling of the Grand Ethiopian Renaissance Dam (GERD) which will benefit Ethiopia and Sudan, although simulations show that it will not significantly affect water users in the Nile Delta, but managing multi-year droughts requires prudence and coordination to avoid harmful risks (Wheeler et al., 2020).

2. Disturbing anomalies and trends

The Mann-Kendall statistical trend of rainfall and its Sen's slope statistical significance during the last forty years shows an overall significative decreasing rainfall trend (Fig. 3.a). The most affected areas are around the Adriatic, Turkey, eastern Morocco, and western Algeria. In scattered and less extensive places, the same trend is observed in Catalonia, southern Tunis, Greece, Nicosia, and the Middle East. Significant positive trends can be observed west of Marseille and, faintly, between Jerusalem and Damascus. Between Libya and Egypt, the significant positive trends will not be reflected in a strong increase in rainfall since these areas currently receive rainfall that barely exceeds 100 mm per year on average. When we put this in its general context revealed by recent simulations (Benabdelouahab et al., 2020; Mathbout et al., 2019), we conclude that the downward trend will come together with extremely concentrated rainfall episodes, generous indeed but unmanageable under current conditions and, therefore, generating more damage than benefit.

The downscaled projected rainfall average by 2050 confirms the overall downward trend (Fig. 3.b). Accordingly, the annual decrease (compared to the average) will exceed 200 mm, especially in the above-mentioned areas of abundance (South) where the decrease is likely to be more severe.

The maximum historical dry spell in a year shows long dry episodes in the South, which lead to a high water deficit (Fig. 3.c). In the North, the maximum droughts are short (less than 10 days) then they gradually increase in the East and West. In the areas of abundance, consecutive dry days are frequent and prolonged, mostly in the Nile Delta and north of Jerusalem, except from the area between Algiers and Tunis which exceptionally shows shorter dry periods.

Certainly, the long wet historical sequences generate benefits for water systems and the environment but may involve risks of flooding, landslides, and erosion, especially taking into account the structural factors of the area such as the morphology of the watersheds, their lithology, the flow evacuation capacity, and land use (mainly downstream). With this in mind, long historical annual wet spells (over 3 consecutive days of more than 10 mm) are observed in the North and in the areas of abundance in the South (except from the Nile Delta) (Fig. 3.d) which joins the strong generalized probability of concentrated rain episodes.

In short, we expect a strange panorama where the precipitation will be less abundant but more and more concentrated, sudden, and sporadic. The dry periods will be even longer, which means that the hydrological and pedological drought will be more severe, the soils and vegetation weakened and the territories more vulnerable to hydroclimatic risks.

To inspect recent NDVI development, the pixel-scale average over a 10-year period (2002-2012) was taken as a reference against which the cumulative anomaly was calculated for last nine years (2013-2021) (Fig. 3.e). The anomaly shows a clear negative trend on the Spanish and Moroccan coasts, in Algeria and Tunisia, in the Nile Delta and in Northern Syria. On the western coasts (Morocco and Spain) this negative anomaly is associated with intense tourist pressure and the use of greenhouses in agriculture on the Spanish side (which distort the reflected spectral signature). In Syria, it is attributed to the repercussions of recent armed conflicts. In the Nile Delta, there is apparently an important metamorphosis, the reasons for which are to be sought later. In any case, the actual magnitude of the short- and medium-term impacts related to the availability of water downstream of the Grand Ethiopian Renaissance Dam is a question that remains open for the moment (Basheer et al., 2021; Wheeler et al., 2020). However, the affected areas between Algeria and Tunisia are shrubs, which is explained by a decrease in their density. In any case, this is again a negative anomaly at or in the immediate vicinity of the areas of abundance in the South, which reiterates their natural structural fragility. It should be noted that in areas where the plant cover is either scarce or non-existent, it is difficult to perceive slight variations, which explains the stable areas in the South.

The good news is that the majority of the transitional fringe has a positive anomaly, which creates hope that rational management of natural resources can ensure a valuable strategic stockpile for the upcoming lean years.

The estimated population increase by 2100 will be greater in the South, especially in the Nile Delta and in the coast (Fig. 3.f). An increase from 500 to over 1,000 inhabitants/km^2 is expected in these areas where the estimate suggests the highest growth rates (+1.8% annual change). Logically, the best natural conditions in the areas of abundance attract inward migratory flows which are added to the normal increase. As a result, we predict larger and larger cities, possibly with disorganized urban planning, and structurally and socially fragile margins.

According to the previous observations, any negative anomaly of climatic-environmental conditions in the future will push the population towards the areas of abundance creating intense inward migratory flows.

3. Migration willingness and convergence

With regard to the percentage of international migrants in relation to the indigenous population (Global Migration data), it is clearly observed that the countries of Southern, Western, and Central Europe and those of the Middle East receive more migrants (Fig. 4.a). Leaving apart the special cases of Monaco and Andorra, there are two already known preferential directions: South-North across the Alboran Sea and several radial directions from Syria and the Palestinian territories to the neighbourhood. The Western Balkans and Southern Europe show very significant rates (between 8 and 16%) likely because they are transit lands from the origins to the Western destinations.

We also observe the impact of armed conflict on the forced displacement of people. Countries like Bosnia and Herzegovina, Syria, and Albania have almost half of their citizens abroad (Fig. 4.b). Apart from that, citizens of Southeast Europe and the Balkans seem to be more disposed to leave their countries (20% in average) perhaps thanks to the geographical and geopolitical ease of transit and because labour market is unable to absorb the high number of job seekers (Jusufi and Ukaj, 2020). In North Africa, the difficulties of crossing borders to Europe are manifested by lower rates (generally between 4 and 10%) but more significant numbers due to the higher number of populations (up to 3.5 million in Egypt and Morocco). Thanks to the small maritime gap through the Strait of Gibraltar (14 km), Morocco is a privileged transit point for migrants from North Africa, sub-Saharan Africa, the Middle East and even Asia. There is another maritime migration route through the Tunisian coast, which is followed by the surrounding population.

The analysis of the difference in the share of migrants in the total population over the last 20 years highlights 3 main groups (Fig. 4.c). A first group where the share has increased: these are reception areas for migrants (Southern, Western, South-eastern and Central Europe, Montenegro, and Lebanon). The second group is formed by a transit area where the share has remained practically stable (North Africa). The third group experienced a decrease in the share: these are areas of departure of migrants (Balkans except Montenegro and Slovenia, and the Middle East except Lebanon). This general trend between 2000 and 2020 remains valid during the last five years (with some slight variations) for the entire Mediterranean fringe except from Lebanon and Syria where the trend has reversed for the first and has fallen colossally for the second in relation to socioeconomic crises and armed confrontations (Fig. 4.d).

The findings of the Anna Lindh Survey and related analysis highlight a singular phenomenon of proximity of opinions on the characteristic elements of the Mediterranean region for groups of individuals of different cultural heritage (Fig. 5). Thus, we observe a widespread agreement on the perception of shared elements in relation to the Mediterranean as characterised by the value of hospitality, a common way of life and food and shared cultural heritage and history as well as a space influenced by migration issues. More negative features such as resistance to change, instability and conflicts appear to be less prominent for the majority of Mediterranean population regardless of ethnic and geographic factors and reflecting most probably the predominance of a 'sociological convergence'.

In relation to the scope of this analysis, it is significant also to identify people's inclination towards migration in order to be able to assess over time the impact that climate change can have on actual migratory flows. The Intercultural Trends research shows that since 2009 Europeans were those with the deepest propensity to migrate to another country and that the destination has been mainly towards other European countries, while comparatively North-African and Eastern Mediterranean populations have registered a lower interest to start their life in a country different from their country of origin. In terms of destination, in 2020, only 20% of the surveyed sample from Southern and Eastern Mediterranean countries would have decided to migrate towards Europe if given the choice. This research is relevant also to know that the natural environment and the impact of climate change are the areas of major interest for people of North, South, East, and West of the Mediterranean about the opposite shore of the Mediterranean (89% of Europeans and 76% of

Southern and Eastern Mediterranean people are very and somewhat interested in this information). This shows the high level of importance that people from the countries object of this analysis recognise to the environment and by crossing this data with the perception of potential benefits that increased Euro-Mediterranean cooperation could bring to solve common challenges we could deduct that there is a solid social foundation to invest more resource from the prevention of forced migration due to the climate emergence. More in particular, 84% of Europeans and 88% of Southern and Eastern Mediterranean people consider that Euro-Mediterranean cooperation could contribute to the environmental sustainability of their society, as well to other important gains in terms of employment, opportunities for young people, respect for cultural diversity, response to the refugee situation. Overall, statistics suggest a good social attitude and a tendency toward acceptance of cultural and religious diversity as a result also of migration waves, stemming from the richness of multicultural historical exchanges, current educational programmes and suggesting a positive response to future challenges.

Even so, special attention should be paid to what people identify as barriers to cross-cultural encounters so that a systemic approach could be adopted for better living together in multicultural societies (Fig. 5). North and South of the Mediterranean, language is seen as the main obstacle to intercultural relations and, with this in mind, terminological (rather than linguistic) differences should be clarified, and ways to promote language diversity and mutual understanding developed; cultural, religious and historic background are also recognised barriers especially for Europeans. In this regards education and intercultural education represent a priority area of attention. Intercultural dialogue and relationships are processes that require a medium and long-term perspective of implementation and cannot be forced upon people not to generate processes of refusal or even worse of extremism.

Discussion

From the environmental point of view, the analysis of the precipitations indicates an irregular pluvial regime spatially and temporally with a clear contrast which oscillates very far from the annual average of 563 mm. The annual low average values of a few millimetres are often recorded in the South between Tripoli and Cairo, while the upper average extremes vary greatly in space and in magnitude. In addition, the interquartile range of rainfall shows paradoxical interannual variations and the standard deviation is very wide (315 mm). Several generalized dry episodes are observed (for instance in the early 90 s and early second half of 2010s) which sustain the dominant negative trend in precipitation regime (Fig. 3.a). At this rate and in the best of cases, an average decrease of 100 mm by 2050 and over 200 mm by 2100 are expected (Fig. 3.g). The decrease will not only affect the annual averages, but it is estimated that the interquartile range will follow this same trend. Noticeably, it should be noted that the real evolution will not have a rectilinear shape but rather a wavy one with alternating interannual wetter and drier episodes. At the intra-annual level, long dry spells will frequently alternate with thunderstorms concentrated in space and time.

Historical measurements show that the mean (air) temperature of the Mediterranean has known oscillations around an ascending trendline of +0.5°C during the hundred years between 1880 and 1980 (Cramer et al., 2018). The difference between the maximum and minimum peaks amplified between the end of the 1930s and the 1960s, during which there is a positive deviation of the Mediterranean trendline from its global counterpart. Since the end of the 1980s, the positive trend has accelerated (Fig. 3.g) and the deviation from the world rate has almost doubled. As a result, maximum historical peaks and heatwaves are recorded in recent years and the average difference reached +1.5°C in 2020 compared to 1880. At this rate, the evolution of the Mediterranean towards warmer and drier conditions is heading towards an increase of +2 to + 4°C on average in 2080s (Cramer et al., 2018). At the level of the transition zone, although it is estimated that the average increase will be slightly softened due to the littoral effect, but the excepted average values are above the Paris Agreement (+1.9 and +2.4°C in the 2050s and 2100s respectively) (Fig. 3.g). Of course, the temperature deviation is expected to be wider, and thus heatwaves may be more frequent and harsher.

In a context already highly strained from water shortages, especially in the South where the potential evapotranspiration is excessive, the expected drier and warmer decades will worsen the lack of water and vegetation, depress biodiversity and ecosystems, and increase the competition between user sectors at unprecedented levels.

The acceleration of anthropogenic growth further complicates the situation. In forty years (1975-2015) the population has grown from 192 to 330 million inhabitants with an average annual rate of 1.8%. At this rate, a population of 538 and 834 million is expected by 2050 and 2100 respectively (Fig. 3.g). Even at the pace of the lowest rate in the past 40 years (1.3%), the current population (356 million inhabitants) will double by 2070. To this is to be added the considerable number of projected internal forced climate migrants by 2050 (between 33.5 and 84 million) who will reach North Africa either from the surroundings or from sub-Saharan Africa (Clement et al., 2021) (Fig. 3.g). This panorama generates unusual water and food needs, more accentuated land use/environment conflicts, and serious risks of pollution, health and security.

Recent estimates (Ali et al., 2022; Clement et al., 2021) show a strong certainty of high levels of climatic in-migration by 2050 in North Africa, Turkey and the Nile Delta (Fig. 6). These estimates are consistent with our results according to which we predict that these areas will relatively experience better climatic and environmental conditions which will favour intense migratory inflows. Under current conditions, the Turkish borders, the Tunisian and in particular Moroccan coasts are very active in terms of migratory transit, and it seems that this phenomenon will be exacerbated by 2050 for two main reasons, in addition to what has been quoted above: i) Recent violent military confrontations have expelled migrants from neighbouring areas, thus creating preferential routes, and ii) Recent intense popular protests, interstate or internal severe political tensions caused disruptions in controlling and regulating immigration processes and contributed to the exacerbation of clandestine migration.

Far from predicting its effects in the med-term, the economic and social repercussions of the pandemic will also play a major role in refining regional migration trends and paths. Although it is currently difficult to include the latter factor, there is great certainty that the projected direction of the dominant migratory flows will be from the South to North Africa and from the East to Turkey (Benassi et al., 2022). Also, there will be preferential internal flows towards the western Turkish border and towards the Strait of Gibraltar (Fig. 6).

A key question in this difficult context is the potential measures to minimize socio-environmental impacts in the Mediterranean. In this sense, climate change mitigation policies are fundamental both at the global and regional level, especially since the timid progress and the commitments made at the COP 26 UN Climate Change Conference make it necessary to prepare the Mediterranean possibly to the worst scenarios of climate and environmental change and their consequences. Thus, the strengthening of multilateral cooperation at international and regional level in all fields becomes even more urgent and essential.

In the advanced stages of writing the article, war broke out in Ukraine, leaving millions of people displaced and refugees across Europe. One of the largest mass movements in recent history is taking place with a humanitarian catastrophe in sight, a huge increase in migratory pressure on EU countries, and long-lasting devastating effects on millions of people (Patel et al., 2022) Converging with the above in our analysis, new factors have emerged to increase the tension regarding forced migrants from the southern shore of the Mediterranean, as it is noted that they face many difficulties and obstacles in gaining similar acceptance of Ukrainians displaced by European authorities (Sajjad, 2022). Simultaneously, the global economic effects on fragile societies are intensifying following the panic over oil prices, especially with Ukrainian and Russian cereal shortages pushing the Middle East and the Maghreb to the brink of social explosion (Arago and Sarmiento; Liadze et al., 2022). In other words, this rapid escalation demonstrates the seriousness of the environmental, socioeconomic, and political structural instability, which is increasing considerably, particularly in the southern shore of the Mediterranean. As a result, less acceptance of forced migrants but at the same time a potential increase in their numbers, with impacts everywhere and for everyone.

Conclusions

The Mediterranean fringe is historically a venue of continuous migratory exchanges. Nothing new, except the socioecological context and climate change which generate controversial factors that may destabilize the fragile balances. What makes this fringe exceptional is not only its distinctive location where three continents are connected combining Sea and Land, but also because it is a unique common space of relation which holds different mainstream cultural and religious traditions deriving from the Christian-Greco-Roman, Islamic and Judaic traditions. Seeing globally, it is a geographical area where many different political regimes and ideologies coexist, where identifying a common ground of understanding is among the main objectives of the Barcelona process in 1995 (Zapata-Barrero, 2020) and Union for the Mediterranean since 2008.

Our findings predict a climatic-environmental degradation in the fringe except in four scattered places of abundance - The Tangier peninsula, the coast between Algiers and Tunis, the Nile Delta, and the coast between Jerusalem and Antalya - likely to be more solicited by human activity by 2050. Without a doubt, failure to take the issue seriously will exacerbate multi-scale socioecological imbalances and potential spread social divide, which will intensify with the expected increase in the number of forced migrants arriving to areas of relative abundance. The diversity of migratory flows means that the host regions will experience varying pressures, but at the European borders (Turkey and Morocco) the confluences will be stressful. Apart from this, forced migration can exacerbate some of the main environmental problems, especially on the southern shore, such as deforestation, overgrazing, and erosion with a clear impact also on loss of biodiversity, degradation of biocultural heritage, and reduction of ecosystem services (Cramer et al., 2018; Cramer et al., 2020).

Long lean periods are likely to alternate with sporadic intense storms which means droughts will be more severe. Indeed, the latter are the main driving force of migrations because they have a substantial impact on the local ecosystem and agriculture, including drops in crop growth and yield, and loss of livestock (FAO, 2018; McAuliffe and Khadria, 2019). Unfortunately, there are many limitations in addressing the issue of forced migration due to the lack of a common definition established in the legal system or at the level of an international declaration, and there is no international human rights instrument to protect people who are forced to migrate because of the climate (Moreno-Lax, 2021). In short, they are generally not given the recognition and status of refugees, which means being in a situation of lack of protection, especially when migration is not the result of a sudden natural disaster, but of a process of progressive degradation of climatic and living conditions that ends up forcing them to leave their homes and being forced to migrate to safeguard their lives (Renaud et al., 2011).

There is a risk that the issue of forced migration could be interpreted exclusively from the perspective of a national security problem, leaving aside its political dimension and potentially encouraging xenophobic reactions in potential receiving countries (Bettini, 2013). Governments cannot evade responsible coordination of balancing odds and interests in order to ensure a life of dignity for all as the supreme common good (OHCHR, 2016).

Beyond the challenge of ensuring food and water security, governments should work together to gradually defuse the conflict between cultures, beliefs, and practices by cultivating a holistic transethnic and transpolitical spirit. Observations show that there is a shared social understanding of common challenges, shared values, and perspectives independent from cultural, religious, ethnic and geographic factors, but particular attention should be paid to factors hindering intercultural encounters which could create dividing opinions or behaviours.

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Author contributions

All the authors of this paper have contributed substantially to the work reported. A.S. conceived the research and methodology, carried out the modelling, analysis, mapping, and led the writing of the paper. J.V.S. provided support in the methodology, carried out the analysis and the writing. E.I. led the Anna Lindh Intercultural Trends Survey, carried out the analysis and the writing. All authors have read and agreed to the published version of the paper.

Competing Interest

The authors declare no competing interests.

Data availability

All the datasets that support the findings of this study are open access. The Land use / Land cover dataset is available from ESRI at https://livingatlas.arcgis.com/landcover/. The WorldPop Global Project Population Data is available from University of Southampton at https://developers.google.com/earth-engine/datasets/catalog/WorldPop_GP_100m_pop. The Gridded Population of World Version 4 (GPWv4), Revision 11 is available from NASA at https://developers.google.com/earth-engine/datasets/catalog/CIESIN_GPWv411_GPW_Population_Count. The MOD13Q1.006 Terra Vegetation Indices 16-Day is available from NASA at https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD13Q1. The MYD13A1.006 Aqua Vegetation Indices 16-Day is available from NASA at https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MYD13A1. The MOD11A2.006 Terra Land Surface Temperature and Emissivity 8-Day is available from NASA at https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD11A2. The CHIRPS Daily: Climate Hazards Group InfraRed Precipitation with Station Data (Version 2.0 Final) is available from the University of California, Santa Barbara at https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY. The NEX-GDDP: NASA Earth Exchange Global Daily Downscaled Climate Projections is available from NASA at https://developers.google.com/earth-engine/datasets/catalog/NASA_NEX-GDDP. The MOD16A2.006 Terra Net Evapotranspiration 8-Day is available from NASA at https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD16A2. The Global Migration Data is available from the International Organization of Migration at www.migrationdataportal.org. The Anna Lindh Intercultural Trends data are available from the Anna Lindh Foundation at https://www.annalindhfoundation.org.

Code availability

Codes are available from the corresponding author upon reasonable request.

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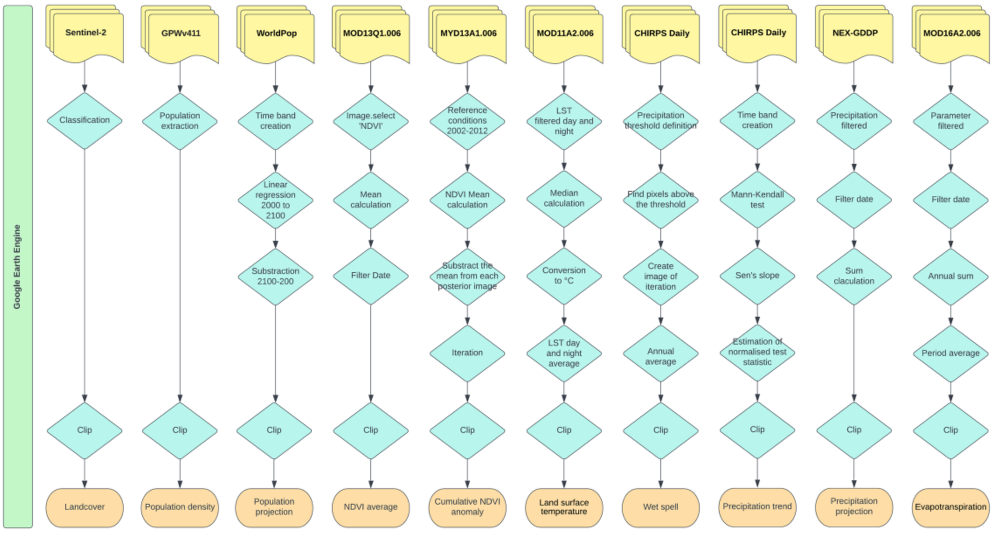

Figure 1. Flowchart of the environmental assessment.

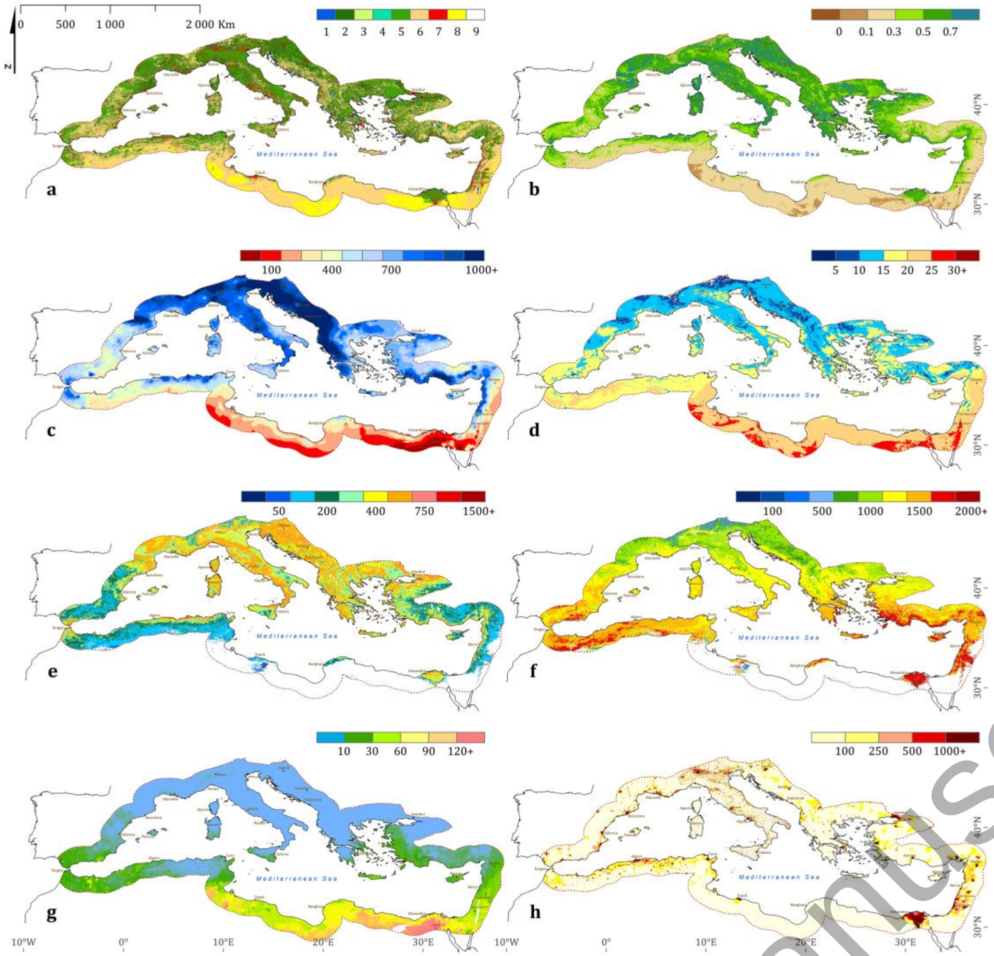

Figure 2. Main characteristics of the Mediterranean transition fringe. a) Land use/land cover in 2020. 1: Water, 2: Trees, 3: Grass, 4: Flooded vegetation, 5: Crops, 6: Scrub/Shrub, 7: Built area, 8: Bare ground, 9: Snow/Ice. **b)** The average Normalized Difference Vegetation Index (NDVI) in 2020 (without unit). **c)** The average rainfall during the last 40 years (in mm). **d)** The average land surface temperature of the last 20 years (°C). **e)** The annual average of the total evapotranspiration during the last 20 years (2001-2020) (in $kg/m^2/8$ days). **f)** The annual average of the potential evapotranspiration during the last 20 years (2001-2020) (in $kg/m^2/8$ days). **g)** The average annual dry spell (consecutive days with precipitations less than 5 mm) in the last 40 years (in days). **h)** Population density in 2020 (inhab./km^2).

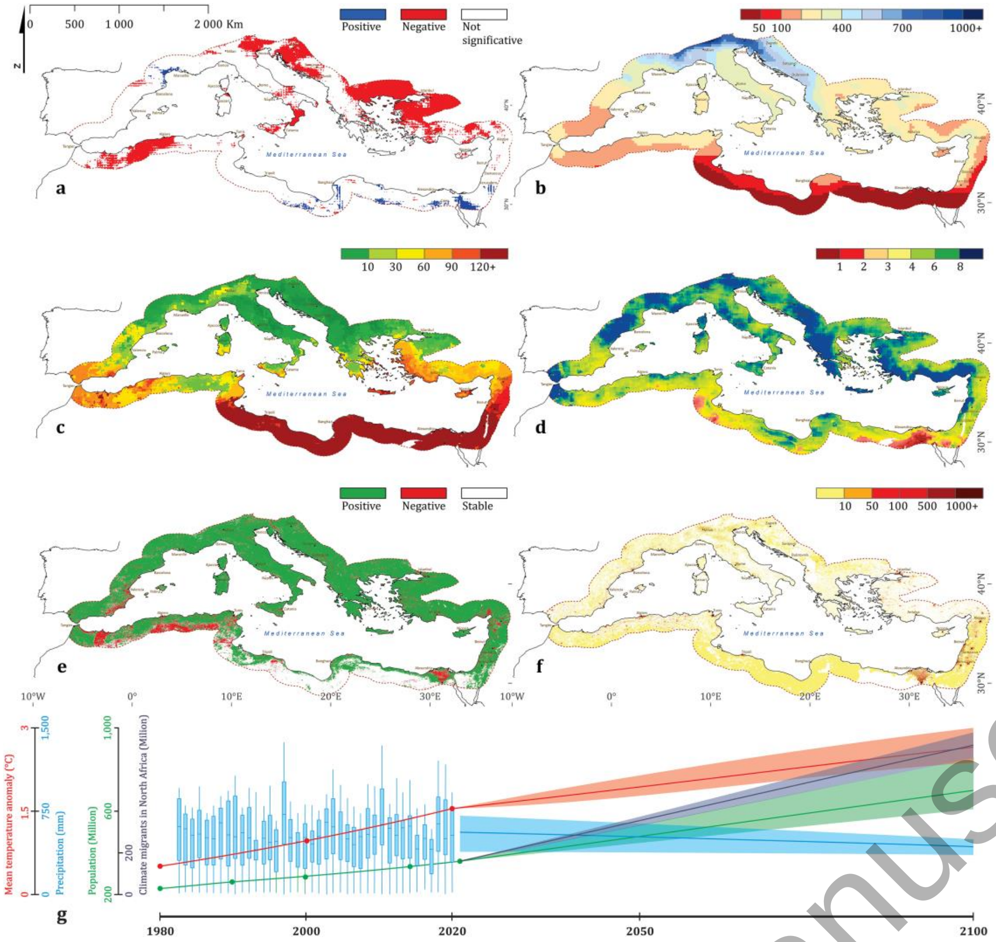

Figure 3. Anomalies, trends and projection. a) Mann-Kendall statistical trend of rainfall and its Sen's slope statistical significance during the last 40 years. **b)** The downscaled projected rainfall average of the year 2050 (in mm). **c)** The maximum historical dry spell in a Gregorian year during the period 1981-2020 (in days). **d)** The maximum annual wet spell in a Gregorian year during the period 1981-2020 (in days). **e)** The Normalized Difference Vegetation Index (NDVI) cumulative anomaly during the last 9 years (2013-2021) compared to the reference period (2002-2012). **f)** the estimated density evolution until 2100 (natural population increase in inhab./km^2). **g)** Estimates of evolution of mean temperature anomaly (in red), precipitation average, quartiles, and minimum and maximum thresholds (in blue), population (in green), and its cumulated increment on the climate migrants in North Africa (in purple).

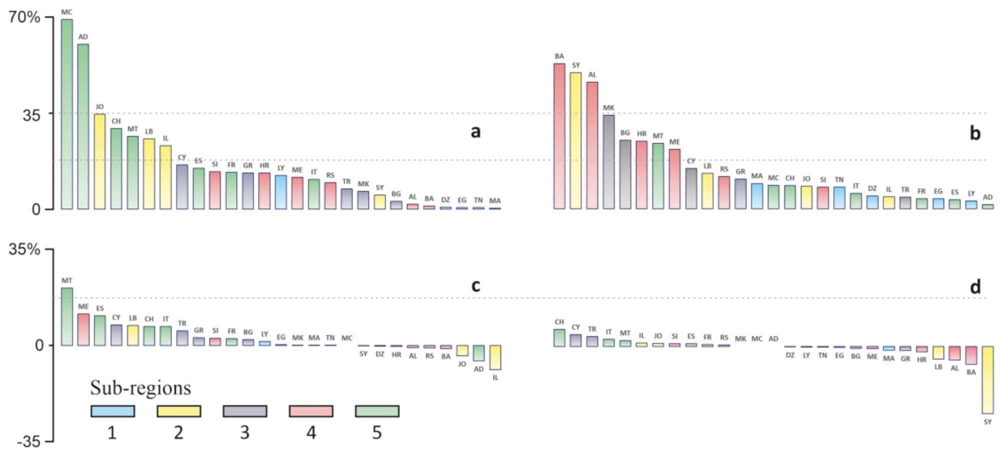

Figure 4. Migration rates per country and per sub-region(Portal, 2021**). a)** The international migrant stock as a percentage of the total population in 2020. **b)** International emigrants in relation to the population in 2020, **c)** Difference in the share of migrants in the total population between 2000 and 2020, **d)** Net migration rate (2015-2020). Sub-regions, 1: North Africa, 2: Middle East, 3: South-eastern Europe, 4: Western Balkans, 5: Southern, Western, and Central Europe.

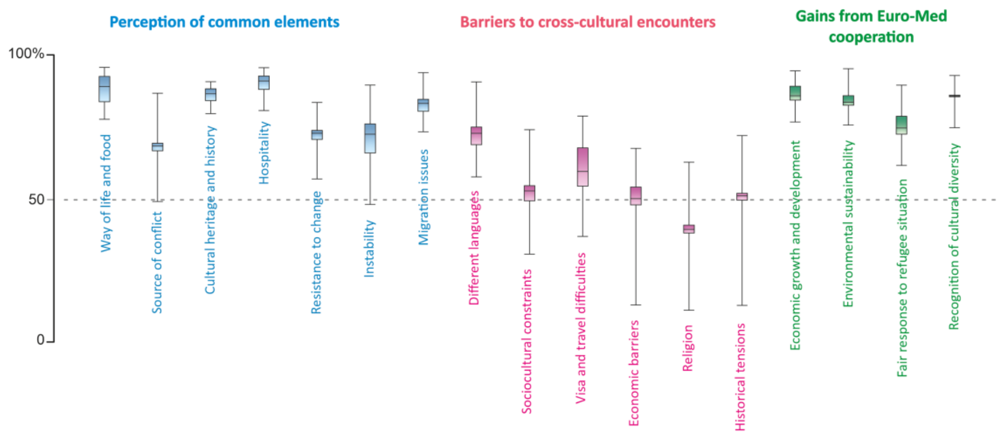

Figure 5. Perception of the Mediterranean population towards the characteristics and challenges of their region in 2020(ALF, 2021**).** Social perception in the boxplots: the upper and lower fences indicate the maximum and minimum values, the boxplot limits represent the averages of European respondents, and of the South and East of the Mediterranean, and the centre indicates the absolute average.

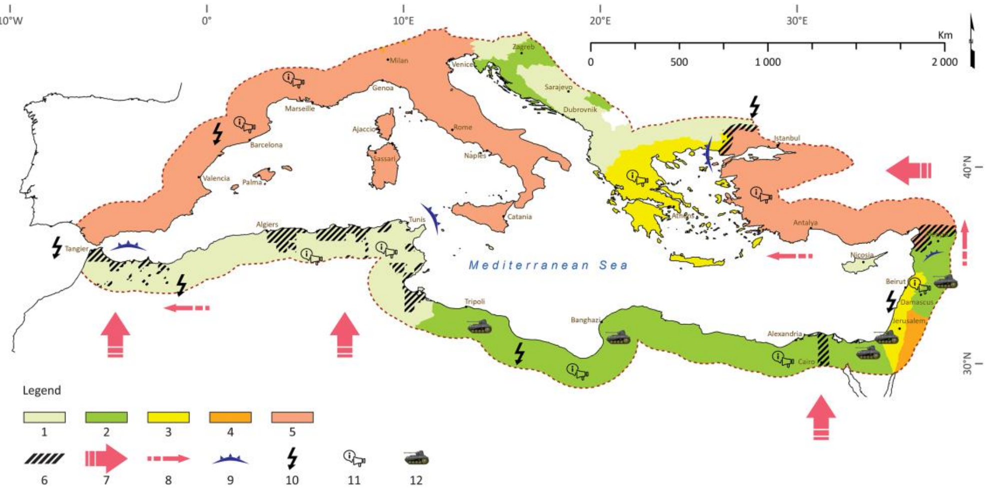

Figure 6. Recent events and migration projections. The total stock of international migrants per country in 2020 (millions)(UN DESA, 2020). 1: ≤ 0.5, 2:] 0.5; 1], 3:] 1; 2], 4:] 2; 5], 5:] 5; 8.5], 6: High certainty in high levels of climate in-migration by 2050(Clement et al., 2021), 7: The projected direction of dominant climate migration flows by 2050(Clement et al., 2021), 8: The predominant flow direction of the internal migrants, 9: Very active migration borders, 10: Recent interstate or internal severe political tensions, 11: Recent intense popular protests, 12: Violent military confrontations.

Table 1. Satellite data used in the environmental assessment.

Dataset	Product	Spatial resolution	Temporal range	Frequency
Sentinel-2	Landuse / land cover (ESRI)	10 m	2020	2020
GPWv411	Population	1 km	2000-2020	Five years
WorldPop	Population	92.77 m	2010-2020	Five years
MOD13Q1.006	Vegetation	250 m	2000-2022	16 days
MYD13A1.006	Vegetation	500 m	2002-2022	16 days
MOD11A2.006	Land Surface Temperature	1 km	2000-2022	8 days
MOD16A2.006	Evapotranspiration	500 m	2001-2022	8 days
CHIRPS Daily	Precipitation	0.05°	1981-2022	Daily
NEX-GDDP	Precipitation	27.83 km	1950-2100	Daily