Greening and Browning in a Climate Change Hotspot: The Mediterranean Basin

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To improve predictions of the future of ecosystems in a changing world, it is necessary to consider fine-scale processes. We propose that for the Mediterranean region (a hotspot of climate change and biodiversity), there are three local processes that have often been overlooked in predictive models and that are key to understanding vegetation changes: rural abandonment that increases wildlands, population changes that boost fire ignitions, and coastal degradation that enhances drought. These processes are not directly driven by global warming and act in different directions (greening and browning). The current balance is still toward greening, because land abandonment is buffering the browning drivers; however, it is likely to switch with increasing warming. The challenge is to mitigate the browning processes. Given that climatic warming is not directly driving these processes, local management can make a difference in reducing the overall impact on the landscape and society.

Keywords: global change, climate change, water cycling, Mediterranean Basin, Mediterranean ecosystems, wildfires, land abandonment, local scale processes

Our planet is going through an unprecedented change that affects all ecosystems and organisms. The magnitude of these effects and the mechanisms involved vary among ecosystems because of differing environmental conditions, varying past and present land uses, and differing historical and evolutionary legacies. Only by acquiring a detailed understanding of the diversity of processes operating at different scales and in different regions can we improve predictions for the future of our planet (Taylor et al. 2017, Tierney et al. 2017). In the present article, we focus on the palearctic Mediterranean region (table 1), which is a biogeographical, environmental, and historical unit, as well as a biodiversity hotspot (Myers et al. 2000, Thompson 2005, Keeley et al. 2012). By the Mediterranean region we refer to the land with a Mediterranean climate that is around the Mediterranean Sea (including all the islands; figure 1). It is a large and highly populated area and a top tourist and retirement destination. The climate dynamics of this region are strongly determined by the enclosed sea (the world's largest inland sea) and the mountains that surround it; these characteristics generate mesoscale atmospheric processes with consequences far beyond the region. Environmental disruptions in the Mediterranean region have consequences in this large densely populated region, as well as in the whole catchment area (which exceeds the Mediterranean climate zone, see figure 1) and elsewhere through atmospheric teleconnections (Gangoiti et al. 2006, Ciarlo and Aquilina 2016, Park et al. 2016).

Anthropogenic increases in greenhouse gases and the associated increase in temperature are affecting all ecosystems including those in the Mediterranean region (IPCC 2014). The region is considered a primary climate change hotspot (Giorgi 2006, Giorgi and Lionello 2008), because the warming of this region is above the global average (approximately 1.3 degrees Celsius [°C] versus 0.85°C worldwide; Guiot and Cramer 2016). There is abundant literature documenting recent climatic changes (e.g., Bolle 2003, Pausas 2004, Mariotti et al. 2008, Lelieveld et al. 2012, Skliris et al. 2018); however, the present article is focused on some local drivers that are more specific (although not exclusive) to the region, and that have often been overlooked in global and regional vegetation models. For instance, Guiot and Cramer (2016) suggest that a warming of 2°C above preindustrial levels in the Mediterranean region (i.e., the threshold proposed by the 2015 Paris Agreement) would generate vegetation changes of a magnitude unprecedented over the past 10,000 years. This is important because the region is currently near this threshold (Guiot and Cramer 2016). The results were obtained by comparing past (pollen reconstructed), present, and future biome distribution using a simulation model. The predictive models were based on the main drivers of global change—that is, temperature (monthly) and CO_2 (annual),

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Table 1. Mediterranean basin facts. Extent, diversity and characteristics of the Mediterranean climate region (figure 1).

Parameter	Value
Extension of the land	2 million square kilometers (km^2)
Sea area	2.5 million km^2
Drainage region (figure 1)	11 million km^2
Population	Approximately 200 million
Population density	Approximately 100 inhabitants per km^2
East–west distance	3800 kilometers (km)
North–south distance	>1000 km
Coast length	> 40,000 km
Number of languages	> 20
Number of countries	18
Number of islands	> 4000
Number of islands larger than 5 km^2	189
Highest altitude	4167 meters
Number of WWF ecoregions	21
Number of plant species	25,000
Number of mammal species	305
Number of reptile species	351
Number of bird species	601

Note: Values are approximate as different sources use slightly different limits of the Mediterranean climate area.

simulated at a coarse scale (grid of 2° latitude × 4° longitude; approximately 222 × 346 kilometers).

Our hypothesis is that to increase the accuracy of vegetation change predictions, we need to integrate processes operating at a smaller scale. Specifically, we propose that the main current dynamic drivers in the Mediterranean region are rural (land) abandonment, wildfires driven by human ignitions, and coastal degradation. These often overlooked drivers are mostly caused by local socioeconomic and human changes not directly linked to global warming, and they are key to understanding the disruption of the natural fire and drought regimes in Mediterranean ecosystems (mainly, increasing frequency, and intensity; figure 2). Although other drivers of change remain very important, we propose that these three drivers have important consequences for understanding and predicting current and future vegetation changes.

The greening: Rural abandonment provides biomass and fuel

Many ecoregions worldwide are suffering from an increase in fragmentation accompanied by a reduction in the area covered by natural ecosystems. Others show the opposite pattern, as is the case of ecosystems in the Mediterranean region. This region has been extensively and intensely used for millennia; it is the cradle of Western civilization, and since then, many cultures have inhabited the region, some with very high population densities. The consequence is that Mediterranean landscapes have been extensively modified by deforestation and overgrazing, and much of the land is farmed. However, recent (late twentieth century) socioeconomic changes in the region (due to industrialization and tourism) have led many people to abandon rural areas. Therefore, these areas are emptying, and urban and periurban areas are increasingly crowded. These processes imply, in many Mediterranean landscapes, an abrupt reduction of land for agriculture, grazing, and wood gathering and poor management of forest plantations. Some imprints of the past land overuse are easily observable (e.g., figure 3).

The first and direct consequence of this process is a sudden increase of wildlands and plant biomass. Old fields are now a primary feature in many Mediterranean landscapes, which increases the amount and connectivity of vegetation in many regions. Many European Mediterranean landscapes are defaunated of large herbivores and resemble grazing exclusion experiments, because the loss of livestock has not been accompanied by an increase in wild herbivores that once occupied the land. In addition, forest plantations are poorly maintained—further increasing the biomass and connectivity of the landscapes. A comparison of the current landscapes with old photographs (Debussche et al. 1999) and old maps (Falcucci et al. 2007) or comparisons among consecutive forest inventories (Vayreda et al. 2012, De Cáceres et al. 2015) show a clear increase in wildlands and forest tree density. Even remote-sensing data gathered over the last 15 years suggest a generalized greening of the region compared with global trends (figure 4a). The atmospheric increase in carbon dioxide (CO_2) may have contributed to biomass growth but is unlikely to be the main driver as the magnitude of the greening is greater than global estimates (figure 4a). The Mediterranean region is a greening hotspot, despite also being a climate change hotspot (Giorgi 2006).

A consequence of this vegetation increase in a warming climate is increased drought stress and mortality in plants. That is, in addition to direct climate-induced drought mortality that may be occurring independently of any recent vegetation changes (Barbeta et al. 2015, Lloret et al. 2016), there is drought stress and mortality attributed to the increased vegetation density, plant competition, and natural self-thinning processes (Vayreda et al. 2012, De Cáceres et al. 2015). These processes are natural in plant communities, but they now occur in a low grazing and high CO_2 environment that increases the magnitude of the plant stress and mortality.

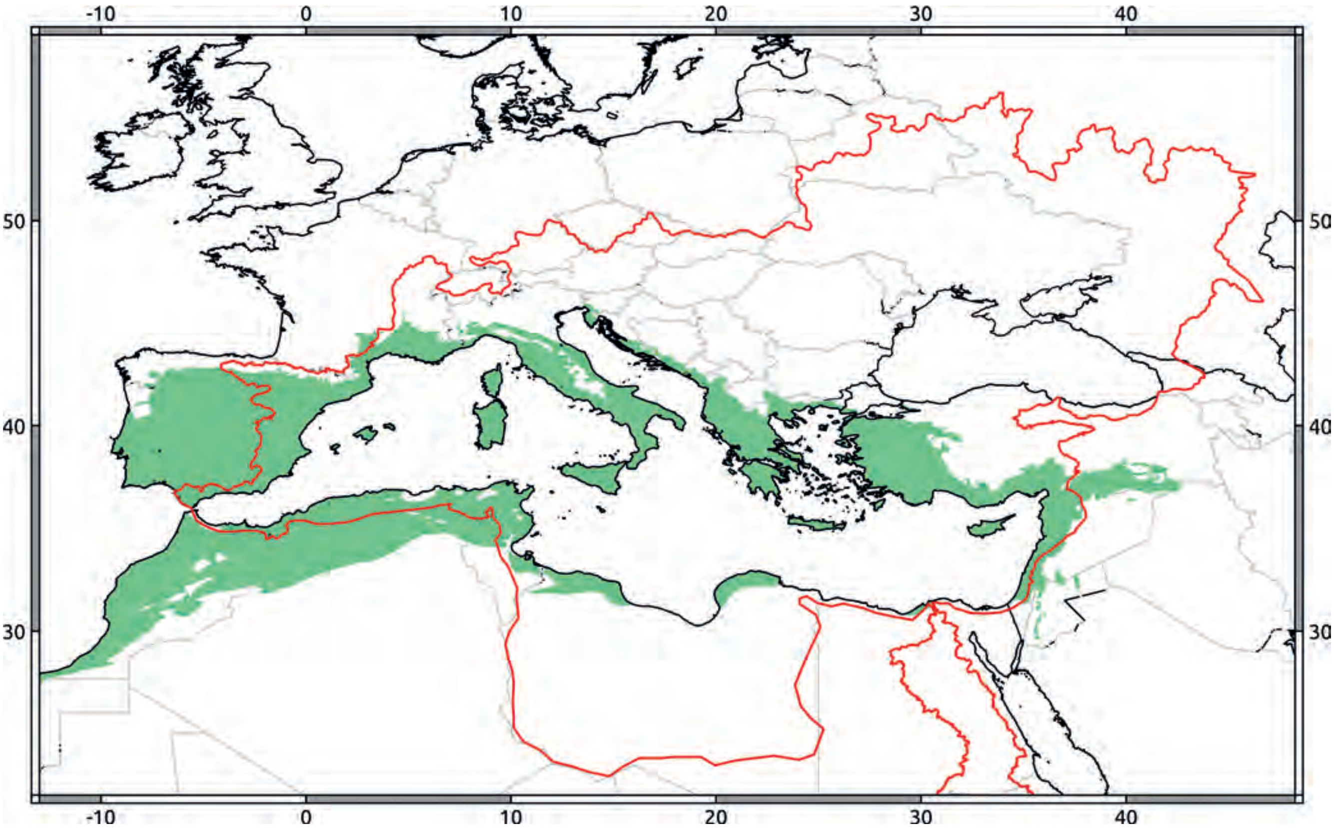

Figure 1. The region with a Mediterranean climate (filled region) surrounds the Mediterranean Sea, but the whole Mediterranean catchment is far larger (the thick red line). Therefore, atmospheric processes occurring in the Mediterranean Sea can have hydrological implications in the central and eastern part of the European continent. Sources: Cortambert (1870), the World Wildlife Fund, Jenness and colleagues (2007), Millán (2014).

Browning: Semiurban population provides ignitions

Land abandonment and the associated increase in vegetation imply an increase in the amount and connectivity of fuels and, therefore, in fire hazard. This is occurring in an area where human population is increasing—especially the urban population (i.e., people not living from the land) in the wildland–urban interface (Modugno et al. 2016). The consequence of such human changes is an increase in fire ignitions (by negligence and arson) and, given the large amount of fuel available in the landscape, an increase in the fire size and annual area burned (Pausas 2004, Moreira et al. 2011, Pausas and Fernández-Muñoz 2012). This leads to an increase in fire recurrence at the local scale. Simultaneously with this increase in fuel and ignitions, there has been a strong policy of fire suppression in most countries, which further promotes fuel accumulation and large fires (Piñol et al. 2007). The increased frequency of conditions conducive to fire (hotter and longer fire seasons due to global warming; Moriondo et al. 2006) have further contributed to this recent fire regime shift (figure 2). However, the major change in fuel amount and distribution is probably the most important driver of abrupt fire regime changes (Pausas and Fernández-Muñoz 2012, Pausas and Keeley 2014). In Mediterranean Europe, fires used to be fuel limited when the rural population was large, and fires are now driven by drought events, because fuel is no longer a limiting factor (Pausas and Fernández-Muñoz 2012, Gouveia et al. 2016). In northern Africa, where the rural population is still significant, fires are smaller and fuel limited (Chergui et al. 2018). Failing to consider land abandonment precludes predicting fire regime shifts and vegetation changes in the Mediterranean region.

Vegetation changes can be depicted by discontinuities in the normalized difference vegetation index (NDVI) from remote sensing (Verbesselt et al. 2010). Abrupt discontinuities in the NDVI are common in the Mediterranean region (figure 4b) and can be produced by major droughts, logging activities, or fires. Fire regime shifts that can generate abrupt vegetation changes are especially important. Mediterranean ecosystems have an evolutionary history linked to fire; however, disruptions in sustainable fire regimes are common (Keeley et al. 2012). For instance, nonserotinous coniferous forests were not historically subject to fire—or were subject to low intensity understory fires that left the forest structure unaffected (Fulé et al. 2008, Slimani et al. 2014). However, some of these forests are now suffering high-intensity crown

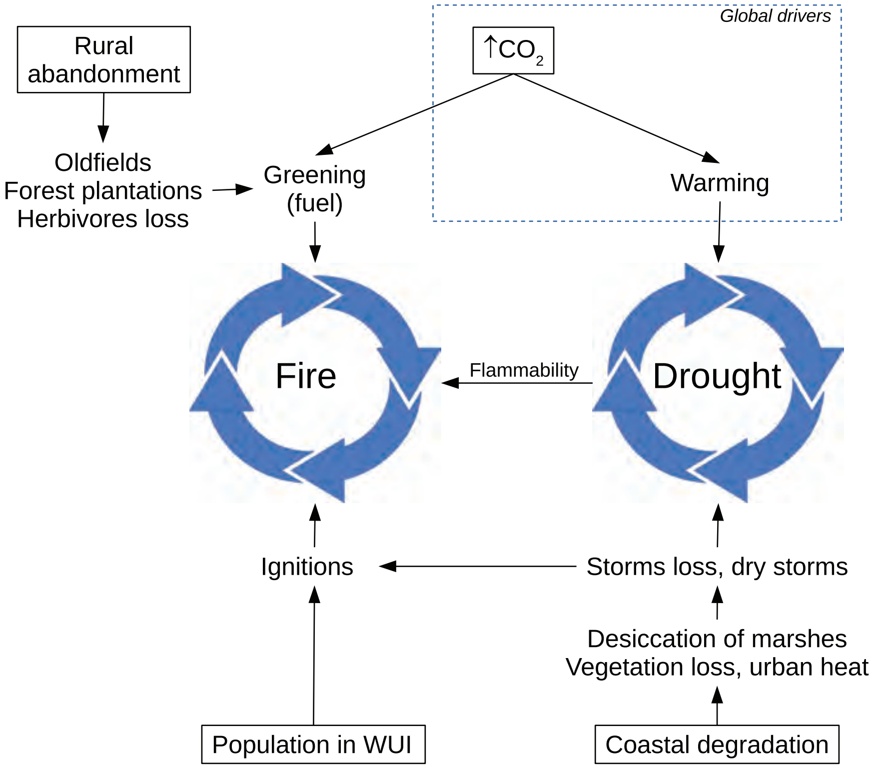

Figure 2. The disruption of the natural fire and drought regimes in the Mediterranean landscapes is driven by global and local drivers. Increased fire activity is a response to the fuel amount and landscape homogeneity generated by rural abandonment (fire hazard) in an environment depauperate of herbivores and with increasing human ignitions (fire risk) and droughts (fire weather). The increased dry conditions are the consequence of global warming—but also of storm losses caused by the disruption of the water cycle generated by the coastal degradation (see the main text and supplementary material S2). Abbreviation: WUI, wildland–urban interface.

fires because of increased crowding (related to reduced grazing and lack of low intensity fires) and warming. A single crown fire in a nonserotinous pine forest abruptly switches the community to a new vegetation state, typically shrubland or oak forest (Retana et al. 2002). In contrast, serotinous pines are well equipped to survive crown fires (Pausas 2015). However, two consecutive fires with an interval shorter than the maturity age of the dominant pine switches the pine forest to shrubland. These vegetation-type switches do not revert easily, especially in human-fragmented landscapes, and are common across the Mediterranean basin (Moreira et al. 2011).

Predictions for the Mediterranean region suggest an increased fire risk in the decades ahead (Bedia et al. 2014, Sousa et al. 2015, Turco et al. 2018). This prediction is often based on climate, and therefore, given the observed and predicted increased temperature and reduced summer rainfall, the conditions for fire spread are increasing. However, for predicting fire regimes (and not just the meteorological conditions conductive to fire—the fire weather), it is necessary to account for other interacting factors, especially those related to fuel amount and contiguity (fire hazard). Recent simulation studies suggest that including CO_2 and human population dynamics (e.g., urbanization) in climate-based global models, switches the predictions from an increase to a decrease in fire activity at a global scale (Knorr et al. 2016). In the Mediterranean region, such a decrease of fire activity in the (near) future is unlikely in much of the region, because fuel increase from land abandonment (the greening above) together with increased climatic conditions conductive to fire (drought and longer fire seasons) and the continuous increase in human ignitions, provide conditions for larger and more frequent fires (figure 2). Only in very dry regions can more severe drought reduce fuels and so limit fires (Pausas and Paula 2012).

Browning: Coastal degradation enhances drought

The Mediterranean coastline was once fully vegetated and rich in marshes and lagoons that contributed to the local water cycle. The sea breeze enriched with the water that evaporated and transpired from these ecosystems increased in altitude when moving inland over the coastal mountains and typically condensed before surpassing the mountains. The rich volatile organic compounds emitted by Mediterranean plants contributed to the nucleation of clouds (Kirkby et al. 2016). This water vapor condensation was responsible for convective showers over the mountains around the Mediterranean Sea (Bolle 2003). The desiccation of the marshes (started by the Romans to prevent malaria), deforestation for agriculture, and more recently, explosive coastal urbanization and tourism have drastically reduced the original ecosystems and, therefore, the water available for the sea breeze. These land-use changes have also increased soil heating (the urban heat island effect). The consequences are the destruction of several ecosystems, changes in species composition, a lowering of the water table, changes in the albedo, but also, with a warmer and drier air breeze, the condensation point has increased in altitude and, therefore, storms develop less often (Millán 2014; supplemental material S2). There is evidence in recent decades of reductions in summer (convective-orographic) rainfall and increases in autumnal (often torrential) rain (Pausas 2004, Millán et al. 2005a, Pastor et al. 2015). These summer storm losses affect downstream vegetation and marshes and, therefore, generate a negative feedback process that can lead to aridification

Figure 3. Terraced slopes are a common feature of the Mediterranean landscapes and illustrate the strong human pressure in the region. Note that most of the terraces are abandoned and covered by early successional (and flammable) plants, except those at the bottom of the mountains that are still in use. The shrubland and dead trees in the foreground are the product of a wildfire. Location: Benicadell (Valencia, Spain), photograph: J.G. Pausas.

and water shortage for humans. This is not driven by global warming but by local changes in land use, and global warming exacerbates this process by further heating and reducing evapotranspiration (figure 2). This disruption of the water cycle also increases dry storms, which are a cause of wildfires. The water vapor that does not precipitate, together with photooxidants (ozone) and aerosols, increase sea temperature, and this facilitates the water vapor to feed torrential autumnal rains in the region (Bozkurt and Sen 2011, Pastor et al. 2015) and leads to flooding in other parts of the catchment and neighboring areas (figure 1; e.g., central-eastern Europe, Gangoiti et al. 2011; North Africa, Park et al. 2016). Note that this accumulation of water vapor and ozone is very relevant as both are greenhouse gases with high global warming potential (Held and Soden 2000), and there is evidence of heat intensification by greenhouse gases along the coast (Diffenbaugh et al. 2007). In other words, the Mediterranean basin can behave like a large cauldron recirculating air masses in different directions; it is also an example of how human activities may affect the dynamics of water vapor (an important greenhouse gas).

Land degradation on the coast is not compensated by the greening from the land abandonment outlined above for two reasons. First, most degradation occurs very close to the coastline and replaces natural systems with urban structures, whereas land abandonment and recolonization by wild vegetation is a general process occurring in the slopes, mainly in low-value land (i.e., not near the coast). The second reason is that degradation of the coastal area implies a reduction in moisture for the water cycle, as well as an increase in air temperature (urban heat effect and soil sealing). As temperatures rise, the capacity for the air to retain vapor (saturated vapor density) increases exponentially, and therefore, the condensation level moves up in altitude (Millán et al. 2005b). Therefore, a small change in air temperature at the coast implies a large increase in the altitude

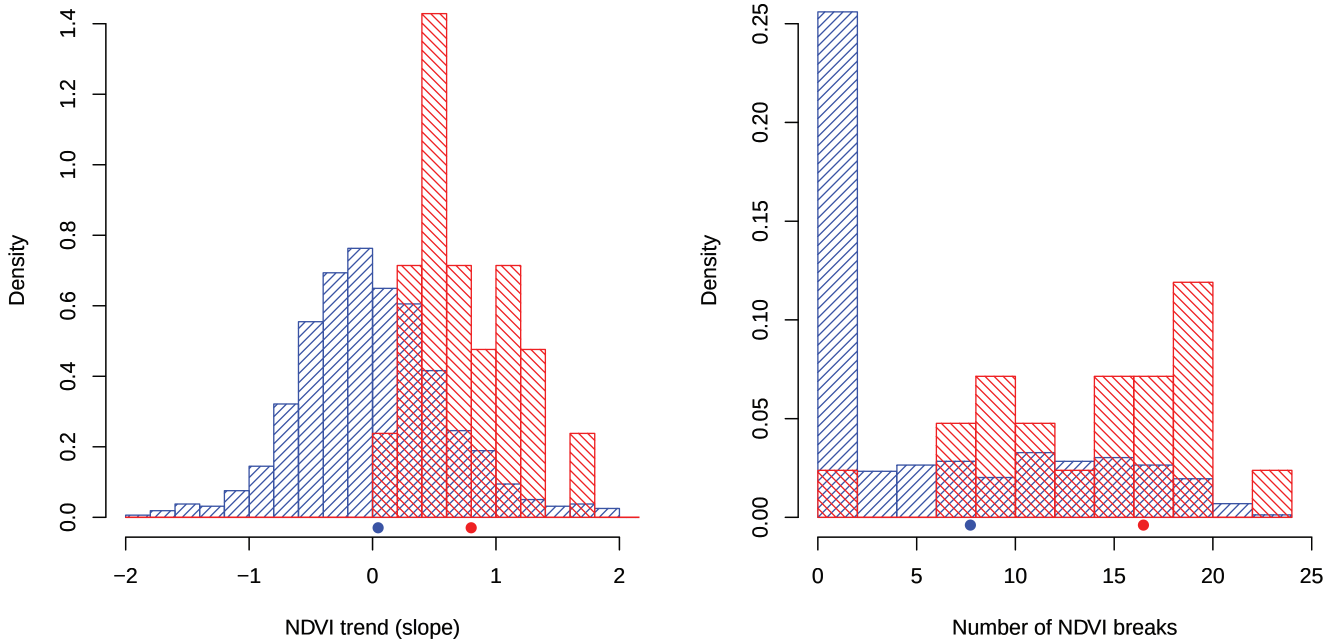

Figure 4. Histogram (probability density) of the slopes (a) and the number of breaks (b) in the NDVI trend for the period 2000–2015 for all world ecoregions (the blue stripes with positive slopes,* n *= 792) and for the ecoregions in the Mediterranean basin (the red stripes with negative slopes,* n *= 21). The dots on the* x*-axes indicate the mean value (weighted by the size of the ecoregion) for all world ecoregions (in blue, to the left) and for the Mediterranean basin (in red, to the right). The figures show that the NDVI dynamics in the Mediterranean basin tend to be stronger (higher slopes and more breaks) than most of the other biomes. The NDVI data by ecoregion are from Pausas and Ribeiro (2017; see supplemental material S1 for details).

at which the water vapor driven by sea breeze precipitates and, therefore, fewer storms occur (Millán 2014). All the feedback processes related to coastal degradation are driven by fine-scale patterns (orography, size of minor catchments), and these patterns are not well captured by most simulation models (Millán 2014, Tierney et al. 2017).

The Mediterranean conundrum: Policy implications

Greening driven by rural abandonment is generally masking the browning effects of increased droughts, unnatural fire regimes, and the disruption of the hydrological cycle that is occurring simultaneously. Both greening and browning processes outlined above are especially occurring in Mediterranean Europe and will be exacerbated as countries from the southern rim (North Africa) abandon their rural life style as a consequence of increasing industrialization and tourism (Chergui et al. 2018).

Land abandonment is, to some extent, buffering the consequences of global warming. Therefore, it may also reduce the social perception of the effects of warming in the region. Drought-induced defoliation and mortality events occur (Barbeta et al. 2015, Lloret et al. 2016), phenological changes are noticeable (in crops and wildlife; e.g., Gordo and Sanz 2005), and soil erosion is observed. However, for the moment, greening is still the dominant trend (figure 4), and this contributes to reduced soil losses (Keesstra 2007). As droughts increase in frequency the balance could switch easily with the browning offsetting the greening. How far are we from the turning point when water availability will limit further greening? Can land management delay reaching this threshold?

The urgent need for global policies to reduce emissions is well known; however, given the importance of fine-scale processes (figure 2), some local actions are also important and probably underestimated by local agencies. In the present article, we outline some local policies and research needed to disrupt the two feedback processes sketched in figure 2.

Fire. Fire requires three components (fuel, ignitions, and dry conditions), and all three are increasing in Mediterranean ecosystems (figure 2); therefore, fires are likely to increase in the coming decades. Fire policies in most Mediterranean countries are based on the zero-tolerance principle—that is, preventing and extinguishing all fires; this is often very effective (at short time scales) but leads to larger high intensity fires (megafires) in the long run (Piñol et al. 2007, Curt and Frejaville 2018). A policy of small or low-intensity fires would be desirable for preventing large catastrophic fires and, therefore, generating a more sustainable fire regime. This can be achieved by the introduction of prescribed burns, currently forbidden in many countries, and by letting some wildfires burn (those that burn in relatively mild conditions; Boisramé et al. 2017). Low-intensity fires can ameliorate water stress in Mediterranean trees (Alfaro-Sánchez et al. 2016, Young et al. 2017) and can prevent large, high-intensity fires. In addition, the introduction of grazing animals (e.g., enhancing pastoralism, prescribed grazing, or rewilding natural herbivores) would be helpful, as long as they are introduced with care (e.g., avoiding overgrazing, especially in postfire environments). Other management options, such as forest thinning, can also be helpful at strategic points to reduce the chance of fire ignitions and spread. Appropriate urban planning is also key, because semiurban areas provide the main fire ignition points. In many Mediterranean ecosystems, fire is a disaster only where human infrastructures are found, because many plants are well adapted to fires, including to high-intensity fires (Keeley et al. 2012). That is, the wildland–urban interface can convert ecologically sustainable fire regimes into a social catastrophes. Therefore, reducing the wildland–urban interface or at least limiting its expansion (e.g., using taxation as a deterrent) is highly desirable.

An important topic for research in relation to fire management is the carbon balance with recurrent Mediterranean fires and the role of fire management in modulating this balance. In the short term, fire releases large amounts of CO_2. However, in the longer term, regeneration (and especially resprouting) quickly fixes large amounts of carbon and, therefore, fires may switch senescent communities to carbon sinks. In addition, charcoal is a recalcitrant carbon contribution to the soil, and therefore, fires increase the carbon sink (Santín et al. 2015). To what extent prescribed fires can be used to optimize the source–sink balance remains to be studied in detail. The dominance of species with high postfire resprouting capacity (and with large underground organs; Pausas et al. 2018) makes studying this balance in Mediterranean ecosystems especially appropriate.

Drought. An important direct policy needed for the Mediterranean regions is to reactivate the water cycle that has been disrupted by coastal degradation. Research in eastern Spain suggests that to generate water condensation on the coastal mountains (e.g. 2000 meters above sea level), the average amount of water needed in the air is greater (at least 21 grams per kilogram) than the average observed (Millán 2014, supplemental material S2). This emphasizes the need to pump water into the cycling system in order to change a negative into a positive feedback and, therefore, prevent a reduction in the number of storms. This could be undertaken by massive revegetation of the lowlands around the coast, including degraded wildlands (revegetation with native plants) and also by greening semiurban and urban areas. This would include encouraging the planting of trees on urban streets, the creation of large urban and semiurban gardens, and conserving and enlarging all patches of native vegetation along the coast. The evapotranspiration of all this vegetation (native, urban, and semiurban) would benefit the water cycle upstream (Ellison et al. 2012). In fact, these actions have social benefits far beyond activating the water cycle (Willis and Petrokofsky 2017, Endreny et al. 2017). Maximum priority should be given to preserving, restoring, and enlarging coastal marshes and wetlands, because they provide very important water inputs into the system, in addition to being hotspots of biodiversity and carbon sinks (Howard et al. 2017). Given that a small change in air temperature on the coast has implications for the upslope rainfall in the mountains, it is important to reduce urban heat as much as possible. Therefore, in urban areas, building using cool materials (i.e., pavement and rooftops with high reflectance and a high emissivity factor) could be considered (Santamouris et al. 2012). Such building techniques would also reduce cooling needs inside buildings and have a positive environmental impact (Santamouris et al. 2008). Installing fog collectors in the coastal mountains would facilitate capturing water from sea breeze (nonrainfall water; Estrela et al. 2008, Kaseke et al. 2017, Kim et al. 2017) that could be used for agricultural irrigation while saving water and reactivating the water cycle.

Mechanisms acting at a fine scale, together with global drivers (CO_2 enrichment and climatic warming) interact and drive current vegetation changes in Mediterranean landscapes. Any model intended to predict the future of our vegetation and climate must include these local mechanisms, and failing to consider them at an appropriate scale is likely to produce inconclusive predictions (Diffenbaugh et al. 2007, Millán 2014, Tierney et al. 2017). Current global and most regional models for the Mediterranean area (e.g., Milano et al. 2012, Guiot and Cramer 2016) still suffer some of these deficiencies. The advantage of the importance of small-scale drivers is that local policies and management actions can make a difference in reducing global change impacts.

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Supplemental material
Supplemental data are available at *BIOSCI* online.

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Supporting Information

Pausas & Millán (2019) Greening and browning in a climate change hotspot: the Mediterranean Basin. *BioScience,* doi: 10.1093/biosci/biy157

The following Supporting Information is available for this article:

S1. Methods for Figure 3.

S2. Summer storms loss on Mediterranean coast

S1. Methods for Figure 3.

The NDVI data used for Figure 1 comes from Pausas & Ribeiro (2017). It is based on 16-day global NDVI images (resolution= 0.05 degrees) from 2/2000 to 7/2015 (355 global images, MODIS MOD13C1 data set obtained from the Land Processes Distributed Active Archive Center, USGS). Each image was crossed with the ecoregion map, and for each ecoregion, we extracted the mean of the NDVI. The 355 NDVI mean values for each ecoregion were treated as a time-series and decomposed into seasonality and trend using the BFAST approach (Verbesselt et al. 2010). The coefficient of the trend is used in Figure 3a, and the number of abrupt changes in the trend is used in Figure 3b.

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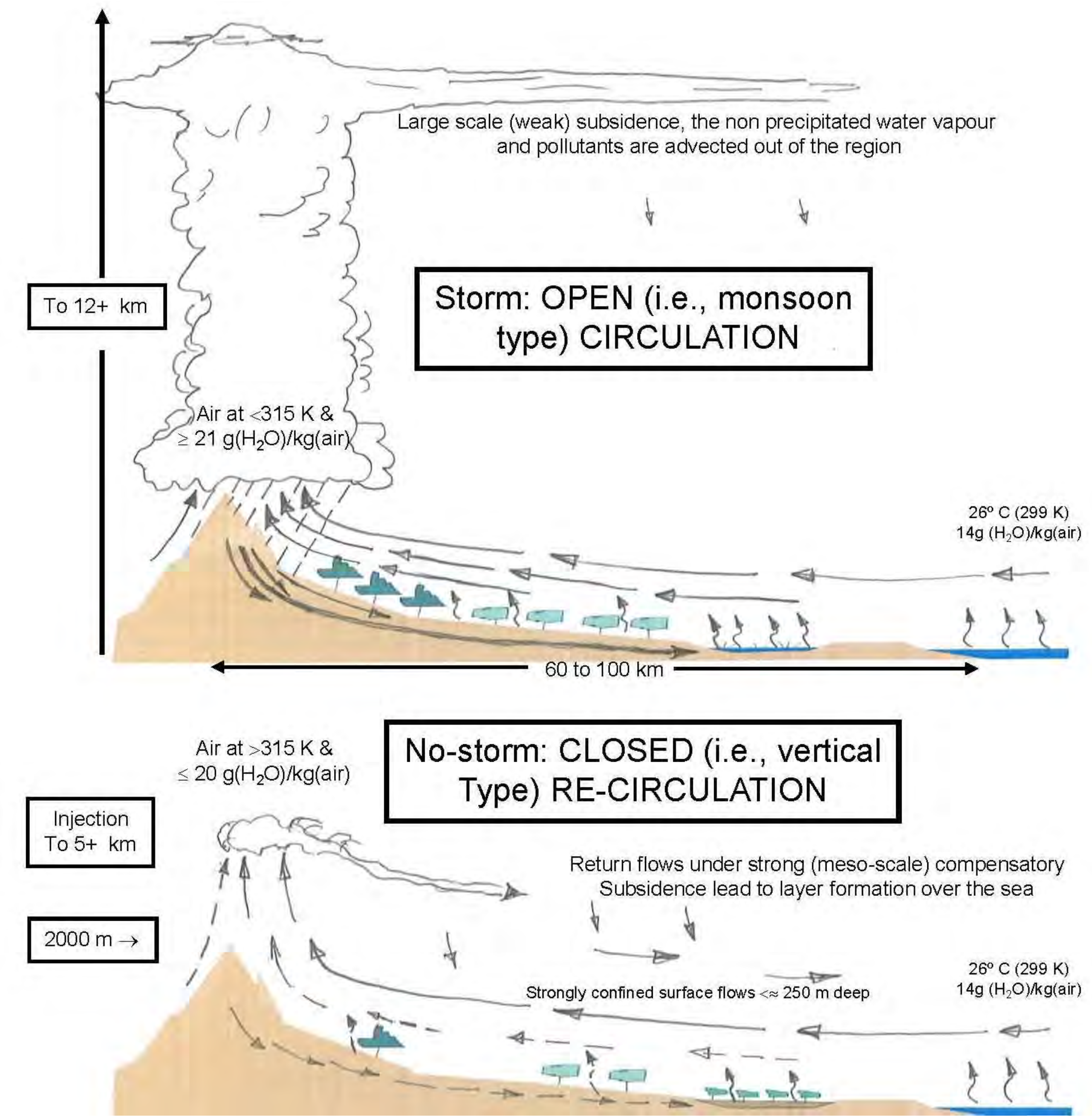
S2. Summer storms loss on Mediterranean coast



Schematic representation of the water cycle on the Mediterranean coasts (from Millán et al. 2005, Millán 2014). **The upper panel** represents the original (natural) conditions with little anthropogenic disturbances (open circulation), where sea breezes and water evapotranspirated from natural ecosystems (marshes, lagoons, shrublands and forests) feed the storms in the mountains. The climatic values of the water vapour mixing ratio and the temperature at the coast of the incoming airmass in Jul-Aug are 14 g/kg and 26 C (299 K), respectively. However, by the time the same airmass reaches the interior, its temperature gain is some 16ºC. Thus the airmass in the combined breeze requires to gain an average of 7 g/kg along its land path to reach a water vapour mixing ratio of >= 21 g/kg to keep its Convective (orographic) Condensation Level (CCL) below the approximate height of the coastal mountain ranges (ca. 2000 m altitude). This additional water vapour comes from the evapotranspiration in natural ecosystems. **The lower panel** shows the conditions where reduced vegetation and desiccated coastal marshes do not generate enough water vapor to feed a storm (closed recirculation). Current observations suggest that the atmospheric circulations over the coasts of the Western Mediterranean Basin in summer had gone from being mostly open in the past (as they still are over central Italy) to being closed on the majority of the coasts nowadays. For more details see Millán (2014).

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