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Assessing the Climate Change Sensitivity of Greek Ecosystems to Wildfires †

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Abstract: Wildfires threaten human lives and ecosystems and have a significant impact on the economy. Greece is one of the most vulnerable countries in the world with respect to wildfires. The purpose of this article is to assess the climate change impact of wildfires on the ecosystems of Greece and to determine areas where prevention measures should be utilized. To achieve this, the variability of the Fire Weather Index (FWI) is examined under the RCP4.5 and RCP8.5 scenarios from 2022 to 2098. Under both scenarios, a significant intensification of fire weather is observed, which increases the likelihood of severe wildfires occurring in various ecosystems in Greece. The worst affected areas are Southern and Eastern Greece, provided that they have sufficient fuel. The results are more pronounced for RCP8.5, especially after the mid-century. By the end of the century, most ecosystems will be prone to intense fire activity under RCP8.5. Even under the milder RCP4.5 scenario, high-intensity wildfires are projected to occur with increasing frequency in places where they are currently rare. This project highlights the necessity of climate change mitigation and the employment of more effective and widespread prevention and firefighting methods. The management of the current fire-prone areas should be emphasized, but the state must be prepared to face extreme fire incidents in a broader range of ecosystems, including mid-altitude and high-altitude forests.

Keywords: wildfires; climate change; ecosystems

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1. Introduction

Wildfires are one of the main environmental threats that Greece faces. They provoke human casualties, damage private property and critical infrastructure and undermine the financial development of the country [1]. Moreover, wildfires pose a great threat to the ecosystems and the biodiversity of Greece. Specifically, they cause deforestation, biodiversity loss, soil erosion, and increased flood risk [2].

The most useful indicator to assess the severity of fire activity is the fire season burned area. However, making predictions about the future burned areas is difficult because of the complex dynamics involved. Therefore, it is more practical to predict future fire weather, which correlates strongly with burned areas in the Mediterranean. Multiple studies have highlighted a strong correlation between the fire weather, which is expressed via the Fire Weather Index (FWI), and the burned area [3,4]. Fox et al. (2018) [3] showed that burned areas in SE France increase nonlinearly with FWI and that 97% of the total burned area occurred during weeks with extreme mean FWI values. Furthermore, Jones et al. (2022) [4] found that Spearman's rank correlation coefficient of the fire season mean FWI and burned area was 0.83, which was statistically significant in the Mediterranean. Generally, it is accepted that fire weather is the best predictor of burned areas in a region [4].

There are concerns that fire weather is intensifying under climate change in the Mediterranean [4,5]. Son et al. (2021) [5] showed that wildfire hazards will rise significantly in the region if the mean global temperature increases to 2 °C above preindustrial levels. Jones et al. (2022) [4] found that the frequency of 95th percentile extreme fire weather in the Mediterranean will increase by 36 days year^{-1} and 54 days year^{-1} under 3 °C and 4 °C global temperature increases over the preindustrial levels, respectively. Accordingly, fire weather season length will increase by 42 days year^{-1} and 58 days year^{-1} under the same future temperature increments.

In this study, we investigate the future fire weather of all Greek ecosystems using FWI projections derived from CMIP5 models for the period of 2022–2098. The aim is to achieve a complete and detailed description of Greece's future wildfire risk and to identify the vegetation zones that will face the greatest threats.

2. Materials and Methods

2.1. Data

The data used in this study were acquired from the "Fire Danger Indicators for Europe from 1970 to 2098 derived from climate projections" package, which is freely available at the Copernicus Climate Data Store (CDS) [6]. This dataset provides projections for the values of FWI over the European domain. The spatial resolution is 0.11° × 0.11°, which is considered sufficient for the scope of this study. The "Seasonal FWI" variable, which is the mean FWI over the European fire season (June–September), was preferred. The motive to use this variable is that it correlates strongly with fire season burned areas [4]. The product type used is the multi-model mean case under the emissions scenarios RCP4.5 and RCP8.5.

2.2. Selection Procedure of Study Areas

The selection of the study areas was based on the vegetation zones of Greece (Table 1). At least one study area was selected for each vegetation zone. For vegetation zones that extended across large areas, two study locations were chosen. The first represents the coolest extreme of that vegetation zone, and the second represents the warmest. The summer mean temperature was the main criterion to identify these areas. Also, the summer mean precipitation was taken into account. For the classification of the vegetation zones in Greece, the study of Skouteri et al. (2013) [7] was used. For the distribution of temperature and precipitation over Greece, the studies of Feidas et al. (2013) [8] and Gofa et al. (2019) [9] were adopted, respectively. Below, there is a brief description of the vegetation zones in Greece and the selected study areas.

Table 1. Vegetation zones and study areas.

Vegetation Zone	Extent	Study Areas
Oleo-Ceratonion (type 1)	Coastal eastern and Southern mainland Greece; Aegean islands; coastal Crete	Sounio
Quercion ilicis (type 2)	Low and mid-altitude Peloponnese, Eastern Central Greece and Crete; low-altitude Western Greece	Olympia (warm subregion), Thesprotia (cool subregion)
Cupression-Cocciferae (type 3)	High-altitude Crete and Aegean islands	Lasithi plateau
Ostryo-Carpinion (type 4)	Mid-altitude Peloponnese and Central Greece; Plains of Macedonia, Thrace and Thessaly	Pharsala (warm subregion), Kalavryta (cool subregion)
Quercion confertae (type 5)	Western Macedonia; Mid-altitude Epirus, Thessaly and Northern Greece	Grevena (warm subregion), Zagori (cool subregion)
Fagion moesiacae (type 6)	Mountainous Epirus, Thessaly and Northern Greece	Aspropotamos region
Abieton Cephalonicae (type 7)	Mountainous Peloponnese and Central Greece	Parnitha (warm subregion), Oeta (cool subregion)
Pinetalia nigrae (type 8)	Northern Pindos	Vovousa
Vacinio-Picetalia (type 9)	Mt. Olympus, Mt. Smolikas and high-altitude Rhodopes	Elatia (Rhodopes)

2.3. Data Analysis

Firstly, Mann–Kendall tests were performed to assess the trends of the time series. After that, the mean Seasonal FWI values were computed for a reference period (2006–2021), for a mid-century time period (2038–2069) and for the end of the century (2070–2098). The mean values were complemented by the maximum Seasonal FWI value for each time period. This is considered necessary because even one year of extreme fire weather is enough to cause substantial damage to the ecosystems.

3. Results and Discussion

3.1. RCP4.5 Experiment

The Mann–Kendall tests revealed increasing and statistically significant trends for the Seasonal FWI in all study areas during the period 2006–2098. The mean and maximum Seasonal FWI for each selected time period is shown in the table below.

The intensification of fire weather in all study areas is apparent considering the data in Table 2. It is worth mentioning that fire weather will substantially worsen already the middle of the 21st century. The intensification of fire weather is rapid until the mid-century and continues at a slower pace thereafter.

Table 2. Mean and maximum Seasonal FWI for each selected time period under RCP4.5. The first value is the mean and the second is the maximum (mean value/maximum value).

Study Area	2006–2021	2038–2069	2070–2098
Sounio	57.74/61.8	62.01/68	62.73/68.3
Olympia	56.06/60.2	58.77/64.3	59.15/62.8
Thesprotia	42.28/47.9	46.28/53.6	47.58/54.3
Lasithi plateau	41.32/47.3	45.55/51.2	46.32/52.4
Pharsala	54.85/58.4	57.43/64.6	58.55/63.5
Kalavryrta	48.64/53	51.01/56.2	51.68/56.7
Grevena	47.06/50.1	48.69/53.6	49.44/54.3
Zagori	19.19/24	22.42/30.8	24.17/34.3
Aspropotamos	18.42/23.5	21.67/28.7	23.67/34.7
Parnitha	40.37/47.3	46.17/52.7	47.09/54.5
Oeta	30.12/35	33.85/43.2	35.4/43.7
Vovousa	17.92/23.1	21.36/28.7	22.8/32.8
Rhodopes	16.8/20.5	20.08/26.7	21.23/28.8

In the Sounio area, Seasonal FWI values greater than 68 will be possible by the end of the century. The mean Seasonal FWI for the 2070–2098 period will be 62.73, which is extreme [10]. The ecosystems of vegetation zone 1 will thus suffer from very intense fire incidents in the future. Many places within this vegetation zone are densely populated, and the state should take appropriate measures to alleviate the fire danger in such areas. The ecosystems of type 1 will probably degrade to the land with herbaceous sparse vegetation due to recurring wildfires.

The fire danger in vegetation zone 2 will vary across its distinct subregions. In the cooler areas (which include Thesprotia, Arta and Preveza), the mean Seasonal FWI value for the 2070–2098 period will be 47.58, which is substantially lower than the current value of Olympia (56.06). Therefore, forests will probably remain in the cooler areas. However, during the worst fire seasons, Seasonal FWI values greater than 50 are possible, and intense wildfires might occur. Thus, prevention and firefighting capabilities in these areas must be enhanced. In the hotter areas, the intensification of fire weather is particularly concerning. These regions are already fire-prone, and the frequency and intensity of extreme fire incidents are expected to grow under climate change. These include Western Peloponnese, Southern Peloponnese (Kalamata, Sparta), Eastern Central Greece, Euboea Island and large regions in Crete. These accommodate a large part of Greece's population and agricultural production; thus, safety measures have to be taken immediately. The ecosystems in some of these areas might suffer significant losses and permanent alteration of their vegetation.

The fire weather in vegetation zone 3 will resemble the conditions in Thesprotia. Thus, forests may remain, but intense fires are to be expected during the worst possible fire seasons.

The ecosystems of vegetation zone 4 will also suffer substantial losses. Fire weather in mid-altitude Peloponnese will resemble the current fire weather in some warm regions of vegetation zone 2. In the Kalavryta region, the mean Seasonal FWI value for the 2070–2098 period will be 51.68 and extreme values greater than 56 will be possible. In Thessaly (Pharsala study area), the mean Seasonal FWI will be 58.55 by the end of the century, whereas today it is 54.85. Furthermore, extreme values of 63.5 will be possible. The Thessalian plain is covered predominantly by arable land and, provided that it is irrigated or the crops are removed before the fire season peak, the danger should be minimized. However, in the mid-altitude Peloponnese and Volos regions, there are shrubs, forests and olive groves alongside villages and industries and precautionary measures have to be taken to prevent extensive devastation from intense wildfires.

Vegetation zone 5 covers large areas with distinct climate characteristics. In the cooler regions such as Zagori, fire weather will intensify but Seasonal FWI values will remain below 35. Wildfires of medium to high intensity might only occur during the worst fire seasons. However, in Grevena, which is a warmer subregion of this vegetation type, by the end of the century, the mean Seasonal FWI will be 49.44, and extreme values greater than 54 might occur. Therefore, wildfires of high intensity might occur in this region. The firefighting and prevention capabilities in these areas should be enhanced. The ecosystems of vegetation zone 5 might suffer extensive losses in the warmest areas, but healthy forests will remain in the cooler areas.

The ecosystems of vegetation zone 7 (Abies Cephalonica native forests) will experience intense fire danger. On Mt. Parnitha, which is the warmest subregion of this vegetation type, by the end of the century, the mean Seasonal FWI will be 47.09, and the maximum possible value will be 54.5. These values are classified as "Very High" and "Extreme", respectively. Parnitha's forest has already suffered substantial losses under the current climate. Therefore, the survival of the forest under the intensification of fire weather in the future seems impossible. Mt. Oeta's fire weather at the end of the century will be slightly better than the current conditions on Mt. Parnitha. However, Mt. Oeta is the coolest subregion of vegetation zone 7; thus, the ecosystems that lie in the middle such as the mountains of Peloponnese might suffer substantial losses.

The remaining vegetation zones (zones 6, 8 and 9) are not expected to suffer significant losses because even under the worst possible circumstances, Seasonal FWI values will remain under 35. Under these conditions, some wildfires of medium intensity might occur in the warmer regions, but healthy forests will likely persist in these ecosystems.

3.2. RCP8.5 Experiment

As expected, the Mann–Kendall tests revealed statistically significant increasing trends for all study areas during the time period 2006–2098. The results of the Seasonal FWI values under the RCP8.5 emissions scenario are presented in Table 3.

The intensification of fire weather under RCP8.5 is rapid and persistent. One can observe that Seasonal FWI values grow rapidly till the end of the century. The mean Seasonal FWI values for the 2070–2098 period are almost equal to the mid-century maximum values for all the study areas. The same applies to the 2006–2021 and 2038–2069 time periods. The pace of fire weather intensification is a little faster than that of RCP4.5 until the mid-century but a lot faster thereafter.

The above results suggest that the ecosystems of vegetation zone 1 will face extreme fire danger in the coming decades. Therefore, such ecosystems may become barren land due to recurring intense wildfires.

The ecosystems of vegetation zone 2 will face extreme fire danger as well. The Olympia region has already suffered from mega-fires; thus, the rapid intensification of fire weather under RCP8.5 is particularly alarming. The preservation of the agricultural landscape and olive groves of western Peloponnese is doubtful under these conditions. Only the ecosystems in the cooler regions of vegetation zone 2 will survive. However, the state must be prepared to deal with wildfires of extreme intensity in all areas of this vegetation type, including the cooler areas.

Table 3. Mean and maximum Seasonal FWI for each selected time period under RCP8.5. The first value is the mean and the second is the maximum (mean value/maximum value).

Study Area	2006–2021	2038–2069	2070–2098
Sounio	60.03/67.6	64.71/69.6	69.51/74.2
Olympia	58.61/60.3	60.48/64.3	64.79/69.6
Thesprotia	42.91/50	49.23/57.3	55.54/62
Lasithi plateau	41.82/46.4	47.19/51.8	52.08/56.7
Pharsala	54.84/59.5	59.64/64.8	63.98/69.8
Kalavryrta	49.21/54.6	52.6/56	56.44/61.4
Grevena	47.18/50	49.71/53.5	53.09/56.9
Zagori	20.13/24.8	25.2/31.5	31.58/39.8
Aspropotamos	19.62/23.5	24.09/28.7	30.19/34.7
Parnitha	42.22/49.1	49.86/56.1	56.52/65.1
Oeta	31.31/36.9	37.01/44	43.67/51.4
Vovousa	18.91/22.7	23.47/30.3	29.42/36.3
Rhodopes	18.43/24.1	22.5/28.5	27.2/36

Furthermore, it is worth mentioning that the fire weather conditions of mid-altitude Peloponnese (Kalavryta region) in 2070–2098 will resemble the current fire weather conditions of Olympia. Thus, mega-fires will probably occur in these regions, threatening local inhabitants and agricultural production. Fire weather in Thessaly will be worse and values of 69.8 will be reached. Thus, vegetation zone 4 ecosystems will be another hotspot for increased fire activity and intensity.

Moreover, intense and fast-spreading wildfires will probably occur in the warmer regions of vegetation type 5. These include large areas of Western Macedonia and Evros. Therefore, forests in these areas are expected to suffer extensive losses. The cooler areas of this vegetation zone will have milder fire weather. End-of-century Seasonal FWI values in Zagori will not surpass the current values in Grevena. Thus, healthy forests will probably persist in these areas and in the ecosystems of vegetation zones 6, 8 and 9. However, during the worst fire seasons, wildfires may spread into these ecosystems and cause significant losses because battling wildfires in mountainous terrains is extremely difficult.

Finally, on Mt. Oeta, end-of-century Seasonal FWI values will be higher than the current values on Mt. Parnitha, which has already lost a large part of its forest. Considering that Oeta is the coolest region of vegetation zone 7, endemic Abies Cephalonica forests may face extinction under RCP8.5.

4. Conclusions

Under RCP4.5, type 1, 2, 3 and 4 vegetation zones will face the greatest dangers. The ecosystems in zone 1 may face extinction. Furthermore, extreme wildfires may occur in the warmer areas of vegetation zone 5. The forests of Abies Cephalonica will suffer from increased fire activity, and significant losses will occur. Healthy forests will likely remain in the ecosystems of type 5, 6, 8 and 9 vegetation zones. The state must take immediate precautionary measures to protect the settlements and industries that lie within vegetation zone 1. Also, it is necessary to enhance the fire-fighting and prevention capabilities in all regions of vegetation zones 2 and 4 in order to protect the human population, agricultural productivity, ecosystems and tourism.

Under RCP8.5, most of Greece's ecosystems will be susceptible to extreme fire activity. Moreover, high-intensity wildfires may spread to cooler ecosystems and cause significant losses. The ecosystems of type 1 and 7 vegetation zones may face extinction. It is doubtful if the state will manage to control such a crisis. Therefore, the collapse of ecosystems, agricultural production and tourism is deemed highly possible under RCP8.5.

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