Fire-induced changes in vegetation, albedo and land surface temperature assessed with MODIS

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Abstract. Wildfires affect the regional and global climate. These local scale changes importantly impact species richness, habitats and community composition. The effect of the large 2007 Peloponnese (Greece) wildfires on changes in vegetation, broadband surface albedo (α), day-time land surface temperature (LSTd) and night-time LST (LSTn) were studied using a two-year post-fire time series of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. Firstly, a pixel-based control plot selection procedure was initiated based on a pre-fire time series similarity of biophysical variables (α, LSTd, LSTn and Normalized Difference Vegetation Index (NDVI)). Then differences in mean NDVI, α, LSTd and LSTn of the control and burned pixels were compared. In Immediately after the fire event mean α dropped up to 0.039 (0.012) (p < 0.001), mean LSTd increased up to 8.4 $\pm$ 3.0 K (p < 0.001), and mean LSTn decreased up to -1.2 (1.5) K (p < 0.001) for high severity (HS) plots (p < 0.001). During the wet Mediterranean winter periods, changes in α and LSTd were small and most of the time statistically insignificant (p > 0.001), while the slight LSTn decrease was occasionally significant. During the subsequent dry Mediterranean summer periods, the magnitudes of changes attenuated with time as a consequence of vegetation regeneration processes, however differences in α and LSTd between control and burned pixels remained significant two summers after the fire (p < 0.001). In contrast to the immediate post-fire α drop, α increased up to 0.016 (0.009) for HS plots, during the subsequent summer periods. This research provides insights in the understanding of short-term fire effects on regional climate.

Keywords. Land Surface Temperature (LST), albedo, NDVI, MODIS, fire

1. Introduction

Biomass burning is a major disturbance in almost all terrestrial ecosystems. At landscape level, wildland fires partially or completely remove the vegetation layer and affect post-fire vegetation composition. The fire-induced vegetation depletion causes abrupt changes in carbon, energy and water fluxes at local scale. Several field studies have assessed these effects of fire on local climate. In this context, the surface

blackening due to charring causes a clear albedo decrease immediately after the fire event [1]. This effect, however, is short-lived since albedo quickly recovers to pre-fire values when char materials are removed by weathering and vegetation starts to regenerate [1]. After the initial short drop, albedo tends to increase during the next post-fire years, especially during the summer season, and the persistency of this increase is function of the rate of vegetation regeneration. Another typical post-fire change is an increase in Bowen ratio, which is defined as the ratio between sensible and latent heat fluxes [2]. This is due to the decrease in latent heat flux and consequently less cooling by evapotranspiration [2]. Conversely, sensible and ground heat fluxes reveal a sharp increase shortly after the fire event. Consequently soil and air temperatures are markedly higher after fire occurrence [2].

Most of these microclimatic studies depend on expensive field measurements which are spatially limited. The synoptic nature and repeated coverage of remote sensing systems offer a valuable alternative for spatially explicit monitoring of bioclimatic variables. Remote sensing of post-fire effects has a long tradition in assessing the fire's impact on vegetation. Remotely sensed albedo and land surface temperature (LST) data have seldom been used to analyze spatio-temporal patterns of post-fire surface characteristics. The few studies that examined the effect of fire on surface heating all reported the expected temperature increase in the immediate post-fire environment [3], while albedo values were halved immediately after the fire [4]. The study of these temporal constraints is facilitated by comparing burned plots with unburned control plots within the same image. [5]. As such, external and meteorological variations are minimized among the compared areas. Lhermitte et al. [6] extended this rationale by making the control plot selection method spatially explicit. This control plot selection is based on the similarity between time series of the burned pixel and the time series of its surrounding unburned pixels for a pre-fire year. So far, the pixel-based control plot selection procedure has only been used to analyze fire-induced changes in vegetation.

Hence, the general objective of this paper to monitor post-fire changes in remotely sensed bioclimatic variables based on the control plot selection procedure. These variables indicate how fire alters the environment. This general objective is fulfilled by evaluating changes in (i) NDVI, (ii) surface albedo, (iii) day-time LST (LST_d) and (iv) night-time LST (LST_n). In the analysis, discrimination is made between different land cover classes.

2. Data and study area

2.1. Study area

The study area is situated at the Peloponnese peninsula, in southern Greece (36°30'-38°30' N, 21°-23° E). After a severe drought period several large wildfires of unknown cause have struck the area in August 2007. The fires consumed more than 150 000 ha of coniferous forest, deciduous forest, shrub lands (maquis and phrygana communities) and olive groves (see figure 1).
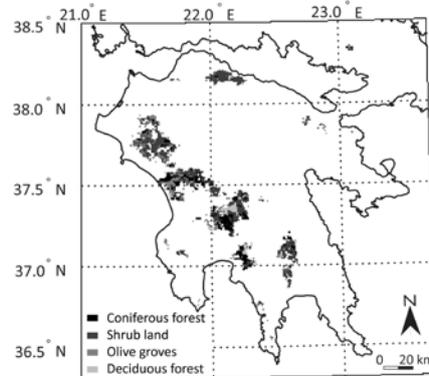
Figure 1. Pre-fire land cover map of the burned areas

2.2. Satellite data

MODIS (Moderate Resolution Imaging Spectroradiometer) satellite time series were used in this study. The MODIS sensor is onboard the Terra and Aqua satellites and provides daily observations at 1:30 AM (Aqua ascending node), 10:30 AM (Terra descending node), 1:30 PM (Aqua descending node) and 10:30 PM (Terra ascending node) local time. Terra MODIS 16-day vegetation indices (1 km) (MOD13A2), combined Terra/Aqua MODIS 16-day albedo (1 km) (MCD43B3), Terra MODIS 8-day LST (1 km) and Aqua MODIS 8-day LST (1 km) with 1 K accuracy tiles covering the study area were acquired from the National Aeronautics and Space Administration (NASA) Warehouse Inventory Search Tool (WIST) (https://wist.echo.nasa.gov) for the period 01/01/2006 till 31/12/2009. NDVI, broadband (0.3-5.0 μ m) white-sky albedo (α), LST_d, LST_n and associated Quality Assurance (QA) layers were subsequently extracted. The preprocessing steps included subsetting, reprojecting, compositing and creating continuous time series.

2.3. Control pixel data

Control pixel data were retrieved making use of pre-fire time series similarity of NDVI, α, and LST and spatial context [6] The control pixel selection procedure assigns a unique control pixel to each burned pixel. This is done based on time series similarity between a burned pixel and its closest unburned neighbor pixels during a pre-fire period. In this approach the averaged time series from the seven most similar out of 120 candidate pixels defines the control pixel time series. This setting accounts for both a beneficial averaging effects and the advantage of spatial proximity. The resulting control pixels reflect the vegetation dynamics of each burned pixel in case that there would not have occurred a fire. Additional information on the control plot selection procedure can be found in [6].

3. Methodology

The control plot selection procedure allowed generating two-year post-fire time series of NDVI, α, and LST (at 1:30 AM, 10:30 AM, 1:30 PM and 10:30 PM local time) as

best estimates of how these variables would have behaved without fire occurrence. The goal of this paper is to quantify the fire induced differences between burned focal and unburned control pixels with regards to (i) NDVI (ii) α and (iii) LST. The mathematical formulation of these differences is:

$$dX_t = X_t^f - X_t^c \qquad (1)$$

where X_t^f is the NDVI, α or LST value of the focal burned pixels at time t, X_t^c is the NDVI, α or LST of the control pixels and dX_t is the difference in NDVI, α or LST between focal and control pixels. The statistical significance of this difference is assessed by performing a z-test of the null hypothesis that dX_t follow a normal distribution with mean 0. Results are separately analyzed for different land cover classes.

4. Results

For the sake of conciseness this section will only provide results of the coniferous and deciduous forest classes.

4.1. NDVI

Figures 2A and 2B show the post-fire development of focal and control pixels' mean NDVI of respectively coniferous and deciduous forest. One can clearly infer the immediate post-fire drop. After this initial decrease, the effects of both vegetation regeneration and seasonality became apparent. Figures 2C-D display the corresponding post-fire dNDVI plots. For both forest types the magnitude of the dNDVI change decreases when time elapses, however, inter-annual differences remain visible. The crosses in the figure indicate when the mean value significantly deviates from zero (p < 0.001). Except from some observations of the deciduous forest class, all post-fire NDVI changes are statistically significant.
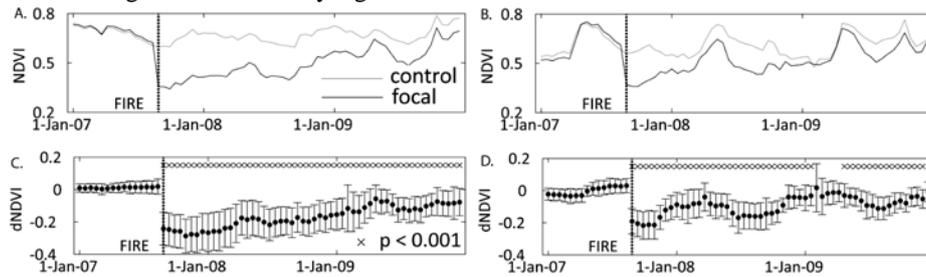

Figure 2. Two-year post-fire temporal evolution of mean NDVI of control and focal pixels for coniferous forest (A) and deciduous forest (B); and two-year post-fire temporal evolution of mean dNDVI for coniferous forest (C) and deciduous forest (D). The crosses in C-D indicate that the mean significantly differs from zero (p < 0.001). In C-D standard deviations are plotted with vertical bars.

4.2. α

In figures 3A and 3B the post-fire trends in α for control and focal pixels are plotted for respectively coniferous and deciduous forest. One can see an immediate post-fire

α drop for both forest covers. During the one-year post-fire summer the focal pixels' α of the coniferous forest excelled the control pixels' values. This α increase was even more explicit during the second post-fire summer. During winter periods α changes are small. In figure 3C-D one can see the corresponding temporal development and significance of dα values per land cover type. In contrast with the majority of the summer observations, winter changes in α are not significant for most of the observations.
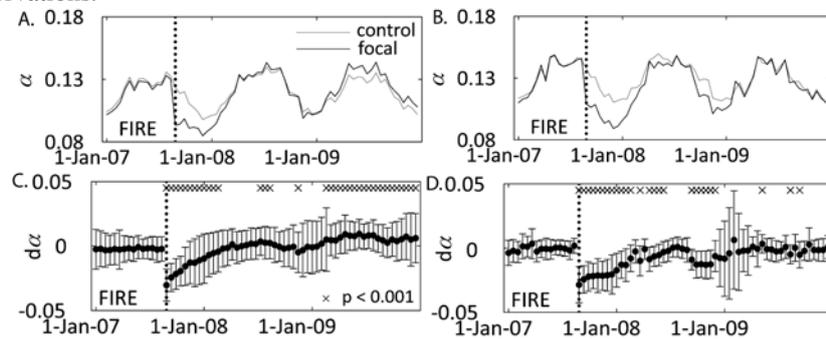

Figure 3. Two-year post-fire temporal evolution of mean α of control and focal pixels for coniferous forest (A) and deciduous forest (B); and two-year post-fire temporal evolution of mean dα for coniferous forest (C) and deciduous forest (D). The crosses in C-D indicate that the mean significantly differs from zero (p < 0.001). In C-D standard deviations are plotted with vertical bars.

4.3. LST_d

Results of the MODIS Terra and Aqua LST analyses revealed very similar trends. As a consequence only the Aqua LST analysis is presented. Figure 4A and 4B depict the mean LST_d of the control and focal pixels for respectively coniferous and deciduous forest. For both covers, the fire caused a clear LST_d increase immediately post-fire and during the subsequent summer periods, while in winter changes are minor. The magnitude of the LST_d increase during subsequent summers became less explicit as time elapsed. In figures 4C-D corresponding mean $dLST_d$ is plotted for the two-year post-fire period. Regardless of forest type, one can see that the post-fire LST_d changes are significant during summer periods, whereas during winter periods many observations did not reveal a significant difference.
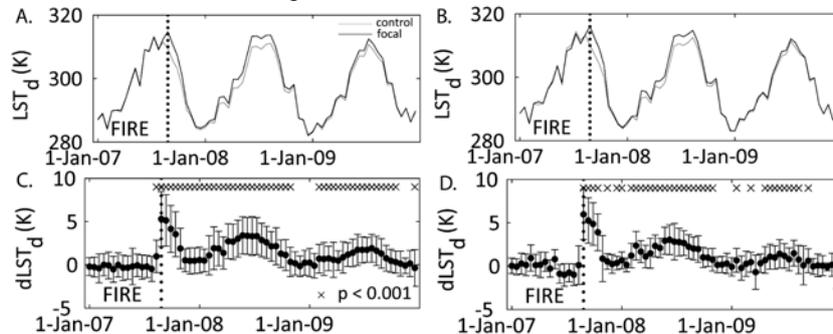

Figure 4. Two-year post-fire temporal evolution of mean LST_d of control and focal pixels for coniferous forest (A) and deciduous forest (B); and two-year post-fire temporal evolution of mean d LST_d for coniferous forest (C) and deciduous forest (D). The crosses in C-D indicate that the mean significantly differs from zero (p < 0.001). In C-D standard deviations are plotted with vertical bars.

4.4. LST_n

Figure 5A and 5B depict the two-year post-fire temporal evolution of mean LST_n of the control and focal pixels for respectively coniferous and deciduous forest. In these plots it is very difficult to discriminate between the control and focal pixels. Thus, changes in LST_n were very small. This is also illustrated in figures 5C-D, which show the corresponding mean $dLST_n$ values per forest type. Results show a tendency of a post-fire LST_n decrease. For the deciduous forest class, however, the majority of changes were insignificant. This contrasts with the persistent significance of the post-fire LST_n decrease in coniferous forest.
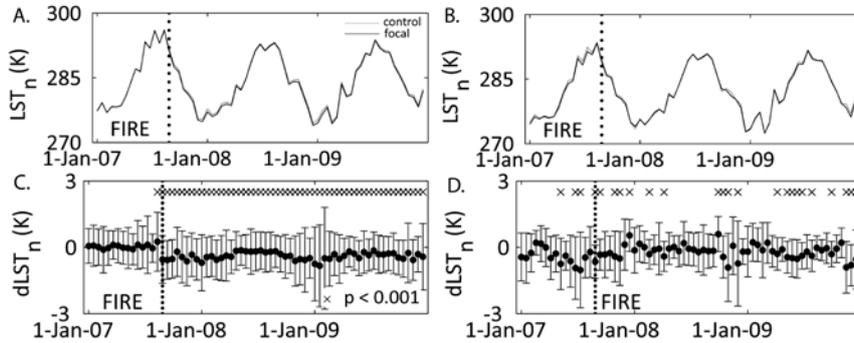

Figure 5. Two-year post-fire temporal evolution of mean LST_n of control and focal pixels for coniferous forest (A) and deciduous forest (B); and two-year post-fire temporal evolution of mean $dLST_n$ for coniferous forest (C) and deciduous forest (D). The crosses in C-D indicate that the mean significantly differs from zero ($p < 0.001$). In C-D standard deviations are plotted with vertical bars.

5. Discussion

5.1. NDVI

Vegetation indices are frequently used to assess post-fire effects. Their usefulness has been demonstrated to detect burn scars, within-burn variability and vegetation regrowth. In figure 2 post-fire effects are clearly visible. The NDVI time series, however, are also subject to seasonal variations. The timing of image acquisition, both in terms of lag and seasonal timing, thus impacts the NDVI response [7]. The seasonality of the NDVI response also depends on land cover type. In our study, deciduous forest shows markedly higher seasonal variations than coniferous species. Despite of these temporal constraints, the fire-induced changes in NDVI were clearly more persistent than changes in α and LST (see figures 3-5). Except for some winter observations over deciduous forest the NDVI appears to be a good discriminator between control and focal pixels. In contrast, seasonality dominates the temporal profiles of α and LST variables. The usefulness of these variables to discriminate fire-affected areas, thus, heavily depends on assessment timing.

5.2. α

The effects of fire on α are multiple. Firstly, an immediate post-fire decrease in α is observed. The main reason for the immediate post-fire α decrease is the large-scale

replacement of living vegetation with black carbon on the surface. Char materials strongly absorb the incoming sunlight and as such they cause a significant reduction of the reflection-to-incoming sunlight ratio. However, this effect had a relatively short duration, as during the first post-fire winter period, which is a period of heavy rainfalls in the Mediterranean, most of the char materials are removed by fluvial and aeolian forces. In figure 3 one can see that the control pixels α values reveal a typical seasonality, which is closely connected with moisture conditions. α values are clearly lower during wet winter periods than during dry summer periods. However, as shown in figure 3, α values of undisturbed plots do not significantly differ from those of burned plots during winter. This suggests that the seasonal variations in surface moisture and the removal of black carbon more importantly drive the α recovery than the early regeneration of vegetation. It is, however, also recognized that leaves and branches of regenerating species have a higher α than mature species. The combination of char removal and regenerating species cause an α increase during the post-fire summer periods. This increase was even more explicit for the second post-fire summer than for the first. This can be explained by the fact that after the first winter period the majority of surface's char coating has been removed and early vegetation regeneration has started, but after the second winter period even more of this char material is ablated and vegetation continued regenerating. This implies the exposure of highly reflective soil and rock combined with regenerating species, which results in an α increase [4]. In a long-term study (30 years post-fire), Amiro et al. [8] ascertained that the α increase progressively weakens as regenerating vegetation matures. Thus, where the immediate fire effect results in an increased absorption of radiative energy, the long-term effect generally is an increased albedo [8-9]. The quantification of these effects, together with an accurate estimation of the amount of greenhouse gasses emitted by the fire and the subsequent post-fire carbon sequestration of regenerating vegetation, are necessary for a holistic comprehension of the effect of wildfires on regional and global climate.

5.3. LST

Besides assessing fire-induced changes in LST with respect to lag and seasonal timing, MODIS imagery also permits a study of diurnal differences. Immediately post-fire LST_d increases. The magnitude of this increase depends on land cover class. For the HS class of coniferous forest the focal pixels' mean excelled the control pixels' mean with 8.4 (3.0) K. This is very similar to the 2-8 K immediate post-fire temperature day-time temperature increases reported by other studies [2-3]. This effect has, however, only a very short duration as by the onset of the wet winter, LST_d differences are minor. These findings corroborate with an analogous study that assessed the influence of the deforestation on LST_d [10]. These authors reported that LST_d is 4 to 8 K higher during the dry season for deforested regions compared to nearby forests. However, during the wet season LST_d of deforested and forested plots reach similar values. One can infer the same trend from figure 4.During the one-year and subsequent post-fire summer seasons mean LST_d increases strongly attenuate. This attenuation can be contributed to vegetation regeneration processes (see figure 2) and char removal. The summer LST_d increase is the driving force of the synchronous increase in sensible and ground heat fluxes [2]. Little research has been conducted so far to assess the post-fire changes in LST_n. The range of changes in LST_n is relatively small. This makes it difficult to infer

post-fire trends for this variable. The fire-induced changes in LST_n are only persistent over coniferous forest. During the one-year post-fire winter for example LST_n drops with -1.4 (1.0) K for the HS class over coniferous forest. Depending on land cover and severity class, fire effects tend to cause a small drop in LST_n. Generally spoken, fire, thus, creates a more extreme environment with warmer days and colder nights.

6. Conclusions

In this study the pixel-based control plot selection procedure allowed a comprehensive understanding of the effects of the 2007 Peloponnese (Greece) wildfires on local climate during a two-year post-fire period based on MODIS satellite imagery. Post-fire changes in vegetation, α and LST were dependent on land cover type. Post-fire NDVI time series were dominated by their post-fire NDVI drop, while changes in α and LST were highly dependent on seasonality. Therefore VIs are more persistent to detect burns and to discriminate severity levels. Surface α sharply decreased immediately after the fire event, however, during subsequent summer period α increased, while during winter α changes were minimal. LST_d was higher after the fire. This increase was especially obvious during summer periods. The temperature increase attenuated as time elapsed, as a consequence of regenerating vegetation. Changes in LST_n were very small and almost not significant, except over coniferous forest where LST_n slightly decreased. This study provides insights on changes in energy fluxes in a fire-altered environment, which can have important ecological implications on a regional to global scale.

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