Frontiers in Earth Science

TYPE Original Research
PUBLISHED 07 April 2023
DOI 10.3389/feart.2023.1174155

EDITED BY
Chong Xu,
Ministry of Emergency Management, China

REVIEWED BY
Jingjing Sun,
Ministry of Emergency Management, China
Zizheng Guo,
Hebei University of Technology, China
Kun He,
Southwest Jiaotong University, China

*CORRESPONDENCE
Tolga Görüm,
✉ tgorum@itu.edu.tr

SPECIALTY SECTION
This article was submitted to Geohazards and Georisks,
a section of the journal
Frontiers in Earth Science

RECEIVED 25 February 2023
ACCEPTED 29 March 2023
PUBLISHED 07 April 2023

CITATION
Yıldız C, Çömert R, Tanyaş H, Yılmaz A, Akbaş A, Akay SS, Yetemen Ö and Görüm T (2023), The effect of post-wildfire management practices on vegetation recovery: Insights from the Sapadere fire, Antalya, Türkiye.
Front. Earth Sci. 11:1174155.
doi: 10.3389/feart.2023.1174155

The effect of post-wildfire management practices on vegetation recovery: Insights from the Sapadere fire, Antalya, Türkiye

Cihan Yıldız[1], Resul Çömert[2,3], Hakan Tanyaş[3], Abdüssamet Yılmaz[1], Abdullah Akbaş[4], Semih Sami Akay[1], Ömer Yetemen[1] and Tolga Görüm[1]*

[1]Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Türkiye, [2]Institute of Earth and Space Sciences, Eskisehir Technical University, Eskisehir, Türkiye, [3]Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, Netherlands, [4]Department of Geography, Faculty of Arts and Science, Bursa Uludag University, Bursa, Türkiye

Post-wildfire management actions mainly targeting the removal of salvage logs and burned trees is a common but controversial practice. Although it aims to regain some of the natural and economic value of a forest, it also requires disturbing burned areas, which may have some negative consequences affecting, for instance, the carbon cycle, soil erosion, and vegetation cover. Observations from different geographic settings contribute to this scientific debate, and yet, the spatiotemporal evolution of the post-fire road network developed as part of fire management practices and its influence on vegetation recovery has been rarely examined. Specifically, we still lack observations from Türkiye, though wildfires are a common event. This research examined the evolution of the vegetation cover in relation to post-fire road constructions and the resultant debris materials in areas affected by the 2017 Sapadere fire in Antalya, Türkiye. We used multi-sensor, multi-temporal optical satellite data and monitored the variation in both vegetation cover and road network from the pre-to post-fire periods between 2014 and 2021. Our results showed that fire management practices almost doubled the road network in the post-fire period, from 487 km to 900 km. Overall, 7% of the burned area was affected by these practices. As a result, vegetation cover in those areas shows only ~50% recovery, whereas undisturbed areas exhibit ~100% recovery 5 years after the event. Notably, such spatiotemporal analysis carried out for different burned areas would provide a better insight into the most suitable post-fire management practices. Our findings, in particular, show that the current practices need to be revisited as they cause a delay in vegetation recovery.

KEYWORDS

wildfire, vegetation recovery, salvage logging, mediterranean, Türkiye

Introduction

Wildfire is a natural phenomenon that occurs in the geological record just after the emergence of terrestrial vegetation cover (Leifeld et al., 2018). Every year, wildfires burn an area of about 400 MHa (Giglio et al., 2018). Climate changes are expected to increase the global area of lands with favorable fire conditions in the coming decades (Senande-Rivera et al., 2022). The change in the fire regime may cause loss of life and property (Moritz et al., 2014) and impact global trends and cycles of ecosystems, including the distribution/structure of vegetation, the carbon cycle (Bowman et al., 2009) and soil erosion (Walstad et al., 1990).

The Mediterranean Basin is not an exception in this global picture. The projected changes in the climate of the Mediterranean region portray a trend above the global average (Guiot and Cramer, 2016). This will cause a reduction in precipitation and an increase in temperature and the frequency of extreme events such as droughts and heatwaves (Russo et al., 2017). As a result, wildfires are also expected to increase significantly in the Mediterranean Basin throughout the next decade (Keeley et al., 2011; Cramer et al., 2018).

The global increase in wildfire probability cannot be solely explained based on the increase in weather extremes as a result of climate change (Flannigan et al., 2013; Jolly et al., 2015) but together with extensive anthropogenic disturbances (Bowman et al., 2011; Bistinas et al., 2014; Doerr and Santín, 2016; Sarricolea et al., 2020). For instance, in the European Mediterranean region, the frequency and magnitude of wildfires have increased dramatically since the 1960s, forced by an increasing warming trend and drying pattern but primarily driven by socio-economic changes, including rural depopulation, land abandonment, and flammable species afforestation (Shakesby, 2011).

Given this summary above, post-wildfire management strategies appear as an important element in coping with some of the consequences of wildfire (Moreira et al., 2012; Robichaud and Ashmun, 2013; Pereira et al., 2018). These management practices are generally implemented shortly after fires to reduce both the risk and severity of wildfires (Francos et al., 2018). However, aggressive post-wildfire interventions may also cause some negative impacts on nature. In this context, there are two competing perspectives on post-fire management practices favoring 1) the rapid removal of salvage logs and burned trees (i.e., salvage logging) (e.g., Santolamazza-Carbone et al., 2011; Fernández and Vega, 2016) and 2) a non-invasive method allowing natural revegetation and leaving burned trees intact (e.g., Beschta et al., 2004; Lindenmayer et al., 2017).

The former approach mainly aims at diminishing post-fire disturbances by removing or modifying the legacies (e.g., beetle infestations) left by the fire event (Santolamazza-Carbone et al., 2011; Fernández and Vega, 2016) to recover some of a forest's natural and economic capital (Leverkus et al., 2020). On the other hand, the main concern of the latter perspective is that salvage logging may alter the soil properties, increase the erosion rate (Wagenbrenner et al., 2016) and the frequency of landslides in the burned hillslopes (Lingua et al., 2020) as it alters land cover (Hürlimann et al., 2022; Guo et al., 2023).

This is an ongoing debate and the literature shows that salvage logging may or may not be the best management practice for a given site, and the method's suitability strongly depends on local conditions (Leverkus et al., 2021). However, quantification of the environmental impacts caused by post-fire management practice, especially the spatiotemporal persistence of excavation waste material as a result of the road construction for salvage logging, and its impact on vegetation recovery rate has been poorly examined in the literature.

Motivated by this research gap, our objective is to quantify the area of debris material derived from road construction for salvage logging, and together with the post-fire road construction how these anthropogenic disturbances affect the vegetation recovery after the 2017 Sapadere wildfire (Antalya), in Eastern Mediterranean, Türkiye. We use high-resolution multi-temporal satellite images, land cover and the normalized difference vegetation index (NDVI) data derived from SPOT 6 and 7 to assess the post-fire changes over the burned areas.

Study area

The study area is located within the Mediterranean Basin, in the western section of the Central Taurus Mountains, Alanya district, Türkiye (Figure 1). In this wildfire-prone territory, annually, thousands of hectares of forests are lost due to fires, specifically in Türkiye's western and southern coasts. Given the local environmental conditions, salvage logging is not suggested in this area as it prolongs the recovery period and prevents the natural regeneration of forests in the burned areas (Tavsanoglu and Pausas, 2022). And yet, salvage logging is a common practice carried out within the scope of the "Rehabilitation of Burnt Forest Areas and Establishment of Fire-Resistant Forests Project" by a public mandate numbered 6,976.

The June 2017 Sapadere wildfire started on 30 June 2017. The fire affected approximately an area of 28 km^2 and was contained 3 days later, on 2 July 2017. The post-fire practices were completed in May 2018, approximately a year after the Sapadere wildfire.

The area affected by the fire is located in mountainous terrain where the highest topographic relief reaches up to 2,250 m (Figure 1A). Within the burned area, in particular, topographic relief ranges from 40 m in foot slopes to 550 m (Figure 2A). The steepest hillslopes (i.e., ~85°) appear at the northern part of the study area (Figure 2B). The area has a semi-arid Mediterranean climate which is characterized by a long dry season and a comparatively short rainy season, with ~90% of the annual precipitation falling between November and April. The mean annual precipitation is 1112.7 mm (Figure 1B). The maximum precipitation falls in January though the minimum amount of precipitation occurs in August.

The study area is mainly composed of Middle-Upper Triassic sandstone, shale, limestones, Cambro-Ordovician schists and phyllites; and also, Permian marbles (Tekin, 1999; Figure 2C). In contrast to the limestone dominated steep topography in the northern sector, the southern part portrays a hilly topography with relatively low slopes where schists and phyllites are dominantly exposed. This topographical contrast in the hillslopes extends the proportion of bedrock-dominated slopes in the north, while the slopes in the south are largely composed of soil-mantle-covered slopes. In this respect, soil thickness also varies due to the topographic divergence.

The 2017 Sapadere wildfire, which started with the effect of low humidity (12%) and high temperature (40 °C), increased the influence area in a short time with the impact of the southerly wind exceeding 50 km/h. The event caused 12 injuries, affected 4 villages, and destroyed 15 houses. The cost of extinguishing the fire was $12.5 million, and the total economic loss is estimated to be $25 million.

Post-fire practices, including logging and service road construction and terracing, were carried out over the study area from July 2017 to May 2018. Based on the forest management maps (1:25000), which were generated by Forest Enterprise Directorate, Antalya Regional Directorate, the majority of the burned vegetation was Turkish pine (Pinus brutia), European black pines (Pinus nigra), Oaks (Quercus), and scrubland (mostly maquis).

Data and methods

We use different optical data sources such as Sentinel-2, SPOT 6/7 and Google Earth historical images to analyze the post-fire evolution of the study area (Table 1). We examine optical images acquired in 2014, 2017, 2019 and 2021 (Figure 3). We mainly use the 2014 (pre-fire) and 2017 (post-fire) images to capture the impact of the 2017 Sapadere wildfire on land cover, whereas the 2019 and 2021 images (post-fire) are chiefly used to understand the influence of the anthropogenic disturbance influencing the vegetation recovery in the study area.

We use Sentinel-2 data, which consists of two identical satellites in the same orbit providing images in 13 different spectral bands. We use pre- and post-fire images to generate the burn severity map, which is calculated as the difference normalized burn ratio (dNBR, Key and Benson, 2006):

$$NBR = \frac{NIR - SWIR}{NIR + SWIR} \tag{1}$$

$$dNBR = \left(NBR_{pre} - NBR_{post}\right)^{*}1000 \tag{2}$$

where NIR refers to the near-infrared and $SWIR$ refers to the short-wave infrared band while NBR_{pre} and NBR_{post} indicate pre- and post-fire conditions. While creating the NBR maps, we resample the 20 m spatial resolution SWIR band to 10 m and couple it with the 10 m spatial resolution NIR band. Ultimately, we categorize the burn severity maps using the United States Geological Survey-Fire Effects Monitoring and Inventory Protocol (Lutes et al., 2006; Table 2).

We use the geometrically and radiometrically corrected, pan-sharpened 4-band multispectral standard SPOT 6/7 ortho product with a spatial resolution of 1.5 m (Astrium Services, 2013) to generate normalized difference vegetation index (NDVI, Rouse et al., 1974) and vegetation recovery rate (VRR, Lin et al., 2005; Yunus et al., 2020; Zhong et al., 2021):

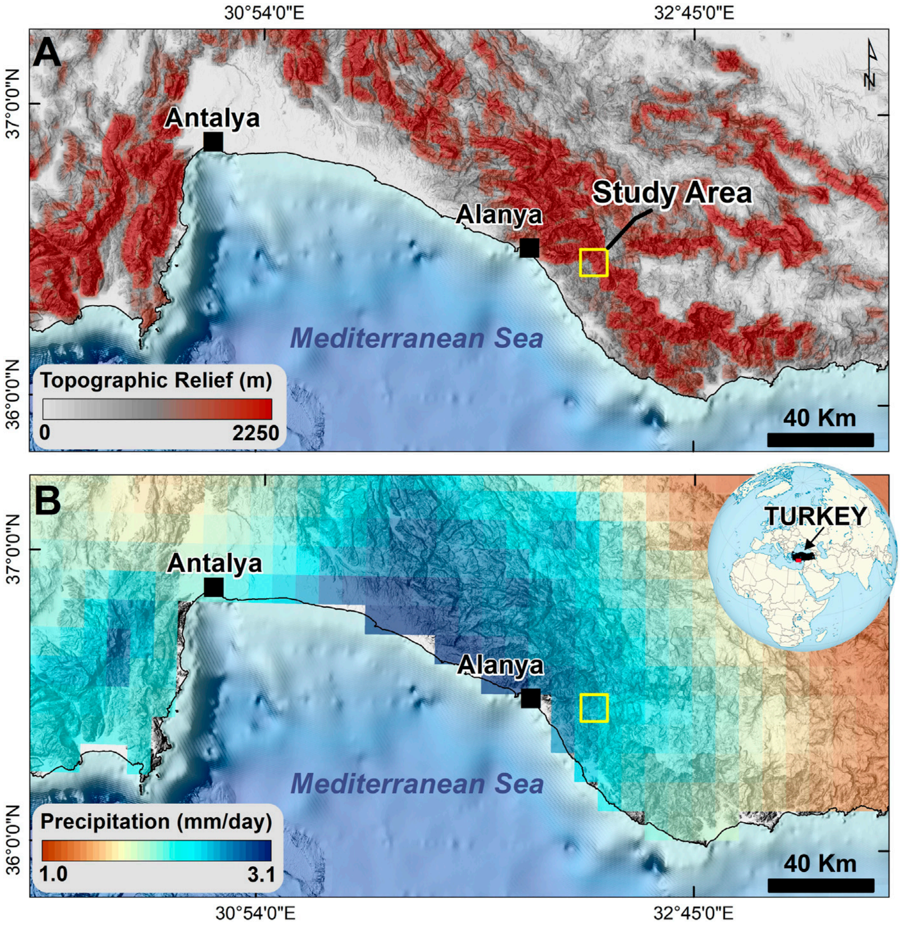

FIGURE 1
The Central Taurus Mountains and the study area are represented in terms of **(A)** topographic relief and **(B)** average daily precipitation (REF) maps.

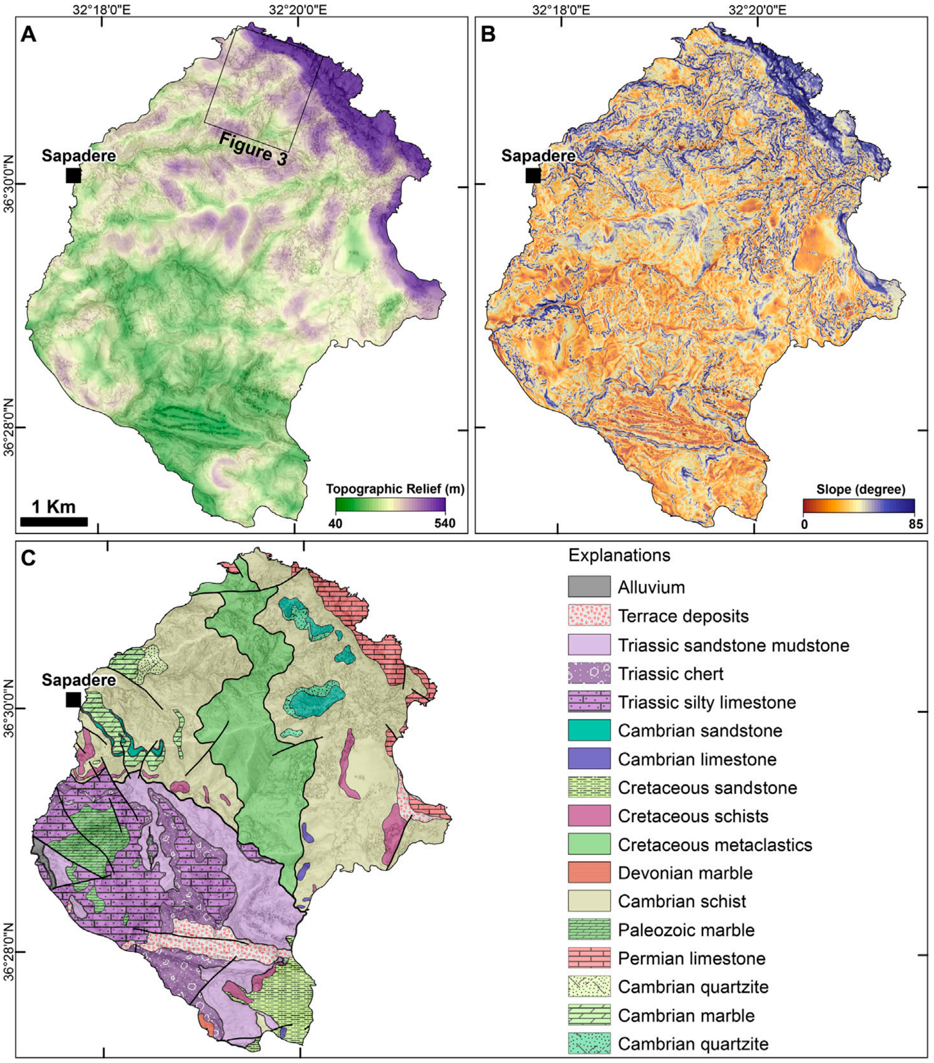

FIGURE 2
Maps showing the distribution of **(A)** topographic relief, **(B)** slope steepness, and **(C)** geological units (Source: MTA, 2010) observed in the study area.

TABLE 1 Data sets used in analysis processes.

Pre-event images	Post-event images	Ancillary data
03/06/2014 (SPOT 6)	14/07/2017 (SPOT 6)	•Google Earth images:
26/06/2017 (Sentinel 2)	06/07/2019 (SPOT 7)	Pre-Event image (03.10.2015)
	07/06/2021 (SPOT 7)	Post-event image (22.04.2021)
	(03/07/2017) (Sentinel 2)	•Geology Map
		•Forest Management Map
		•Soil maps

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{3}$$

$$VRR = \frac{NDVI_i - NDVI_1}{NDVI_0 - NDVI_1} X\,100 \tag{4}$$

where NIR refers to the near-infrared band, RED indicates the red band and $NDVI_i$ indicates the NDVI value of post-event for the year i, $NDVI_1$ represents the NDVI value just after the fire event, and $NDVI_0$ defines the NDVI value before the event.

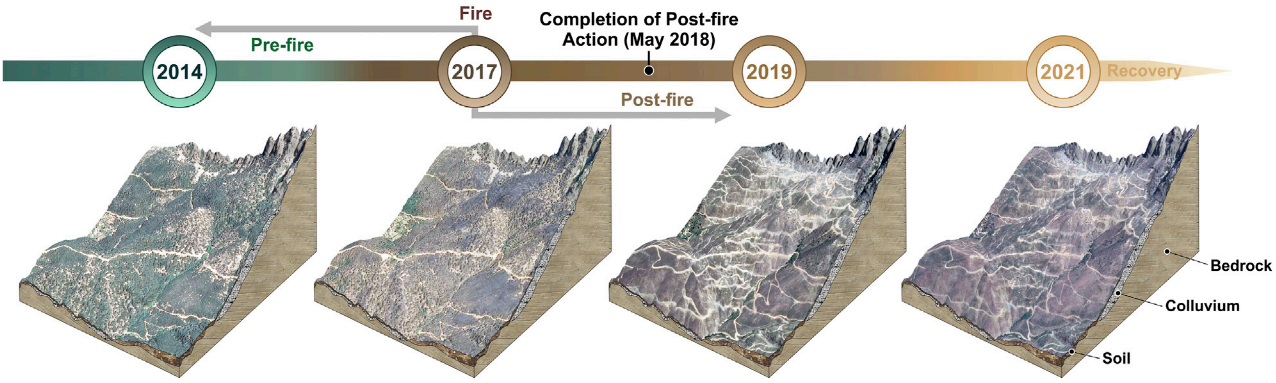

FIGURE 3
The evolution of the study area from pre-to post-fire conditions using SPOT 6 and 7 images for a selected area.

TABLE 2 Ordinal severity levels and example range of dNBR (scaled by 10^3).

Severity level	dNBR range
Unburned	−100 to +99
Low severity	+100 to +269
Moderate-low severity	+270 to +439
Moderate-high severity	+440 to +659
High severity	+660 to +1300

TABLE 3 Vegetation Recovery Rate (VRR) categories.

VRR (%)	Categories
<0	Very Poor
0–25	Poor
25–50	Average
50–75	Good
75–100	Very Good
>100	Excellent

For a clearer understanding of the VRR, obtained values are divided into six categories, as shown in Table 3 (Lin et al., 2005; Yunus et al., 2020; Zhong et al., 2021).

We also use historical images from Google Earth and manually map the existing (pre-fire roads) and newly created roads (post-fire roads), as well as road excavation material (artificial debris) and post-fire landslides.

Results

We examined pre- and post-wildfire Sentinel-2 images to identify the burn severity map of the study area (Figure 4). Results show that the fire burned a total area of 22.2 km^2, where the aerial coverage of low, moderate-low, moderate-high, and high severity patches are 8.5, 7.9, 4.1, and 1.7 km^2, respectively. This indicates moderate-high, or high-level severity is observed at 27% of the burned area.

To systematically examine the evolution of the study area from the pre-to post-fire periods, we created the false color composites of SPOT images (Figure 5). There, the areas converted from red to green from 2014 to 2017 indicate the burned areas. From 2017 onward, the two other post-wildfire images acquired in 2019 and 2021 show the re-vegetated areas. Aside from the revegetation, these two images also show a growing road network and the resultant excavation of waste materials along the road network, which was chiefly developed to carry out salvage logging.

Using SPOT images, we also generated NDVI maps for 2014, 2017, 2019, and 2021. Figure 6 shows how the NDVI values over the entirety of the study areas dramatically decrease from 2014 to 2017 following the Sapadere wildfire. Specifically, the median NDVI value drops from ~0.5 to ~0.18 after the fire. Results also show a gradual increase in NDVI values through the post-fire period in 2019 and 2021. Four years after the fire, the median NDVI value (~0.4) is still lower than its pre-fire counterpart.

We also examine this variation in NDVI for different burn severity classes (Figure 6F). The high severity patches correspond to the areas with the highest median NDVI value in the pre-fire conditions (i.e., 2014) and from high to low severity classes, NDVI values gradually decrease. Also, after the fire (i.e., 2017), we observe more prominent reductions in NDVI in the zones with a higher level of burn severity. In 2019, NDVI values in every burn severity zone equalize and increase compared to conditions in 2017. A similar increase in NDVI in all severity classes occurs also in 2021, though the recovery rate from 2019 to 2021 is smaller compared to the ones between 2017 and 2019.

In the post-fire NDVI maps, the footprint of the post-fire road network is noticeable because of relatively smaller NDVI values compared to the adjacent landscape (Figures 6D, E). This implies a delay in vegetation recovery in areas exposed to post fire road excavations. To better understand this influence, we manually mapped both pre- and post-fire roads and excavation

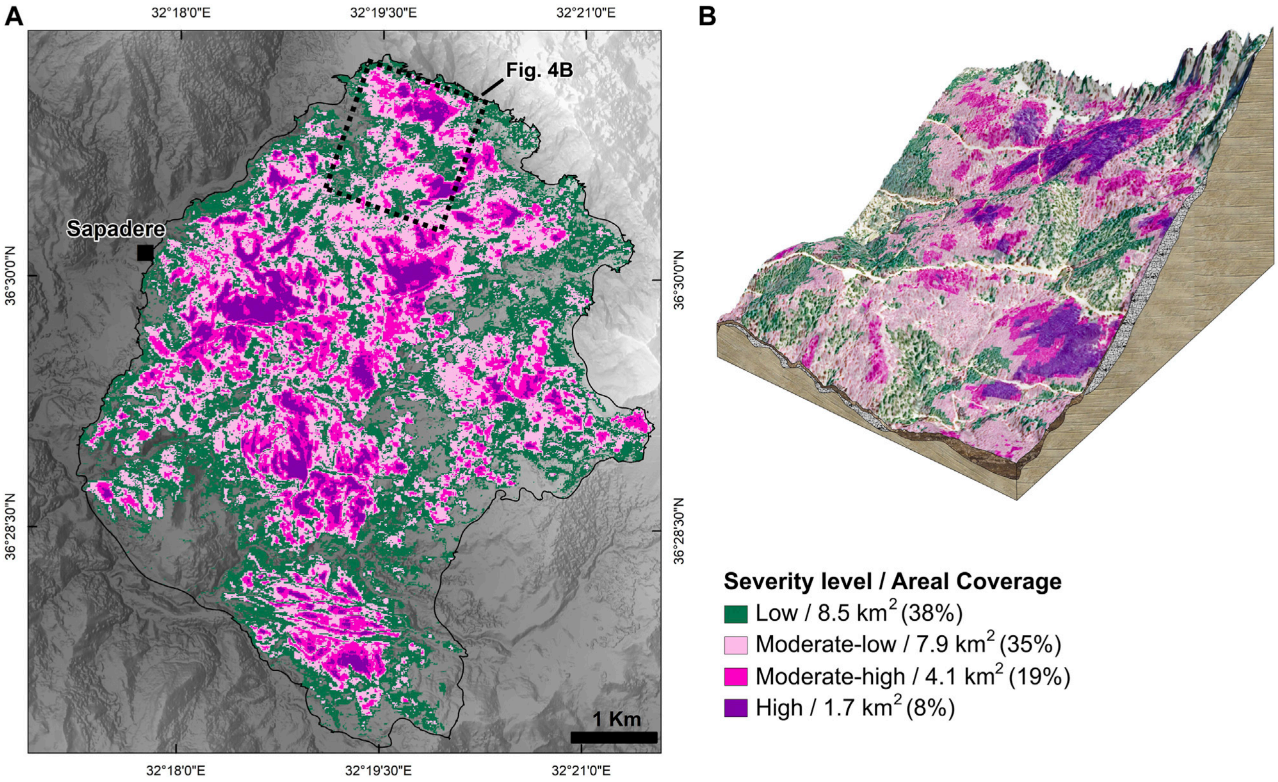

FIGURE 4
Burn severity map **(A)** of the study area. **(B)** The three-dimensional schematic diagram shows the burn severity degrees in the Northeast section of the Sapadere.

waste materials using Google Earth images (Figure 7). Aside from roads and dumped materials, we also mapped 34 post-fire landslides with a total area of 0.01 km^2. They are shallow-seated, small landslides that do not show any significant pattern in terms of their spatial distribution. The spatial distribution of these features for the conditions captured in 2019 is presented in Figure 8. Results show that during the post-fire practices, between July 2017 and May 2018, the total length and area of the constructed road (48 and 0.7 km^2) is almost equal to the size of the pre-fire road network (500 and 0.83 km^2).

Notably, the road construction resulted in some excavated materials being dumped from the road network. However, we also noticed the presence of dumped materials along the existing road network. This shows that the post-fire operations also involved an expansion of existing roads.

Overall, we identified the cumulative surface area of the post-fire waste materials as 0.92 km^2. This means that approximately 7% of the burned area (22.2 km^2) was directly influenced by the post-fire management practices including both roads and dumped materials.

To further examine the influences of these road excavations on the study area, we calculated VRR for the period following the completion of fire management practices (Figures 9A, B) and intersected these VRR maps with the spatial footprint of post-fire waste material and post-fire road network.

Results show that mean NDVI values in areas affected by post-fire management practices have ~50% recovery between 2017 and 2021. On the other hand, undisturbed areas show ~100% recovery in NDVI values within the same period. Also, from 2019 to 2021, the percentage of the area exhibiting average or worse VRR decreases from 49% to 27%. This implies an overall recovery in the vegetation cover in the post-fire period. However, Figure 9 also reveals that in 2019 and 2021, 27% of the study area exhibiting average or worse VRR is directly associated with either road construction or dumped materials. This stability in VRR indicates a delay in the natural regeneration caused by post-fire management practices.

Variations in NDVI associated with post-fire road and waste material and the rest of the study area (i.e., non-disturbed areas) also highlight the postponing influence of post-fire management practices on vegetation recovery. Figure 9C shows that non-disturbed areas had a rapid recovery than those directly exposed post-fire management practices.

Discussion and conclusion

There is a common agreement that burned forested areas are more sensitive to anthropogenic disturbances than their unburned counterparts (Beschta et al., 2004). However, salvage logging as part of post-fire management practices has been a subject of scientific debate (Leverkus et al., 2021).

More specifically, post-wildfire management practices are implemented shortly after fires to reduce both the risk and

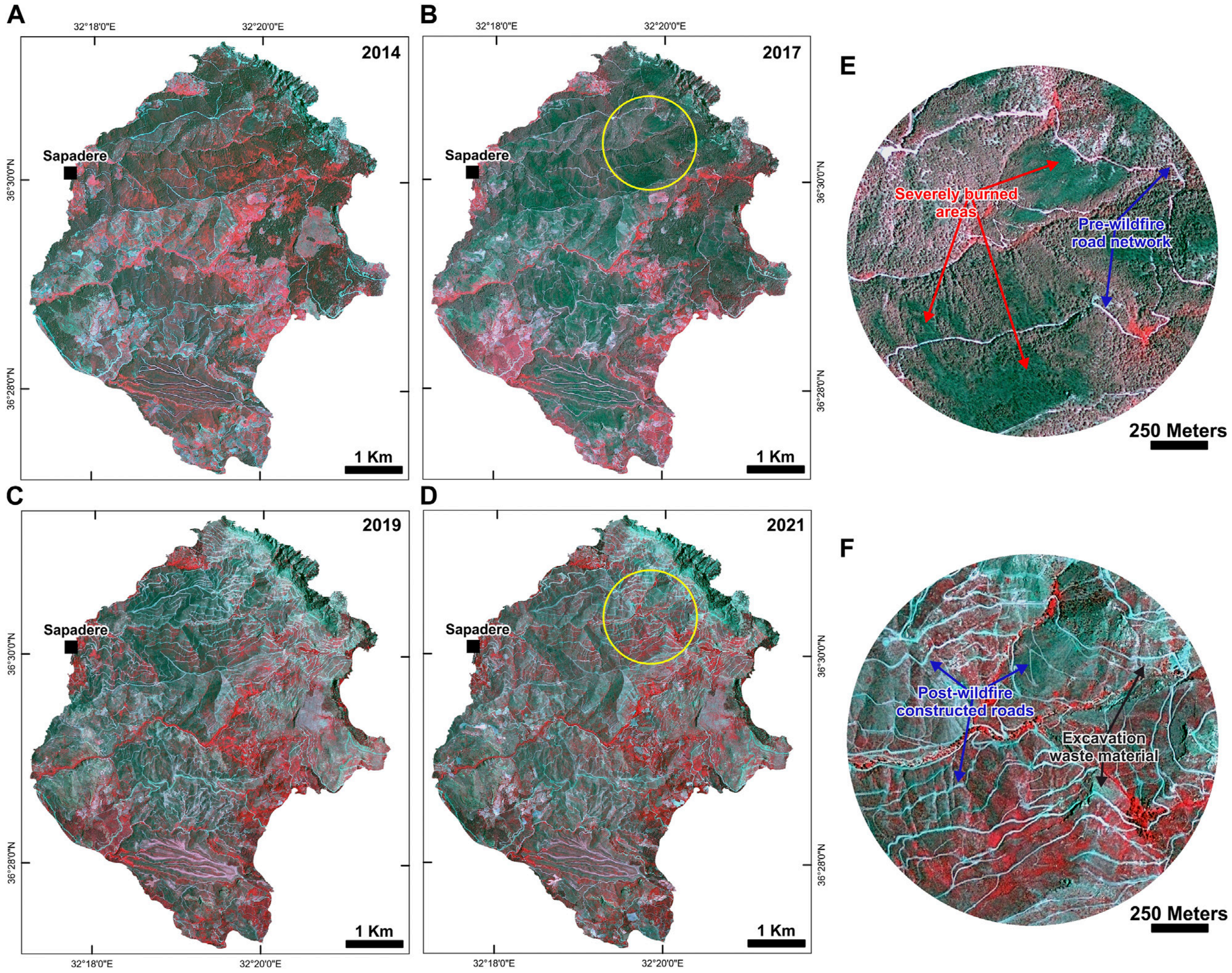

FIGURE 5
False color composites of SPOT images showing **(A)** pre-fire, **(B)** freshly after the fire, and **(C, D)** post-fire conditions of the study area. The inset magnified areas (yellow circles) indicate the conditions **(E)** immediately after the wildfire and **(F)** post-fire management practices.

severity of wildfires (Francos et al., 2018); moreover, it also includes road construction for salvage logging of dead trees and terracing to reduce soil erosion rate. However, post-fire management practices such as road excavations after a fire for salvage logging may alter the soil properties and increase the erosion rate, frequency of landslides, and debris flows in the burned hillslopes (Keller et al., 1997; Roering and Gerber, 2005; Reneau et al., 2007; Shakesby, 2011; Abrahams et al., 2018). Such anthropogenic disturbances may reduce the vegetation recovery rate (e.g., Tanyaş et al., 2022), cause certain ecological and excessive sediment load problems (e.g., Yunus et al., 2020), limit natural regeneration of the ecosystem, increase reforestation costs, and cause economic losses.

Quantifying the adverse effects of salvage logging has rarely been done in the context of spatiotemporal variation of vegetation cover (Vlassova and Pérez-Cabello, 2016; Robichaud et al., 2020). In Türkiye, in particular, only a few studies focused on salvage logging (Bilici and Abdullah, 2015; Bilici et al., 2017; Gülci, 2021; Tavsanoglu and Pausas, 2022) and yet, quantification of negative influences of road constructions associated with salvage logging has been mostly ignored.

This study focused on the 2017 Sapadere, Türkiye wildfire and examined the spatiotemporal variation of road construction and the resultant debris materials from pre-to post-fire phases to assess the role of salvage logging in vegetation recovery quantitatively.

The previous studies indicate that salvage logging causes soil compaction (Wagenbrenner et al., 2015), leading to a decrease in soil water holding capacity and a delay in vegetation recovery (Gomez et al., 2002). Also, our results show that the areas directly exposed to post-fire management practices exhibited a delayed vegetation recovery compared to undisturbed areas. Specifically, mean NDVI values in those areas show ~50% recovery in 5 years after the wildfire, while undisturbed areas exhibit ~100% recovery

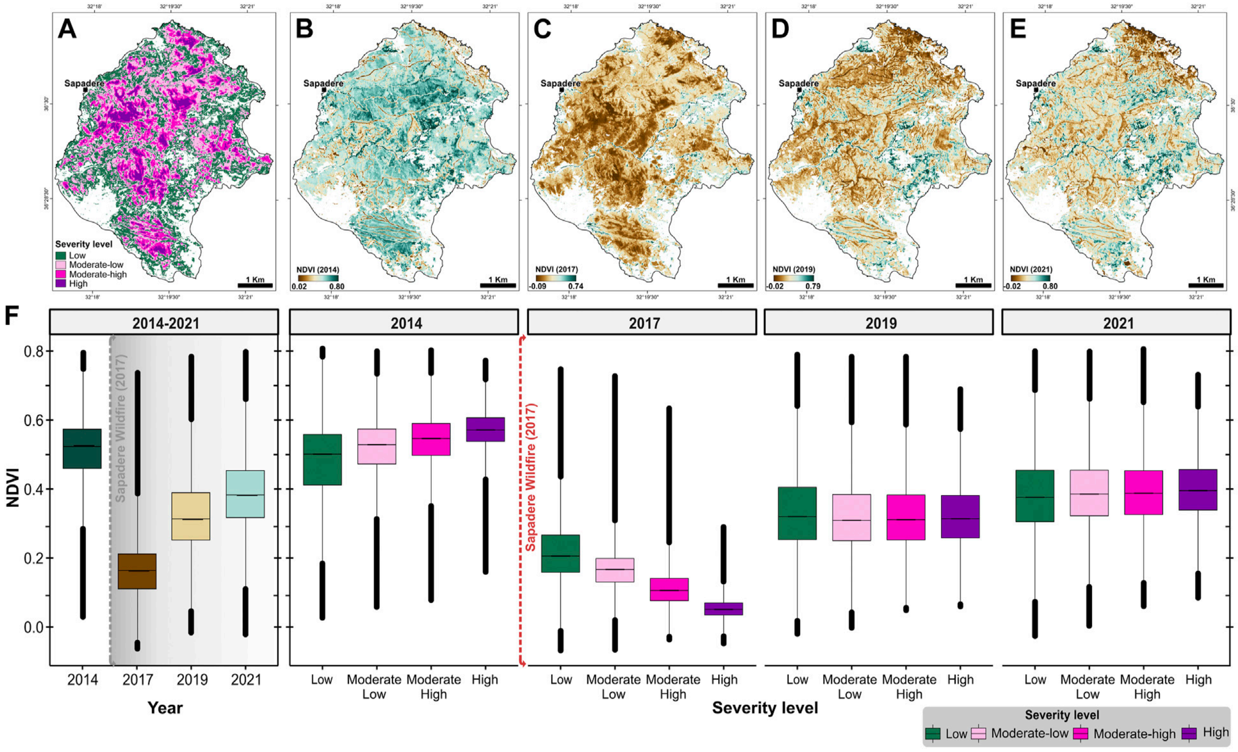

FIGURE 6
Temporal evolution of NDVI values in the study area with burn severity classes. **(A)** Burn severity and **(B)** 2014, **(C)** 2017 wildfire, and post-fire **(D, E)** NDVI maps and **(F)** pre-fire NDVI and temporal NDVI changes after the 2017 Sapadere wildfire event.

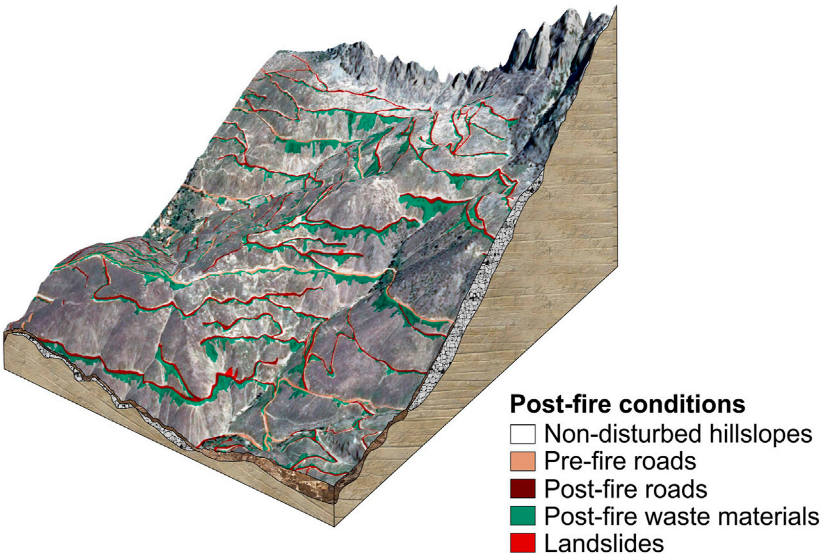

FIGURE 7
3D plot showing a subset of the study area with post-fire land cover classes.

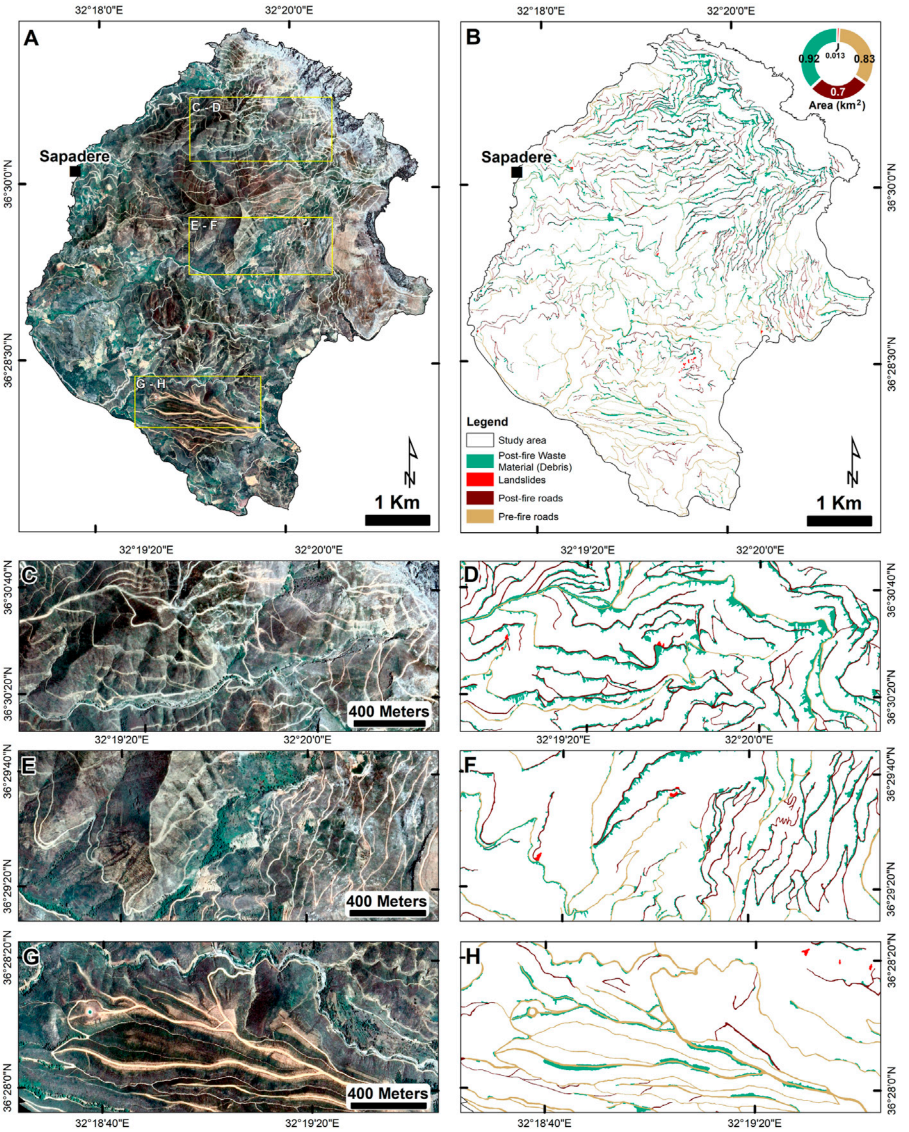

FIGURE 8
The spatial distribution of post-fire management practices after the 2017 Sapadere wildfire. **(A)** The satellite image of the post-fire salvage logging practice and **(B)** the digitized information on pre-and post-fire roads, waste material, and landslides over the study area. The inset areas in Panel A show enlarged areas of post-fire salvage logging practice conditions from satellite images **(C, E, G)** and digitized information on pre-and post-fire roads, waste material, and landslides **(D, F, H)**.

within the same period. In total, 7% of the burned area was affected by these post-fire management practices. Also, 27% of the areas characterized by average or aggravated (i.e., poor or very poor) VRR intersected with the footprint of the post-fire management practices. In fact, these numbers do not deliver the full spectrum of consequences that post-fire management practices may have caused. Our observations are bounded by the aerial coverage of road network and debris materials and we lack their possible long-term indirect effects. For instance, salvage logging could reduce plant diversity and negatively affect the resilience to future wildfires (Leverkus et al., 2014; Leverkus et al., 2021). These aspects need to be examined further in the area affected by the Sapadere wildfire. Considering the limited research on the topic focusing on the events that occurred in Türkiye, long-term monitoring of the Sapadere area as well as similar sites affected by wildfires in the southern section of Türkiye, could provide better insight into the consequences of salvage logging.

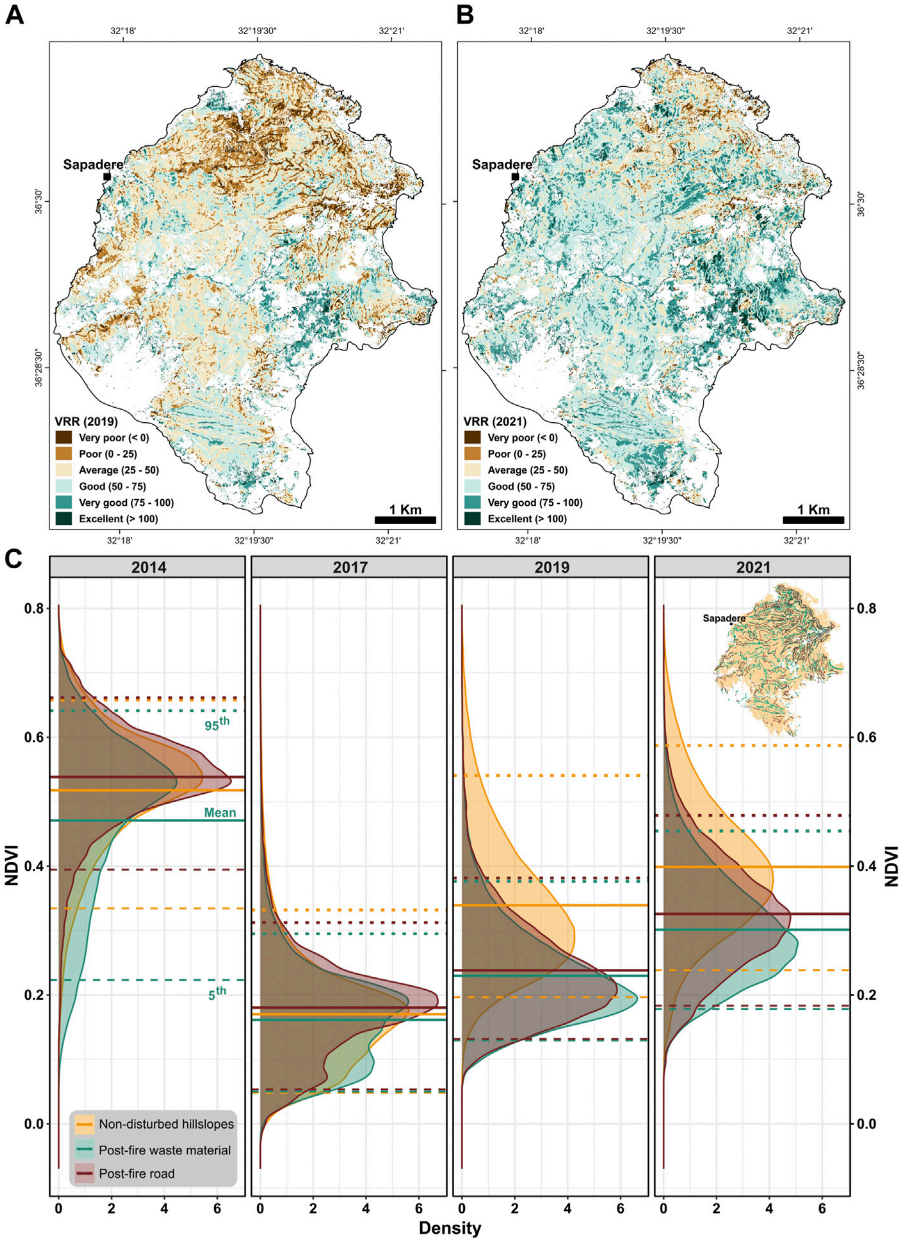

FIGURE 9
Plots showing **(A–B)** VRR maps and **(C)** variations in NDVI in different post-wildfire management practices types from pre-to post-fire periods.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

CY, RC, HT, ÖY, and TG designed the study. AY, RC, and SA performed the remote sensing processing with input from CY, and conducted the statistical analyses with AA. All authors interpreted and discussed the results. TG and HT wrote the paper with input from all co-authors.

Funding

This work was funded by the Istanbul Technical University BAP project [grant number TGA-2019-41755] and 2232 International Fellowship for Outstanding Researchers Program of the Scientific and Technological Research Council of Türkiye (TUBITAK) through grant 118C329. The financial support received from

TUBITAK does not indicate that the publication's content is approved in a scientific sense by TUBITAK. Data sources are listed below for the given datasets: SPOT images (Istanbul Technical University Implementation and Research Center for Satellite Communications and Remote Sensing); Sentinel-2 images (European Space Agency); Soil, geology, and Forest management maps (General Directorate of Mineral Research and Exploration (MTA) and Forest Enterprise Directorate, Antalya Regional Directorate).

Acknowledgments

We thank the Istanbul Technical University, Implementation and Research Center for Satellite Communications and Remote Sensing (CSCRS) for supporting SPOT satellite data.

Conflict of interest

Publisher's note

References

Abrahams, E. R., Kaste, J. M., Ouimet, W., and Dethier, D. P. (2018). Asymmetric hillslope erosion following wildfire in Fourmile Canyon, Colorado. *Earth Surf. Process. Landforms* 43, 2009–2021. doi:10.1002/esp.4348

Astrium Services (2013). *SPOT 6 and SPOT 7 imagery user guide*. France: Astrium Services.

Beschta, R. L., Rhodes, J. J., Kauffman, J. B., Gresswell, R. E., Minshall, G. W., Karr, J. R., et al. (2004). Postfire management on forested public lands of the western United States. *Conserv. Biol.* 18, 957–967. doi:10.1111/j.1523-1739.2004.00495.x

Bilici, E., and Abdullah, E. A. (2015). Risks factors associated with post-fire salvage logging operations. *Journal* 1, 93–100.

Bilici, E., Eker, M., Hasdemir, M., and Akay, A. E. (2017). Assessment of post-fire sal vage logging operations in mediterranean Region of Türkiye. *Sumar. List.* 7–8, 363–373. doi:10.31298/sl.141.7-8.3

Bistinas, I., Harrison, S. P., Prentice, I. C., and Pereira, J. M. C. (2014). Causal relationships versus emergent patterns in the global controls of fire frequency. *Biogeosciences* 11, 5087–5101. doi:10.5194/bg-11-5087-2014

Bowman, D. M. J. S., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'Antonio, C. M., et al. (2011). The human dimension of fire regimes on Earth. *J. Biogeogr.* 38, 2223–2236. doi:10.1111/j.1365-2699.2011.02595.x

Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., et al. (2009). Fire in the Earth system. *Sci. (80-* 324, 481–484. doi:10.1126/science.1163886

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J. P., Iglesias, A., et al. (2018). Climate change and interconnected risks to sustainable development in the Mediterranean. *Nat. Clim. Chang.* 8, 972–980. doi:10.1038/s41558-018-0299-2

Doerr, S. H., and Santín, C. (2016). Global trends in wildfire and its impacts: Perceptions versus realities in a changing world. *Philos. Trans. R. Soc. B Biol. Sci.* 371, 20150345. doi:10.1098/rstb.2015.0345

Fernández, C., and Vega, J. A. (2016). Effects of mulching and post-fire salvage logging on soil erosion and vegetative regrowth in NW Spain. *For. Ecol. Manage.* 375, 46–54. doi:10.1016/j.foreco.2016.05.024

Flannigan, M., Cantin, A. S., de Groot, W. J., Wotton, M., Newbery, A., and Gowman, L. M. (2013). Global wildland fire season severity in the 21st century. *For. Ecol. Manage.* 294, 54–61. doi:10.1016/j.foreco.2012.10.022

Francos, M., Pereira, P., Mataix-Solera, J., Arcenegui, V., Alcañiz, M., and Úbeda, X. (2018). How clear-cutting affects fire severity and soil properties in a Mediterranean ecosystem. *J. Environ. Manage.* 206, 625–632. doi:10.1016/j.jenvman.2017.11.011

Giglio, L., Boschetti, L., Roy, D. P., Humber, M. L., and Justice, C. O. (2018). The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sens. Environ.* 217, 72–85. doi:10.1016/j.rse.2018.08.005

Gomez, A., Powers, R. F., Singer, M. J., and Horwath, W. R. (2002). Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. *Soil Sci. Soc. Am. J.* 66, 1334–1343. doi:10.2136/sssaj2002.1334

Guiot, J., and Cramer, W. (2016). Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Sci.* 354, 465–468. doi:10.1126/science.aah5015

Gülci, N. (2021). Estimating costs of salvage logging for large-scale burned forest lands: A case study on Türkiye's mediterranean coast. *J. For. Res.* 32, 1899–1909. doi:10.1007/s11676-020-01255-y

Guo, Z., Ferrer, J. V., Hürlimann, M., Medina, V., Puig-Polo, C., Yin, K., et al. (2023). Shallow landslide susceptibility assessment under future climate and land cover changes: A case study from southwest China. *Geosci. Front.* 14, 101542. doi:10.1016/j.gsf.2023.101542

Hürlimann, M., Guo, Z., Puig-Polo, C., and Medina, V. (2022). Impacts of future climate and land cover changes on landslide susceptibility: Regional scale modelling in the val d'Aran region (pyrenees, Spain). *Landslides* 19, 99–118. doi:10.1007/s10346-021-01775-6

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., et al. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Commun.* 6, 7537. doi:10.1038/ncomms8537

Keeley, J. E., Bond, W. J., Bradstock, R. A., Pausas, J. G., and Rundel, P. W. (2011). *Fire in mediterranean ecosystems: Ecology, evolution and management*. Cambridge, United Kingdom: Cambridge University Press.

Keller, E. A., Valentine, D. W., and Gibbs, D. R. (1997). Hydrological response of small watersheds following the southern California painted cave fire of June 1990. *Hydrol. Process* 11, 401–414. doi:10.1002/(sici)1099-1085(19970330)11:4<401:aid-hyp447>3.0.co;2-p

Key, C. H., and Benson, N. C. (2006). *Landscape assessment: Ground measure of severity, the composite burn index; and remote sensing of severity, the normalized burn ratio*. Ogden, UT: Cambridge University Press. Available at: http://pubs.er.usgs.gov/publication/2002085.

Leifeld, J., Alewell, C., Bader, C., Krüger, J. P., Mueller, C. W., Sommer, M., et al. (2018). Pyrogenic carbon contributes substantially to carbon storage in intact and degraded northern peatlands. *L. Degrad. Dev.* 29, 2082–2091. doi:10.1002/ldr.2812

Leverkus, A. B., Buma, B., Wagenbrenner, J., Burton, P. J., Lingua, E., Marzano, R., et al. (2021). Tamm review: Does salvage logging mitigate subsequent forest disturbances? *For. Ecol. Manage.* 481, 118721. doi:10.1016/j.foreco.2020.118721

Leverkus, A. B., Gustafsson, L., Lindenmayer, D. B., Castro, J., Rey Benayas, J. M., Ranius, T., et al. (2020). Salvage logging effects on regulating ecosystem services and fuel loads. *Front. Ecol. Environ.* 18, 391–400. doi:10.1002/fee.2219

Leverkus, A. B., Lorite, J., Navarro, F. B., Sánchez-Cañete, E. P., and Castro, J. (2014). Post-fire salvage logging alters species composition and reduces cover, richness, and diversity in Mediterranean plant communities. *J. Environ. Manage.* 133, 323–331. doi:10.1016/j.jenvman.2013.12.014

Lin, W. T., Chou, W. C., Lin, C. Y., Huang, P. H., and Tsai, J. S. (2005). Vegetation recovery monitoring and assessment at landslides caused by earthquake in Central Taiwan. *For. Ecol. Manage.* 210, 55–66. doi:10.1016/j.foreco.2005.02.026

Lindenmayer, D., Thorn, S., and Banks, S. (2017). Please do not disturb ecosystems further. *Nat. Ecol. Evol.* 1, 0031. doi:10.1038/s41559-016-0031

Lingua, E., Bettella, F., Pividori, M., Marzano, R., Garbarino, M., Piras, M., et al. (2020). "The protective role of forests to reduce rockfall risks and impacts in the Alps under a climate change perspective," in *Climate change, Hazards and adaptation options* (Genève, Switzerland: Springer Nature), 333–347.

Lutes, D. C., Keane, R. E., Caratti, J. F., Key, C. H., Benson, N. C., Sutherland, S., et al. (2006). *Firemon: Fire effects monitoring and inventory system*. USA: CreateSpace Independent Publishing Platform.

Moreira, F., Arianoutsou, M., Vallejo, V. R., de las Heras, J., Corona, P., Xanthopoulos, G., et al. (2012). "Setting the scene for post-fire management," in *Post-fire manag. Restor. South. Eur. For* (Berlin, Heidelberg: Spinger).

Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., et al. (2014). Learning to coexist with wildfire. *Nature* 515, 58–66. doi:10.1038/nature13946

Pereira, P., Francos, M., Brevik, E. C., Ubeda, X., and Bogunovic, I. (2018). Post-fire soil management. *Curr. Opin. Environ. Sci. Heal.* 5, 26–32. doi:10.1016/j.coesh.2018.04.002

Reneau, S. L., Katzman, D., Kuyumjian, G. A., Lavine, A., and Malmon, D. V. (2007). Sediment delivery after a wildfire. *Geology* 35, 151–154. doi:10.1130/G23288A.1

Robichaud, P. R., and Ashmun, L. E. (2013). Tools to aid post-wildfire assessment and erosion-mitigation treatment decisions. *Int. J. Wildl. Fire* 22, 95–105. doi:10.1071/WF11162

Robichaud, P. R., Lewis, S. A., Brown, R. E., Bone, E. D., and Brooks, E. S. (2020). Evaluating post-wildfire logging-slash cover treatment to reduce hillslope erosion after salvage logging using ground measurements and remote sensing. *Hydrol. Process.* 34, 4431–4445. doi:10.1002/hyp.13882

Roering, J. J., and Gerber, M. (2005). Fire and the evolution of steep, soil-mantled landscapes. *Geology* 33, 349–352. doi:10.1130/G21260.1

Rouse, J. W., Haas, R. H., Schell, J. A., and Deering, D. W. (1974). Monitoring vegetation systems in the great plains with ERTS. *NASA Spec. Publ.* 351, 309.

Russo, A., Gouveia, C. M., Páscoa, P., DaCamara, C. C., Sousa, P. M., and Trigo, R. M. (2017). Assessing the role of drought events on wildfires in the Iberian Peninsula. *Agric. For. Meteorol.* 237–238, 50–59. doi:10.1016/j.agrformet.2017.01.021

Santolamazza-Carbone, S., Pestaña, M., and Vega, J. A. (2011). Post-fire attractiveness of maritime pines (*Pinus pinaster* Ait.) to xylophagous insects. *J. Pest Sci.* 84, 343–353. doi:10.1007/s10340-011-0359-0

Sarricolea, P., Serrano-Notivoli, R., Fuentealba, M., Hernández-Mora, M., de la Barrera, F., Smith, P., et al. (2020). Recent wildfires in Central Chile: Detecting links between burned areas and population exposure in the wildland urban interface. *Sci. Total Environ.* 706, 135894. doi:10.1016/j.scitotenv.2019.135894

Senande-Rivera, M., Insua-Costa, D., and Miguez-Macho, G. (2022). Spatial and temporal expansion of global wildland fire activity in response to climate change. *Nat. Commun.* 13, 1208. doi:10.1038/s41467-022-28835-2

Shakesby, R. A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Science Rev.* 105, 71–100. doi:10.1016/j.earscirev.2011.01.001

Tanyaş, H., Görüm, T., Kirschbaum, D., and Lombardo, L. (2022). Could road constructions be more hazardous than an earthquake in terms of mass movement? *Nat. Hazards* 112, 639–663. doi:10.1007/s11069-021-05199-2

Tavsanoglu, Ç., and Pausas, J. G. (2022). Turkish postfire action overlooks biodiversity. *Sci.* 375, 391. doi:10.1126/science.abn5645

Tekin, U. K. (1999). *Biostratigraphy and systematics of late Middle to late triassic radiolarians from the Taurus Mountains and ankara region*. Türkiye: Springer.

Vlassova, L., and Pérez-Cabello, F. (2016). Effects of post-fire wood management strategies on vegetation recovery and land surface temperature (LST) estimated from Landsat images. *Int. J. Appl. Earth Obs. Geoinf.* 44, 171–183. doi:10.1016/j.jag.2015.08.011

Wagenbrenner, J. W., MacDonald, L. H., Coats, R. N., Robichaud, P. R., and Brown, R. E. (2015). Effects of post-fire salvage logging and a skid trail treatment on ground cover, soils, and sediment production in the interior Western United States. *For. Ecol. Manage.* 335, 176–193. doi:10.1016/j.foreco.2014.09.016

Wagenbrenner, J. W., Robichaud, P. R., and Brown, R. E. (2016). Rill erosion in burned and salvage logged Western montane forests: Effects of logging equipment type, traffic level, and slash treatment. *J. Hydrol.* 541, 889–901. doi:10.1016/j.jhydrol.2016.07.049

Walstad, J. D., Radosevich, S. R., and Sandberg, D. V. (1990). *Natural and prescribed fire in Pacific Northwest forests*. Corvallis, OR: Oregon State University Press.

Yunus, A. P., Fan, X., Tang, X., Jie, D., Xu, Q., and Huang, R. (2020). Decadal vegetation succession from MODIS reveals the spatio-temporal evolution of post-seismic landsliding after the 2008 Wenchuan earthquake. *Remote Sens. Environ.* 236, 111476. doi:10.1016/j.rse.2019.111476

Zhong, C., Li, C., Gao, P., and Li, H. (2021). Discovering vegetation recovery and landslide activities in the wenchuan earthquake area with landsat imagery. *Sensors* 21, 5243. doi:10.3390/s21155243