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Monitoring forest canopy cover change with ICESat-2 Data in fire-prone areas: A case study in Antalya, Türkiye

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Abstract This study presents an innovative approach for monitoring forest canopy cover changes in Antalya, Turkey, a region characterized by rich biodiversity, recurrent forest fires, and rapid rehabilitation efforts. Employing advanced remote sensing techniques, the research integrates ICESat-2 ATL08 segment data, Landsat satellite imagery, and Esri Sentinel-2 Land Cover datasets to generate forest canopy cover (FCC) maps for the years 2019 and 2022. The study area was chosen due to its high population, significant tourism industry, and frequent forest fires, making it a critical region for biodiversity and forest resources in Turkey. The Canopy Cover Estimation Method (CCEM) was employed, achieving accuracy percentages ranging from 77% to 86%, demonstrating its efficacy in estimating FCC without the need for fieldwork. The integration of annual updates from the Esri Sentinel-2 Land Cover dataset as auxiliary data greatly enhanced the reliability and accuracy of the analyses. Despite challenges posed by the study area and differences in spatial resolution among the datasets, the study successfully demonstrated the utility of integrating ICESat-2 segment data and Landsat imagery for understanding the dynamics of FCC in a complex environment. The results contribute to more informed decision-making in forest management and conservation efforts. Future research should focus on refining the methodologies to minimize spectral misclassification, improving the spatial resolution of the FCC maps, and leveraging advancements in remote sensing technology to obtain more accurate and reliable results.

Keywords: Forest canopy cover, ICESat-2, Landsat, Canopy cover change, Google Earth Engine

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Introduction

As the lungs of our planet, forests provide us with the oxygen we need to breathe, making them essential for the survival of countless species and the very existence of human life itself. At a time when climate change is an increasingly pressing global concern, forests stand out as a critical ally in our efforts to combat its effects, as they not only sequester carbon but also provide a range of vital ecological services essential to sustaining life on Earth. Given the pivotal role of forests as our allies in the fight against climate change, it is of utmost importance to not only protect them from degradation but also to accurately assess their current status and predict their future trajectories to inform effective conservation and management strategies. Accurately predicting forest stand characteristics is therefore crucial, as it enables us better to understand the structure and functioning of forest ecosystems, assess their ecological health and resilience, and develop evidence-based policies and management practices to manage these invaluable natural resources sustainably (Husch et al. 2002).

Forest canopy cover (FCC) is one of the aforementioned important forest stand characteristics, and it is defined as the percentage of the area occupied by the vertical projection of tree crowns in the forest (Avery & Burkhart 1994, Korhonen et al. 2006). FCC provides an important indication of forest health (Lausch et al. 2017, Pyngrope et al. 2021, Nasiri et al. 2022), and as such, accurate assessment and monitoring of this parameter is vital for understanding the overall status of forests and their contribution to mitigating climate change. This parameter has broad applications in numerous fields, including but not limited to assessing forest degradation (Qin et al. 2021), estimating habitat suitability (Latif et al. 2020), predicting above-ground biomass (AGB) (Narine et al. 2020), and understanding the impacts of disturbances on forest ecosystems (Yin et al. 2020).

Traditional methods of estimating FCC using only ground-based field sampling measurements can be costly, time-consuming, and prone to bias and uncertainties, particularly for large-scale studies (Stojanova et al. 2010, McPherson et al. 2011). Remote sensing technologies such as satellite images and light detection and ranging (lidar) point cloud data have been increasingly employed to efficiently estimate FCC at various scales by integrating these data sources with ground-based measurements to overcome these limitations (Smith et al. 2009, Tang et al. 2019). Additionally, the use of spaceborne laser altimeter systems, such as the Ice, Cloud, and land Elevation Satellite (ICESat), has demonstrated promising results in estimating FCC, providing accurate and reliable data for FCC modeling and estimation (Herzfeld et al. 2013, Narine et al. 2019, Narine et al. 2022, Akturk et al. 2023).

The National Aeronautics and Space Administration (NASA) launched the first ICESat as the first-ever space-borne laser altimetry mission in 2003 (Schutz et al. 2005). Although the primary goal of the ICESat mission was to measure ice sheets and estimate global sea level rise using the Geoscience Laser Altimeter System (GLAS) (Zwally et al. 2002), it was recognized that the data collected during the mission could also be valuable for other applications such as vegetation studies (Garcia et al. 2012, Los et al. 2012). Building on the success of ICESat, NASA launched the Advanced Topographic Laser Altimeter System (ATLAS) onboard ICESat-2 in 2018 (Markus et al. 2017). The ATLAS system employs a new laser-based distance estimation technology, which allows it to make measurements at the photon level, reducing operating laser energy and increasing the sampling frequency significantly (Neuenschwander & Pitts 2019). This technological advancement is one of the key differences between ICESat and ICESat-2, enabling more accurate and efficient data collection. The ICESat-2 laser emits 10,000 light beams per second, with six laser beams emitted simultaneously at a distance of 3.3 km from each other. These beams are carried in different energies as weak and strong beams, with each beam creating a footprint of approximately 14 meters in diameter (Markus et al. 2017, Neuenschwander & Magruder 2019, Neuenschwander & Pitts 2019).

The photon counting technology of ICESat-2 has been the subject of several studies investigating its potential for estimating different forest stand parameters (Narine et al. 2020, Li et al. 2020, Nandy et al. 2021, Luo et al. 2023). However, there are also limitations and challenges associated with using ICESat-2 data for these estimations, such as the influence of topography, data preprocessing, and selecting appropriate variables for modeling. In the existing literature, four studies have tested the use of this technology for estimating FCC (Narine et al. 2019, Narine et al. 2022, Akturk 2023, Akturk et al. 2023, Narine et al. 2023). These studies have investigated the accuracy of estimating FCC using ICESat-2 data, both in small and large-scale study areas. One such study, conducted by Narine et al. (2019), utilized airborne lidar data as a dependent variable for estimating FCC and canopy height for an approximately 50 km² study area. Based on this data, a regression model was developed for estimating FCC. The study found that FCC and canopy height estimations achieved R2 values between 0.56 and 0.93. The study has been recognized as the first in this field and highlights the potential of using ICESat-2 data for accurate and reliable forest canopy cover estimations. Subsequently, Narine et al. (2022) conducted a study to examine the FCC estimation accuracy of six different formulas created using various variables from ICESat-2's ATL08 products in two similarly scaled study areas. The study highlights the potential of using ICESat-2 data to improve the estimation of FCC and underscores the importance of selecting the appropriate variables to maximize estimation accuracy. A recent study conducted by Akturk et al. (2023) aimed to assess the efficacy of cloud-based platforms for large-scale categorized FCC mapping using ICESat-2's ATL08 variables. Google Earth Engine (GEE)-based Canopy Cover Estimation Model (CCEM) was created to generate an FCC map for Türkiye with an accuracy of 71.9% for the year 2021 in the study. Using cloud-based platforms for FCC mapping has shown great potential for efficient, accurate, and cost-effective forest management and conservation efforts. The study highlights the effectiveness of the GEE-based CCEM for large-scale FCC mapping and its potential for widespread implementation in the future.

Despite the advancements and promising results shown by studies using ICESat-2 data for estimating forest canopy cover, several challenges and limitations warrant further investigation. For instance, data preprocessing and filtering techniques, as well as the influence of complex topography, may impact the accuracy of FCC estimations (Tian et al. 2021, Fernandez-Diaz et al. 2022, Zhu et al. 2022). Furthermore, developing robust models that can account for various forest types, stand structures, and environmental conditions is essential to ensure the applicability of ICESat-2 data for FCC estimation across diverse ecosystems. In addition to these challenges, assessing temporal changes in FCC is of utmost importance for determining the status of forests and monitoring their health and response to various disturbances and management practices. To date, a study has yet to be conducted to specifically investigate the potential of ICESat-2 data for examining forest canopy cover changes over time, highlighting a significant gap in the literature that warrants further exploration.

This study aims to generate FCC maps for the Antalya province of Türkiye for 2019 and 2022 using ICESat-2 ATL08 data and Landsat satellite imagery to address the gap in the literature. The CCEM (Akturk et al.

2023), which was previously introduced in the literature, was utilized with some modifications within the GEE to generate the FCC maps. Specifically, this study aims to achieve the following objectives:

• Evaluate the impact of using the ESRI 10m Land Use/Land Cover dataset for the years 2017-2022 (Karra et al. 2021) instead of the 2019 100m Copernicus Land Cover dataset (Buchhorn et al. 2020), which has been identified as a significant source of error in the CCEM (Akturk et al. 2023), on the accuracy of the FCC maps generated using the modified CCEM within the GEE platform;

• Test the suitability of the proposed methodology for mapping categorical FCC changes in an area, such as the Antalya province, where forest fires (Karabacak et al. 2019) and tourism (Akis 2011) have significant impacts on the forest ecosystem; and

• Discuss the advantages and limitations of using ICESat-2 data and Landsat imagery for generating FCC maps, particularly in areas with high levels of disturbance and human activity.

Overall, the study's findings could have significant implications for informing sustainable forest management and conservation strategies, particularly in areas where human activities and disturbances such as forest fires threaten forest ecosystems.

Materials and Methods

Study area

Antalya province, located in the southwestern region of Türkiye, was selected as the study area in this study. Antalya covers an area of approximately 20,000 km² and is located between 29°20’ and 32°35’ east longitudes and 36°07’ and 37°29’ north latitudes (Fig. 1).

With a population of approximately 2.7 million, it ranks as the fifth most populous city in the country and is often referred to as Türkiye’s “tourism capital” (Erkuş-Öztürk 2010). The region’s climate is predominantly characterized by the Mediterranean climate type, with hot and dry summers and mild, rainy winters. Antalya’s diverse geography and climate support various plant species, making it a biodiversity-rich region. The province encompasses approximately 1 million hectares of forested areas, which exhibit varying characteristics depending on the altitude (Orman Genel Mudurlugu 2020). At elevations between sea level and 500-600 meters, maquis shrublands, which are evergreen and highly resistant to extreme summer droughts, dominate the landscape. Between 600 and 1,200 meters, mixed forests consisting primarily of red pine (*Pinus brutia*) and oak (*Quercus* spp.) species are predominant. In areas above 1,200 meters, the high forest belt is composed of cedar (*Cedrus* spp.), fir (*Abies* spp.), Scots pine (*Pinus sylvestris*), beech (*Fagus* spp.), and juniper (*Juniperus* spp.) species.

Antalya province was chosen as the study area for several reasons. Firstly, the city’s substantial tourism activities and high population could

Figure 1 Location and geographical borders of Antalya, Türkiye. The borders of Antalya are highlighted in red, and neighboring provinces are labeled for reference.

exert pressure on forests, making changes in FCC highly likely. Secondly, the study area lies within a region where forest fires frequently occur (Orman Genel Mudurlugu 2021), providing an opportunity to observe both the impacts of forest fires on FCC, such as the destruction of forests, and the forest regeneration following post-fire rehabilitation efforts (Tavsanoglu & Gurkan 2009, Tonbul et al. 2016).

In addition to the reasons mentioned above, the distinct vegetation zones and diverse forest ecosystems in Antalya offer a suitable context for assessing the applicability and accuracy of the proposed methodology in monitoring FCC change using ICESat-2 ATL08 data and Landsat satellite imagery.

Data acquisition, filtering, and CCEM

Generating at least two FCC maps corresponding to different dates is necessary to monitor temporal FCC changes. In this study, the CCEM algorithm developed by Akturk et al. (2023) was employed, with some modifications, to generate FCC maps for different dates for Antalya province. The study began with the initial phase of the case study, which involved collecting and filtering appropriate segments. Firstly, ICESat-2/ATLAS Level 3A ATL08 Version 5 products in HDF5 format for 2019 and 2022, covering the study area boundaries, were downloaded from the NASA Earth Data web-based platform (The National Aeronautics and Space Administration 2022). The corresponding segment data were used as training and test datasets for generating FCC maps of Antalya province for 2019 and 2022. To ensure the most accurate estimation of FCC, ATL08 tracks were chosen between June 1 and August 31, during which trees in the region were leaf-on status. For 2019, 26 ATL08 tracks with 60,556 segments were collected, while for 2022, 29 ATL08 tracks with 80,691 segments were gathered. Before starting further analysis, the geographic center of each segment was determined using the coordinate attributes of each segment, and the segments were subsequently geolocated accordingly.

Apart from the coordinate attributes of the segments, canopy, top of the canopy (TOC), and ground photon counts were used for estimating the percentage FCC (Equation (1):

$$\boldsymbol{Percentage\ of\ FCC} = \frac{\boldsymbol{n\_ca\_photons}}{\boldsymbol{n\_ca\_photons} + \boldsymbol{n\_te\_photons}} \times \mathbf{100} \quad (1)$$

The ‘n_ca_photons’ attribute represents both label 2 (canopy) and label 3 (TOC) returns, while ‘n_te_photons’ represents only label 1 (ground) returns. The ‘n_toc_photons’ attribute has been used solely for distinguishing erroneous segments, as TOC return counts are already provided within the ‘n_ca_photons’. In addition, the ‘h_canopy’ attribute, which represents the 98% height of all individual relative canopy heights (height above terrain), was utilized for estimating the land cover of segments (Neuenschwander et al. 2021). Limiting the prediction of FCC to only forests is critical for the study’s accuracy. Therefore, in addition to the ‘h_canopy’ attribute, the 2019 and 2022 Esri Sentinel-2 Land Cover maps (Karra et al. 2021) were utilized as an auxiliary dataset to distinguish forests.

Within the scope of this study, the collected segments for the years 2019 and 2022 were filtered according to specific criteria, and the most suitable segments for FCC estimation were planned to be used for further analyses. The filtering criteria were as follows:

1. The study should be conducted only for forests, and the ATL08 product provides land cover class attributes for each segment. However, this attribute was obtained from the 2019 Copernicus Land Cover dataset, and Akturk et al. (2023) found that using this dataset reduced the success of FCC estimation of CCEM. Therefore, in this study, the Esri Sentinel-2 Land Cover maps for the years 2019 and 2022 were used to identify forests, determine segments belonging to forests, and filter out the remaining segments. The annual production of these Esri Sentinel-2 Land Cover

maps is also expected to minimize issues arising from possible land cover changes.

2. According to the Food Agriculture Organization (FAO)'s forest definition (FAO 2014), an area must have at least 10% canopy cover and trees with a minimum height of 5 meters to be considered a forest. Segments with a percentage FCC value below 10% and an average tree height below 5 meters were filtered out.

3. A segment containing less than 50 classified photons was deemed as noise and removed for further analysis (Neuenschwander et al. 2021).

4. Similarly, segments with fewer than 10 canopy photons were considered unreliable and subsequently eliminated from the segment pool (Neuenschwander et al. 2021).

5. Additionally, some segments displayed a higher count of TOC photons compared to canopy photons, which encompass both TOC photons and mid-level canopy photons. These segments were regarded as noise and thus excluded from the dataset.

Following the filtering processes based on the criteria mentioned above, a total of 27,462 segments remained for 2019, and 35,460 segments remained for 2022 (Fig. 2).

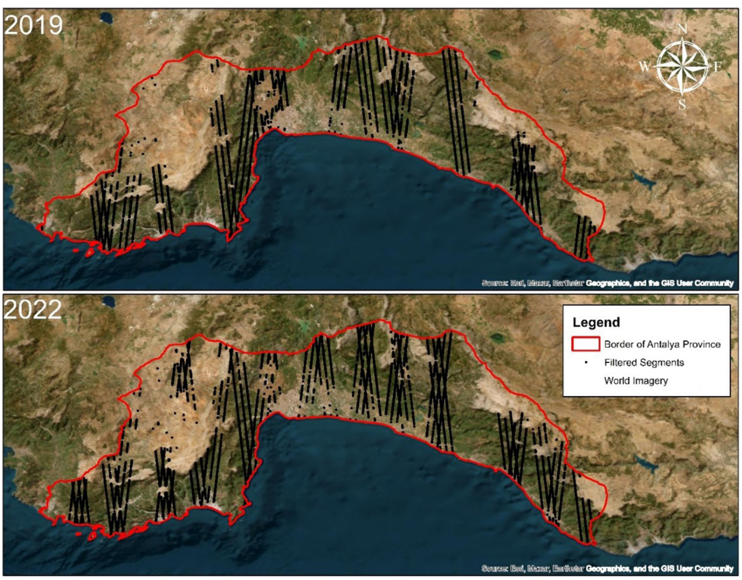

Figure 2 Distribution of filtered segments in the study area for 2019 and 2022.

The CCEM algorithm used for generating FCC maps consists of four stages, each coded within GEE (Akturk et al. 2023). The first stage, 'Image Acquisition and Preparation,' involves obtaining suitable Landsat satellite images and preparing spectral information from the bands for use. For FCC 2019, 40 Landsat 8 Level 2, Collection 2, Tier 1 raw satellite images with a spatial resolution of 30 meters were employed, while 36 such images were used for FCC 2022. These raw satellite images were atmospherically corrected and made ready for use with the help of the Landsat Simple Composite algorithm in GEE.

The spectral bands of the prepared Landsat composite images for each year were utilized to calculate commonly used 26 different vegetation indices, which are correlated with FCC (Huete 1988, Glenn et al. 2008). This constitutes the second stage of the CCEM, 'Generating Vegetation Indices'. These vegetation indices were stacked as bands on the corresponding Landsat composite image, and the resulting image was resampled to a 100-meter resolution to match the size of the ATL08 segments. Subsequently, with the aid of Esri Sentinel-2 Land Cover maps, non-forest pixels were masked, ensuring that the study focused exclusively on forested regions.

The third stage, 'Machine Learning Classification,' involves the categorical classification of 2019 and 2022 Landsat composite images containing vegetation indices. First of all, FCC categories must be determined. Since the study focuses on Antalya province, the FCC categories were defined according to Turkish forest management principles

(Diker 1946). Consequently, FCC was divided into three categories: Sparse Forest Canopy Cover (SFCC) for areas with 10-40% canopy cover, Moderate Forest Canopy Cover (MFCC) for areas with 40-70% canopy cover, and Dense Forest Canopy Cover (DFCC) for areas with over 70% canopy cover. Following this, FCC categories were assigned to all segments used for this study. The CCEM employs a decision tree-based machine learning algorithm called the Random Forest classifier for the classification stage (Pal 2005). In the classification, the multi-band Landsat composite image was designated to be a classified image, and 80% of the filtered ATL08 segments were used to train this image. The remaining 20% of the segments were set aside to test the generated maps, and the accuracy assessment, which is the final stage of the CCEM algorithm, was conducted using these segments.

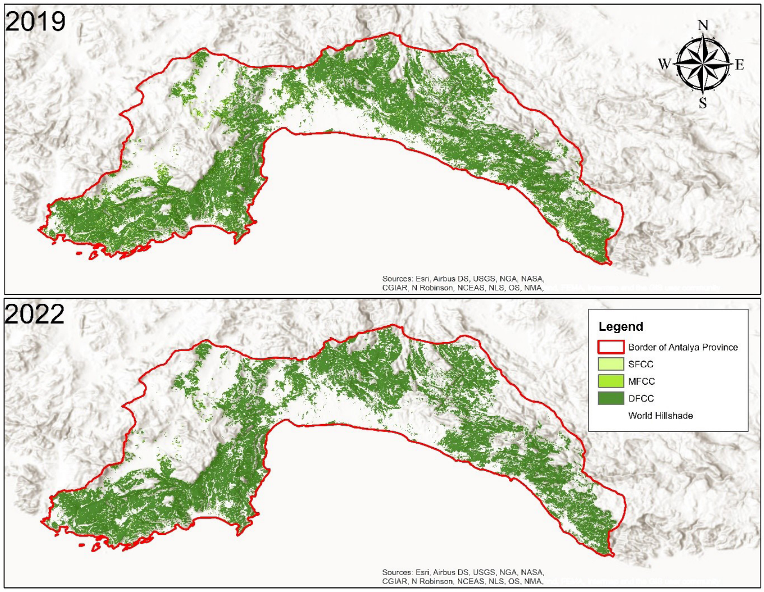

Figure 3 FCC Maps of Antalya province for 2019 and 2022.

Results

FCC maps of Antalya

According to the Esri Sentinel-2 Land Cover 2019 data, it was determined that 39.5% of Antalya province, equivalent to an area of over 800,000 hectares (ha), was classified as forests. In 2022, there was an observed decline of approximately 10% in the forests of Antalya, with the total forest coverage decreasing to 720,000 ha. The reduction in forest cover can be attributed to numerous forest fires that occurred in the region between 2019 and 2022, which caused significant damage to the forests (Orman Genel Mudurlugu 2021).

Upon examining the data obtained from the FCC map generated using CCEM for 2019, it was determined that 93% of Antalya's forests belonged to the DFCC class, representing dense, closed forests (Table 1). This percentage value increased to 98% in 2022, despite the overall decline in total forest areas (Fig. 3). This increase could result from afforestation efforts carried out in previous years, aimed at rehabilitating the damaged forest fields. When assessing other FCC classes, it was observed that the canopy cover averages in Antalya for 2021 were considerably lower than the national canopy cover averages for Türkiye

Table 1 Comparison of FCC classes for Antalya in 2019 and 2022, displaying the area (in hectares) and percentage of each FCC class (SFCC, MFCC, and DFCC) in relation to the total forests.

FCC Class	FCC 2019		FCC 2022	
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
SFCC (10-40%)	9,572	0.84	5,078	0.49
MFCC (40-70%)	78,994	6.92	17,841	1.71
DFCC (70-100%)	1,062,240	93.08	1,026,821	98.29
Total	1,141,234	100.00	1,044,662	100.00

(Akturk et al. 2023), indicating that Antalya's forests predominantly consist of productive and dense forests. Furthermore, based on the data presented in Table 1, it can be inferred that there was a transition, particularly from the MFCC class to the DFCC class. However, this inference can only be confirmed through a temporal change analysis.

The accuracy of the FCC maps generated using CCEM for 2019 and 2022 was calculated using the 20% of segments reserved for testing and presented in Table 2.

Table 2 Comparison of overall accuracy and Kappa coefficient for FCC maps generated using Esri Sentinel-2 Land Cover and Copernicus Land Cover auxiliary datasets for Antalya in 2019 and 2022.

Auxiliary Dataset	FCC 2019		FCC 2022	
	Overall Accuracy (%)	Kappa Coeff.	Overall Accuracy (%)	Kappa Coeff.
Esri Sentinel-2 Land Cover	77.1	0.89	85.9	0.93
Copernicus Land Cover	76.7	0.86	78.4	0.84

The achievement of over 75% accuracy in the maps for both years enhances the reliability of the method that was used in this study. Additionally, FCC maps were regenerated using the Copernicus Land Cover dataset, which was the auxiliary data source used in the original CCEM study (Akturk et al. 2023), and subjected to the same accuracy assessment for comparison with the maps derived from the Esri Sentinel-2 Land Cover dataset. As a result, it was determined that the maps obtained from the Esri Sentinel-2 Land Cover dataset had higher average accuracy and Kappa coefficients than those produced with the Copernicus Land Cover dataset. Moreover, it was observed that the average accuracy for 2022 was higher than for 2019, which could be resulted from the larger number of total segments collected for both training and testing the 2022 image.

FCC change map of Antalya

In this subsection, we present the findings from the subtraction of the 2019 FCC map from the 2022 FCC map to analyze and map the changes in canopy cover over the three-year period (Fig. 4). Our analysis reveals that 92% of the forests within the study region did not experience any change in FCC class during that three-year period. The changes observed in the remaining 8% of the forest are presented in Table 3.

One notable finding is the 592-hectare

Table 3 FCC class transitions between 2019 and 2022. The table displays the area (in hectares) of observed changes between the SFCC, MFCC, and DFCC classes.

		FCC 2022		
		SFCC (10-40%)	MFCC (40-70%)	DFCC (70-100%)
FCC 2019	SFCC (10-40%)	No Change	11.6	59.9
	MFCC (40-70%)	17.9	No Change	592.6
	DFCC (70-100%)	16.6	86.9	No Change

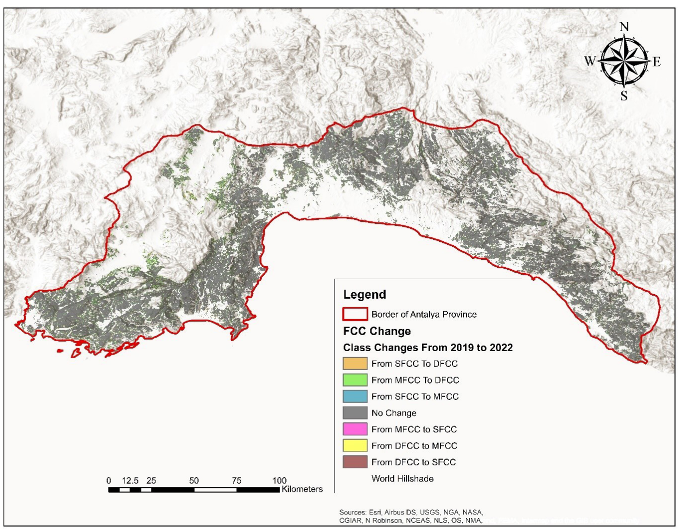

Figure 4 FCC Change Map between the years 2019 – 2022.

conversion from the MFCC class to the DFCC class, accounting for 75% of the total class changes. As previously mentioned, this transformation could result from the rehabilitation efforts following forest fires in the area, particularly choosing the rapid growth of species such as the red pine (Kavgaci et al. 2017). This change may impact the ecosystem by enhancing carbon sequestration, altering wildlife habitats, and affecting the overall health of the forests. In contrast, the second-highest change, covering 87 hectares, was observed in the transition from the DFCC class to the MFCC class. Although these changes between the two classes are plausible within a three-year timeframe, the transformation from the SFCC class to the DFCC class is considerably more challenging to achieve and may provide insight into the type of plantation or indicate tall sapling planting activities. This suggests that different management approaches have been implemented in certain areas to foster faster forest recovery. On the other hand, the inverse situation, i.e., transitions from the DFCC class to the SFCC class, may suggest that the forests in these pixels have been damaged due to fires or harmful anthropogenic activities. This highlights the ongoing vulnerability of forests to such activities and emphasizes the importance of continued monitoring and management efforts.

When examining class changes, it can be generally concluded that the forest canopy density is on a positive trend in the study area. However, it is important to note that the total forests in Antalya have decreased by approximately 10%, and non-forest areas, which do not have an FCC class, are not considered in Table 3. This highlights the need for further research to understand the drivers behind these changes and evaluate the impact of the loss of forested areas on the region's overall ecosystem and biodiversity.

In summary, this study has successfully identified changes in the forest canopy cover in Antalya province between 2019 and 2022 using the CCEM method. The results provide valuable insights into the ongoing efforts to rehabilitate the forested areas affected by fires and other anthropogenic activities, as well as the challenges faced in achieving dense, closed forests. This information is crucial for informing future forest management and conservation strategies to ensure the long-term health and sustainability of the region's forests.

Discussion

In recent years, advancements in remote sensing and geospatial computing techniques have become essential for understanding the dynamics of forests and addressing environmental issues. Spaceborne laser-based systems, such as ICESat-2, enable highly accurate estimations of crucial physical forest properties, including canopy height, cover, and biomass. In this study, an example application was performed for Antalya, a province in Türkiye known for its rich biodiversity. FCC maps for Antalya between 2019 and 2022 were generated, and the changes in canopy cover during these three years were revealed using ICESat-2 ATL08 segment data and Landsat satellite imagery.

The average accuracy percentages obtained in this study, ranging from 77% to 86%, are considered highly successful, given the size of the study area and the fact that the maps were generated without fieldwork. These results demonstrate the efficacy of the CCEM method in estimating FCC. In Akturk et al. (2023) study, the Copernicus Land Cover dataset was used for determining forests and filtering segments. However, this dataset overestimated the spatial extent of forest land cover, leading to inaccuracies in the analysis. To address this issue, Esri Sentinel-2 Land Cover datasets were used as auxiliary data for both 2019 and 2022 in the current study, significantly reducing the error rate. Another significant advantage provided by the Esri Sentinel-2 Land Cover dataset is its annual updates. This feature ensures access to suitable land cover auxiliary data for each year in which ICESat-2 segment data is collected. Consequently, integrating such auxiliary data greatly enhances the reliability and accuracy of the analyses, making it a valuable tool for future research and applications in forest monitoring and management.

Antalya was selected for this study because of its high population, significant tourism industry, and frequent forest fires during the summer months. It is an essential province in Türkiye concerning biodiversity and forest resources. When examining Figure 3, it can be observed that a large portion of the forest in the southeast of the 2019 map is absent in the 2022 map. This change was due to the Manavgat forest fire, which occurred on July 28, 2021, and is considered one of the largest fires in Turkish history (Guler & Kalkan 2022). The frequent forest fires in the region and subsequent rehabilitation efforts make the area suitable for this study while potentially subjecting the results to spectral misclassification during the image processing. For instance, after a fire event in an area classified as SFCC with low canopy cover, newly planted saplings that have not reached their mature tree form may be spectrally similar to a DFCC-classified forest, causing misclassification.

Within the scope of this study, some areas where FCC change was observed were examined using Google Earth to verify the actual existence of the change. However, obtaining high-resolution satellite imagery for both 2019 and 2022 for the region was only possible in some instances, resulting in inconclusive findings that were not included in the final results of this study. Antalya's vulnerability to forest fires and the rapid rehabilitation efforts following these events present unique challenges when monitoring forest canopy cover changes using remote sensing techniques. Despite these challenges, this study has successfully demonstrated the utility of integrating ICESat-2 segment data and Landsat imagery for understanding the dynamics of FCC in such a complex environment. Future research should focus on refining the methodologies for minimizing spectral misclassification and integrating additional sources of information to improve the accuracy and reliability of FCC change analyses.

This study has differences in spatial resolution among the three primary datasets used. ICESat-2 ATL08 segments have a size of 100 meters, Landsat satellite images have a resolution of 30 meters, and the Esri Sentinel-2 Land Cover dataset has a resolution of 10 meters. Combining these three datasets with different resolutions at a 100-meter segment size can inevitably result in errors and produce a lower-resolution product compared to the individual datasets. This issue can be addressed by altering the ATL08 segment size with the help of additional software (Malambo & Popescu 2020) and also using higher-resolution satellite images such as Sentinel-2. However, decreasing the resolution can introduce storage-related challenges and make it more difficult to conduct large-scale studies within the GEE platform. Taking these factors into account, future studies could focus on improving the spatial resolution of the FCC maps and obtaining more precise results. This can be achieved by exploring alternative methods for integrating datasets with varying resolutions or by leveraging advancements in remote sensing technology that provide higher-resolution data. Additionally, developing more efficient storage and processing techniques may help overcome the challenges associated with large-scale studies in the GEE environment.

Conclusions

This study demonstrates the potential of integrating ICESat-2 ATL08 segment data, Landsat satellite imagery, and Esri Sentinel-2 Land Cover datasets to effectively monitor forest canopy cover changes in regions like Antalya, which are characterized by rich biodiversity, recurrent forest fires, and rapid rehabilitation efforts.

The CCEM method proved to be successful, achieving accuracy percentages between 77% and 86%, despite the inherent challenges posed by the study area and the differences in spatial resolution among the datasets.

Future research should focus on refining the methodologies to minimize spectral misclassification, improving the spatial resolution of the FCC maps, and leveraging advancements in remote sensing technology to obtain more accurate and reliable results.

By addressing the limitations identified in this study and building upon the current findings, researchers and practitioners can enhance forest monitoring capabilities and contribute to more informed decision-making in forest management and conservation efforts.

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