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Assessing the Influence of Acquisition Time in Forest Canopy Cover Estimation Using ICESat-2 ATL08 Dataset

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Abstract

Aim of study: This study investigates the estimation success of using day and night segments in producing Forest Canopy Cover (FCC) maps with the Canopy Cover Estimation Model (CCEM) for the years 2020 and 2022.

Area of study: The study area covers 17 interconnected counties situated in the southeastern part of Texas state, adjacent to the state of Louisiana, and near the southern coastlines, known for their extensive forested areas.

Material and methods: This study incorporated both day and night acquisition segments from Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) data for a comprehensive comparison of their effectiveness in mapping the forest canopy cover using the CCEM.

Main results: The study's findings reveal that night segment-derived FCC maps outperform those derived from day segments, showing higher kappa coefficients of 0.77 and 0.83 for the years 2020 and 2022, respectively. In addition, notable differences were observed among classes of FCC estimations successes for day and night segment-derived maps.

Research highlights: This study introduces a significant finding that the FCC maps derived from night segments yield more accurate results than those derived from day segments. The study further discovers a notable difference in the forest canopy cover classification success, particularly with a lower accuracy observed in the Moderate Forest Canopy Cover (MFCC) category.

Keywords: Canopy cover, ICESat-2, ATL08, Google Earth Engine, Acquisition Time

ICESat-2 ATL08 Verileri Kullanılarak Veri Toplama Zamanının Orman Kanopi Örtüsü Tahmini Üzerindeki Etkisinin Değerlendirilmesi

Öz

Çalışmanın amacı: Bu çalışmada, 2020 ve 2022 yılları için Orman Kanopi Örtüsü Tahmin Modeli (CCEM) ile Orman Örtü Örtüsü (FCC) haritalarının üretilmesinde gündüz ve gece segmentlerinin kullanılmasının tahmin başarısı üzerine etkisi araştırılmaktadır.

Çalışma alanı: Çalışma alanı, geniş ormanlık alanlarıyla bilinen, Louisiana eyaletine bitişik, Texas eyaletinin güneydoğu bölgesinde yer alan ve güney sahil şeridine yakın olan 17 birbirine bağlı ilçeyi kapsamaktadır.

Materyal ve yöntem: Çalışma, ICESat-2/ATLAS verilerinden alınan hem gündüz hem de gece segmentlerini kapsayacak şekilde, orman kanopi örtüsü haritalarını CCEM kullanarak tahmin başarısı kapsamlı bir karşılaştırmasını gerçekleştirdi.

Temel sonuçlar: Çalışmanın bulguları, gece segmentlerinden elde edilen FCC haritalarının, sırasıyla 2020 ve 2022 yılları için 0.77 ve 0.83 daha yüksek kappa katsayıları göstererek, gündüz segmentlerinden elde edilenlere göre daha üstün olduğunu ortaya koymaktadır. Ek olarak, gündüz ve gece segmentlerinden türetilen haritalar için FCC tahmin sınıflarının başarıları arasında belirgin farklılıklar gözlemlenmiştir.

Araştırma vurguları: Bu çalışma, gece segmentlerinden türetilen FCC haritalarının, gündüz segmentlerinden türetilenlere göre daha doğru sonuçlar verdiğini ortaya çıkan önemli bir bulguyu ortaya çıkartmıştır. Çalışma ayrıca, özellikle Orta Seviyede Orman Kanopi Örtüsü (MFCC) sınıfından elde edilen daha düşük FCC sınıflandırma başarısını tespit etmiştir.

Anahtar Kelimeler: Kanopi Örtüsü, ICESat-2, ATL08, Google Earth Engine, Veri Toplama Zaman

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Introduction

Forests are one of our planet's most significant sources of oxygen and hold critical importance for sustaining the earth's biodiversity. Covering approximately one-third of the earth's landmass, forests provide habitat for more than half of terrestrial species. Forests constitute a delicate balance of an ecosystem, comprising not just a collection of trees but other flora, fauna, fungi, soil, water, and climate, all in a symbiotic relationship (Arnold et al., 2011). Amidst the current global climate crisis, protecting our forests has become one of our primary objectives. The initial stage of protection involves identifying the current state of forest ecosystems and determining necessary interventions. In this regard, the accurate and effective determination of stand parameters related to forests is of utmost importance.

Forest canopy cover (FCC) stands out as a key attribute among various forest stand characteristics, primarily defined as the proportion of forest ground covered by the vertical projection of tree crowns (Avery & Burkhart, 1994; Korhonen et al., 2006). The health of a forest can be substantially inferred through this parameter, making the accurate assessment and continual monitoring of FCC essential for comprehending the overall forest conditions and their role in climate change mitigation (Lausch et al., 2017; Pyngrope et al., 2021; Nasiri et al., 2022). This vital parameter finds its utility in a multitude of arenas, not confined to the evaluation of forest degradation (Qin et al., 2021) and the prediction of above-ground biomass (AGB) (Narine et al., 2020). It further extends to estimating habitat suitability (Latif et al., 2020) and analyzing the effects of disturbances on forest ecosystems (Yin et al., 2020). Thus, maintaining a comprehensive understanding of FCC is fundamental in forest-related studies.

While essential, traditional ground-based field sampling methods for FCC estimation can often be constrained by high costs, extensive time investment, and possible bias and uncertainties. These limitations become more pronounced when applied to larger-scale studies (Stojanova et al., 2010; McPherson et al., 2011). To overcome these challenges, integrating remote sensing technologies like satellite images and lidar point cloud data with ground-based measurements has become increasingly prevalent. This combination has significantly improved the efficiency of FCC estimation across various scales (Smith et al., 2009; Tang et al., 2019). Furthermore, the application of spaceborne laser altimeter systems, notably the Ice, Cloud, and land Elevation Satellite (ICESat), has shown potential in FCC estimation. These systems provide precise and reliable data that can be effectively used for FCC modeling and estimation (Herzfeld et al., 2013; Narine et al., 2019a; Narine et al., 2022; Akturk et al., 2023b).

Launched in 2018, the ICESat-2 satellite and its integrated Advanced Topographic Laser Altimeter System (ATLAS) (Markus et al., 2017) have instituted a pivotal role in the estimating of FCC and other forest stand parameters by performing meticulous measurements at the photon level. The ICESat-2 laser emits an impressive 10000 light beams per second toward the target object, comprising approximately 20 trillion photons within each beam. This innovative active system reduces the energy required for laser operation and achieves a remarkably high repetition frequency, leading to a substantial increase in sampling (Neuenschwander & Pitts, 2019). The system simultaneously projects six laser beams arranged in three pairs, spaced 3.3 km apart. Each pair features horizontal beam intervals of 90 meters. Furthermore, these beams vary in energy, comprising both weak and strong beams, with each beam creating a footprint of roughly 14 meters in diameter (Markus et al., 2017; Neuenschwander & Pitts, 2019).

The collected geolocation of photons procured from the ATLAS instrument produces the ATL03 Global Geolocated Photon product. This product, in synergy with the ATL08 Land and Vegetation Height product—a staple in forestry research—generates a comprehensive database, offering plenty of attributes segmented over 100-meter along-track segments to the end-users (Neuenschwander & Pitts, 2019). These attributes lay the groundwork for the execution of FCC estimations. Intriguingly, ATL08 comprises an attribute that signifies the timing of data collection, offering a selection to users between data acquisition during day or night segments. Given that active remote sensing technologies such as Lidar are not light-dependent, unlike optical sensors, this opens the door for night-time data aggregation. Furthermore, when operational at night, these systems extend a range of benefits, including proficient functioning in low-light conditions, heightened visibility, superior object detection, minimal disruption from light sources, expedited data processing, resilience to diverse weather conditions, and sophisticated 3D mapping capabilities (Wu et al., 2011; Luo et al., 2018). These noteworthy advantages could potentially escalate the prediction precision of specific forest stand parameters. As an illustration, several academic studies employing ICESat-2 data have discerned that data amassed during night hours can augment the predictive success in assessing aboveground biomass (Narine et al., 2019b; Varvia et al., 2022).

While previous research has investigated the effectiveness of photon data gathered at night in enhancing the accuracy of an AGB estimation, there needs to be more literature concerning the potential impact of photon data acquisition time on FCC estimation. This gap highlights a significant opportunity for further research, which this study aims to address. The primary objective of this study is to assess the influence of data acquisition time, particularly the distinction between day and night, on the accuracy of FCC estimation using ICESat-2 photon data. By utilizing the unique capabilities of the ICESat-2 and the ATL08 Land and Vegetation Height product, this study will endeavor to deliver new insights into the potential advantages and considerations of using night-collected data for FCC estimation. Additionally, the findings from this research are expected to contribute to the broader understanding of forest stand parameter estimation, which plays a vital role in understanding and managing our global forest resources effectively. In light of the global climate crisis, the importance of maintaining the health and stability of our forest ecosystems cannot be overstated. Precise and reliable FCC estimation is a crucial part of this effort. Thus, any enhancement in our understanding and methodologies in this area, such as the potential advantages of using night-collected data, is of utmost importance. This study, therefore, holds significant potential value for the field of forestry and the broader fight against climate change.

Material and Methods

Study Area

The designated study area for this research is strategically located within the United States. It encompasses 17 interconnected counties positioned in the southeastern part of Texas state, adjacent to the state of Louisiana, and near the southern coastlines (Figure 1). This specific selection was not arbitrary but rather a careful consideration, giving prominence to regions with a significant extent of forest cover. The rationale was to incorporate within the study domain a considerable share of the counties in Texas known for their extensive forested areas. The cumulative area of these selected counties provides a substantial study field, spanning an approximate total of 38000 square kilometers. This vast landscape presents a diverse array of natural resources and ecosystems, with a significant portion constituting forests. As corroborated by Esri's 2022 land use/cover data (Karra et al., 2021), forests make up around 67% of this area, indicating the prevalence and importance of forestry within this region.

The region's climate is characterized by warm and rainy summers, with substantial sunshine illuminating the area for a significant part of the year. This climatic condition is of particular interest to our study as it implies that the study area remains exposed to sunlight's influence, a key element with the potential to affect laser-based systems, for a considerable duration throughout the year. Hence, the study's geographic and climatic selection aligns with the research objectives and offers a dynamic field to explore the research questions.

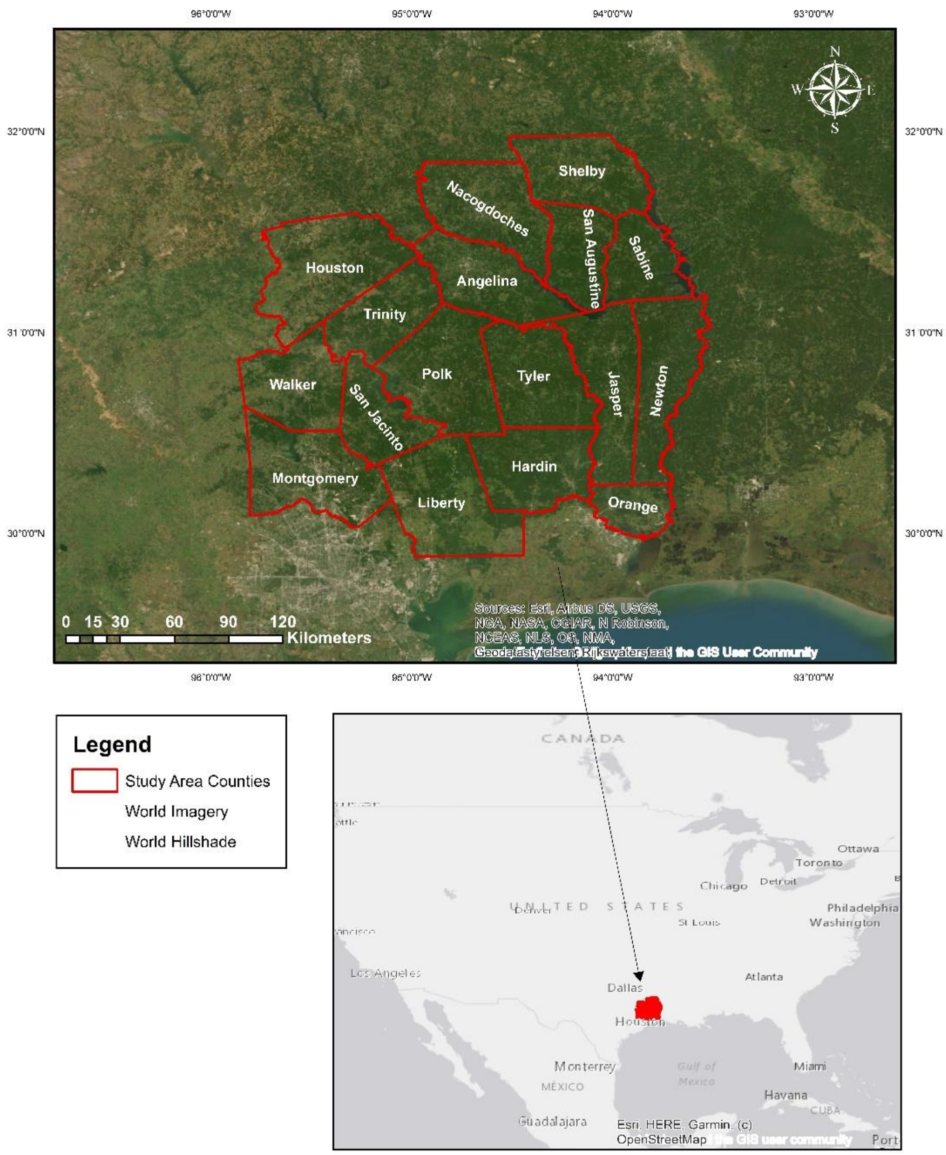

Figure 1. Study area and location of selected counties

Dataset and Canopy Cover Estimation Model (CCEM)

In this study, the ICESat-2/ATLAS Level 3A ATL08 Version 5 data products, formatted in HDF5, have been utilized. Access to these data was facilitated through NASA's Earth Data platform (The National Aeronautics and Space Administration, 2023). The data were filtered according to the defined boundaries of the study area and downloaded separately for 2020 and 2022. The ATL08 data collected during the leaf-on season of the trees in the study area, which spans from June to August, were selected to enhance the estimation success. A total of 17 appropriate granules for the year 2020 and 21 for the year 2022 were identified. The segment data in these granules were then compiled, creating two distinct datasets for the respective years. Just as we scrutinized the study area, the primary objective here is to discuss the selection and processing of the data that underpin this research. An integral part of this involves delineating the strategic choice of ATL08 data during the leaf-on season, which potentially optimizes the success of the canopy cover estimation. Furthermore, this section expounds upon the steps taken in data processing, including filtering and data downloading for different years and merging segment data within granules for each year. This meticulous and systematic approach to data selection and processing is paramount to achieving the research objectives and enhancing the reliability and validity of the results.

This study utilizes the Canopy Cover Estimation Model (CCEM), developed by Akturk et al. (2023b), employing a few modifications to estimate FCC. Fundamentally, the implementation of CCEM involves three critical stages:

1. Identifying the necessary ATL08 attributes required for the application of the model, defining FCC classes, and eliminating noise segments,
2. Determining and processing the satellite images to be used for generating comprehensive wall-to-wall FCC maps, followed by the production of vegetation indices,
3. Ultimately, conducting classification through an advanced machine learning algorithm, followed by rigorous model performance testing.

To effectively deploy the CCEM, one must gather several attributes for each segment, such as latitude, longitude, canopy height (h_canopy), the number of terrain photons (n_te_photons), the number of top of canopy photons (n_toc_photons), and the number of canopy photons (n_ca_photons). Notably, this study employs the night_flag attribute to determine the acquisition time, thus segregating the segments into day and night categories (Neuenschwander et al., 2021).

Data concerning the quantity of canopy and terrain canopy photons is important in determining the percentage FCC with CCEM according to a specified Equation (1):

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

The geographic locations of the segments are determined using latitude and longitude attributes, while the remaining attributes help filter out noise segments. For more detailed information on these filtering processes, please refer to the original CCEM article (Akturk et al., 2023b).

FCC classes can be customized within CCEM to cater to user needs. In this study, we adhered to the classes outlined in the sample study provided by CCEM (Akturk et al., 2023b). Areas demonstrating less than 10% FCC were excluded from classification, being beyond the scope of the Food Agriculture Organization (FAO) forest definition (FAO, 2014). Areas with 10-40% coverage were designated as Sparse Forest Canopy Cover (SFCC), 40-70% as Moderate Forest Canopy Cover (MFCC), and those with more than 70% coverage were classified as Dense Forest Canopy Cover (DFCC).

ICESat-2 ATL08 segments in 100 meters size and require auxiliary data to produce comprehensive wall-to-wall FCC maps (Liu & Popescu, 2022). CCEM is a model created using Landsat 8 satellite images with a spatial resolution of 30 meters, and these satellite images were preferred in this study. A composite image was generated by selecting the most suitable pixels for 2020 and 2022 between June 1 and August 31, from which 26 unique vegetation indices were established (Akturk et al., 2023b). For the same years, the forest classes of ESRI 10m Land Use/Land Cover maps (Karra et al., 2021) were employed to mask index images. This dataset was the preferred choice to circumvent the margin of error derived from the Copernicus Land Cover 2019 data (Buchhorn et al., 2020) used in the CCEM example study and offset any temporal discrepancies among the data (Akturk et al., 2023b).

The Canopy Cover Estimation Model (CCEM) was originally created as a JavaScript-based model for Google Earth Engine (GEE) use. However, to make it suitable for the specific needs of this study, certain modifications were implemented to enable it to separately utilize day and night segments for the years 2020 and 2022. As a result of these changes, four different 100-meter resolution FCC maps were produced for the study area. During the creation of these maps, 80% of the filtered segments were employed to train the model, while the remaining 20% were reserved for testing the output of the model. The Collect Earth platform was deployed to visually assess the output FCC maps across approximately 1500 cells using high-resolution satellite imagery (Akturk et al., 2023a). This thorough and detailed evaluation provided a highly valuable means of accurately evaluating the accuracy of the study.

Results

In alignment with the objectives of this study, the CCEM was employed to generate four different FCC maps for the years 2020 and 2022. The approach was taken to separately utilize day and night segments in creating these maps, which are shared in Figure 2. As previously stated, the CCEM strategically uses 80% of all segments introduced into the GEE for training the model. The remaining 20% is reserved for validating and testing the model's performance. Adopting this method, the FCC map for 2020, derived from day segments, yielded an average accuracy rate of 74.8%. Similarly, for the 2022 FCC map produced with the day segments, the model exhibited an accuracy of 77.1%. In comparison, the FCC maps generated from night segments demonstrated a slightly different model performance, reaching a success rate of 73.2% for 2020 and 77.4% for 2022.

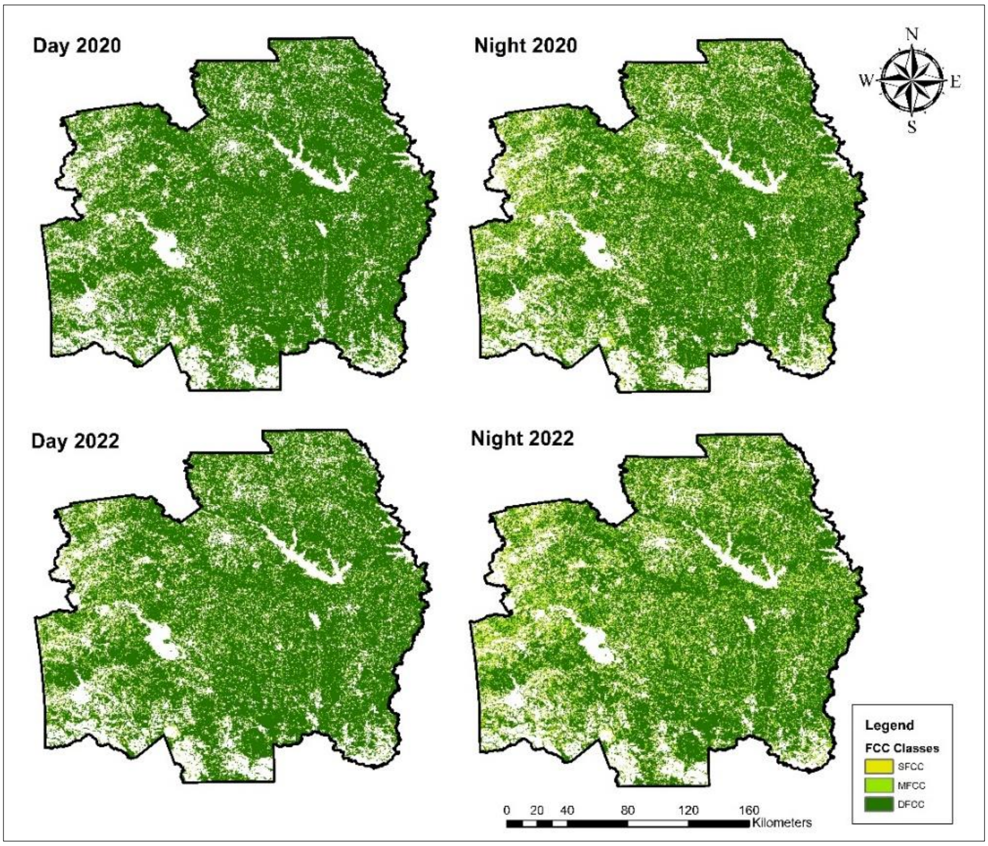

Figure 2. 2020 and 2022 FCC maps derived from day and night segments separately. FCC classes are; Sparse Forest Canopy Cover (SFCC ‹ 40%), Moderate Forest Canopy Cover (MFCC between 40-70%), and Dense Forest Canopy Cover (DFCC › 70%).

The quantitative results, categorized according to FCC classes derived from maps, are outlined in Table 1. A notable observation from these findings is the contradictory trend of decreasing canopy cover within the study area from 2020 to 2022, despite the concurrent increase in the total area covered by forests. This highlights an intriguing dynamic in forest development and canopy spread during the specified period. Furthermore, a noteworthy difference was observed in the FCC class distributions between maps generated using day and night segments. The maps produced using day segments estimated the DFCC class to be approximately 10% higher than the estimates produced with night segments. Conversely, the day-segment-derived maps were estimated less than those generated from night segments for other classes.

Table 1. Areal distribution of FCC maps of 2020 and 2022 produced with day and night segments according to canopy cover classes

FCC Classes		Percentage Area (%)		
		SFCC	MFCC	DFCC
Day	2020	5.37	7.79	86.84
	2022	6.92	10.43	82.65
Night	2020	11.67	14.71	73.63
	2022	13.55	16.32	70.13

The interpretation of these divergent results necessitates an examination of prediction accuracies and the subsequent accuracy assessment values. The above information about prediction success must conclusively establish whether the day or night segments yield more accurate canopy cover predictions. Therefore, the results from visual evaluations on many segments are essential to comprehensively understand the outcomes (Table 2).

Table 2. Confusion matrix results for 2020 and 2022 FCC maps produced with day and night segments. 2020 results colored red while 2022 results colored blue. OA stands for Overall Accuracy.

FCC Maps		Confusion Matrix Metrics							
		User's Accuracy (%)			Producer's Accuracy (%)			OA (%)	Kappa
		SFCC	MFCC	DFCC	SFCC	MFCC	DFCC		
Day	2020	94.71	76.08	89.64	78.53	75.88	93.23	86.66	0.75
	2022	91.71	83.05	92.23	87.19	81.88	93.92	89.60	0.81
Night	2020	84.68	77.15	92.31	86.34	79.69	90.56	87.13	0.77
	2022	87.15	83.87	93.92	92.68	84.47	92.20	90.08	0.83

In this study, a total of 1500 segments for both 2020 and 2022 were visually evaluated using the Collect Earth methodology (Akturk et al., 2023a), examining high-resolution satellite imagery corresponding to each segment. Due to the unavailability of satellite imagery for some segments in either 2020 or 2022, additional segments were incorporated to ensure a total of 1500 evaluated segments each year, resulting in an overall assessment of more than 3000 segments. For some visual evaluations, the Normalized Difference Vegetation Index (NDVI) values of the geographic areas where the segments were located were also examined with GEE for each respective year. This additional analysis of NDVI values, coupled with the satellite imagery, aimed to enhance the reliability of these segments when used as ground truth data. The results shared in Table 2 provide valuable insights addressing the research questions. Both for 2020 and 2022, it is observed that the FCC maps produced using night segments demonstrated a higher accuracy than those derived from day segments. Interestingly, regardless of the time of segment collection, the FCC maps generated for 2022 achieved higher Kappa values than those for 2020. This might be an indicator of the advanced processing or increased reliability of data over the years. Upon examining the confusion matrix metrics, it is notable that the Moderate Forest Canopy Cover (MFCC) prediction success significantly trails that of other classes. This points towards an area that might require further model tuning or investigation. Conversely, the Dense Forest Canopy Cover (DFCC) class was consistently well-defined across all maps, signifying the model's effectiveness in distinguishing dense canopy coverage areas. This attests to the accuracy of the CCEM in predicting areas of high forest density.

Discussion and Conclusion

The CCEM presents a robust tool for forest canopy cover estimation. Its application in this study has proven beneficial in estimating the FCC, emphasizing its role in helping us understand and monitor forest dynamics over time. However, like any model, the CCEM is not without its limitations. One area of potential refinement is within the MFCC class classification, where accuracy trailed those of the SFCC and DFCC classes. However, in addition to this finding, this study also provided us with important information about the study's main question.

The study's findings have drawn attention to the intriguing variation in FCC estimations between day and night segment acquisitions. The higher accuracy rates associated with night acquisitions resonate with the results from biomass estimation studies conducted by Narine et al. (2019b) and Varvia et al. (2022). In another study, Neuenschwander et al. (2020) validated canopy and terrain heights obtained from ICESat-2 in Finland using airborne lidar data. This investigation not only assessed the impact of weak and strong beams on prediction accuracy but also examined the variations due to seasons and differences between day and night acquisitions. The results align with findings from this study, indicating that the highest prediction accuracy is achieved through strong beam/night/summer ATL08 acquisitions. The superiority of night-time data may be tied to fewer atmospheric disturbances and reduced sun glint, which poses challenges to the accuracy of the estimations. Further research into the difference between day and night data acquisition and its potential benefits would prove insightful.

The model's relatively lower success rate in predicting the MFCC class warrants closer inspection. The heterogeneity of forest areas with moderate canopy cover, which often contains a diverse mix of tree species, sizes, and densities, presents a challenge for any model. A more granular approach, including high-resolution imagery or integrating species-specific parameters, could help enhance the model's predictive power in these areas.

Regarding the difference in FCC map accuracies between 2020 and 2022, the study has noted higher accuracy for the latter year. This implies that there have been advancements in data processing techniques or perhaps an increase in data reliability, demonstrating the evolving nature of remote sensing technologies and their capacity for improvement over time.

Future research should explore the observed differences in the day versus night acquisitions and annual map accuracies in more depth and find ways to refine classification methods for the MFCC class. An enhanced understanding of these areas can only lead to the development of more accurate, reliable tools for forest cover estimation.

In conclusion, this study has illuminated the value of the CCEM in predicting FCC, emphasized the crucial role of selecting the correct time for data acquisition, and highlighted the continuous need for model refinement. These findings hold significant implications for the field of forestry research and sustainable forest management practices, marking a step forward in our capacity to monitor and understand forest dynamics on a global scale.

Ethics Committee Approval

N/A

Peer-review

Externally peer-reviewed.

Author Contributions

Conceptualization: E.A..; Investigation: E.A.; Material and Methodology: E.A.; Visualization: E.A.; Writing-Original Draft: E.A.; Writing-review&Editing: E.A. Author has read and agreed to the published version of manuscript.

Conflict of Interest

The authors have no conflicts of interest to declare.

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