Quantifying Hakalau Forest Recovery from 1990 to 2024 Using Landsat and Sentinel NDVI Data

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Introduction

Tropical forest ecosystems are the most biodiverse on Earth[1]. Housing 80% of known species, they are critical habitats that support important ecological processes and ecosystem services[2]. Over the past few centuries, deforestation has threatened these ecosystems, putting thousands of species at risk of endangerment and extinction[3]. The Hawaiian islands support tropical ecosystems with approximately 90% endemic species and are a region of primary concern for forest restoration and management.

The decline of Hawaiian forests began with the introduction of livestock in the late 1700s. Cattle, goats, and pigs grazing freely on native plants decimated them, leading to the proliferation of grasses and invasive shrubs[4]. Additionally, the arrival of non-native species brought new diseases to the islands, with avian malaria particularly devastating native forest bird populations[5]. In response to declining bird species on Hawaii's Big Island, the U.S. Fish and Wildlife Service (FWS) established the Hakalau Forest National Wildlife Refuge in 1985 on Mauna Kea's eastern slope. Covering nearly 33,000 acres, the reserve aims to conserve habitats for species such as the ʻākepa, ʻakiapōlāʻau, and ʻiʻiwi[5]. In 2006, the Friends of Hakalau Forest National Wildlife Refuge was established to further support these conservation efforts.

While replantation has been widely considered successful by the Friends of Hakalau, a quantitative measure of forest regrowth is needed to fully understand the impact of conservation in Hakalau. The application of remote sensing technologies can be applied to the region to understand forest regrowth since replantation began in the 1980's. Here, we apply remote sensing analysis of Landsat data to quantify tree growth in the Hakalau Forest from 1990 to 2024. Understanding tree growth will allow conservationists to better assess the success of their efforts and update their strategies.

Methods

Here, we use Normalized Difference Vegetation Index (NDVI) to quantify Hakalau Forest regrowth from 1990 to 2024. NDVI values are derived from imagery obtained from satellites such as Landsat and Sentinel-2. These satellites offer enhanced spatial, spectral, and temporal resolution, providing accessible data for land monitoring[7]. Landsat, operational since 1972, captures up to 11 spectral bands, making it valuable for tracking long-term land-use changes. Sentinel-2 was launched in 2015, and samples 13 multispectral bands every five days, providing finer spatial resolution (up to 0.3 meters) that is particularly suited for forest analysis and change detection[8]. However, the higher resolution data from Sentinel-2 results in larger data packages, which can present accessibility challenges. Landsat's lower resolution (30 meters) and extensive historical record make it a more user-friendly option.

Combining data from both satellite programs, we aim to create a simple, free, and easy to follow resource for non-profit organizations actively restoring Hakalau Forest to continue to monitor their progress.

To calculate the NDVI and perform associated analyses, satellite data from the Landsat 8-9 OLI/TIRS C2 L1 mission was utilized. The data was obtained using the USGS Global Visualization Viewer (GloVis) by first locating the Big Island of Hawaii (approximately 20N, 155W) on the map interface. The dataset was selected by filtering for the acquisition date of July 16, 2024, and downloading the relevant bands, specifically Band 4 (Red) and Band 5 (Near-Infrared). These bands were chosen because they are required for NDVI calculation, with Band 4 used for vegetation detection and Band 5 used for assessing vegetation health[9].

Image selection included carefully reviewing GloVis frames to avoid cloud coverage issues and patterned lines from Landsat 7 scan line corrector failures[10].

After downloading the necessary data, it was uploaded into ArcGIS Pro. The first step in the processing was to ensure that all datasets were projected correctly. The map was set to the WGS 1984 UTM Zone 5N projection, and both Band 4 and Band 5 rasters were reprojected using the "Project Raster" tool to match the required coordinate system. A new shapefile, New_Forest, was created to clip the projected raster layers to the study area, ensuring only relevant data was retained to facilitate a timely analysis.

The next step was to calculate the NDVI using the reprojected and masked raster bands. NDVI was calculated using the formula[11]: (Band 5−Band 4)/(Band 5+Band 4)(Band 5−Band 4)/(Band 5+Band 4), which was executed using the "Raster Calculator" in ArcGIS Pro. The resulting NDVI raster was then symbolized using a "Minimum Maximum" stretch, with pixel values scaled between 0 and 1 to represent the range of vegetation cover, where higher values indicate dense[11].

To perform Boolean analysis on the NDVI raster, threshold values were determined by examining pixel values in areas of interest. Three threshold values were tested (0.34, 0.35, and 0.36) to generate more conservative or liberal estimates of tree cover. Using the "Raster Calculator," a conditional function was applied: `Con(your_raster_name > 0.35, 1, 0)`, where pixel values above the threshold were classified as trees (1) and those below the threshold as non-tree cover (0). The output raster was symbolized using the "Unique Values" option to differentiate between tree and non-tree cover.

Finally, to calculate the area of tree cover, the "Attribute Table" of the Boolean raster was opened. The total number of pixels with a value of 1 (representing tree cover) was multiplied by the pixel area (900 m^2, assuming a 30-meter cell size) to obtain the total area of tree cover in square meters.

Additionally, the NDVI data from Sentinel-2 was accessed through ArcGIS Online, with the data sourced from the "USA NAIP Imagery" collection. Boolean analysis for tree cover classification was performed by selecting a threshold value of 0.29, based on pixel values identified during data inspection. The "Raster Calculator" was again employed to apply a conditional function to the dataset, classifying pixels as tree cover or non-tree cover. This analysis followed similar procedures as those used for the Landsat NDVI dataset, ensuring consistent processing and classification. To ensure accuracy, threshold value results were visually compared with Google Earth satellite imagery

Due to high NDVI background levels (likely due to green grass cover in the clear-cut regions), we then performed a similar analysis with NDMI to supplement our threshold value determination.

To do this, we used the Copernicus Sentinel-2 L2A dataset, which has a higher spatial resolution (but a much more limited temporal range). The moisture index data was obtained from the focusing on NDMI bands 8 (Near-Infrared) and 11 (Short-Wave Infrared)[11]. This dataset was downloaded using the Copernicus Open Access Hub by selecting the appropriate forest reserve area and specifying the image format as TIFF 16-bit, with a high resolution and a coordinate system set to UTM 5N. The moisture index layer was used for reference purposes, while the raw bands 8 and 11 were processed in a similar manner to the NDVI bands. The data was reprojected and masked using the same methods as for the NDVI dataset, ensuring consistency in spatial reference and study area coverage.

A similar Boolean analysis was performed on the moisture index data, where pixel values were thresholded based on observed data points. The threshold values chosen for this analysis were 25,000, 25,500, and 26,000, which were tested to produce more accurate or conservative estimates of tree cover. Using the "Raster Calculator," a conditional expression was applied to classify areas of tree cover based on the moisture index values. Finally, the total area of tree cover was calculated by counting the number of pixels with a value of 1 and multiplying by the corresponding pixel area (354.3156 m^2, based on an 18.825-meter cell size).

Landsat NDVI, Sentinel 2-derived Moisture Index, and Sentinel-2 NDVI values were then compared. Using this information, we concluded that the most conservative Landsat NDVI threshold values were likely to provide the most accurate estimate for tree cover. These conservative estimates were therefore applied to the historical Landsat images to determine changes in forest through time.

Results

To quantify reforestation efforts in Hakalau Forest, we measured changes in Landsat-derived NDVI from 1990 to 2024. Landsat imagery was chosen for this study due to its long temporal record, which allowed us to track changes in reforestation over several decades. This method is particularly advantageous for land management organizations with limited resources, as it provides a cost-effective and accessible approach to monitoring reforestation progress over time. Our initial approach was focused on using NDVI to measure tree growth, distinguishing "green" areas (tree cover) from "non-green" areas (clear-cut), though the process was more complicated than initially anticipated due to the presence of grasses, which could also register as green.

Assumptions and Data Selection

For the initial analysis, we assumed a 100% clear cut area in 1990, which was based on visual inspection of imagery from that year and confirmation from the Friends of Hakalau that the area had been largely cleared before reforestation efforts began. The year 1990 also offered the earliest available consistent Landsat imagery for the area and was a reliable starting point for tracking the reforestation process.

Landsat and Sentinel NDVI Analysis

Applying different NDVI thresholds to Landsat imagery led to varying reforestation estimates, ranging from 6.83 km^2 to 10.9 km^2, or 49% to 78% regrowth (Fig. 1). To refine our estimates, we utilized USA NAIP Sentinel-2-derived NDVI calculations, which estimated regrowth at 45.3%, corresponding to 7.67 km^2 (Fig. 2). Sentinel imagery was not used for the full study due to its limited temporal range, starting only in 2014, and the large dataset size, which proved computationally intensive and less user-friendly.

Sentinel Moisture Index Analysis

In an effort to improve the accuracy of our estimates further, we explored the use of Sentinel-derived Moisture Index data. The Moisture Index provides information on the water content of vegetation, which can help in distinguishing tree cover from other vegetation types. We applied three different threshold values to the Moisture Index data, ranging from least to most conservative. The estimates generated by this method were 7.492 km^2 (53.2%), 7.959 km^2 (56.5%), and 8.368 km^2 (59.4%) regrowth, respectively (Fig. 3). This analysis helped us refine our threshold values and provided a further layer of confidence in our reforestation estimates.

Final Estimate of Reforestation Progress

By combining the threshold findings from both Landsat-derived NDVI and Sentinel-derived Moisture Index data, we determined that the most conservative Landsat NDVI threshold provided the most reliable estimate of tree cover through time. Using this threshold, we were able to track reforestation progress from 1990 to 2024 (Fig. 4). The first data point, from 1990, reflects no forest cover (0%) at the time of analysis. By 2000, green area had increased to 1.22 km², or 8.82%. By 2014, the green area had expanded to 4.74 km², representing 34.13% regrowth. In 2024, our estimate places the forest recovery at 49.1%, or 6.83 km². These findings demonstrate that approximately 50% of the forest has been restored since the initiation of reforestation efforts in 1989, highlighting the significant progress made in Hakalau Forest's restoration over the past three decades.

Discussion

This study provides a comprehensive analysis of the reforestation efforts in Hakalau Forest, utilizing Landsat-derived NDVI data to track changes in forest cover from 1990 to 2024. Our results demonstrate significant progress in reforestation, with an estimated 50% regrowth in the clearcut area (6.83 km²). The combination of Landsat NDVI analysis, Sentinel-2 imagery, and Sentinel-derived Moisture Index data offered a comprehensive approach to monitoring and refining the accuracy of our estimates. Our findings highlight the potential of using Landsat as a cost-effective and accessible tool for organizations with limited resources to track long-term reforestation progress.

One of the primary challenges included establishing an appropriate NDVI threshold to distinguish between Koa forest and other vegetation types, such as grasses. High background NDVI values, in addition to frequent cloud cover, resulted in a large range of restoration estimates. Such variability highlights the challenge of using NDVI alone to differentiate between vegetation types. Our analysis demonstrated that slight changes in threshold values had significant impacts in determining reforestation area, with a range from 6.83 km² to 10.9 km².

The use of Sentinel-2 imagery was a valuable tool for refining this. While the higher spatial resolution of this data allowed for a more precise classification of vegetation types and an estimate of 45.3% regrowth (7.67 km²), it failed to offer an extensive analysis of change throughout time. This limitation in temporal coverage highlights the importance of Landsat data for long-term forest monitoring.

Incorporating Sentinel-derived Moisture Index data into our analysis further improved the accuracy of our estimates. The Moisture Index provided additional insight into vegetation water content, helping to refine the NDVI thresholds and enabling more accurate differentiation between tree cover and other vegetation types. By using three different threshold values, we obtained a range of estimates that helped validate our findings and provided a more nuanced understanding of the extent of reforestation.

Ground truthing, however, is a necessary next step in confirming the success of restoration efforts. Verification of the results of this remote sensing analysis will be necessary to assess the accuracy of our estimates and provide a comprehensive measure of ecological impacts of reforestation in the Hakalau Forest.

Conclusion

This study provides a detailed analysis of the reforestation progress in Hakalau Forest. Using Landsat-derived NDVI data, we found significant progress in the restoration efforts, with reforestation reaching approximately 6.83 km^2 since restoration began in 1985. The restoration of Koa trees has been a key part of this success, helping to revive critical habitat for endangered species, such as the i'iwi and akiapōlāʻau. While the results are promising, the forest still faces challenges from disease, invasive species, and climate change. Continued efforts from volunteers and staff, along with sustained monitoring, will be essential to ensure the long-term success and resilience of the restoration process in the face of these ongoing threats.

References

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Figures

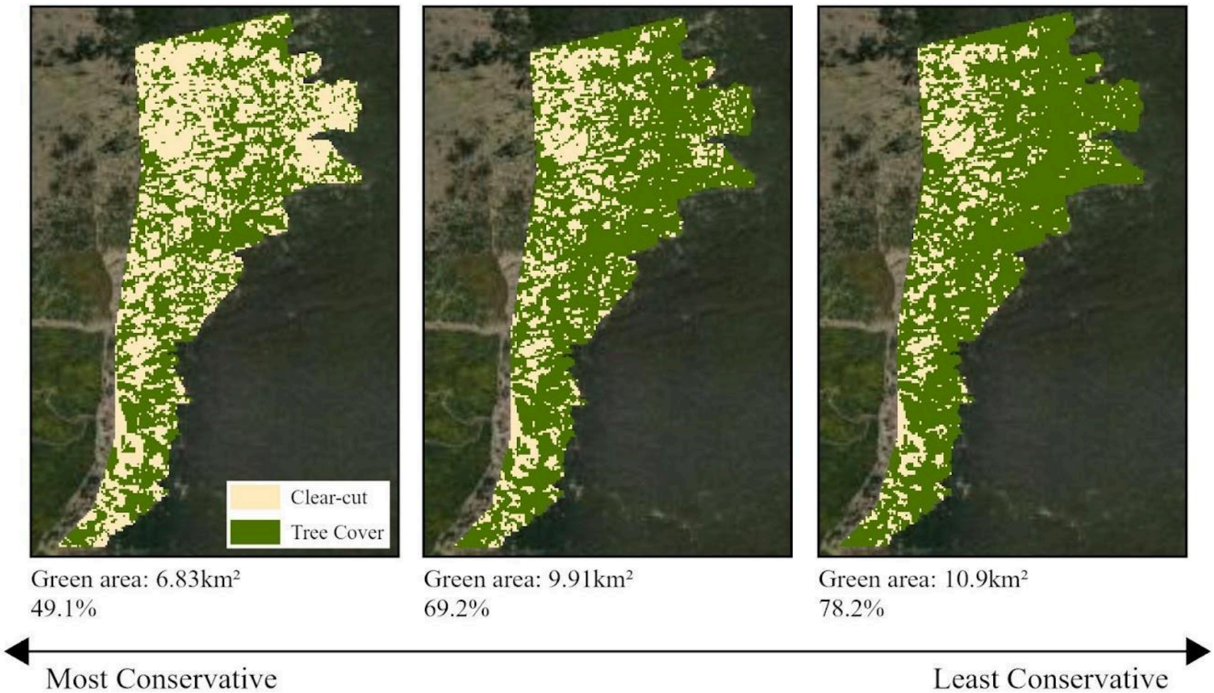


Fig. 1. Boolean NDVI threshold analysis of Landsat 8-9 OLI/TIRS-derived imagery, ranging from the most conservative to the least conservative estimate of tree cover regrowth in Hakalau Forest. The analysis applied varying NDVI threshold values to identify areas of tree cover. The resulting estimates of forest regrowth varied from 6.83 km^2 (49%) to 10.9 km^2 (78%), reflecting different levels of conservatism in estimating tree cover.

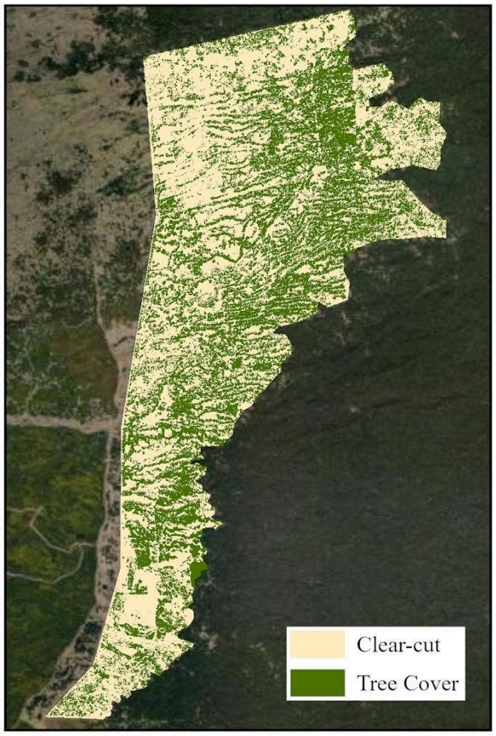
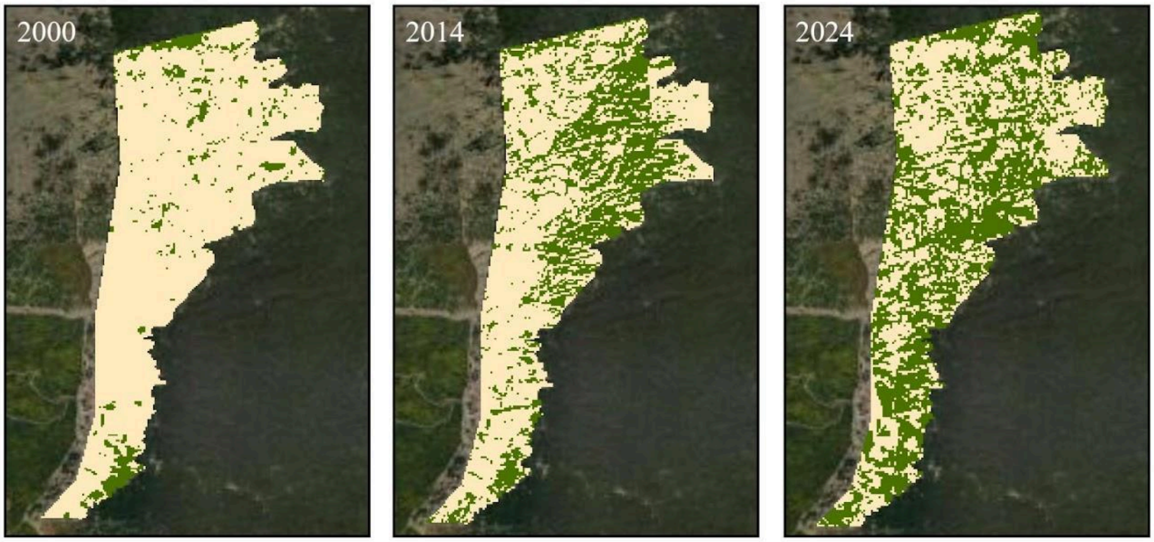


Fig. 2. Boolean analysis of Sentinel NDVI Imagery from USA National Agriculture Imaging Program (NAIP), assessing tree cover regrowth in Hakalau Forest. This image provides a high-resolution look into tree cover and serves as a reference for evaluating reforestation progress over time.

Green area: 7.67km²
45.3%

Fig. 3. Boolean Moisture Index (NDMI) threshold analysis of Sentinel-2-derived imagery, from the most to least conservative estimate of tree regrowth in Hakalau Forest. The analysis applied varying NDMI threshold values to identify areas of tree cover based on moisture level. The resulting estimates of forest regrowth varied depending on the threshold, reflecting different assumptions about moisture-related tree cover. This analysis provides an alternative method of assessing reforestation progress, particularly in areas with high moisture variability.



Green area: 1.227km²
8.82%

Green area: 4.74km²
34.13%

Green area: 6.83km²
49.1%

Fig. 4. Final estimate of reforestation progress in Hakalau Forest (1990–2024), based on a conservative Landsat-derived NDVI threshold. The figure tracks the expansion of tree cover, starting with 0% forest cover in 1990 and ending with 49.1% cover by 2024.