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Integration of very high-resolution stereo satellite images and airborne or satellite Lidar for Eucalyptus canopy height estimation

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ABSTRACT

Eucalyptus plantations cover extensive areas in tropical regions and require accurate growth monitoring for efficient management. Traditional in-situ measurements, while necessary, are labor-intensive and impractical for large-scale assessments. Very high-resolution satellite stereo imagery is playing an increasingly important role in the estimation of fine Digital Surface Models (DSMs) across landscapes. However, its ability to estimate canopy height models (CHMs) has not been widely investigated. This study investigates the integration of high-resolution satellite stereo imagery from the Pleiades sensor with airborne or satellite Lidar data to estimate canopy height over eucalyptus plantations. Two study sites were selected in Brazil, representing flat and semi-mountainous topographies, Mato Grosso do Sul (MS) and Sao Paulo (SP), respectively. Digital Surface Models generated from Pleiades images (DSM_P) were combined with Digital Terrain Models extracted from airborne Lidar data (DTM_{ALS}) to create Canopy Height Models (CHM_{ALS}). The evaluation of the CHM_{ALS} was based on two in situ canopy height measurements (H_{max} and H_{mean}). For the SP site, the CHM_{ALSmax}, which is the average height of top 10% pixel values within each plot, correlated well with in situ H_{mean}, which is the average height of 10 central trees (r = 0.98), showing a bias of 1.4 m, RMSE of 3.1 m, and rRMSE of 18.5%. At the MS site, CHM_{ALSmax} demonstrated a bias of 1.9 m, RMSE of 2.3 m, rRMSE of 17.3%, and r correlation of 0.92. Despite a tendency to underestimate heights below 20 m in young tree plantations with open canopy, the results indicate reliable canopy height estimation. The study also investigates the potential of Global Ecosystem Dynamics Investigation (GEDI) elevation data as an alternative to DTM_{ALS} in absence of airborne Lidar data. The resulting CHM_{Gedi} is promising but slightly less accurate than Lidar-based CHMs. The best GEDI-based CHM ($CHM_{Gedimax}$) showed a bias and rRMSE of 1.3 m and 20.5% for the SP site, and 2.2 m and 24.9% for the MS site. These findings highlight the potential for integrating Pleiades and Lidar data for efficient and accurate canopy height monitoring in eucalyptus plantations.

Abbreviations: DSM, Digital Surface Model; DSM_P, Digital Surface Models generated from Pleiades images; ALS, Airborne Lidar System; DTM_{ALS}, Digital Terrain Models extracted from airborne Lidar system; MS, Mato Grosso do Sul; SP, Sao Paulo; H_{max}, Maximum height; H_{mean}, Mean height; CHM_{ALS}, Canopy Height Model extracted from DSM_P and DTM_{ALS}; CHM_{ALSmax}, Maximum height from CHM_{ALS}; $CHM_{ALSmean}$, Mean height from CHM_{ALS}; GEDI, Global Ecosystem Dynamics Investigation; DTM_{Gedi}, The GEDI elev_lowestmode_a1 metric; CHM_{Gedi}, Canopy Height Model extracted from DSM_P and DTM_{Gedi}; $CHM_{Gedimax}$, Maximum height from CHM_{Gedi}; $CHM_{Gedimean}$, Mean height from CHM_{Gedi}; SGB, Brazilian Geodetic System.

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1. Introduction

Eucalyptus plantations cover approximately 20 million hectares worldwide to produce raw material for the industry like pulp and paper, timber wood and wood panels as well as large amount of firewood and charcoal for domestic use in tropical and subtropical countries (CIRAD - FRA et al., 2018). Monitoring canopy height is important for optimizing harvesting practices and promoting sustainable forest management. Conducting in-situ measurements, especially in mountainous areas, is laborious, costly, and time-consuming, often requiring extensive fieldwork that may not be practical or feasible on a large scale or at high frequency.

Remote sensing approaches has provided advantages over traditional inventory methods for mapping Eucalyptus plantation (Silva et al., 2013; Chen et al., 2021; Zhang et al., 2023) and specifically canopy height estimation using Lidar technology (Baghdadi et al., 2014; Picos et al., 2020; Fayad et al., 2021a). Freely available spaceborne Lidar like Ice, Cloud, and land Elevation Satellite (ICESat) and Global Ecosystem Dynamics Investigation (GEDI), with its global coverage, offers a practical solution for large-scale assessments. While providing reasonable accuracy, especially in areas with gentle slopes, the data density and revisit time is relatively low compared to airborne Lidar data. On the other hand, airborne Lidar data, with its higher spatial resolution, provides a more detailed representation of the forest canopy, but is more expensive to acquire. Balancing these considerations, the synergistic integration of Lidar and high resolution optical data has been used to optimize the accuracy of canopy height estimation over natural forest, while overcoming the challenges associated with data cost, resolution and acquisition methods (Li et al., 2020; Tolan et al., 2024).

High-resolution satellite stereo imagery allows periodic measurement of forest canopy, with advantages in temporal resolution and regional coverage. Studies have evaluated the feasibility of mapping forest height based on image photogrammetry using IKONOS stereo imagery (St-Onge et al., 2008) and Worldview-1/2/3 stereo imagery (Montesano et al., 2019). Ni et al. (2014) found that canopy height derived from ALOS/PRISM stereo imagery was correlated well with airborne large footprint Lidar data (RMSE = 2.6 m, R2 = 0.74). Lin et al. (2020) estimated forest canopy height using a combination of ICESat-2 data and ZY-3 satellite stereo images, achieving an RMSE of 3.34 m–3.47 m and an R^2 of 0.51. Liu et al. (2019) produced a canopy height map of poplar plantations using a combination of stereo and multispectral data from China's ZY3-02 stereo mapping satellite with an R^2 of 0.72 and an RMSE of 1.58 m. Du et al. (2024) evaluated the potential of China's Gao Fen-7 (GF-7) satellite, equipped with a two-line array stereo mapping camera and a laser altimeter, for measuring forest terrain and canopy height. The study demonstrated the capability of GF-7 data in forest resource monitoring, achieving an R^2 of 0.88 and RMSE of 2.98 m for canopy height estimates compared to Airborne Laser Scanning (ALS) data, and even higher accuracy ($R^2 = 0.96$, RMSE = 1.23 m) when accounting for forest types at the sub-compartment scale. A recent study by Wang et al. (2023), further investigated the capability of stereo-based canopy height model (CHM) from WorldView-2 over five woody parks in Columbus, Ohio. Their study found that the stereo imagery captured similar spatial patterns to those derived from ALS data but tended to overestimate CHM when used alone. By integrating stereo-based CHM with vegetation indices from Landsat 7 and applying machine learning methods, they significantly improved CHM estimation. Among six tested machine learning methods, the Gradient Boosting Regression method provided the most reliable CHM estimates, with a correlation coefficient of 0.64 and an RMSE of 3.1 m (11.1%). In a study by Piermattei et al. (2019) in Alpine forests, forest metrics including maximum height (H_{max}), height percentile (H_{p95}, H_{p50}) and canopy gaps within each cell of a 50m grid were derived from the Pleiades canopy height model and the reference aerial CHM provided by the Swiss national forest inventories (NFI) with a spatial resolution of 1 m. They reported that for a study site with aerial and satellite images acquired almost at the same time, the medians of H_{max} and H_{p95} errors were −0.25 m and 0.33 m, respectively. Based on their results, Pleiades CHM could be a useful alternative to aerial image-matched CHM for monitoring forest metrics and canopy gaps in mountain forests when acquired during leaf-on conditions.

Very high resolution Pleiades data (70 cm at nadir for panchromatic spectral mode) with a 20 km swath and short repeat intervals (26 days), available from authorised distributors or directly from Airbus Defence and Space, although not freely available, could provide a cost-effective option to replace expensive airborne Lidar datasets. This study, which aims to provide a cost-effective solution for periodic monitoring of canopy height over Eucalyptus plantations, uses Pleiades stereo imagery to generate Digital Surface Models (hereafter referred to as DSM_P) and an existing Digital Terrain Model extracted from ALS point cloud data (hereafter referred to as DTM_{ALS}). ALS has the ability to penetrate vegetation and provide accurate DTM_{ALS} (Ressl et al., 2016). As the terrain elevation remains almost unchanged over time, the DTM_{ALS} can be archived and used for periodic surveys.

Unlike natural forests, forest plantations have more uniform tree spacing and height, which can affect the accuracy of remote sensing methods. The derived heights were compared with those obtained from accurate in-situ measurements.

We also investigated the potential of Global Ecosystem Dynamics Investigation (GEDI) elevation data as a replacement for DTM_{ALS} when Lidar flights are not available. GEDI data have been utilized in numerous studies for direct forest height extraction and terrain elevation estimation, capitalizing on its global availability and moderate resolution (Fayad et al., 2021a, 2022; Piermattei et al., 2019; Ressl et al., 2016; Adam et al., 2020). Guerra-Hernández et al. (Guerra-Hernández and Pascual, 2021) utilized GEDI and airborne LiDAR data to assess height growth dynamics in fast-growing species in Spain, revealing a strong correlation between GEDI-derived ground elevation and airborne laser scanning (ALS) data, with an RMSE of 4.48 m. Similarly, Liu et al. (2021) evaluated GEDI's performance for terrain height estimation emphasizing its limitations in dense canopies and steep slopes but also its utility in global-scale assessments.

The advantage of using GEDI data lies in its freely accessible global coverage, offering an alternative to ALS data for DTM extraction, particularly in regions where ALS data availability is limited or cost-prohibitive.

In summary, this study contributes by providing a cost-effective method for periodic canopy height monitoring using Pleiades stereo imagery, validated against in situ measurements, and by exploring the use of GEDI data as a viable alternative to airborne Lidar in Eucalyptus plantations. The objectives of this study are.

- To assess the accuracy of canopy height estimates derived from Pleiades stereo imagery by comparing them with in-situ measurements.
- To evaluate whether canopy height estimates from Pleiades stereo imagery are more accurate in areas with gentle slopes compared to areas with steeper terrain.
- To investigate the feasibility of using GEDI elevation data as an alternative to ALS data for Digital Terrain Model (DTM) extraction in the context of canopy height estimation.

The findings could provide a novel approach to large scale canopy height estimation and highlight the potential for integrating these remote sensing technologies for efficient and accurate canopy height monitoring.

2. Study sites and dataset

2.1. Study sites

This research was conducted in two study sites. The first study area is located in the state of Sao Paulo (SP) in Brazil, where the climatic conditions are mild and moderate, classified by Köppen and Geiger as humid subtropical. The temperature averages 19.5 °C and the precipitation is about 1356 mm per year (São Paulo climate). The surface of SP state is about 248000 km^2, and the Eucalyptus plantation surface in the area is 1.03 million hectares (Couto et al., 2011). Eucalyptus plantations are often established in diverse ecosystems, including areas with steep slopes, soils with low natural fertility, and lands degraded by agriculture (da Silva et al., 2014). In the current study site Eucalyptus plantations are located in a semi-mountainous area with an altitude of 600–1050 m, and average slope of 18° (maximum slope of 28°).

The second study area is located in the state of Mato Grosso do Sul (MS) in Brazil, with a tropical savanna climate according to the Köppen and Geiger classification. The mean annual temperature and precipitation recorded are 24.7 °C and 1340 m, respectively (Climate Mato Grosso do Sul, 2024). The surface of MS site is about 357000 km^2, and the Eucalyptus plantation surface is 0.2 million hectares in this site (Couto et al., 2011). The study site is located in a flat area with an altitude of 250–400 m, and average slope of 2°.

Fig. 1 shows the location of the two study sites and the distribution of in situ plots in each site.

Clonal plantations of *Eucalyptus urophylla* and *Eucalyptus grandis* and various hybrids are planted in rotations of about 7 years. Trees are planted at an average density of 1200 trees per hectare. Plantation stands are single species, but genotypes varies from one stand to the other. The vertical structure of the plantations is generally characterized by a sparse understory and herbaceous layer (Fayad et al., 2021b). In both study sites, stand homogeneity is a key management objective as it has a direct impact on stand productivity (Stape et al., 2010). More than 82% of the Brazilian Eucalyptus plantations are cultivated on flat to gentle slopes due to the huge harvesting and logging operation costs on high slopes (Fayad et al., 2021b). However, they can also be planted on slopes as steep as 28°, as in the SP site.

2.2. Pleiades imagery

Stereo products from the Pleiades optical satellites, distributed by Airbus Defense and Space, were provided by DINAMIS, the French national facility for the institutional acquisition of very high resolution satellite imagery (Available at https://dinamis.data-terra.org/en/archives-and-tasking/). Panchromatic (PA) bands (470–830 nm) from 1B satellites dated on September 2020 for the SP site and May 2021 for the MS site were used to generate the digital surface model (DSM_P). The products are corrected for radiometric and sensor distortions, using internal calibration parameters, ephemeris and attitude measurements (Amram, 2012). Table 1 shows the characteristics of the pair of Pleiades stereo images over the study sites.

2.3. Airborne lidar data

Lidar datasets with high point density was acquired over the area of interests during several airborne surveys in 2017. The dataset were collected using the Harrier 68i Lidar sensor and other interconnected sensors installed on the CESSNA model 06 aircraft. The Lidar point density was set to 5.0 pt/m^2 collected in footprints of 31 cm at a flying height of 629.23 m. The data acquisition and the process of generating the DTM_{ALS} product from it were carried out by Fototerra, a Brazilian geo information technology company.

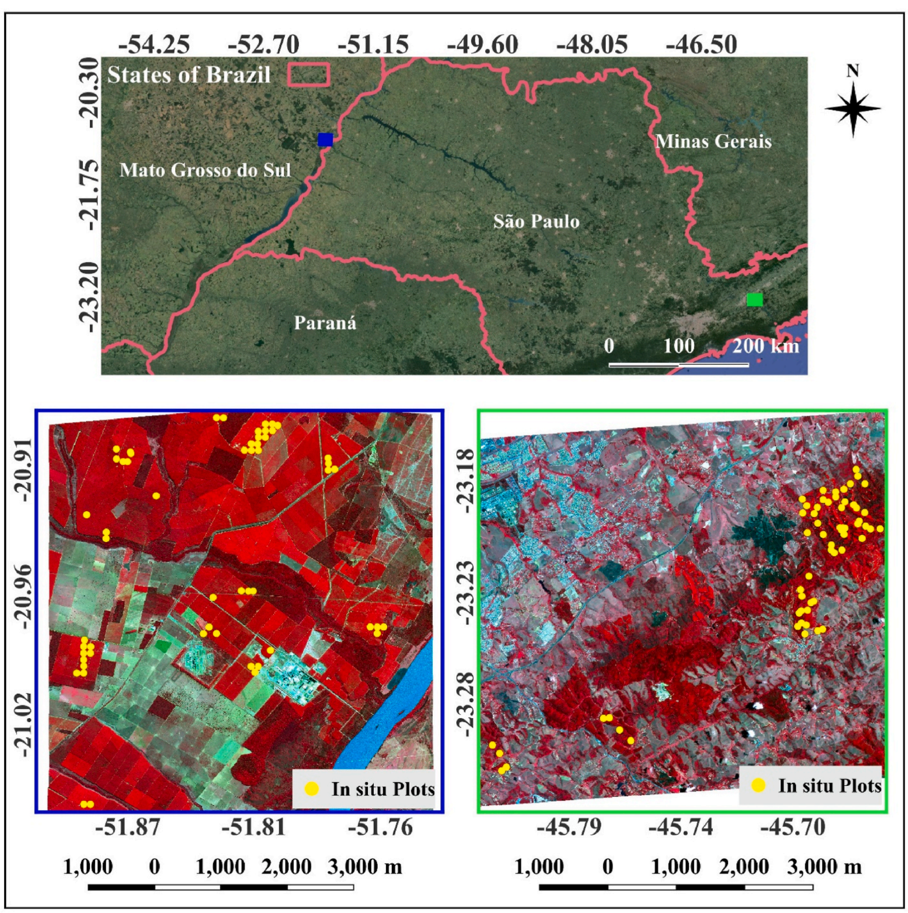

Fig. 1. Location of our two study sites, SP site (green spot) and MS site (blue spot) in Brazil, and distribution of in situ plots (EPSG: 4326). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Main characteristics of the pleiades stereo images.

Product	Date	GSD[a] (m × m)	Viewing angle[b]		Incidence angle[c]		B/H ratio[d]
			Across track	Along track	Across track	Along track	
SP_{PA1}	2020/09/25	0.72 x 0.72	−5.18°	−8.88°	4.12°	10.51°	0.57
SP_{PA2}		0.80 x 0.78	−6.92°	19.46°	11.28°	−20.54°	
MS_{PA1}	2021/05/06	0.82 x 0.77	8.88°	19.45°	−6.64°	−22.95°	0.78
MS_{PA2}		0.80 x 0.80	11.31°	−19.10°	−15.64°	19.44°	

[a] Ground Sample Distance.
[b] The angle between the look direction from the satellite and nadir.
[c] The angle between the look direction from the satellite and the ground normal (the line perpendicular to the surface).
[d] The Base-over-Height ratio of a stereo pair which reflects the angular difference between the two images (Amram, 2012).

The DTM_{ALS} was created through interpolation of the filtered point cloud, which included only the points classified as ground. It has been generated by the DTM Toolkit software, which uses a linear prediction algorithm. Its execution considers the elevation of the terrain as a stochastic process, and an autocorrection is applied to the data, resulting in an adaptive way of fixing the covariance. Linear prediction is a method that integrates the elimination of gross terrain interpolation errors into a single process. Its aim is to calculate an individual weight for each irregular distribution point so that the modelled surface represents the terrain. It works in the following steps.

1. Interpolation using a surface model with weights for each point (initially all points are equally spaced).
2. Calculation of the filter weight "1" (distance oriented from the surface to the measured point) for each point.
3. Calculate a new weight for each point according to its value filter.

The above steps are repeated until a stable situation is reached or a maximum number of iterations is performed.

The DTM_{ALS} was only acquired in areas where in situ plots were available. This product, with a spatial resolution of 0.5m and an elevation accuracy of 5 cm, has UTM plane coordinates in the Brazilian Geodetic System (SGB): SIGARS2000 planimetric datum and Imbituba – SC altimetric datum. It is important to note that the orthometric altitudes were obtained using the MAPGEO2004 Geoidal Ripple Model.

According to (Gruber et al., 2012), the mean difference between the Imbituba tide gauge station and the EGM2008 geoid is about −0.5 m. To convert the DTM_{ALS} elevations from the national vertical datum (Imbituba) to the global vertical datum (EGM2008), a correction of 0.5 m was subtracted from the DTM_{ALS} values.

2.4. GEDI data

The GEDI L2A data acquired between 2019 and 2023, which include information on ground elevation, were used after applying the preprocessing steps. To ensure data quality, waveforms affected by noise or significant discrepancies were filtered out. This included removing waveforms with zero detected modes, a signal-to-noise ratio of zero, a large difference between the GEDI and SRTM elevations, and those with incomplete waveform data. These steps, which were detailed in our previous study (Rajab Pourrahmati et al. (Rajab Pourrahmati et al., 2023), helped improve the accuracy of the GEDI-derived elevation data used in this study. The GEDI L2A includes metrics obtained with six different algorithm group configurations. In this study, algorithm a1 was used as it provided the most accurate information in the context of Eucalyptus plantations (Fayad et al., 2021a). The GEDI elev_lowestmode_a1 metric (hereafter referred to as DTM_{Gedi}), which corresponds to the elevation of the center of the lowest mode of the received waveform detected using algorithm 1 relative to WGS84 ellipsoid (ATBD Documents, 2024), was used as ground elevation to replace the DTM_{ALS}. Extraction and usage of the DTM_{Gedi} in this context is explained further in section methodology.

2.5. In-situ canopy height measurements

Extensive field measurements were carried out on the Eucalyptus stands, based on inventory plots of 400 m^2 located in a quasi-systematic grid every 10 ha. In each plot, a large number of forest biophysical parameters were measured periodically at different ages of the plantation, from 2018 to 2023 in the MS site and from 2012 to 2023 in the SP site. In this study, the mean height (H_{mean}), which is the average height of 10 central trees, and the dominant height (H_{max}) were used to validate canopy height models derived from remote sensing data. H_{max} is defined here as the height of the four tallest trees within each 400 m^2 plot. The H_{mean} and H_{max} values for each plot were taken for the dates closest to the Pleiades acquisition time and further interpolated to the Pleiades date (see Methodology section). Table 2 shows the number of plots used in the current study and the range of H_{mean}, H_{max} and age of trees at the Pleiades date for the two study sites, SP and MS.

Table 3 provides an overview of the sources, type, availability, and resolution of the datasets used in this study.

3. Methodology

3.1. Extraction of CHM_{ALS}

To estimate canopy height, we first extracted the canopy surface model (DSM_P) from Pleiades stereo images and then calculated its elevation difference from the available DTM_{ALS}.

The DSM_P was produced through DSM-OPT (Digital Surface Models from OPTical stereoscopic very high resolution imagery) which is an on-demand processing service operated by ForM@Ter, the French Solid Earth research infrastructure (available at https://www.poleterresolide.fr/services-de-calculs-a-la-demande). The service provides relative elevation values without the introduction of Ground Control Points (GCPs). It includes tie-point extraction, adjustment of the Rational Polynomial Coefficients (RPCs) models, refined image orientation, dense matching and resampling for orthorectification. It builds on the MicMac (Multi-Image Matches for Auto Correlation Methods) open-source project (Rupnik et al., 2016, 2017) and ad-hoc specific developments for image pre/post-processing and DSM denoising (Stumpf, 2013). The service correct relative offsets and horizontal and vertical geolocation errors by aligning the relative DSM to an absolute elevation grid (Copernicus GLO30 for the world). The output is a 1m DSM de-noised image in the EGM2008 vertical reference system, which was later resampled to 0.5 m to match the DTM_{ALS} produced from the Lidar

Table 2
Number of plots, range of canopy height metrics, age of plantations, and density of trees in the two sites (The average difference between H_{max} and H_{mean} is 2.8m and 1.5m for the SP and MS sites respectively).

Site	Number of plots	H_{mean} (m)	H_{max} (m)	Age (yr)	Mean Density (Trees/ha)
SP	60	6.6–30.4	8.2–36.9	1.9–10.7	1220
MS	55	9.3–19.9	11–21.9	1.8–4.5	1190

Table 3
An overview of the sources, type, availability, and resolution of the datasets used in this study.

Dataset	Source	Nature	Availability	Resolution/Point Density
Pleiades Imagery	DINAMIS (French national facility) via Airbus Defense and Space	Optical satellite imagery	Paid	~50 cm (panchromatic)
Airborne LiDAR Data (ALS)	Fototerra (Brazilian geo-information technology company)	Airborne LiDAR	Paid	5.0 pt/m^2
GEDI Data	NASA (GEDI mission)	Spaceborne LiDAR	Free	footprint: ~25 m
In-situ Measurements	Field surveys conducted on Eucalyptus plantations	Ground-based measurements	N/A (Field Survey)	Plot size: 400 m^2

data.

Comparing DSM_P and DTM_{ALS} elevation values over the main roads of the study sites, we observed an average overestimation of the DSM_P by 2.0 m in the SP site, and an average underestimation of the DSM_P by 5.5 m in the MS site. In general, the bias can be either positive or negative, depending on the site characteristics (i.e. slope) and the image acquisition parameters (i.e. viewing angle). According to (Matteo et al., 2018) in a study of generating DSM based on the combination of multiple Pleiades images taken with different acquisition geometries, the bias of all the DSMs produced was consistently within 2 m in the horizontal plane. In some instances, this margin extended to 3–4 m or possibly more, given the large uncertainties in a few cases. In the vertical dimension, the accuracy was around 3 m, with occasional deviations of up to 4 m in certain cases. Given the documented uncertainties associated with Pleiades imagery (Matteo et al., 2018; Piermattei et al., 2018), we corrected the DSM_P by reducing the elevations by 2.0 m for SP site, and increasing them by 5.5 m for MS site.

The CHM was produced by subtracting DTM_{ALS} from corrected DSM_P, hereafter referred to as CHM_{ALS} (Figure A1). Mean and maximum heights were then calculated from CHM_{ALS} in each plot, which will be referred to as $CHM_{ALSmean}$ and CHM_{ALSmax} respectively throughout the paper. It is worth noting that the maximum height was determined by averaging the heights of the top 10% with the highest values within each plot. The average height is calculated from all heights in each plot.

3.2. Extraction of CHM_{Gedi}

We also investigated the possibility of using GEDI terrain elevation information (DTM_{Gedi}) to replace DTM_{ALS}. The selection of GEDI shots was conducted visually using QGIS, based on their location relative to the forest inventory plots and the overall homogeneity of the forest stand. In addition, to minimize vertical errors due to the fact that the GEDI points are not in the same location as the in-situ plots, the GEDI elevation (DTM_{Gedi} given by the metric elev_lowestmode_a1) corresponding to the ground elevation was corrected using the delta elevation derived from the Copernicus Global Digital Elevation Model (GLO-30, TanDEM-X mission) between the location of the GEDI shots and the location of in situ plots. Indeed, GEDI shots and in situ plots are in the same stand, which is homogeneous in terms of canopy height, but the ground elevation may differ. In this way, the GEDI points and the in-situ plots are adjusted to match the ground elevation at the locations of the in-situ plots, compensating for the spatial mismatch between the GEDI points and the in-situ plots. For example, if the ground elevation of a GEDI point from GLO-30 is E_{Gedi} and the ground elevation of the corresponding in situ plot is E_{plot}, then DTM_{Gedi} will be corrected by $\Delta = E_{Gedi} - E_{plots}$ according to the following equation:

$$DTM_{Gedi} = elev\_lowestmode\_a1 + \Delta \quad (1)$$

As the ground elevation DTM_{Gedi} is defined relative to the WGS84 ellipsoid, it was necessary to have the same vertical reference system for the DSM_P. In order to convert the DSM_P orthometric heights to ellipsoid heights:

$$h_{WGS84} = HEGM2008 + NEGM2008 \quad (2)$$

Where *hWGS84* is derived ellipsoidal heights of DSM_P, *HEGM2008* is the original orthometric heights of DSM_P, and *NEGM2008* represents the EGM2008 gravimetric geoid heights derived from a global geoid model (available at: https://www.agisoft.com/downloads/geoids/).

Finally, the CHM was produced by subtracting DTM_{Gedi} from DSM_P, hereafter referred to as CHM_{Gedi}. It should be noted that there are one or more GEDI shots around each in situ plot, and therefore the DTM_{Gedi} corresponding to a given in situ plot is calculated as the average of the GEDI heights around it. The mean and maximum values of DSM_P within each plot were then extracted. The maximum represents the average of the 10% highest heights within each in situ plot. The difference in elevation between the mean DSM_p and DTM_{Gedi} was called $CHM_{Gedimean}$ and the difference in elevation between the maximum DSM_p and DTM_{Gedi} was called $CHM_{Gedimax}$.

3.3. Evaluation of CHMALS and CHM_{Gedi}

The evaluation of the accuracy of CHM_{ALS} and CHM_{Gedi} was based on in situ canopy height measurements (H_{max} and H_{mean}). To account for the time difference between the in situ measurements and the Pleiades acquisition date, linear interpolation was performed using the nearest in situ measurements taken before and after the Pleiades date, with a maximum time interval of six months. The calculation of canopy height at the time of Pleiades acquisition is important for such fast growing plantations, especially for young stands. According to the in situ measurements, a one year difference in age, i.e. from 2 to 3 years old, corresponds to an increase in height of approximately 1.7 and 2.0 m for the mean (H_{mean}) and maximum (H_{max}) canopy heights, respectively. Conversely, the increase in height is less than 50 cm for both H_{mean} and H_{max} when the age of the plantation changes from 12 to 13 years. It is important to note that the majority of our dataset includes canopy heights greater than 10 m. Thus, the error introduced by a six-month interpolation is typically less than 50 cm, which is relatively small.

In this study, the timing of ALS and GEDI data acquisition relative to the Pleiades imagery is not critical, as these datasets were only used to extract terrain elevation, which remains constant over time, rather than canopy characteristics. As eucalyptus plantations are evergreen, the accuracy of the terrain elevation derived from ALS and GEDI data is not significantly affected by seasonal changes in vegetation.

All canopy height estimates ($CHM_{ALSmean/max}$ and $CHM_{Gedimean/max}$ for the both sites) were validated using both H_{mean} and H_{max}. In addition, the dataset built from both the SP and MS sites has been used to investigate the effect of terrain slope (between 0° and 28°) on the accuracy of Pleiades canopy height estimates. Statistical criteria including root mean square error (RMSE), relative RMSE (rRMSE), Pearson's correlation coefficient (r) and bias (mean difference between in situ height and CHM) were calculated to assess the agreement between the CHM and the in situ measurements, for both SP and MG sites (Equations (1)–(4)).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_i - \hat{h}_i)^2} \quad (3)$$

$$rRMSE = \frac{RMSE}{\bar{h}} \times 100 \quad (4)$$

$$r = \frac{\sum_{i=1}^{n}(h_i - \overline{h})(\widehat{h_i} - \overline{\widehat{h}})}{\sqrt{\sum_{i=1}^{n}(h_i - \overline{h})^2 \sum_{i=1}^{n}(\widehat{h_i} - \overline{\widehat{h}})^2}} \tag{5}$$

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(h_i - \widehat{h_i}) \tag{6}$$

where h_i is the in situ height, $\widehat{h_i}$ is the CHM-derived height, n is the total number of observations, $\overline{h}$ and $\overline{\widehat{h}}$ are the average of the in situ and CHM-derived heights, respectively.

4. Results

4.1. Canopy height estimation using pleiades and ALS data

Table 4 presents the statistics for all CHMs derived from Pleiades and ALS ($CHM_{ALSmean}$ and CHM_{ALSmax}) for both sites, SP and MS. The best result corresponds to the CHM_{ALSmax} when compared to in situ H_{mean} for both sites. The distribution map of the height difference between CHM_{ALSmax} and in situ H_{mean} over SP and MS sites is shown in Figure A2. For the SP site, the CHM_{ALSmax} exhibits a bias of 1.4 m and an RMSE of 3.1 m when compared to in situ H_{mean}, with an rRMSE of 18.5% and an r correlation of 0.98. For the MS site, the CHM_{ALSmax} displays a bias of 1.9 m and an RMSE of 2.3 m for in situ H_{mean}, with an rRMSE of 17.3% and an r correlation of 0.92. Fig. 2 shows the relationship between CHM_{ALSmax} and H_{mean} for both study sites. For both sites, Pleiades underestimates the canopy height for heights below 20 m (bias is 1.9 m for MS site and 2.8 m for SP site).

We have also investigated how Eucalyptus height and terrain slope affect the canopy height of the Pleiades. Fig. 3 shows a box plot of residuals (i.e. height difference H_{mean} - CHM_{ALSmax}) versus H_{mean} and slope. We have used CHM_{ALSmax} and H_{mean}, which showed the best results in relation to SP_3 and MS_3 in Table 4. In this figure we used datasets from both SP and MS sites to ensure adequate representation of a range of slope conditions. Two points are highlighted: 1) for all slope ranges, Pleiades underestimates canopy height; 2) the variation of the residuals is higher for slopes greater than 10°. The calculation of the unbiased RMSE (It is calculated by first removing the bias from the predictions and then calculating the RMSE of these adjusted predictions, and provides a clearer measure of the model's true accuracy.) for slopes below and above 10° confirms this observation (unbiased RMSE of 1.6 m for slopes <10° and 2.6 m for slopes >10°).

4.2. Canopy height estimation using pleiades and GEDI elevation data

We investigated the potential of using ground elevation information derived from the GEDI data (DTM_{Gedi}) as a replacement for the DTM_{ALS}. Fig. 4 shows that there is a high correlation between DTM_{Gedi} and DTM_{ALS} ($r = 0.99$) at both sites, SP and MS.

Both $CHM_{Gedimean}$ and $CHM_{Gedimax}$ derived from the Pleiades and GEDI elevations were validated using both in situ H_{mean} and H_{max} (Table 5). Similar to CHM_{ALS}, the best result was obtained by comparing $CHM_{Gedimax}$ with the in situ H_{mean}. The distribution map of the height difference between $CHM_{Gedimax}$ and in situ H_{mean} over SP and MS sites is shown in Figure A3. For the SP site it shows a bias and RMSE of 1.3 and 3.6 m respectively, with an rRMSE of 20.5% and an r correlation of 0.92. For the MS site, $CHM_{Gedimax}$ shows a bias of 2.2 m and an RMSE of 3.4 m for the in situ H_{mean}, with an rRMSE of 24.9% and an r correlation of 0.76. The relationship between $CHM_{Gedimax}$ and H_{mean} for both study sites is shown in Fig. 5. For both sites, Pleiades underestimates the canopy height for heights below 20 m (bias is 2.2 m for MS site and 1.5 m for SP site).

Table 4
Validation of CHM_{ALS}: statistical comparison.

Site_#	CHM_{ALS}	In situ Height (m)	Bias (m)	RMSE (m)	rRMSE (%)	r
SP_1	$CHM_{ALSmean}$	H_{mean}	2.8	4.0	23.9	0.96
SP_2	$CHM_{ALSmean}$	H_{max}	5.6	6.1	31.1	0.96
SP_3	**CHM_{ALSmax}**	**H_{mean}**	**1.4**	**3.1**	**18.5**	**0.98**
SP_4	CHM_{ALSmax}	H_{max}	4.2	4.6	23.6	0.98
MS_1	$CHM_{ALSmean}$	H_{mean}	2.5	2.8	20.9	0.92
MS_2	$CHM_{ALSmean}$	H_{max}	3.9	4.1	28.1	0.92
MS_3	**CHM_{ALSmax}**	**H_{mean}**	**1.9**	**2.3**	**17.3**	**0.92**
MS_4	CHM_{ALSmax}	H_{max}	3.3	3.6	24.3	0.92

5. Discussion

5.1. Canopy height estimation using pleiades and DTM_{ALS}

In this study, CHM was estimated using Pleiades stereo images as the source of canopy surface extraction and ALS for ground elevation extraction (CHM_{ALS}). As shown in Fig. 2a, at the mountainous site of SP, where the range of in-situ H_{mean} extends from 6.6 to 30.4 m and the H_{max} from 8.2 to 36.9 m, the CHM_{ALSmax} derived from Pleiades stereo imagery and ALS shows a good correlation with the in situ H_{mean}. However, there is a tendency to underestimate canopy height by about 2.8 m for H_{mean} below 20 m. This underestimation is also observed in CHM_{ALSmax} compared to H_{mean} for the flat site of MS, with a bias of 1.9 m (Fig. 2b).

Comparing to other research results, Piermattei et al. (Du et al., 2024) reported median errors of 0.25 m and 0.33 m for Pleiades H_{max} and H_{p95} (the 95 height percentile), respectively. It is important to note that they used the aerial CHM provided by the Swiss NFI as reference data with accuracies ranging between 1.76 and 3.94 m (evaluated with manual stereo measurements) in terms of normalized median absolute deviation. In contrast, our study used in-situ measurements for accuracy assessment, which are generally more precise and thus potentially lead to a more reliable assessment of the accuracy of canopy height estimation. Ni et al. (2014) obtained an RMSE of 2.6 m and an R^2 of 0.74 for the canopy height derived from ALOS/PRISM stereo imagery, which was evaluated with large footprint airborne lidar data. Although the rRMSE is not provided in the Ni et al. (2014) study to allow for a direct comparison, our results remain comparable given our RMSE of 2.3 m and r correlation of 0.92 at the MS site and RMSE of 3.1 m and r correlation of 0.98 at the SP site. In another study by Wang et al. (2024), they found that CHM derived from WorldView-2 stereo imagery showed a similar spatial pattern to CHM derived from ALS data, but significantly overestimated CHM in five woody parks in east Columbus, Ohio, USA. They integrated stereo-based CHM with Landsat 7 vegetation indices to improve the CHM accuracy. The best result was obtained using the gradient boosting regression method with an r of 0.64 and an RMSE of 3.1 m (11.1%). This combination of structural and spectral information explained more than 70% of CHM variability (Wang et al., 2023). It can be inferred that incorporating spectral information, such as vegetation indices, with the structural data derived from Pleiades stereo images could potentially improve the accuracy of CHM estimation in our study area as well. The synergy between the spectral and structural data may help to better capture the variability in canopy height, particularly in areas where the stereo imagery alone tends to underestimate or overestimate the CHM. Future studies could explore such integration using advanced machine learning methods to further enhance the reliability and applicability of canopy height monitoring in Eucalyptus plantations.

While still demonstrating a strong correlation with the in-situ measurements, the observed pattern in our study suggests that Pleiades imagery may underestimate height of trees shorter than 20 m. This may be attributed to different reasons: 1) gaps in the canopy due to tree mortality at early stage, generally corrected with local replanting but sometimes not entirely, and these gaps are partly filled with neighboring trees when the plantation ages; 2) the underestimation may be increased in areas planted at lower tree density, due to larger space between trees, with some Pleiades pixels partly measuring the reflectance from forest

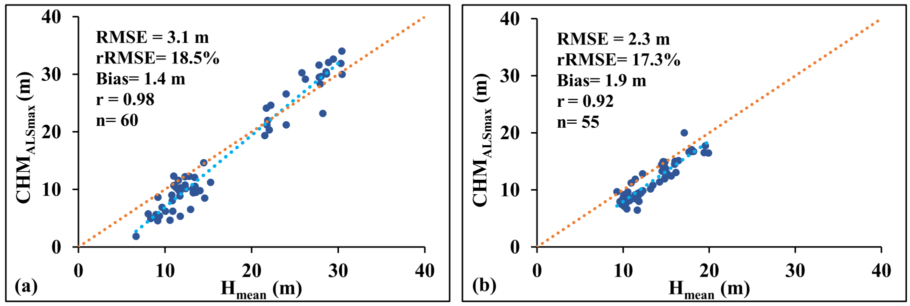

Fig. 2. CHM_{ALSmax} versus in situ H_{mean} for a) SP site, and b) MS site.

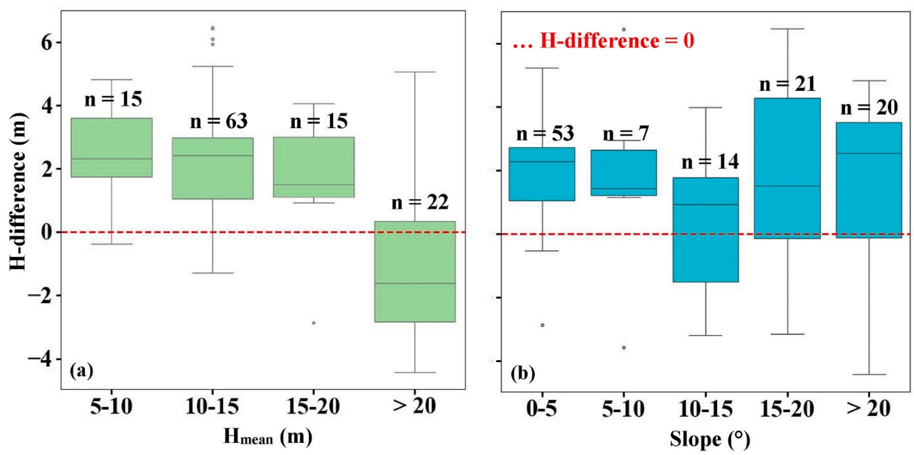

Fig. 3. Box plots of H-difference (H_{mean} – CHM_{ALSmax}) with respect to a) in situ H_{mean}, b) slope.

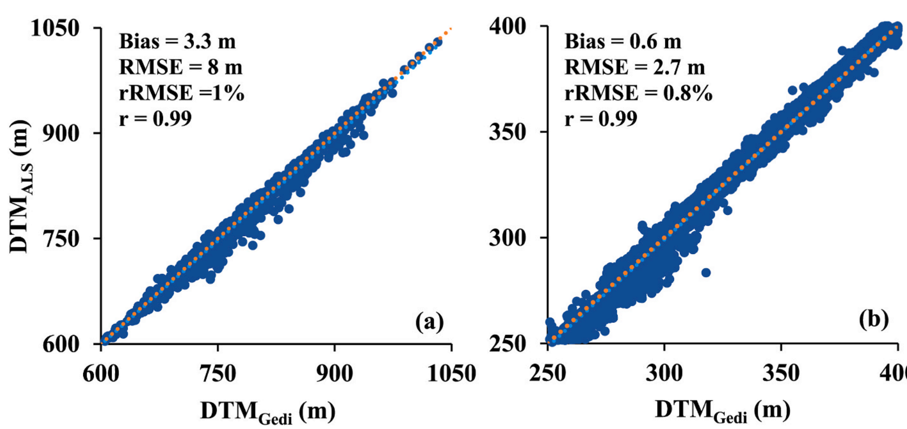

Fig. 4. Relationship between DTM_{ALS} and DTM_{Gedi} for a) SP site, b) MS site.

Table 5
Validation of CHM_{Gedi}: statistical comparison.

Site_#	CHM_{Gedi}	In situ Height (m)	Bias (m)	RMSE (m)	rRMSE (%)	r
SP_1	$CHM_{Gedimean}$	H_{mean}	4.4	5.8	33.1	0.90
SP_2	$CHM_{Gedimean}$	H_{max}	7.2	8.3	40.7	0.90
SP_3	**$CHM_{Gedimax}$**	**H_{mean}**	**1.3**	**3.6**	**20.5**	**0.92**
SP_4	$CHM_{Gedimax}$	H_{max}	4.1	5.4	26.6	0.93
MS_1	$CHM_{Gedimean}$	H_{mean}	2.8	3.7	27.7	0.76
MS_2	$CHM_{Gedimean}$	H_{max}	4.3	4.9	33	0.77
MS_3	**$CHM_{Gedimax}$**	**H_{mean}**	**2.2**	**3.4**	**24.9**	**0.76**
MS_4	$CHM_{Gedimax}$	H_{max}	3.7	4.4	29.7	0.77

floor; 3) the progressive closing of the canopy at early growth stage. These three sources of gaps in canopy cover can lead to inconsistencies in the estimation of canopy height from Pleiades imagery, as the satellite may struggle to accurately capture the true height of individual trees when gaps are present. This may explain the better agreement between CHM_{ALSmax}, which is a calculation of the 10% of maximum heights within each plot, and in situ H_{mean} than H_{max} (see Table 4, SP_3 and MS_3).

In areas with younger trees and lower canopy heights, such as MS, the underestimation by Pleiades is greater when CHM_{ALSmax} is compared with H_{max} and $CHM_{ALSmean}$ with H_{mean} than when CHM_{ALSmax} is compared with H_{mean}. In situ maximum height (H_{max}) is a measure of the height of the four tallest tree in the plot, whereas CHM_{ALSmax} is obtained using the 10% top heights in the plot. This leads to an underestimation of

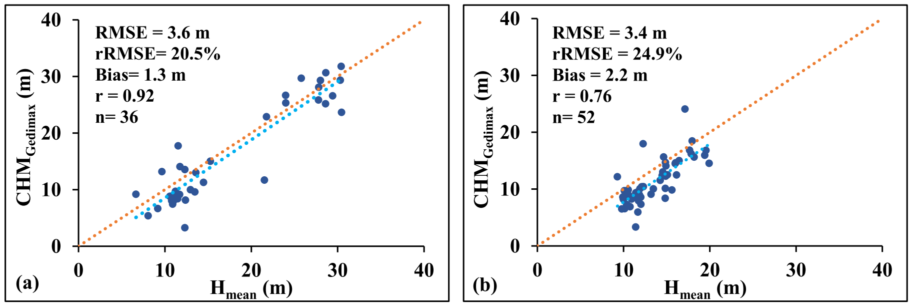

Fig. 5. $CHM_{Gedimax}$ versus in situ H_{mean} for a) SP site, and b) MS site.

canopy height by Pleiades. On the other hand, the in situ mean height (H_{mean}) takes into account the mean height of 10 central trees within the plot, but $CHM_{ALSmean}$ takes into account all pixels, including those not at the top of the trees. In fact, trees are planted approximately every 6 m^2, so there are ~6 pixels of height per tree (24, given the fact that we oversampled DSM_P to 0.5 m). Some of these crown height pixels are at the surrounding of tree crowns, or between 2 trees. Eucalyptus trees have a rather conical shape on the top of the canopy. The average height computed from Pleiades stereo ($CHM_{ALSmean}$) is therefore likely to be underestimated compared to the inventory mean height (H_{mean}). Comparing $CHM_{ALSmean}$ with H_{max} logically shows the highest error and the highest underestimation.

Looking at Fig. 3a, the median of the H-difference (H_{mean} - CHM_{ALSmax}) decreases from a positive value towards zero as the H_{mean} values increases up to H_{mean} class of >20 m.

In our analysis of the impact of terrain slope on Pleiades canopy height estimation, we observed no significant correlation between the derived canopy height models (CHM_{ALS}) and terrain slope, and no clear pattern in the relationship between the residuals (H_{mean} - CHM_{ALSmax}) and the slope, as shown in Fig. 3b. Thus, despite initial expectations, it cannot be said that Pleiades canopy heights are more accurate on plantations with gentle terrain, or at least that tree height contributes more to the accuracy of CHM_{ALS} models than slope, as discussed above. It should be noted that the maximum average slope in our analysis is 28°, and it is possible that even higher slopes may reveal different patterns or correlations not captured in this study.

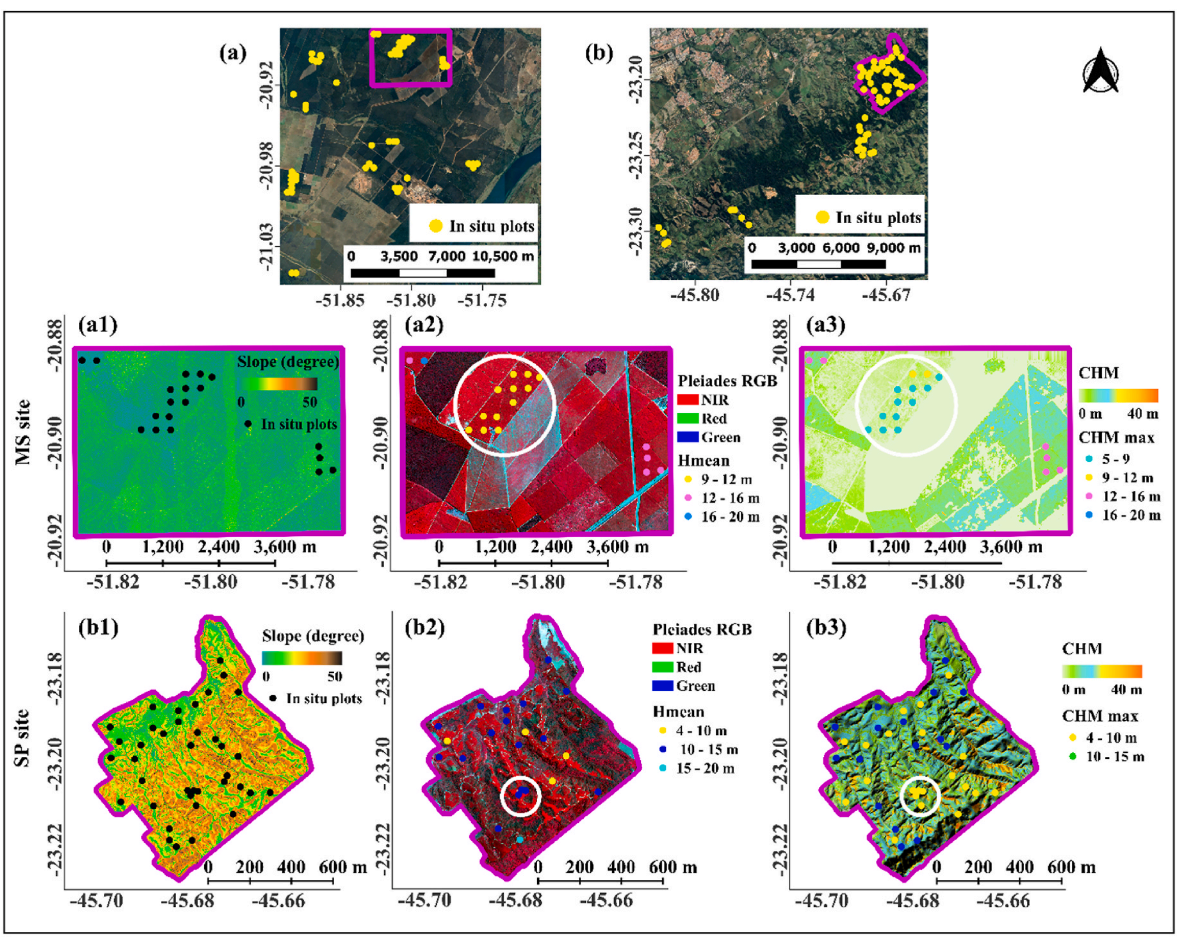

Fig. 6. Distribution of total in situ plots over MS (a) and SP (b) sites. The enlarged part of each site, marked by the purple polygon, shows from left to right: the location of some plots over the slope map (a1 and b1), in situ plots classified based on in situ H_{mean} over the Pleiades RGB psedocolor image (a2 and b2), and in situ plots classified based on CHM_{ALSmax} values over a CHM_{ALS} map overlayed on the hillshade of the sites (a3 and b3). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 6a and b visualize the distribution of total in situ plots over each study site, SP and MS. As can be seen, regardless of the slope of the terrain, some plots in the in situ H_{mean} class of 9–12 m at the MS site or 10–15 m at the SP site (white circle, Fig. 6-a2 and 6-b2) are in the lower class of CHM_{ALSmax}, 5–9 and 4–10 m respectively (white circle, Fig. 6-a3 and 6-b3).

In line with our results, Piermattei et al. (2019) reported that the correlation of ΔHp95 (the difference between the Pleiades and aerial 95 percentile) versus hillshade, aspect, and slope, is not significant (R^2 ranges from 0.001 to 0.207). Regarding the effect of slope, the most notable result was a large increase in the error variance of ΔH for steep terrain (>50°) in all four of their different study sites (Du et al., 2024). Fig. 3b shows a similar pattern with high error variance for slopes less than 10° and slightly higher error variance for slopes greater than 10°.

In addition to the influence of the presence of canopy gaps on the accuracy of DSM_P in plots with young and short trees discussed earlier, our investigation suggests that the errors could be due to the in situ measurement errors, particularly in distinguishing the top of tall trees, or the quality of the DSM_P model. DSM_P quality depends on the characteristics of the stereo pair (especially the B/H ratio) and the method used to calculate the DSM_P. Hobi and Ginzler (2012) reported that the accuracy of a DSM_P varies also with land cover, and forested areas emerged as the most difficult land cover type for height modelling (Hobi and Ginzler, 2012). According to the Pleiades image user manual, the optimum B/H ratio for processing 3D models by automatic correlation is in the range of 0.25 and above, depending on the relief, i.e. it should be lower in mountainous areas than in flat areas with little relief. A large B/H ratio (>0.4) in a mountainous area increases the rate of hidden areas (in between two high mountains) and decreases the global automatic matching accuracy (Amram, 2012). In the current research, the study site of SP is located in a semi-mountainous area, and the B/H ratio is 0.57, which exceeds the optimal range. Therefore, this B/H ratio may contribute to discrepancies in the accuracy of the DSM_P, especially in regions with complex terrain, potentially leading to higher errors in canopy height estimation. The B/H ratio for the MS site was set at 0.78, which is higher than the SP site, as recommended. However, a study by Goldbergs (2021) in a relatively flat region found that stereo imagery with a B/H ratio of 0.2–0.3 was optimal for image-based DSM_P in hemiboreal closed canopy forest areas. He noted that in a dense, closed canopy condition with the conical crown structure of coniferous tree species, the number of pixels comprising the canopy surface decreases with increasing B/H ratio due to insufficient reflection and occlusions, with the likelihood that the similarity of neighboring pixels also decreases. Consequently, the ability to correctly estimate the canopy height decreases (Goldbergs, 2021).

It has been also confirmed that, besides the B/H ratio, the canopy height estimation efficiency is affected by a complex mixture of variables, including crown shape, canopy structure, species composition, partial crown transparency, leaf orientation, and shadows, sensor-target and sun-sensor geometry (Goldbergs, 2021; Yin et al., 2023; Goldbergs et al., 2019). Thus, further investigation into the impact of the B/H ratio and other acquisition configuration on DSM_P quality and subsequent CHM accuracy in different topographical condition is required to better understand and mitigate this source of errors specifically for Eucalyptus plantations.

While sources of potential errors have been mentioned, further analysis is required to quantify the impact of each error source and develop more robust mitigation strategies.

5.2. Canopy height estimation using pleiades and DTM_{Gedi}

We investigated the potential of using ground elevation information derived from the GEDI data as a replacement for the DTM_{ALS}. Correlation analysis between GTM_{Gedi} and DTM_{ALS} demonstrated a robust agreement, yielding an r value of 0.99 in both sites. However, the bias and RMSE values differ between the two sites, with a bias of 3.3 m and RMSE of 8 m (rRMSE = 1.0%) at the SP site, and a bias of 0.6 m and RMSE of 2.7 m (rRMSE = 0.8%) at the MS site. These results are consistent with the findings by Guerra-Hernández and Pascual (2021), who reported a high correlation (r = 0.99) between ALS-derived DEM and Full GEDI ground elevation data in an area in the Northwest of Spain. However, the RMSE in our study varies more significantly between sites compared to their reported value of 4.48 m. This variation could be attributed to the different environmental conditions and landscape characteristics at our study sites. For example, the higher RMSE observed at the SP site may be due to factors such as more complex terrain or less uniform canopy structure compared to the MS site. Wang et al. (2022) reported that GEDI's ground elevation accuracy is influenced by factors such as land surface attributes and sensor system characteristics. Geolocation error was also identified as a significant factor affecting the performance of GEDI, particularly in areas with diverse forest and land cover types. However, in our study, the relatively uniform structured nature of eucalyptus plantations might have mitigated some of these errors, resulting in consistent performance of GEDI-derived terrain elevation data. The high correlation between DTM_{Gedi} and DTM_{ALS} in our analysis suggests that, despite its lower spatial resolution, GEDI data can provide reliable ground elevation estimates for eucalyptus plantations, where canopy structures are less complex.

Referring to Table 5 and Fig. 5, similar to the CHM_{ALS}, the best result is related to the $CHM_{Gedimax}$ compared to the in situ H_{mean} with RMSE, rRMSE and r correlation of 1.3 m, 20.5% and 0.92 for the SP site and 2.2 m, 24.9% and 0.76 for the MS site. Despite high correlation between DTM_{Gedi} and DTM_{ALS}, the low spatial resolution of GEDI shots (diameter = 25 m) leads to the slight decrease in accuracy observed in the $CHM_{Gedimax}$ in comparison to CHM_{ALSmax}. Our analysis shows that while DTM_{Gedi} can be a viable replacement for DTM_{ALS} specifically for surveying canopy height of plantations over large areas, the $CHM_{Gedimax}$ has a reduction in accuracy of approximately 2% in SP site and 7.6% in MS site compared to CHM_{ALSmax}. These results are consistent with those reported by Du et al. (2024), who used spaceborne lidar from the GF-7 satellite to derive terrain elevation and GF-7 stereo imagery to generate DSM and subsequently CHM (GF-7 DSM - GF-7 DTM). Their study achieved an R^2 of 0.88 and RMSE of 2.98 m for canopy height estimates compared to CHM derived from ALS data and an even higher accuracy (R^2 = 0.96, RMSE = 1.23 m) when accounting for forest types at the sub-compartment scale. An analysis by Liu et al. (2021) to explore the error factors for terrain elevation retrievals from ICESat-2 and GEDI data in different natural forest types in North America revealed that steep slopes (>30°) present the greatest challenge for both datasets, and tall (>20 m) and dense canopies (>90%) also reduce the accuracy of terrain elevation estimates (Liu et al., 2021). However, in our analysis, we did not observe a critical decrease in the accuracy of $CHM_{Gedimax}$ compared to CHM_{ALS} for plots with canopy height greater than 20 m. This could be due to the unique characteristics of eucalyptus plantations, which often have a conical shape of the Eucalyptus crowns that may allow better penetration of lidar into the canopy, thus providing more accurate ground elevation measurements. Additionally, the relatively uniform and structured nature of eucalyptus plantations might contribute to the consistent performance of GEDI data in these environments.

Moving forward, these results can be used to produce continuous height maps that provide valuable spatial information on canopy height over large plantation areas. By estimating and compensating for bias using ground truth measurements, researchers can develop a correction factor and apply it to the canopy height estimates from the integration of Pleiades and GEDI data, providing a continuous height map with greater spatial coverage and resolution compared to traditional inventory plots. GEDI provides global coverage and the ability to penetrate the canopy and provide appropriate ground elevation measurements across the study area. This approach allows a more comprehensive monitoring of canopy dynamics and facilitates informed decision making in forest management and conservation efforts.

It should be noted that while GEDI data offers global coverage and accessibility, its relatively low spatial resolution might limit its application in areas with complex terrain or dense canopy cover. Future work should focus on improving the integration of GEDI data with high resolution datasets to overcome these limitations across different forest types.

6. Conclusion

Our study highlights the effectiveness of the integrated approach using Pleiades stereo imagery and airborne Lidar data for estimating canopy height in Eucalyptus plantations (CHM_{ALS}). Although less accurate than traditional field measurements, the quality of the $CHM_{ALS\text{-}max}$ estimates with a RMSE of 3.1 m and r correlation of 0.98 for the semi mountainous site in SP, and RMSE of 2.3 m and r correlation of 0.92 for the flat site in MS, is sufficient for many types of forest dynamics studies.

Using GEDI derived ground elevation data as a replacement for ALS showed high correlation ($R^2 = 0.99$) with ALS derived DTM. The $CHM_{Gedimax}$, although slightly less accurate than the CHM_{ALSmax}, still provided robust estimates with an r correlation of 0.92 for the SP site and 0.76 for the MS site. The loss of accuracy was approximately 2% for SP and 7.6% for MS, indicating the viability of GEDI for large area canopy height surveys.

Future investigations should focus on refining methodologies and addressing sources of errors particularly in open forests to enhance the reliability of CHM outputs for effective forest management and monitoring applications.

CRediT authorship contribution statement

Manizheh Rajab Pourrahmati: Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Nicolas Baghdadi:** Supervision, Methodology. **Henrique Ferraco Scolforo:** Data curation. **Clayton Alcarde Alvares:** Data curation. **Jose Luiz Stape:** Resources, Data curation. **Ibrahim Fayad:** Resources. **Guerric le Maire:** Supervision, Resources.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Nicolas Baghdadi reports was provided by French Space Study Center. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

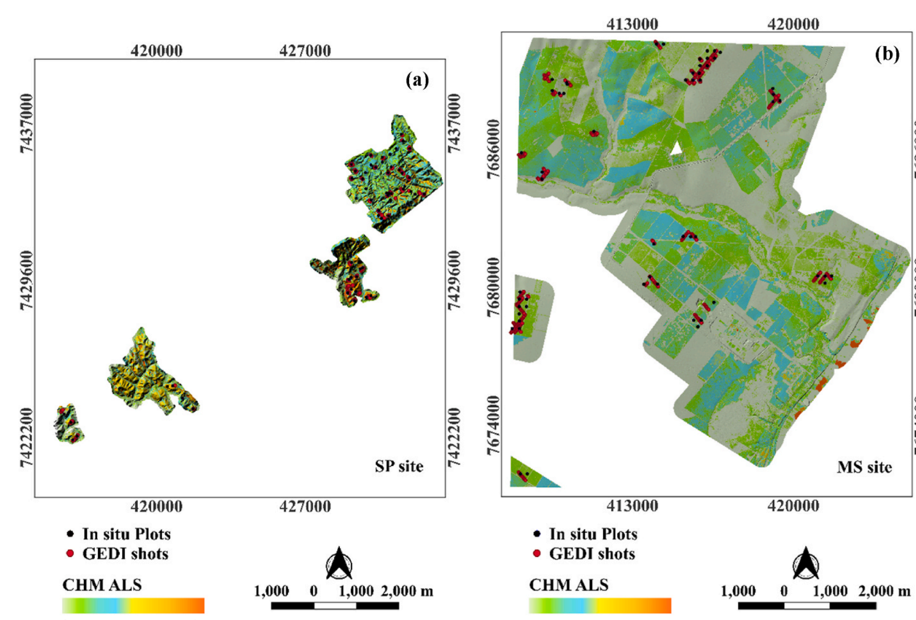

Fig. A1. CHM_{ALS} map over SP (a) and MS (b) sites, and distribution of GEDI shots and in situ plots on the maps. ALS data were only collected over specific locations where field measurements were available.

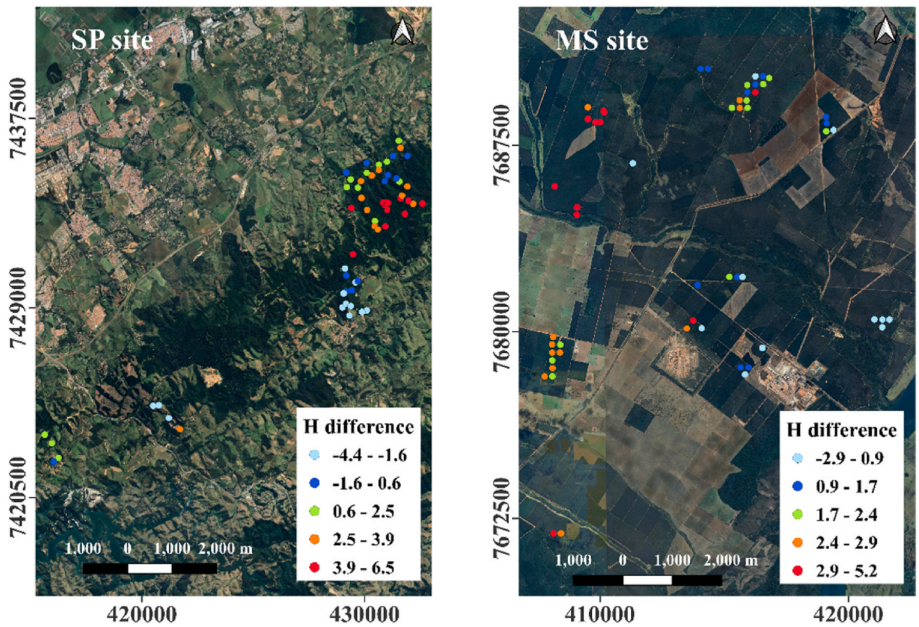

Fig. A2. Height difference between CHM_{ALSmax} and in situ H_{mean} over SP and MS sites.

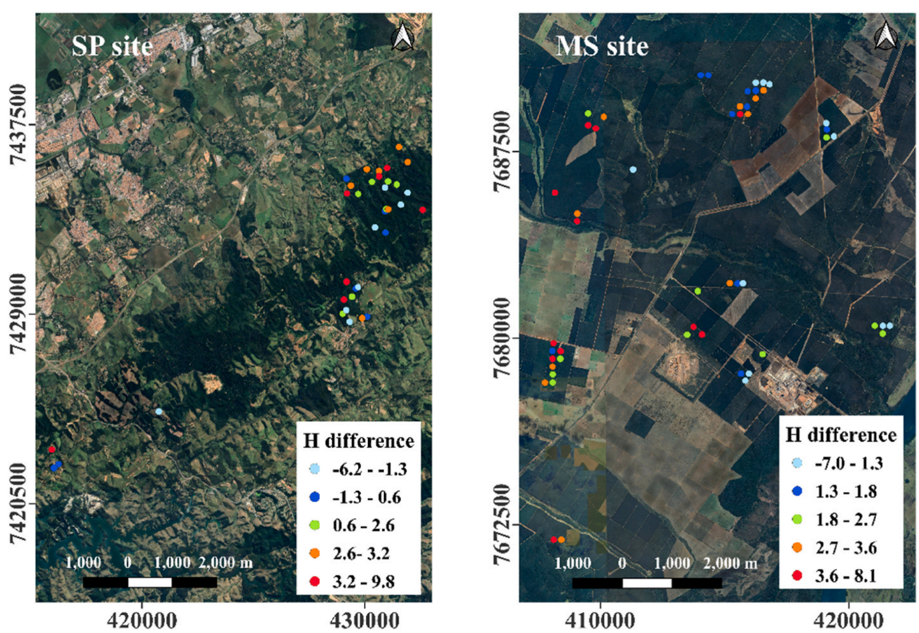

Fig. A3. Height difference between $CHM_{Gedimax}$ and in situ H_{mean} over SP and MS sites.

Data availability

The authors do not have permission to share data.

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