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ORIGINAL PAPER

Understanding environmental factors affecting forest canopy heights in the Philippines using remote sensing data from ICESat

Alex S. Olpenda✉

Center for Geomatics Research and Development in Mindanao, College of Forestry and Environmental Science, Central Mindanao University, Bukidnon 8710, Philippines

ABSTRACT

This study uses remote sensing datasets to assessenvironmental factors affecting forest canopy heights in the Philippines. Data for a total of 144 point locations with information on maximum canopy height and Lorey's mean height (the latter defined as the crown-area-weighted canopy heights) were extracted from the Geoscience Laser Altimeter System (GLAS) LiDAR instrument that was aboard the Ice, Cloud, and land Elevation Satellite (ICESat). Waveform LiDAR data were collected between October 2004 and March 2008. Maximum canopy heights were evaluated fordifferent geographic classes generated from the digital elevation model (DEM). Maximum canopy heights at elevations above 1000 m, and those at slopes below 18% and above 50%, were statistically different from other classes, indicating different forest formations. Although differences in canopy height did not differ significantly across aspect classes (p=0.172), there was a conspicuous pattern of canopy heights being lower on north, east and south facing slopes, and generally higher on northeast, southeast and southwest aspects. Furthermore, the influence of soil type, climate and topography were evaluated by univariate regression to evaluate whether they influenced Lorey's canopy heights. Rasterized soil types were based on the FAO-UNESCO project while climate parameters were from the WorldClim global data. Mean canopy heights were significantly affected by elevation and slope (p<0.010), soil type (p<0.050), and diurnal temperature range, annual temperature range and isothermality (p<0.050). It is important to note that the three climatic variables are functions of maximum and minimum temperatures. These findings could be useful for modeling forest type distribution and consequently for adaptive forest management with climate change. Obtaining additional data on canopy heights and using updated information on soil types are recommended to improve the analysis of the relationships explored in this study.

KEY WORDS

Philippines, forest canopy height, Lorey's height, LiDAR, GLAS, ICESat

Introduction

Understanding factors influencing tree development is crucial to forest ecology because of the significance of growth to forest structure and biomass (Coomes and Allen, 2007), their use as

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✉e-mail: alecsolpenda@cmu.edu.ph

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inputs to species distribution modeling (Pearson, 2009), and to improve forest management for the expansion of forest cover (Worrell and Malcolm, 1990). The growth and structure of a forest is largely dictated by environmental factors. Furthermore, the relationships between climate and topography are primary forces shaping earth's major biomes, including forests (Mucina, 2019), and together they control the distribution of vegetation (Sharma *et al.*, 2017). With rising temperatures and altered precipitation already being experienced due to climate change (IPCC, 2007), it is increasingly important to understand how geo-climatic variables affect vegetation distribution and forest growth, including mortality and reproduction of trees (Yang *et al.*, 2006; Marshet and Fekadu, 2019; Sharma *et al.*, 2017). Even small changes in climate may have major effects on forests and thus society (Rustad *et al.*, 2012). In addition, soil types and elevational variation affect numerous climatic and physical variables, directly influencing forest community composition and structure (Rahbek, 2005; Sinha *et al.*, 2018; Xu *et al.*, 2017; Rodrigues *et al.*, 2018; Guerra *et al.*, 2013).

In the Philippines, the natural vegetation is generally a mosaic of different kinds of forests, commonly known as forest formations (Malabrigo *et al.*, 2017). Heaney and Regalado (1998) identify Philippine forest formations as divided across three elevational layers (Fig. 1), with altitude of the layers directly related to rainfall but inversely proportional to temperature. However, such observations on physical factors are too general to be predictive and quite a common knowledge. Only a handful of studies globally have examined the correlation between these factors and forest structure (Sharma *et al.*, 2017; Gairola *et al.*, 2014; Rawat and Chandra, 2014; Hatfield and Prueger, 2015), with few of these conducted in the Philippines and even fewer using remote sensing (RS) data. Ong *et al.* (2002) used a geographic information system (GIS) to overlay topography, forest cover, river systems and other thematic maps to identify biodiversity hotspots, but failed to explain forest structure, at least in the publicly available report. Ramos *et al.* (2011) developed a geodatabase of the country's threatened species based on historical records and biodiversity literature; although the study established species spatial distribution and elevation range as inputs that could be used for modeling forest types, statistical analysis was not carried out. The primary aim, therefore, of this study is to explain differences in forest structure in the Philippines by relating remotely sensed canopy heights to geographic and climatic gradients.

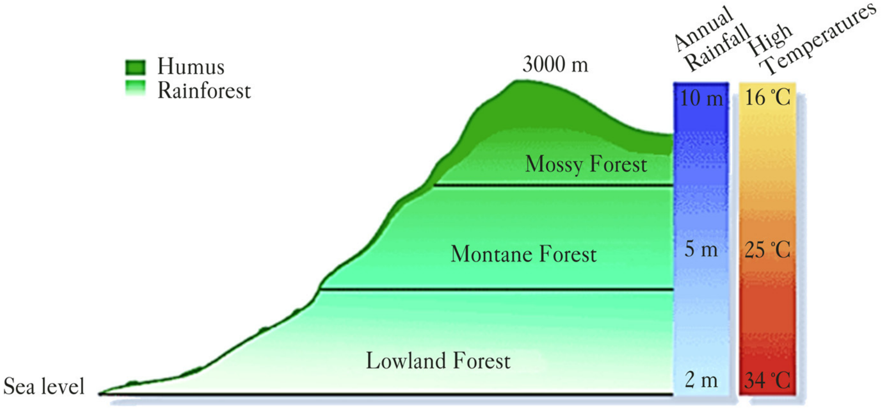

Fig. 1.

General forest formations in the Philippines along the elevational gradient. (Image source: Heaney and Regalado, 1998)

Brief Description of Philippine Forests. Fernando *et al.* (2008) identified 12 Philippine forest formations. However, for brevity, this paper describes only the general picture of Philippine forests, following Figure 1. In lowland forest, evergreen species are prevalent, with the family Dipterocarpaceae dominant and species reaching heights of 40 to 50 m and some emergent trees towering up to 60 m tall with diameters as much as 100 to 200 cm (Whitford, 1911; Fernando *et al.*, 2009). Dipterocarp species present include *Dipterocarpus grandiflorus*, *Parashorea plicata*, *Pentacme contorta*, *Shorea polysperma*, *S. almon*, *S. negrosensis*, and *S. guiso*. Lowland forest develops in areas where rainfall is more or less uniform throughout the year or where there is only a short dry season. It is found on nearly all types of topography, from immediately behind the beach frontal zone to an altitude of 800 m, though most Dipterocarpaceae do not occur above 1,100 m ASL (Whitford, 1911; Fernando *et al.*, 2009). The diffuse canopy structure of lowland forest allows sufficient light penetration to the understory to permit highly dense growth of rattans, lianas, epiphytes and herbaceous plants on the forest floor (ERDB, 2012).

The middle forest layer, typically occurring from 800 m up to 1,500 m ASL, is the tropical lower montane rainforest as described by Fernando *et al.* (2009). For Whitford (1911), this is called the tanguile-oak dipterocarp forest. This forest connects the lowland evergreen rainforest below with the mossy forest above and has evenly distributed rainfall and high relative humidity. This forest is usually found on the sides of mountains, with gentle to steep ridges and slopes alternating with deep ravines and gorges. Tanguile (*S. polysperma*) is the predominating tree species, with heights reaching up to 50 m. Among oak species, the most common is *Lithocarpus*, with heights ranging from 25 m to 35 m (Soepadmo and Wong, 1995). Other species occurring in this type of forest are *Elaeocarpus*, *Litsea* and *Syzygium* (Razal *et al.*, 2003; Fernando *et al.*, 2009; ERDB, 2012).

The highest elevation forests occur on high mountainous regions at elevations greater than 1,500 m. These are termed mossy forests and are found in areas of rugged topography with steep ridges and canyons (Fig. 2). High rainfall and humidity promote the growth of mosses, liverworts, ferns and other epiphytes on tree trunks, while ferns and grasses occupy open areas (Razal *et al.*, 2003; ERDB, 2012). Strong winds prevent tall trees; hence, most of the trees are dwarfed in height, seldom reaching 20 m and usually not over 5 m tall (Whitford, 1911). Common tree species are *Dacrydium*, *Dacrycarpus*, *Podocarpus*, *Symplocos* and *Myrica*. The Philippine oak (*Lithocarpus* spp.) can still be found, especially within the transition zone between montane and mossy forest (ERDB, 2012).

In addition to the above three forest formations, the abundant coastal areas surrounding the country support mangrove forest, which are present on coastlines and along river mouths. There are about 310,531 hectares of mangrove forest in the Philippines (4.5% of worldwide mangrove forest) (FMB, 2014). Common mangrove species, such as *Rhizopora*, *Bruguierra*, *Ceriops*, *Avicennia and Sonneratia* can reach 4 m to 14 m tall (Lunar, 2013; Abino *et al.*, 2014; Cañizares and Seronay, 2016), with mature stands exceeding 20 m (Benecario *et al.*, 2016).

Methodology

Study Area. The scope of this analysis encompasses the entire country of the Philippines (Fig. 3). Belonging to the region of Southeast Asia, the Philippines is a tropical country lying just above the equator, between 4°15'N and 21°25'N latitude and between 112°15'E and 127°E longitude. Within a total land area of 30 million hectares on the Philippine archipelago, 7,014,154 hectares (23.4%) have forest cover including mangroves (FMB, 2014). In general, the topography is mountainous with narrow coastal lowlands. The coolest month is January with a mean temperature of

Fig. 2.
A high elevation mossy forest showing dwarf trees on Mount Hamiguitan (1,637 m), south Philippines
Image source: Mt. Hamiguitan Summit trail by Long Henson, licensed under Creative Common BY 4.0

25.5°C, while the warmest month is May with a mean temperature of 28.3°C. Average annual rainfall in the Philippines varies from 965 to 4,064 millimeters. On a yearly basis, 20 to 22 cyclonic typhoons visit the Philippines (ERDB, 2012).

GEOGRAPHIC PARAMETERS. The digital elevation model (DEM) used was version 2 of Global DEM (GDEM) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which has a 30m spatial resolution. This version was released to the public in 2011, noting substantial improvements in quality over the original GDEM (Tachikawa *et al.*, 2011). Accordingly, it has fewer artifacts than the preceding version and is comparable to other DEMs in terms of horizontal resolution and vertical accuracy. Reclassifications for elevation and slope were generated (Table 1) based on the Mapping Guidebook (Galido-Isorena, 2011), while aspect classes were from Burrough and McDonell (1998).

Soil types were based on the joint project of the Food and Agriculture Organization (FAO) and United Nations Educational, Scientific and Cultural Organization (UNESCO), published between 1974 and 1978 at 1:5,000,000 scale. As mentioned in their official website, the project was 'the fruit of world-wide collaboration between innumerable soil scientists and remained until recently the only global overview of soil resources.' According to metadata for the database, the digital soil map of the world (version 3.6, released in 2003) 'had been cleaned of errors both in the database and in the lines constituting the digitized map itself.'

CLIMATIC DATA. Climatic values are from WorldClim version 2.1 (Fick and Hijmans, 2017), a database of high spatial resolution global weather and climate data that can be used for species mapping and plant growth modeling. Taken from different sources, the dataset integrates long-term average values, time-series of monthly averages by year, and daily weather data, before aggregating all to monthly climate averages for the years 1970 to 2000. Fick and Hijmans (2017) include monthly temperature (mean, minimum and maximum), precipitation and solar radia-

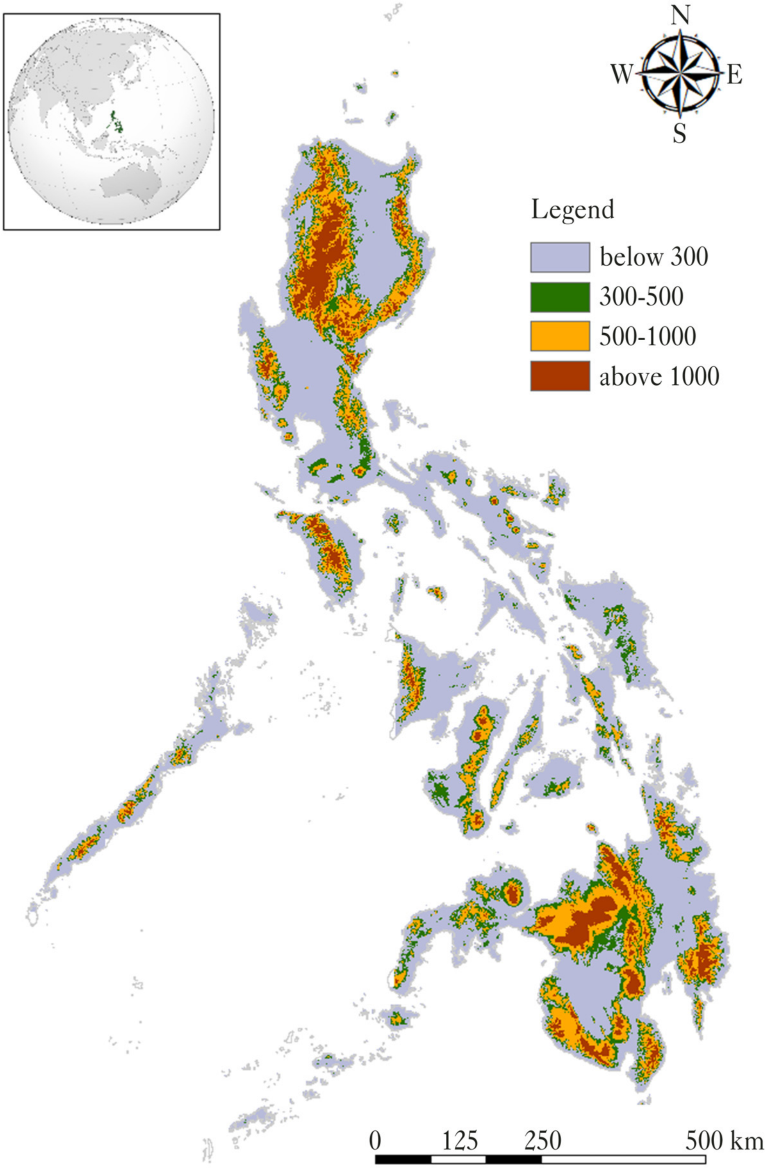

Fig. 3.

The Philippine archipelago and its land elevations (DEM source: ASTER GDEM)
Inset globe image credit: Wikimedia Creative Commons

tion by interpolating data from 9,000 to 60,000 weather stations with elevation, distance to the coast, satellite-derived land surface temperature and cloud cover as covariates. The bioclimatic variables used in the present study are shown in Table 2. They were obtained from WorldClim in raster format with a spatial resolution of 1 km^2.

LiDAR Data. Estimates of forest canopy heights were taken from Healey *et al.* (2015) via the Distributed Active Archive Center (DAAC) website of the National Aeronautics and Space

Table 1.
Geographic parameters from DEM derivatives used with reclassifications

Parameter	Classes	Description
Elevation (meters, ASL)	≤500	low
	501-1,000	middle
	>1,000	high
Slope (percentage)	0-18	level to rolling
	18-30	rolling to hilly
	30-50	steep hills to mountainous
	>50	cliff-like, stream side, rugged mountainous
Aspect (degrees)	0-22.5	North
	22.5-67.5	Northeast
	67.5-112.5	East
	112.5-157.5	Southeast
	157.5-202.5	South
	202.5-247.5	Southwest
	247.5-292.5	West
	292.5-337.5	Northwest
	337.5-360	North

Table 2.
Climatic variables used in the analysis

Parameter	Description / Formula
Annual mean temperature	average temperature (°C) per year
Annual precipitation	average rainfall (mm) per year
Temperature seasonality	standard deviation ×100
Mean diurnal range (MDR)	mean of monthly (max temp – min temp)
Temperature annual range (TAR)	max temp of warmest month – min temp of coldest month
Isothermality	(MDR/TAR)×100
Monthly solar radiation	monthly average (kJ m^{-2} day^{-1})
Annual solar radiation	total per year (kJ m^{-2} day^{-1})

Administration (NASA). The processed data were derived from the Geoscience Laser Altimeter System (GLAS) LiDAR instrument that was aboard the Ice, Cloud and land Elevation (ICESat) satellite. The downloaded file (in .csv type) as per description contained 18,578 statistically selected globally distributed forested sites using an algorithm described by Lefsky *et al*. (2007). The original file was in waveform format and was collected between October 2004 and March 2008. The dataset contains two measures of canopy height: maximum height and crown-area-weighted Lorey's height. The assignment of forest class was based on the 2010 MODIS International Geosphere-Biosphere Programme (IGBP) global land cover. From the global dataset, the selected points of height were extracted within the boundaries of the Philippines.

DATA ANALYSIS. Points of canopy height were superimposed on the physical factors in rasterized format so that values could be extracted. Maximum heights were subjected to analysis of variance (ANOVA) to check whether group mean differences were statistically significant based on the DEM derivatives. The study also used the univariate general linear model (GLM) procedure to test the effects of multiple variables on the means of Lorey's canopy height for various groupings. Geographic and climatic variables served as covariates while soil type was used to partition the population into groups.

Results and Discussion

From the 18,578 sampled points of forested sites worldwide, a total of 144 were extracted from the GLAS estimates that fell within the Philippines (Fig. 4). The lowest elevation for a point is 2 m while the highest is 2,425 m. Mean and maximum Lorey's canopy heights are 17.85 m and 40.33 m, respectively. Maximum heights of the shortest and tallest trees are 1.58 m and 58.34 m, respectively.

Fig. 5 provides boxplots of maximum canopy heights grouped based on (left to right) elevation, slope and aspect class, respectively. Differences in canopy heights based on elevation (p=0.022) and slope (p<0.001) are significant, especially for higher classes (above 1,000 m elevation and >50% slope). The range of canopy heights at elevations above 1,000 m is also distinctly narrower than at lower elevations, signifying a sharper boundary with the adjacent class which canbe interpreted as indicating a different forest formation. Whitmore (1984) emphasized that tree species typical of one formation can occur in other formations, which could possibly be the case in areas below 500 m and 1,000 m. As the Philippines is archipelagic, lowland forest species tend to be widely distributed across the islands (Ong *et al.*, 2002). This is evidently true for Dipterocarp species that dominate the lowland forest. Brown and Mathews (1914) observed that although Dipterocarps do not grow on sandy beaches or muddy flats, they may extend prac-

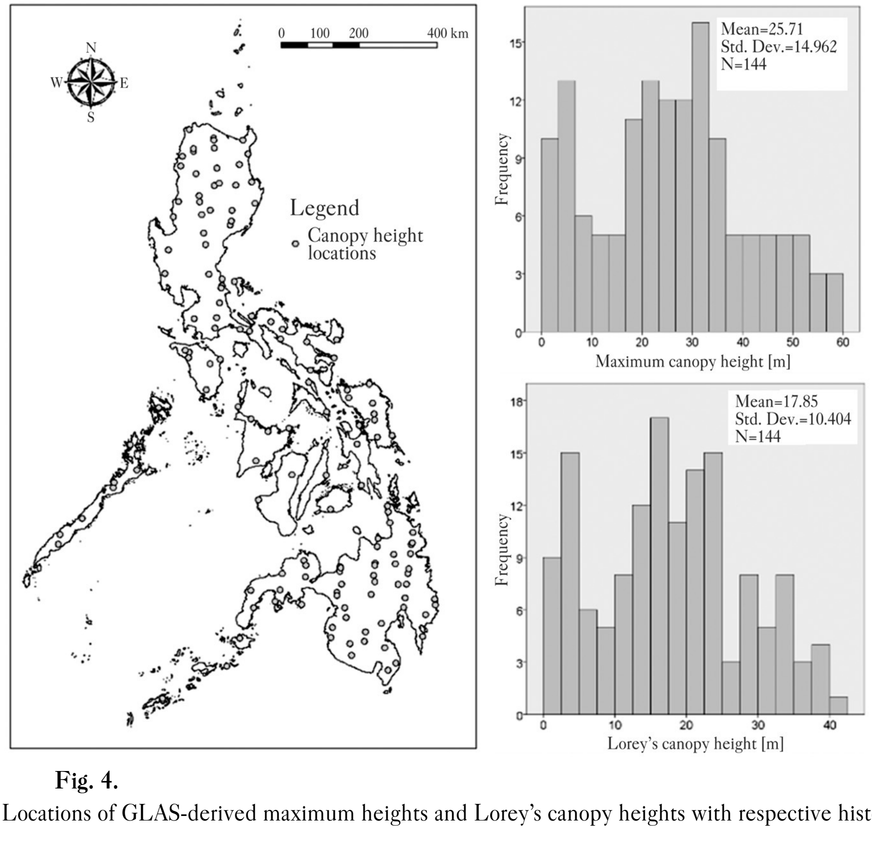

Fig. 4.

Locations of GLAS-derived maximum heights and Lorey's canopy heights with respective histograms

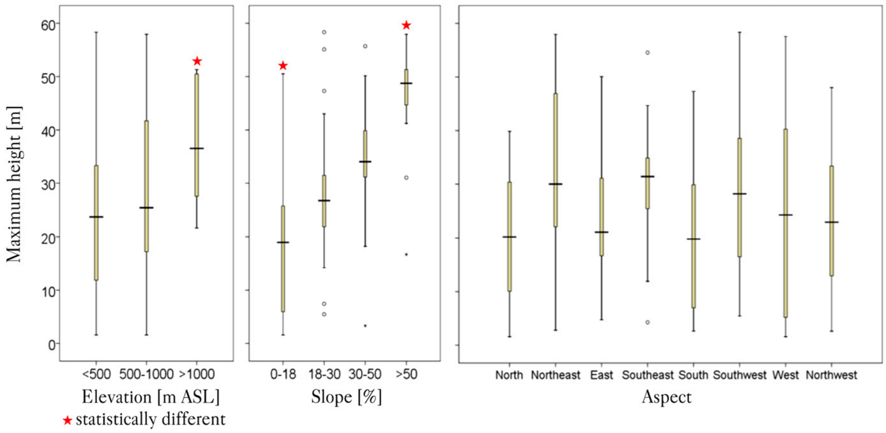

Fig. 5.

Boxplots of canopy heights based on geographic classes for elevation, slope and site aspect

tically to the sea where situations are favorable. Furthermore, since diversity generally decreases with increasing elevation (Aiba and Kitayama, 1999; Homeier, 2008a), this could explain why there is higher standard deviation in the two lower elevation classes (15 m and 16 m, respectively) compared to elevations above 1,000 m, for which standard deviation is only 10 m. With the presence of a larger number of species having different ecological characteristics and habits, a wider range of heights was expected at lower elevations. It is highly noticeable as well that tree heights were shorter at elevations above 1,000 m, as was expected for trees in the mossy forest type or at the upper limit of the montane forest. At higher elevations, the vegetation of the upper montane forest, as identified by Fernando *et al.* (2008), is generally characterized by the dominance of small, woody dicots with microphyllous-sclerophyllous leaves, which form a low dense canopy (ERDB, 2012).

Slope had a more noticeable effect on heights than elevation or aspect (Fig. 5, middle image). There is a trend of increasing canopy heights with greater slope, while the range of heights decreased at greater slopes. Maximum canopy heights at slopes <18% and >50% are significantly different than those within the 18-30% and 30-50% slope classes. A similar result was observed in the southern Ecuadorian forest by Homeier *et al.* (2008b), who noted that ravine forest trees on slopes at elevations from 1,850 to 2,200 m are up to 35 m taller than trees growing on ridges. Gebretsadik (2012), on the other hand, observed the opposite trend, with decreasing heights of oak trees (*Grevillea robusta*) as the slope steepens in tropical forests of Ethiopia. More statistically robust comparisons in the current study may have been possible if tree species in this study were identified and evaluated separately, as species may have different ecological traits, affecting heights.

In contrast, maximum canopy heights do not differ significantly when grouped based on aspect (p=0.172) (Fig. 5, right image). However, there is a visually striking wave pattern of canopy height with aspect, oscillating through different slope directions. In the study of Yang *et al.* (2006) in northern China, tree diameter and heights are higher on north-facing slopes but lower in trees on southwest- and south-facing slopes. In the current study, canopy heights are generally lower on north, east and south facing slopes but higher on northeast, southeast and southwest slopes. The differences between the findings in the current paper and the result of Yang *et al.* (2005) could be attributable to the amount and quality of solar radiation, which varies from the equator going northward. The highest maximum canopy height (58.34 m) and the highest mean canopy height (31.32 m) were recorded in the southwest and northeast, respectively. In contrast, lowest maximum (39.86 m) and mean canopy heights (20.54 m) were both found on north-facing slopes.

While inaccuracies in the DEM used in this study's topographical analysis are recognized, the magnitude of this effect is anticipated to be minimal because comparisons were made on the same land cover for the same parameters (e.g., elevation, aspect and slope). This means that DEM errors affected all classes relatively equally. Uuemaa *et al.* (2020) found that DEMs report systematically higher elevations than the actual land surface in forested areas and that errors differed generally more between land cover types than between DEMs. The quality of the assessment is probably more affected by slope than by elevation or aspect, since vertical accuracy decreases most with terrain slope (González-Moradas and Viveen, 2020; Uuemaa *et al.*, 2020; Yao *et al.*, 2020). The positive elevation bias for sites with tree canopies was expected for an imaging system like ASTER (Gesch *et al.*, 2012; Uuemaa *et al.*, 2020). In the evaluation by Tachikawa *et al.* (2011) in Japan, it was noted that ASTER DEM v2 differed from the referenced national elevation grid by –0.7 m over bare land, and by 7.4 m over forested areas. Nonetheless, the overall vertical offset of the ASTER DEM v2 improved significantly over its previous version (from –3.69 m to –0.20 m) (Gesch *et al.*, 2012).

All of Lorey's canopy height points originally fell within 11 soil types, but because some of these soil types had fewer than five samples, they were excluded from further analysis. This resulted in a total of 129 samples distributed across five soil classes. Although error variances of canopy heights cannot be concluded as equal for all soil classes (p=0.050), the analysis was nevertheless carried out so as not to decrease further the amountof data to be analyzed. Further, log-transformation was conducted on all variables to produce normality of the data. The results of the univariate GLM are displayed in Table 3. In statistics, the sum of squares (Type III) measures the deviation of data points away from the mean value, while degrees of freedom (df) is the maximum number of independent values that have the freedom to vary in the sampled data. The mean square is the ratio of the sum of squares and degrees of freedom. The last two columns in Table 3 are the results of the F-test and the associated significance value, respectively. The latter indicates how closely the independent variables are statistically correlated to the dependent variable (in this case Lorey's canopy height). Topographic, soil and climatic factors all significantly affected canopy height. The significant influence of soil type on Lorey's canopy height (p=0.033) is similar to Rodrigues *et al.* (2018) and Baldeck *et al.* (2013), who also show that soil variables affect both vegetation structure and species diversity. Lillo *et al.* (2019) found that on Dinagat Island in the Philippines, soil type was associated with different forest types, with both lowland evergreen and montane forests appearing on ultramafic rocks, while a different forest type occurred over limestone substrate.

The GLM analysis also supports the findings shown in Figure 4, that significant effects on canopy heights relate to both elevation and slope (p<0.001), but that height was not related to aspect. This particular finding validates the suggestion of Webb *et al.* (1999) and Takyu *et al.* (2002), as cited by Homeier (2008b), 'that changes in species composition and forest structure along topographical gradients are similar to those along elevational gradients.'

Climate effects tree and sapling growth in natural forests (Marshet and Fekadu, 2019). This is corroborated by the result of the current study, where mean diurnal temperature range, isothermality and annual temperature range were significantly related to forest canopy height (p<0.050). All of these climate variables are functions of maximum and minimum temperature. According to Hatfield and Prueger (2015), the rate of plant growth and development is dependent upon temperature and each species has a specific temperature range for best growth, represented

Table 3.
Result of GLM regression between canopy heights and various physical and climatic factors

Source	Type III SS (a)	df (b)	MS (a÷b)	F	Sig.
Corrected Model	9.974a	15	0.665	11.391	0.000
Intercept	0.315	1	0.315	5.399	0.022
Aspect	0.138	1	0.138	2.358	0.127
Soil types	0.633	4	0.158	2.713	0.033*
Elevation	0.503	1	0.503	8.613	0.004*
Slope	2.721	1	2.721	46.612	0.000*
Annual mean temperature	0.198	1	0.198	3.388	0.068
Mean diurnal temperature range	0.365	1	0.365	6.256	0.014*
Isothermality	0.370	1	0.370	6.332	0.013*
Temperature seasonality	0.003	1	0.003	0.043	0.836
Annual temperature range	0.358	1	0.358	6.137	0.015*
Annual precipitation	0.000	1	0.000	0.005	0.944
Mean monthly solar radiation	0.000	1	0.000	0.001	0.978
Total yearly solar radiation	0.190	1	0.190	3.260	0.074
Error	6.596	113	0.058		
Total	199.808	129			
Corrected Total	16.570	128			
a. R Squared = 0.602 (Adjusted R Squared = 0.549)					

Note: SS – sum of squares; df – degrees of freedom; MS – mean square; F – test value
*Significance values indicate significantly differences among classes of the relevant parameter

by particular minimum, maximum, and mean values. In this vein, Sinha *et al.* (2018) developed regression models for both maximum and minimum temperatures that were used to quantify factors affecting forest composition and structure. They found that these factors showed a significant relationship with diversity and elevation, which shapes the state of the forest community. Their findings are similar to those of the current study and are crucial for developing forest adaptation strategies that can reduce the impacts of extreme climate events, particularly those resulting from El Nińo and La Nińa phenomena that both affect the Philippines.

Conclusion

While the correlation between forest structure and environmental factors has previously been established, this study provides more specific detailed information on its nature in the Philippines. Nationwide spatial analysis in a GIS platform using remote sensing datasets revealed relationships and patterns in Philippine forests which could not be identified and evaluated with traditional methods. The ecological relationships identified in this study, if coupled with projections of climate change, have the potential to model future changes in the distribution and composition of species. Moreover, findings in this study on topographical effects on forest growth can be used to develop more appropriate silvicultural interventions and management strategies. The present analysis can be improved by increasing samples of dependent variables carried out in this study through other means (e.g., using airborne or drone LiDAR) and by using updated soil data.

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Conflicts of interest

The author declare the absence of potential conflicts of interest.

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STRESZCZENIE

Poznanie wpływu czynników środowiskowych na pomiar wysokości okapu drzewostanu na Filipinach na podstawie danych ICESat

Poznanie czynników wpływających na rozwój drzew jest kluczowe dla ekologii leśnej, gdyż wzrost drzew wpływa na strukturę lasu i ilość biomasy (Coomes, Allen, 2007). Wykorzystywany jest on w modelowaniu rozmieszczenia poszczególnych gatunków (Pearson, 2009) i zwiększania się obszarów pokrytych lasami w kontekście gospodarki leśnej (Worrell, Malcolm, 1990). Wzajemnie powiązane efekty topografii i klimatu są głównymi czynnikami kształtującymi największe biomy Ziemi, takie jak lasy (Mucina, 2019), i kontrolującymi rozmieszczenie roślinności (Sharma *et al.*, 2017). W związku z potencjalnym wzrostem temperatury i ilości opadów atmosferycznych spowodowanym zmianami klimatycznymi (IPCC, 2007) należy uwzględnić zmienne geoklimatyczne przy ocenie rozmieszczenia roślinności oraz prognozowaniu rozwoju lasów, w tym śmiertelności i rozmnażania się drzew (Yang *et al.*, 2006; Marshet, Fekadu, 2019; Sharma *et al.*, 2017).

Na całym świecie przeprowadzono pewną liczbę projektów badawczych dotyczących korelacji między tymi czynnikami a strukturą leśną (Sharma *et al.*, 2017; Gairola *et al.*, 2014; Rawat, Chandra, 2014; Hatfield, Prueger, 2015), ale tylko kilka z nich realizowano na Filipinach, ze szczególnym uwzględnieniem analizy danych z systemów teledetekcji (remote sensing, RS). Podstawowym celem artykułu jest analiza struktury lasu i jej zmienności przy wykorzystaniu informacji o wysokości okapu drzewostanu uzyskanego z danych RS, w połączeniu z gradientami geograficznymi i klimatycznymi.

Analiza obejmuje swoim zakresem całe Filipiny (ryc. 3). Na obszarze archipelagu, wynoszącym 30 milionów hektarów, aż 23,4% pokryte jest przesz lasy, w tym lasy namorzynowe (FMB, 2014). Łącznie w ramach prac wykorzystano 144 statystycznie wybrane lokalizacje na obszarze kraju, w których określono wysokość okapu drzewostanu na podstawie danych pochodzących z satelity Ice, Cloud and Land Elevation (ICESat). Dane zbierano w okresie między październikiem 2004 roku a marcem 2008 roku dla dwóch rodzajów wysokości koron drzew: maksymalnej wysokości i wysokości Loreya ważonej powierzchnią koron. Następnie nałożono je na różne czynniki środowiskowe w formacie rasteryzowanym, aby można było pozyskać wartości. Maksymalne wysokości poddano analizie wariancji (ANOVA), aby zweryfikować, czy średnie

dla grup są statystycznie istotnie różne w kontekście trzech parametrów geograficznych: wysokości, nachylenia i aspektu. Zastosowany numeryczny model wysokościowy (DEM) to ulepszona wersja 2 Global DEM (GDEM; Advanced Spaceborne Thermal Emission and Reflection Radiometer – ASTER). Z jednej strony stwierdzono, że maksymalne wysokości przekraczające 1000 m lub spadek w zakresie poniżej 18% i powyżej 50% różnią się istotnie statystycznie od pozostałych klas, co wskazuje na inną formację leśną. W dużej mierze widać to samo we wszystkich klasach wystawy ($p=0{,}172$), chociaż zauważyć można widoczny wzorzec wysokości okapu drzewostanu, gdzie wartości są niższe na zboczach północnych, wschodnich i południowych, ale generalnie wyższe na północno-wschodnich, południowo-wschodnich i południowo-zachodnich. Z drugiej strony, wartości Loreya wykorzystano w analizie regresji jednoczynnikowej, w ramach której typy gleby, klimat i parametry topograficzne były zmiennymi objaśniającymi wysokość okapu drzewostanu (zmienna objaśniana). Określenie typu gleby oparto na danych z projektu FAO-UNESCO v3.6 (opublikowanym w 2003 roku), zaś wartości klimatyczne zaczerpnięto z WorldClim v2.1 (Fick, Hijmans, 2017), który jest zwykle używany do mapowania gatunków i modelowania wzrostu roślin. Wyniki wskazują, że wzniesienie i nachylenie ($p<0{,}010$), typ gleby ($p<0{,}050$), dobowy zakres temperatur oraz roczny zakres temperatury i izotermy ($p<0{,}050$) wpływają na różnice średnich wysokości okapu drzewostanu. Warto zwrócić uwagę na to, że ostatnie trzy zmienne są funkcjami najwyższej i najniższej zarejestrowanej temperatury. Ustalenia te mogą być przydatne do modelowania rozmieszczenia typów lasów, a co za tym idzie – właściwej gospodarki leśnej.