Potential stereoscopic tree height measurement of teak plantations using Pléiades high-resolution satellite imagery

Naoyuki Furuya[1)*], Iwao Noda[2)3)], Woraphun Himmapan[4)]

[1)] Hokkaido Research Center, Forestry and Forest Products Research Institute, 7 Hitsujigaoka, Toyohira, Sapporo, Hokkaido 062-8516, Japan.
[2)] Forestry Division, Japan International Research Center for Agricultural Sciences, 1-1 Ohwashi, Tsukuba, Ibaraki 305-8686, Japan.
[3)] Present address: Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan.
[4)] Silvicultural Research Division, Forest Research and Development Bureau, Royal Forest Department, 61 Phaholyothin Rd., Chatuchak, Bangkok 10900, Thailand.
* *Corresponding author; E-mail: nfuruya@ffpri.affrc.go.jp*

Abstract

There is a broad demand for technical development of methodologies for large-scale monitoring of tree plantations. Stereoscopic tree height measurement using optical high resolution satellite imagery is one of the potential means. In this study, the potential of dominant tree height estimation was examined in teak plantations located in the agricultural land mosaics of the northeast Thailand. Terrains were modeled based on the surface measurements surrounding teak plantations. Tree height was estimated as the difference between the tree top position and the estimated terrain. The result was evaluated based on the comparison with the field surveyed dominant tree height. There was a correlation between the estimated and the field-surveyed dominant tree heights. The root-mean-square error was under 2 m. The result clarified the potential of stereoscopic tree height measurement using stereo-paired high resolution satellite imagery targeting on small-scale teak plantation established in the moderate terrain area. Large deviations of dominant tree estimation (< 4 m) were mainly caused by the deviations of terrain modeling. The accuracy of terrain modeling also caused the underestimation and/or the overestimation of dominant tree height at some cases.

Keywords: Thailand, Teak plantation forest, High-resolution satellite imagery, Stereoscopic measurement

Introduction

Teak (*Tectona grandis*) is one of the premier hardwood timbers in the world (Pandey and Brown 2000), but supplies from natural forests have dwindled in most countries. In Thailand harvesting from natural forests was banned in 1989, and thereafter supplies from plantation-grown teak have increased (Pandey and Brown 2000). Across Thailand, large areas of teak plantation had been established through a private tree plantation promotion program using subsidies by the government (Mahannop 2004; Sharp and Nakagoshi 2006). It is important to meet the demand for teak wood with supplies from teak plantations in a sustainable manner. However, there is currently no system or database for monitoring resources, demand, or supply (Mahannop 2004). Therefore, the growth of teak plantations or even information about whether they are still present is unknown because of a lack of monitoring schemes after the large-scale establishment of teak plantations. In the shortage of human resources and budgets for field data collection, an efficient large-scale monitoring scheme using remote sensing is highly expected.

Dominant tree height (DTH) and age are used for estimating the site index, a productivity index derived from tree height, which can be used for modeling stand yields over time (Ritchie et al. 2012). A yield table was created for teak plantation in the northeast of Thailand based on field survey data (Vacharangkura et al. 2011). Although the growth of teak plantations showed large variations among sites depending on site conditions and management status, DTH was considered to be a good parameter that was independent of stand density or the intensity of stand management (Ishibashi et al. 2010). Forest stand height information, such as mean canopy height, was also found to be an important parameter that can be used for biomass or stand volume estimation (Asner et al. 2012; Drake et al. 2002). Forest stand height information has been collected by intensive field surveys. However, considering the application of large-area assessment of tree plantations, tree height information is expected to be efficiently retrieved from remote sensing techniques.

There are a number of potential methods for height measurement using remote sensing techniques (Sirmacek et al. 2012): 1. Optical stereo image analysis (aerial photos and high resolution satellite imagery), 2. Interferometric SAR processing, and 3. LiDAR data processing. Among these methods, optical stereo satellite image analysis has an advantage in its world-wide applicability over large-scale areas. There are multiple satellites or sensors observing land coverage at very high spatial resolution (Poli and Caravaggi 2012). A new generation of high-resolution satellites or sensors also have an up-to-date acquisition capacity. For example, the French Pléiades satellite has high acquisition capacity combined with a constellation of four satellites, Pléiades 1A and 1B and SPOT 6 and 7 (Astrium 2012). The high agility of the Pléiades satellite also allows for flexible acquisition and especially stereo and tri-stereo acquisition along a single orbit (Astrium 2012). Such technical development in satellites or sensors is rapidly opening up a new era of high-resolution optical image monitoring.

In general, to extract tree height information using optical stereo imagery, there are two basic elements: 1. identification of tree top position or tree canopy surface modeling and 2. terrain modeling. Tree height can simply be calculated as the difference between these two models. Tree top identification or surface modeling can be conducted using very high resolution satellite imagery. However, in general it is difficult to estimate terrain height in forested areas. This is because forests expand in large area and on rugged terrain, and forests also hide the terrain under their tree canopies. This is the reason why there have been few studies on tree height measurement using stereo satellite imagery, while there are plenty of such studies conducted using LiDAR observations that can extract both information on a digital surface model (DSM) and a digital terrain model (DTM) simultaneously. However, in the northeast of Thailand, teak plantations are located on moderate terrain and surrounded by patches of agricultural land. In such a case, the hidden terrain was considered to be estimated by the measurement of terrain surfaces of surrounding teak forests. Errors in such terrain modeling will be relatively small when the terrain is flat or moderate. Therefore, in such a region, there is potential for tree height measurement on a large scale using stereo paired high resolution satellite images.

Therefore, the objective of this study was to examine tree stand height measurements through stereoscopic measurement using high resolution satellite imagery in order to evaluate the potential of stereo observation for extracting height information for growth assessment and resource monitoring of plantation forests over a large area.

Study area

The study area was located in the northern part of Nong Bua Lam Phu province in the northeast of Thailand (Fig.1). Small-scale teak plantations managed by farmers were the target of this study. The terrain in the northeast of Thailand is rather moderate. Therefore, agricultural land is widespread across this region. Teak plantations have also been established in a mosaic pattern intermixed with agricultural lands such as paddy fields, farmland of cassava, sugarcane, and maize, orchards and tree plantations of rubber and short-rotation eucalyptus. The size of the teak plantations was rather small with a mean size of several hectares (Mahannop 2004), which was also separated into several small parcels. Almost all teak plantations were established by a subsidy program in 1990s. Narrow spacing, such as 2 m × 2 m, 2 m × 3 m, and 2 m × 4 m, was mainly applied as the initial plant spacing.

Materials and methods

Paired Pléiades very-high-resolution satellite imagery (Forward and Nadir observation), captured in a triplet mode on 14 November, 2012, was utilized for stereoscopic measurement. Descriptions of the satellite data acquisition are shown in Table 1.

An outline of the Dominant tree height (DTH) estimation by stereoscopic measurement on satellite imagery is shown in Fig.2. A total of 20 rectangular size-variable survey plots (plot size α = 0.06 to 0.16 ha) was set in the teak plantations to measure DTH at the field and on the satellite imagery. Stereoscopic measurement was conducted using the 3-dimensional measurement tool of Stereo analyst (Hexagon Geospatial 2010) of ERDAS

Imagine image processing software (Hexagon Geospatial) to measure the altitudes of tree tops and the bare lands surrounding the teak plantations. Terrain was modeled based on the surrounding bare land altitudes that could be depicted by visual interpretation. A triangular interpolation method of a surface modeling tool of TNTmips GIS analysis software (MicroImages Inc.) was applied for the terrain modeling in each plot (MicroImages 2013). Terrain model was created in raster format at spatial resolution of 0.5 m. Individual tree height was calculated as the vertical difference between the top canopy position and the estimated terrain model at which the tree top was located. Because of difficulties in matching individual trees on the satellite imagery with the field-measured individual trees,

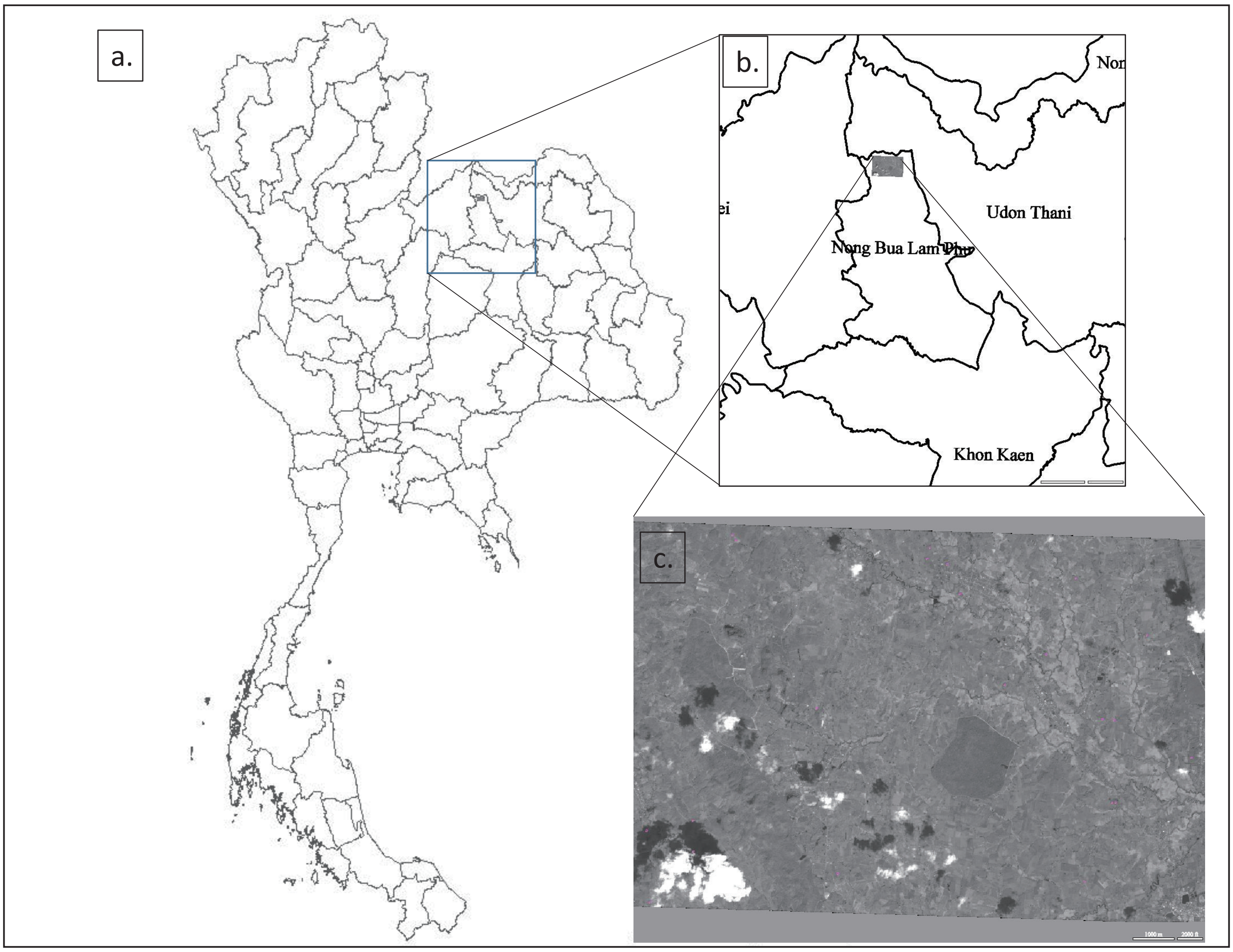

Fig. 1. Location of the study area (a. the Kingdom of Thailand, b. location of Nong Bua Lam Phu province, and c. coverage of Pléiades high-resolution satellite imagery)

Table 1. Description of stereo-paired Pleiades satellite images in triplet mode

Satellite/Sensor	Pléiades 1A	Pléiades 1A
Image ID	Forward	Nadir
Acquisition date	2012/11/14	2012/11/14
Acquisition time	3:54:49	3:55:06
Image size (column × row)	29796 × 18067	30279 × 18976
Global incidence (deg.)	13.1	5.8
Across track incidence (deg.)	−3.0	−5.4
Along the track incidence (deg.)	−12.7	−2.2
Solar azimuth (deg.)	156.3	156.7
Solar elevation (deg.)	51.1	51.2

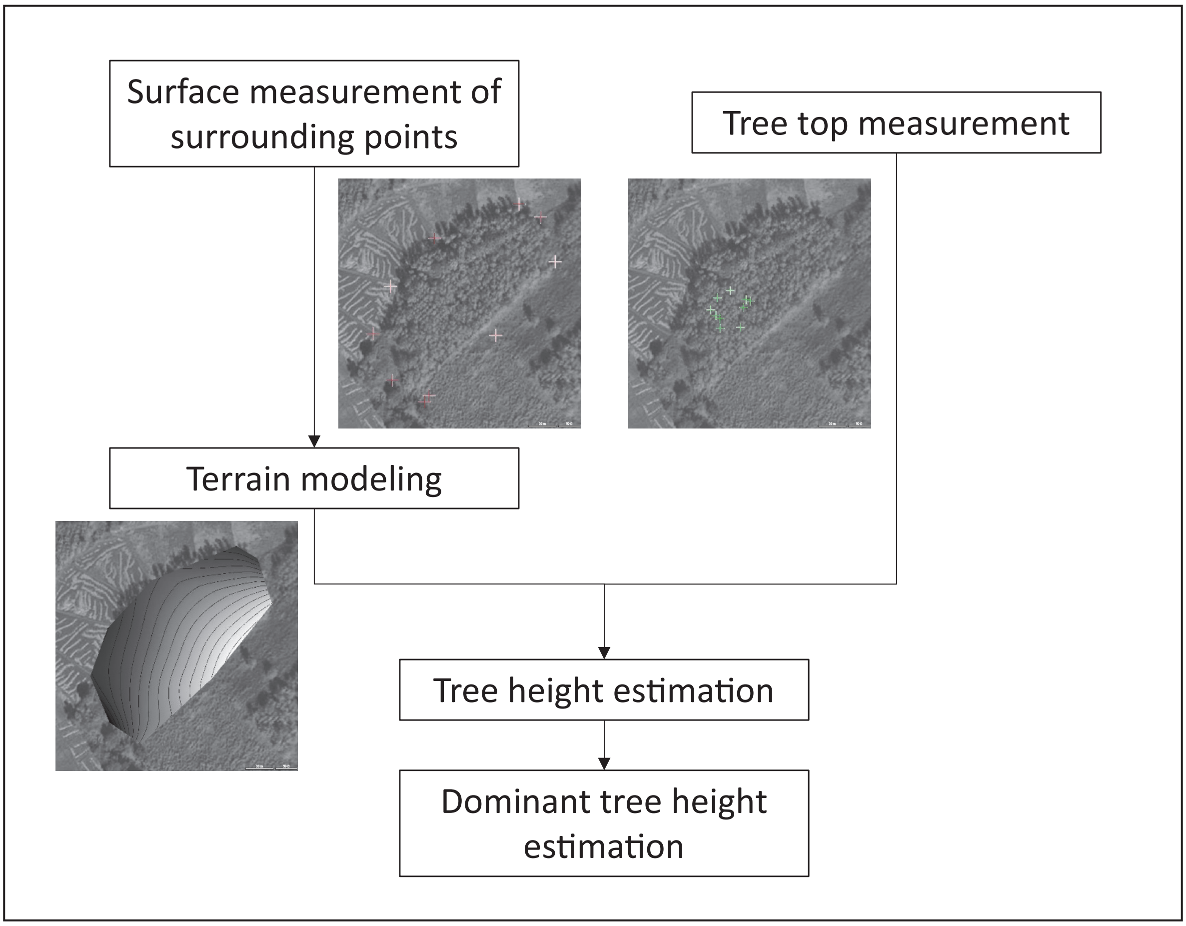

Fig. 2. Flowchart of DTH estimation by stereoscopic measurement of satellite imagery

dominant trees inside the field survey plot were sampled independently on the satellite image and the tree top positions of these dominant trees were identified by visual interpretation. DTH for each plot was calculated as the mean value of the measured tree heights. In this study, DTH was defined as the mean height of the top 100 trees per hectare. The number of dominant trees for calculating DTH were decided individually plot by plot as below,

$$m = 100 \times a$$

where m is number of sampled dominant tree and a is plot size in hectare. Three replicative measurements both of dominant tree top (p = 1 to 3) and terrain (q = 1 to 3) were conducted independently by the same interpreter in a same procedure. In summary, the estimated DTH (eDTH) on satellite imagery was calculated as below,

$$\mathrm{eDTHpq} = \frac{1}{m}\sum_{j=1}^{m} (DSMp(i) - DTMpq(i))$$

where p is number of p th tree top measurement, q is number of q th terrain estimation, m is number of height estimated dominant trees, DSMp(i) is altitude of i th tree top based on the p th tree top measurement, and DTMpq(i) is altitude of estimated ground position of i th tree top based on the p th tree top measurement and the q th terrain estimation.

The field survey was conducted in December 2012. Tree height measurement was conducted using a Vertex ultrasonic hypsometer (Haglöf Sweden) for trees sampled by the planting line. More than half of the trees inside the plot were intended to be sampled in each stand. The field-surveyed DTH (sDTH) was calculated for each plot based on the direct height measurement as below,

$$\mathrm{sDTH} = \frac{1}{m}\sum_{j=1}^{m} h(j)$$

where m is number of sampled dominant trees, and h(j) is tree height of the j th tallest tree of the height measured tree. Although the sampling ratio was different plot by plot, the number of dominant trees of m, same with the satellite analysis, was used for each plot for calculating sDTH in this study.

The eDTHpq were compared with sDTH to discuss the accuracy, and the applicability of the methodology were discussed. A total nine estimates (eDTHpq) calculated as the combinations of three tree top measurements (p = 1 to 3) and three terrain measurements (q = 1 to 3) were examined.

Results and discussion

Error factors of height measurement

Fig. 3 shows the results of estimations of the DSM, DTM, and DTH in each plot. Fig. 3a shows variations in $\overline{DSMp}$ and $\overline{DTMpq}$ for each plot. Relative variations in $\overline{DTMpq}$ was larger than those in $\overline{DSMp}$, although the absolute values of $\overline{DSMp}$ and $\overline{DTMpq}$ varied depending on the altitude of the plots. Fig. 3b shows the distribution of eDTHpq in relation to the sDTH. There was a correlation between eDTH and sDTH for each combination of measurements (R^2 = 0.53 to 0.75 at slope values close to 1 (0.97 to 1.02)). However, overestimation was observed in Plot 13 and Plot 20, and underestimation was observed in Plot 1. Fig. 3c shows the deviations of eDTHpq from sDTH. For each combination of p and q, distribution of the deviation through the plots showed the normal distribution with the mean of close to zero (-0.38 to 0.52). However, as seen above, there was remarkable overestimations in Plot 13 and Plot 20 and remarkable underestimation in Plot 1. The maximum deviation of eDTHpq of each combination of measurement was about 4 m. The deviations were mainly caused by inaccurate and unstable DTM estimations. In Plot 1, the variation in eDTHpq was small but underestimation of DTH by around 3 m was observed.

The reasons for the overestimations and underestimations were examined in some plots. In Plot 20, an overestimated plot, the terrain was rather flat according to the field observation. However, it was located on a slightly hilly area. The area, where the surface of surrounding the teak plantation was measurable, was located at the lower end of a small hill. As a result, estimated DTM obtained from triangle interpolation was lower than actual, and then the resultant DTH was overestimated. The case of Plot 1 was a case of underestimation of DTH. The terrain was concave in contrast to the case of hilly Plot 20. As a result, the terrain might be estimated as being higher than it actually was, and then DTH was underestimated. The variation in estimation was small because the locations of measurable surrounding surfaces were limited and fixed, and the terrain was inevitably modeled constantly.

Studies on building height measurement by space-borne observation has shown height estimation accuracy of root-mean-square error (RMSE) of 0.6 to 1.3 m (Abduelmula et al., 2015). In our study on DTH measurement, it ranged from 1.43 to 1.96 m. The sources of errors can be separated into three factors. Firstly, error in tree top detection by visual interpretation. Secondly, errors can be caused by terrain modeling. The accuracy of terrain modeling based on surrounding point measurements becomes worse if the surrounding land is covered by vegetation. Rugged terrain is easily simplified in the current surface modeling procedure. These factors occasionally cause large estimation errors in tree height estimation. Therefore, precise terrain estimation and the subsequent tree height estimation will be more difficult in rugged terrain than in flat and moderate terrain areas. Thirdly, the sensor model that decides the position and attitude of the sensor. This factor was not evaluated in this study but the height estimation calculated as the relative difference between two measurements of surface and terrain will diminish any influence of this source of error.

Terrain modeling

In this study area, as illustrated in Fig. 4, all the teak plantations were located amongst a mosaic of agricultural lands. Road networks have also developed and tend to stick to the teak plantations. Therefore, the positions of surfaces surrounding the teak plantations were measureable. This enabled the terrain estimation of teak plantations, although the terrain estimation had large variations in some cases. As a result, DTH of all the plots could be estimated. On the other hand, the direct terrain measurement of teak plantations was more difficult using the current leaf-on imagery captured at the beginning of the dry season because there is, in general, no space to enable direct surface measurements inside the teak plantations. Only the surfaces of a small number of large canopy gaps was measurable. Therefore, terrain estimations based on surface measurements in surrounding locations of the teak plantations was needed. The probability of direct terrain measurement inside teak plantations from leaf-off imagery should be checked as a further step.

Future work

This study clarified the potential of stereoscopic tree height measurement using high-resolution satellite imagery targeting small-scale teak plantations in a moderate terrain area. In this study, human interpretation was conducted to search for adequate locations to estimate terrain heights. However, there is potential for automation for large-

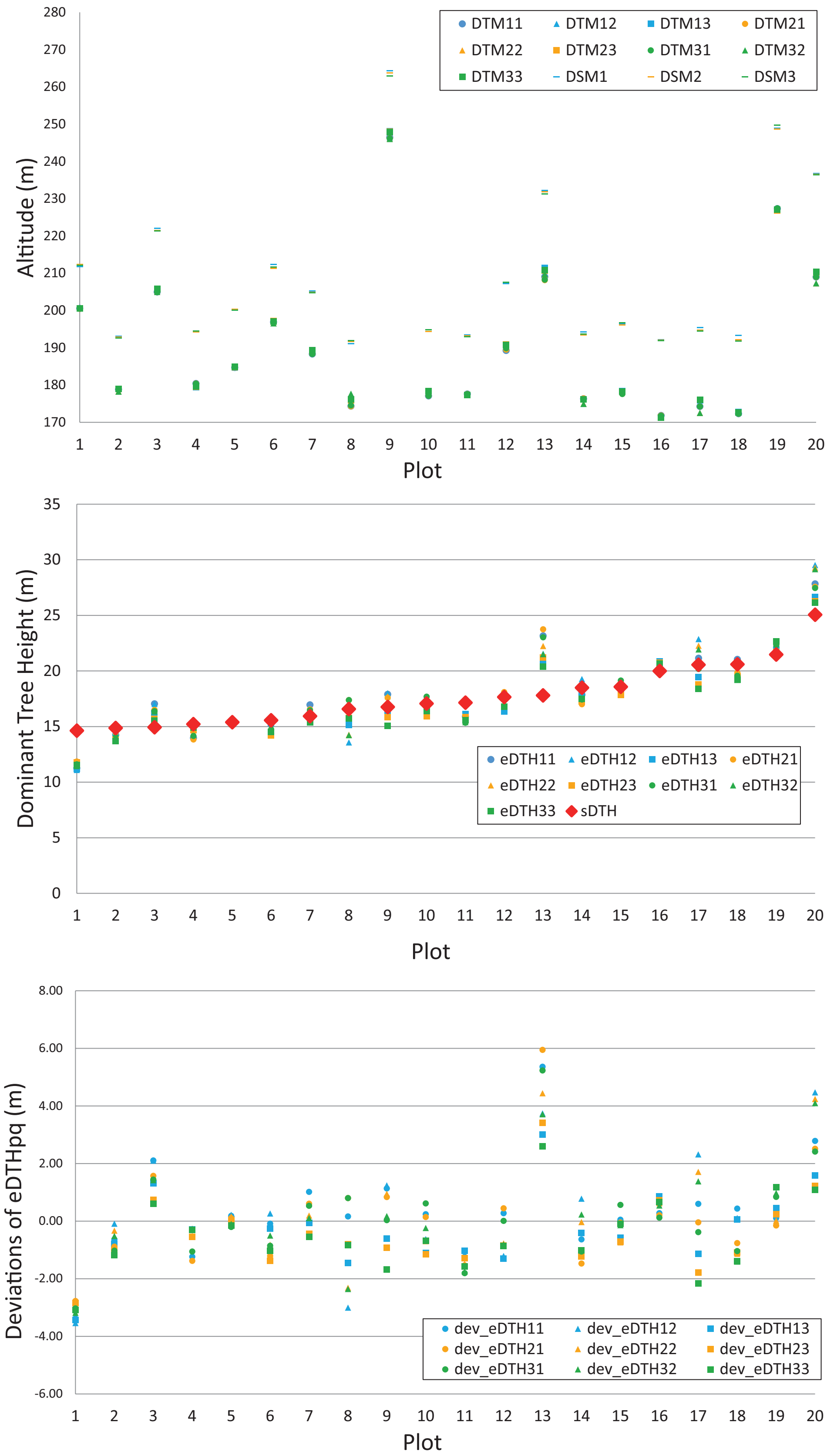

Fig. 3. Distribution of $\overline{DSMp}$, $\overline{DTMpq}$, and eDTHpq and the deviations (Fig. 3a (upper). Variations in the $\overline{DSMp}$ and $\overline{DTMpq}$ in each setting; Fig. 3b (middle). Variations in eDTHpq in each setting; Fig. 3c (lower). Variations in the deviations of DTH estimation (eDTHpq minus sDTH) in each setting) Here, mean DSMp was calculated as $\overline{DSMp} = \frac{1}{m}\sum_{i=1}^{m} DSMp(i)$ and $\overline{DTMpq}$ was defined as $\overline{DTMpq} = \frac{1}{m}\sum_{i=1}^{m} DTMpq(i)$.

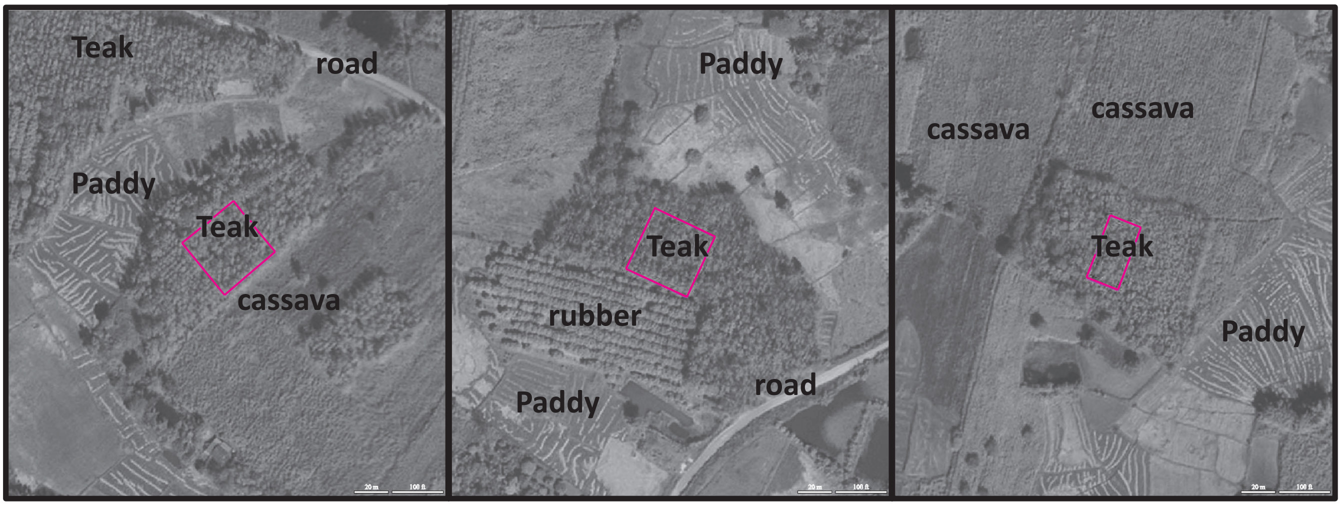

Fig. 4. Examples of teak plantations located amongst an agricultural land mosaic (the rectangular polygon indicates the location of the survey plot).

area monitoring. For building height measurement in urban areas, some studies have reported good results for automatic building height estimation by analyzing an automatically created DSM and DTM (Abduelmula et al. 2015). Simplification of complicated land mosaics and tree canopy surface modeling will be more difficult than city modeling. However, the procedure for automatic extraction of tree height by automatically creating the DSM and DTM should be further developed in future studies. Some studies on DSM extraction using space-derived imagery examined the influences of B/H (base to height) ratio both on the accuracy and on the applicability of height estimation (ex. Jacobsen and Topan 2015). In this study, only a pair of forward and nadir images was used for stereoscopic measurement. However, other combinations of image, such as a backward-nadir and forward-backward image, can also be examined in future studies. For example, short base length will influence the possible vertical accuracy, but it will enable better image matching (Jacobsen and Topan 2015). In any cases, estimated DTH information will contribute to the growth assessment and resource monitoring of teak plantations in large areas.

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References

Abduelmula A, Bastos MLM, Gonçalves JA (2015) High-Accuracy Satellite Image Analysis and Rapid DSM Extraction for Urban Environment Evaluations (Tripoli-Libya). Int. J. Comp. Elec. Auto. Cont. Inf. Engin. 9: 661-666.

Asner GP, Mascaro J, Muller-Landau HC, Vieilledent G, Vaudry R, Rasamoelina M, Hall JS, van Breugel M (2012) A universal airborne LiDAR approach for tropical forest carbon mapping. Oecologia 168: 1147-1160.

Astrium (2012) Pléiades imagery- User Guide. Astrium GEO-Information Services, Paris, France.

Drake JB, Dubayah RO, Knox RG, Clark DB, Blair J (2002) Sensitivity of large-footprint lidar to canopy structure and biomass in a neotropical rainforest. Remote Sens. Environ. 81: 378-392.

Hexagon Geospatial (ERDAS, Inc.) (2010) ERDAS Stereo Analyst User's Guide. Leica Geosystems GIS & Mapping Division, Atlanta, GA, USA.

Ishibashi S, Sakai M, Noda I, Vacharangkura T, KrongkitsiriV, Kamolpanit D, Himmapan W (2010) Yield Prediction Table on *Tectona grandis* (Teak) in Northeast Thailand [Revised edition]. Study report under RFD-JIRCAS Joint Research Project, JIRCAS, Tsukuba, Japan.

Jacobsen K, Topan H (2015) DEM generation with short base length Pleiades triplet. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XL-3/W2, p.

PIA15+HRIGI15.

Mahannop N (2004) The Development of Forest Plantations in Thailand. In: Enters T, Durst PB (eds.) What Does It Take?: The Role of Incentives in Forest Plantation Development in Asia and the Pacific. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, pp. 211-236.

MicroImages (2013) Surface Modeling (tutorial). MicroImages, Inc., Raymond, NB, USA.

Pandey D, Brown C (2000) Teak: a global overview. Unasylva 51: 3-13.

Poli D, Caravaggi I (2012) Digital surface modelling and 3D information extraction from spaceborne very high resolution stereo pairs. Publications Office of the European Union, Luxembourg.

Ritchie M, Zhang J, Hamilton T (2012) Effects of stand density on top height estimation for ponderosa pine. Western J. Appl. For. 27: 18-24.

Sharp A, Nakagoshi N (2006) Rehabilitation of degraded forests in Thailand: policy and practice. Landscape and Ecol. Engineering 2: 139-146.

Sirmacek B, Taubenbock H, Reinartz P, Ehlers M (2012) Performance Evaluation for 3-D City Model Generation of Six Different DSMs From Air- and Spaceborne Sensors. IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens. 5: 59-70.

Vacharangkura T, Ishibashi S, Noda I, Himmapan W, Krongkitsiri V, Kamolpanit D (2011) Yield table for Teak plantation in the Northeast of Thailand. RFD-JIRCAS Project, Bangkok Thailand (in Thai).