Social forest inventory

Digital surface models based on UAV aerial images – evaluation and comparison to LiDAR data

Aarne Hovi
University of Helsinki
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Summary

Digital surface models (DSMs) generated by image matching from aerial images obtained using UAV were evaluated against field reference data and compared to LiDAR data. The performance of DSMs was evaluated both visually and with quantitative tests. In quantitative tests, the ability of DSM to estimate 1) individual tree heights, 2) canopy height and 3) crown projection area were evaluated. The UAV based DSMs were provided to UH by MosaicMill. Also the point clouds from which DSM was calculated were provided. The LiDAR based DSMs were generated from discrete-return LiDAR data obtained in summer 2010. Three different flying altitudes (1.3 km, 2 km and 3 km) were used. Field reference data consisted of 5 plots in seedling stands and 4 plots in mature stands. For the estimation of canopy height and crown projection area, reference DSM was calculated for each plot using field-measured tree heights and allometric models for crown width and shape.

In visual evaluation, UAV based DSMs followed canopy surface reasonably well in seedling stands whereas in mature stands treetops were missed and the DSM did not penetrate to lower canopy layers except when there were large canopy gaps. In seedling stands (mean h 1.6–2.2 m), both LiDAR and UAV underestimated individual tree heights. On 4 of the 5 seedling stand plots UAV (RMSE 0.50–0.81 m) was equally accurate or somewhat better than LiDAR (RMSE 0.85–0.98 m, 0.82–1.09 m, 0.83–1.11 m for 1.3 km, 2 km and 3 km data sets, respectively). On one plot, UAV was notably more inaccurate than LiDAR, which can be due to problems with stereo coverage. In mature stands (mean h 16.0–24.5 m), LiDAR underestimated tree heights by 0.29–1.43 m. In UAV data, bias for tree heights ranged between -4.50 m and 0.81 m which shows that there are large systematic differences in elevation values. RMSE in mature stands was notably larger for UAV (4.28–7.52 m) than for LiDAR (1.06–2.92 m, 0.78–3.28 m and 1.87–3.23 m for 1.3 km, 2 km and 3 km data sets, respectively). Systematic offsets in X and Y coordinates were tested by moving the DSM around the original coordinates and searching minimum RMSE. There were systematic XY offsets in UAV data (up to 0.64 m) in mature stands. Results for the canopy height were similar to individual tree heights, but the differences between UAV and LiDAR in seedling stands were smaller than for individual tree heights. Analyses of the crown projection area showed what already could be seen from visual interpretation: In mature stands UAV underestimates crown projection area near treetops and overestimates it in lower canopy layers.

Conclusions are:
1) Image matching of UAV based aerial images produces DSMs equal or slightly better to those obtained from high pulse density (10–15 pts m^{-2}) LiDAR data in seedling stands.
2) In mature stands, LiDAR is superior to UAV. The accuracy of the UAV is poor and there are systematic offsets both in Z and XY information. Large differences in Z-information between plots cause difficulties if stand variables are estimated for large areas using UAV data.

1. Introduction

Airborne laser scanning (ALS) systems use LiDAR (Light Detection and Ranging) remote sensing technology, in which a short laser pulse is transmitted to the target and the backscattered signal is detected. From time-of-flight of the pulse and position and orientation information of the sensor, the 3D position of the target can be calculated. Point clouds from the ALS measurements allow accurate reconstruction of the reflecting surfaces in forest canopy. This information can be used in derivation of important forest parameters as tree height and timber volume.

An alternative method for LiDAR technology is to calculate photogrammetric surface points by image matching of multiple accurately orientated aerial images. There are some fundamental differences between LiDAR and photogrammetric surface point calculation. Photogrammetric surface point calculation is based on finding corresponding points in multiple images. If the target is visible to only one image, corresponding points cannot be found. Therefore, in the case of forest canopy, photogrammetric surface point calculation is more sensible to occlusion and shading of the trees. LiDAR measures the target in monoscopic geometry i.e. the illumination and viewing directions are equal. LiDAR is therefore not so sensible to shading and produces geometric information deeper from the canopy. Photogrammetric method provides continuous sampling of the forest canopy whereas LiDAR produces discrete 3D points. Discontinuity can be a problem especially if low pulse density LiDAR data is used.

In ALS based forest inventory, accuracy comparable to traditional field methods is achieved in mature forests. However, in seedling stands, the accuracy of the LiDAR is not good enough to provide reliable estimates on the stand characteristics. This is mainly due to that LiDAR pulse seldom reflects from the outer surface of the canopy but penetrates to the canopy. LiDAR typically underestimates the tree heights by 0.5–1.5 m, which is acceptable with large trees but not with seedlings.

From aerial image surface points or LiDAR data, a digital surface model (DSM) describing the outer surface of the canopy can be calculated. DSM can be used in many forestry purposes, including derivation of canopy height and canopy volume or detection of individual heights (in mature stands). In addition to derivation of stand characteristics, DSM can be used in retrieval of radiometric (image) data from the canopy (3D to 2D mapping) and in computation of illumination conditions in the canopy, which is particularly important in the interpretation of the radiometric (image) data. An ideal DSM follows the outer surface of the canopy and is unbiased (no under- or overestimation of canopy height). Ideal DSM penetrates near ground in the canopy gaps, and on the other hand, reaches the treetops.

In this report, DSMs and point clouds created by multi-image matching from aerial images obtained with unmanned aerial vehicle (UAV) are evaluated by comparing to field reference data. DSMs and point clouds from LiDAR data are used as benchmark. The aim is to evaluate whether added value is achieved by using UAV images instead of LiDAR data.

2. Materials

2.1 Field reference

Study sites were located near Hyytiälä forest station in southern Finland (61°50´N, 24°20´E). Two areas were selected for UAV image acquisition and field data collection (image blocks 1 and 2, Fig. 1). Areas were selected to represent typical managed forest with both mature and seedling stands. Sizes were 350×400 m and 450×500 m for image blocks 1 and 2, respectively.

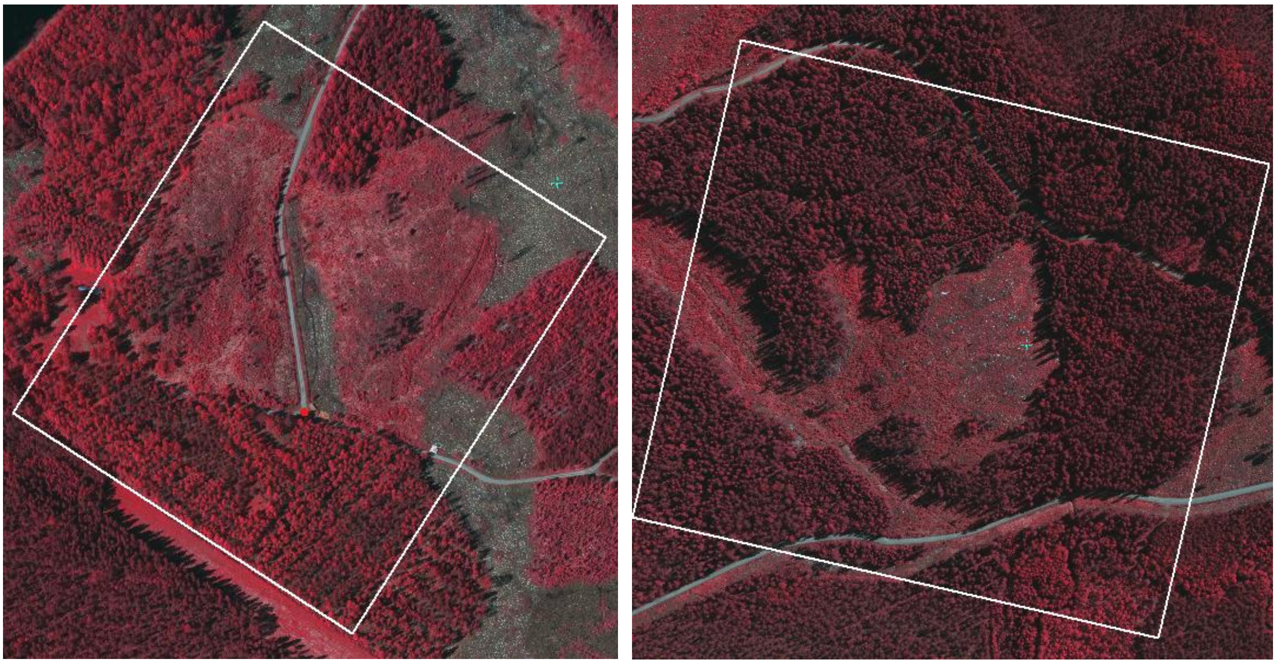

Fig. 1. Aerial photographs of image blocks 1 (left) and 2 (right).

Six rectangular plots (0.01–0.02 ha) were established in three seedling stands (Fig. 2). Measurements in seedling stands were conducted in summer 2010. All trees with height over 0.3 m were mapped to global coordinate system using Network-GNSS, and measured for tree species and height.

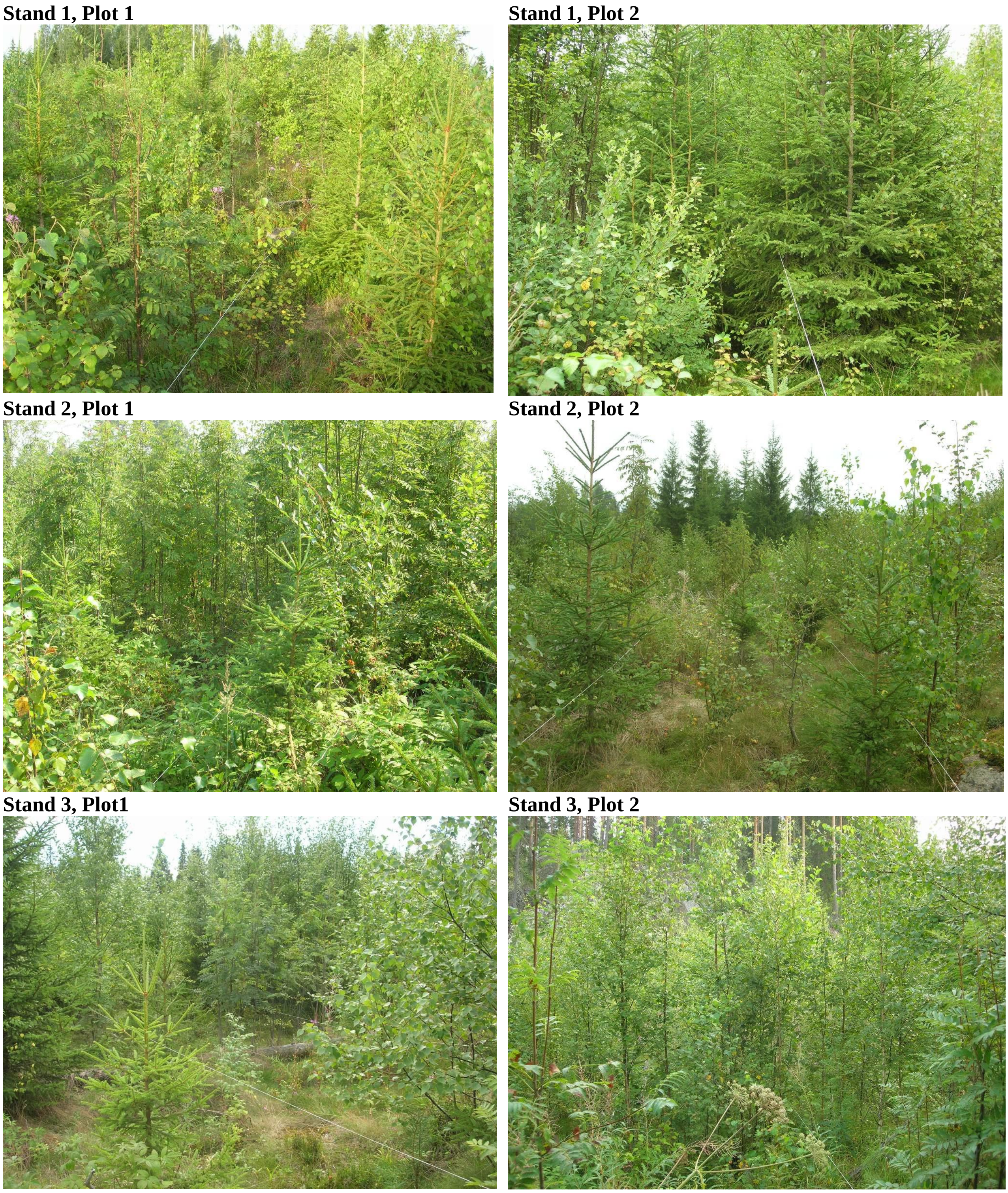

Fig. 2. Photographs from the six seedling stand plots.

In addition, there were 4 rectangular plots in mature stands, measured in 2008–2010. Trees visible to aerial images were positioned and measured for height using a photogrammetric monoplotting-method. Trees not visible to aerial images but above a certain diameter threshold were mapped in the field with triangulation/trilateration using photogrammetrically positioned trees as control points. All trees were measured in the field for diameter at breast height. Tree height was measured in sample trees. Tree heights used in the analyses were derived by calibrating the photogrammetric heights with field measurements. If photogrammetric height was not available, height for a tree was obtained 1) from field measurements or 2) using species-specific regression models. Height values were updated for growth between field measurements and UAV data acquisition (0–2 yr) by adding 0.30 m per year.

Summary of tree data on the study plots is presented in Table 1.

Table 1. Summary of tree data on the study plots.

	Area, ha	Stems/ha	H_{dom}, m	BA, m^2 ha^{-1}	DBH, cm	Vol, m^3 ha^{-1}
Seedling_A1_S1_P1	0.02	19534	2.5	-	-	-
Seedling_A1_S1_P2	0.01	52643	4.4	-	-	-
Seedling_A1_S2_P1	0.01	38279	3.4	-	-	-
Seedling_A1_S2_P2	0.01	18652	3.0	-	-	-
Seedling_A2_S3_P1	0.02	17497	4.0	-	-	-
Seedling_A2_S3_P2	0.02	17907	4.7	-	-	-
Mature_A1_M10_P1	0.50	514	18.1	16.1	21.4	123.8
Mature_A2_M08_P3	1.00	504	29.0	32.3	30.4	387.0
Mature_A2_M09_P2	0.81	505	29.4	31.7	29.8	381.8
Mature_A2_M10_P5	0.51	436	27.3	29.6	30.1	321.1

2.2 UAV point clouds and surface models

UAV image acquisition on the image block areas was carried out in august 2010. Images were taken in 8-bit JPEG format. Orientation of the images was done in autumn 2010 using accurately georeferenced signals. Signals were either artificial signals, positioned using Network-GNSS (in seedling stands), or natural objects (tree tops, stones etc.) that were positioned photorammetrically using accurately orientated aerial images acquired earlier from the study area.

Digital surface models (DSM) for the field reference plots were created from UAV image data by MosaicMill. Due to errors in image acquisition, stereo coverage was not complete on the image blocks. Therefore, surface model was not available for one seedling stand plot. In addition, one seedling stand plot ("Seedling_A2_S3_P1") and one mature stand plot ("Mature_A2_M08_P3") were not covered entirely by the surface models. Plots were delineated to exclude those parts with no UAV DSM coverage. Areas where UAV DSM was clearly erroneous in visual assessment were excluded also. Hereafter, all analyses were performed for the delineated areas only.

In the calculation procedure of the DSM, surface points (x,y,z) were extracted from UAV image data. A rough surface model was first created using EnsoMOSAIC software. New elevation points were calculated using Espa 3D software, allowing +- 3 m (in seedling stands) or +- 5m (in mature stands) deviation from the base elevation. Surface points were divided into lower, middle and upper points. Middle and upper points were used in the derivation of surface model. Surface points were converted into raster format (0.2 m resolution in seedling stands, 0.4 m in mature stands). MosaicMill provided UH with the surface model in raster format and the middle/upper surface point data.

2.3 LiDAR data and surface models

LiDAR data from summer 2010 was used as benchmark for UAV surface models. The LiDAR data were obtained using Leica ALS60 -sensor with full waveform digitizer. The sensor recorded also discrete returns for each pulse, which were used in this study. LiDAR data consists of three different data sets according to flying altitude. Nominal flying altitudes for the data sets were 1.3 km, 2 km and 3 km.

First returns were extracted from the LiDAR data, and digital surface models in raster format were created from these for each study plot. DSMs were generated for each LiDAR data set separately and for the combined LiDAR data. This resulted in four different LiDAR surface models in each stand. DSM was produced by searching highest LiDAR return in each pixel. Pixels with no first returns were filled by calculating average z-value from neighboring cells. Pixel sizes of the DSMs were 0.5 m, 0.8 m, 1.1 m and 0.4 m for the 1.3 km, 2 km, 3 km and combined point cloud, respectively. The pixel size was selected visually and was set high enough to avoid large areas with no first return in a pixel. Pits (single pixels with low z value within the canopy) were searched by comparing each pixel to its neighbors. If all 8 neighboring pixels around the evaluated pixel had z-value 2 m above the evaluated pixel, average z of the neighboring pixels was calculated and assigned to the evaluated pixel. Pulse densities of the LiDAR at the field reference plots varied considerably depending on the plot position in relation to flight lines. (Table 2).

Table 2. LiDAR point densities (points m^{-2}) on the study plots.

Plot	Data set			
	Combined	**1.3km**	**2km**	**3km**
Seedling_A1_S1_P1	10.73	4.94	2.18	3.62
Seedling_A1_S1_P2	18.76	10.22	7.37	1.19
Seedling_A1_S2_P1	12.08	5.49	2.89	3.64
Seedling_A1_S2_P2	22.28	16.95	2.22	3.06
Seedling_A2_S3_P1	21.18	14.88	3.03	3.26
Seedling_A2_S3_P2	16.11	10.24	2.41	3.45
Mature_A1_M10_P1	15.63	8.63	5.91	1.07
Mature_A2_M10_P5	19.48	10.28	5.83	3.37
Mature_A2_M09_P2	23.15	11.98	6.44	4.76
Mature_A2_M08_P3	17.21	11.48	2.33	3.39

2.4 Reference surface model

For quantitative assessment of the UAV and LiDAR surface models, a reference digital surface model was created from field measurements. Height was known for each tree, and dbh for mature trees. Crown width for each tree was predicted using species-specific regression models from earlier studies in the Hyytiälä area. A crown envelope was modeled using equation 1:

$$r(x) = a + b \cdot x^{c} \tag{1}$$

where x is relative distance (0-1) between treetop and crown base height, a is a constant, b is the crown radius at crown base and c is a shape parameter. Species-specific averages from earlier studies were used as values for parameter c.

Tree height information had to be brought into world coordinate system. In seedling stands this was straightforward, because GPS-measured z-coordinate at tree base were known for each tree. In mature stands, an elevation model created from LiDAR data acquired in 2004 was used. It was created using TerraScan software (Terrasolid Ltd., Finland).

As a result from crown modeling procedure, crown shape was available for each tree. This information was converted into raster surface. At each raster pixel, crown models were traversed. If there was a crown surface present at the pixel, the z value of the outer surface of the crown model at pixel location (x,y) was assigned to that pixel. If no crown surface was present in a given pixel, value for reference surface was taken from LiDAR elevation model (in mature stands) or by interpolating from GPS-measured ground points (in seedling stands).

3. Analyses and results

3.1 Visual assessment

To visually evaluate the performance of UAV surface point extraction procedure, surface points were superimposed on aerial images (fig. 3). From these images, it can be seen that in seedling stands, points are extracted from all objects (trees, ground). In mature stands, no points can be extracted from tree tops which likely causes underestimation of tree heights when a surface model is created from the point data. Also, ground points are extracted only from large canopy gaps.

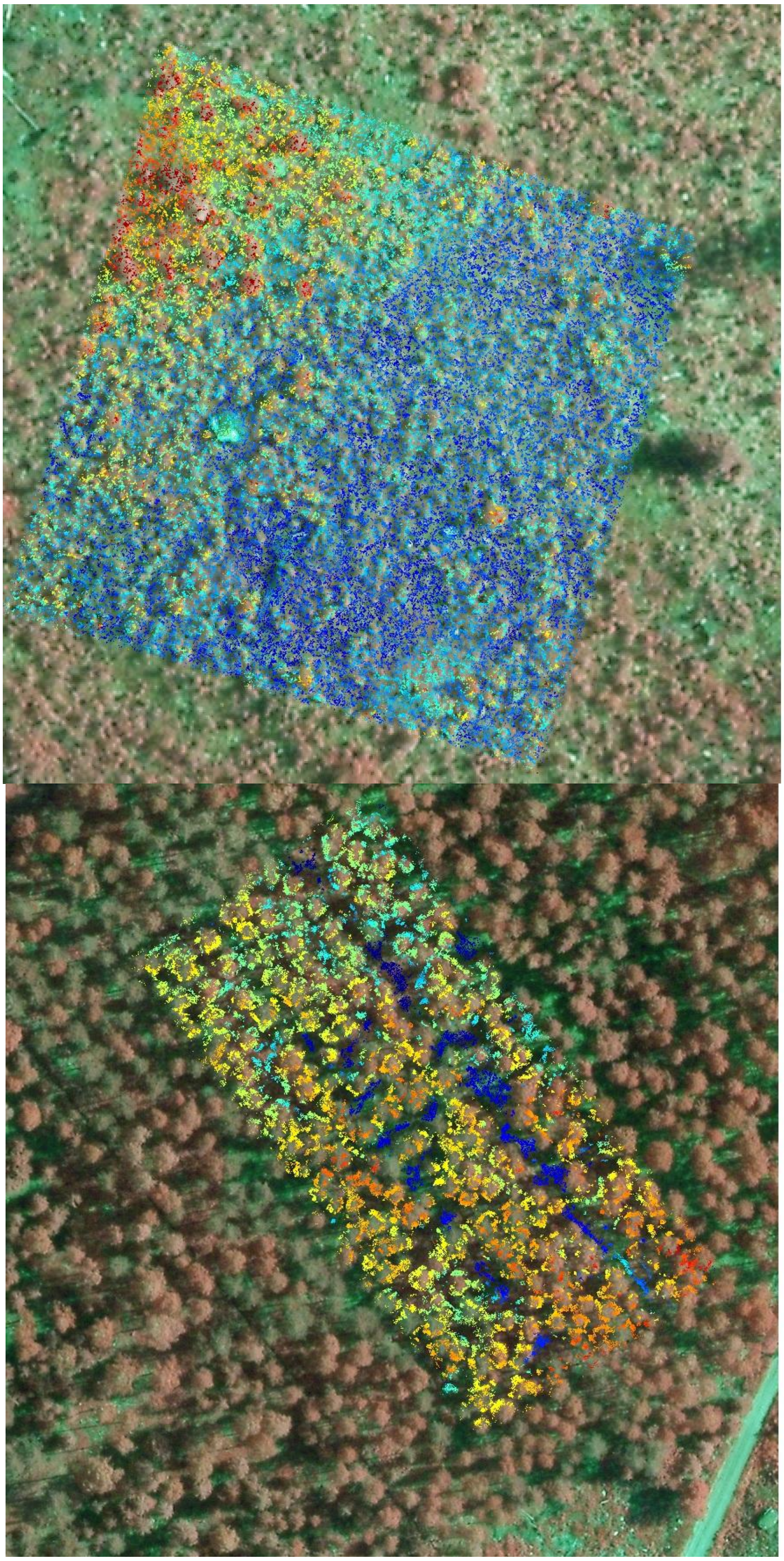

Fig 3. UAV point clouds superimposed on an aerial image. In a seedling stand (upper), points follow the canopy surface. In a mature stand (lower) no points are found from treetops. When there are wide gaps in the canopy, points can be extracted from the forest floor also.

Vertical profiles from each of the study plots were calculated using 1) the reference DSM, 2) the LIDAR DSM and 3) the UAV DSM and compared to each other (Fig. 4). In seedling stands, there is some noise in LiDAR data. UAV DSM follows the reference surface with reasonable accuracy although underestimating the canopy height. When there are many small trees and gaps between the trees (e.g. on “Seedling_A1_S2_P2”), UAV DSM is not able to follow this surface variation. IN mature stands, LiDAR DSM follows the canopy surface more accurately than UAV DSM.

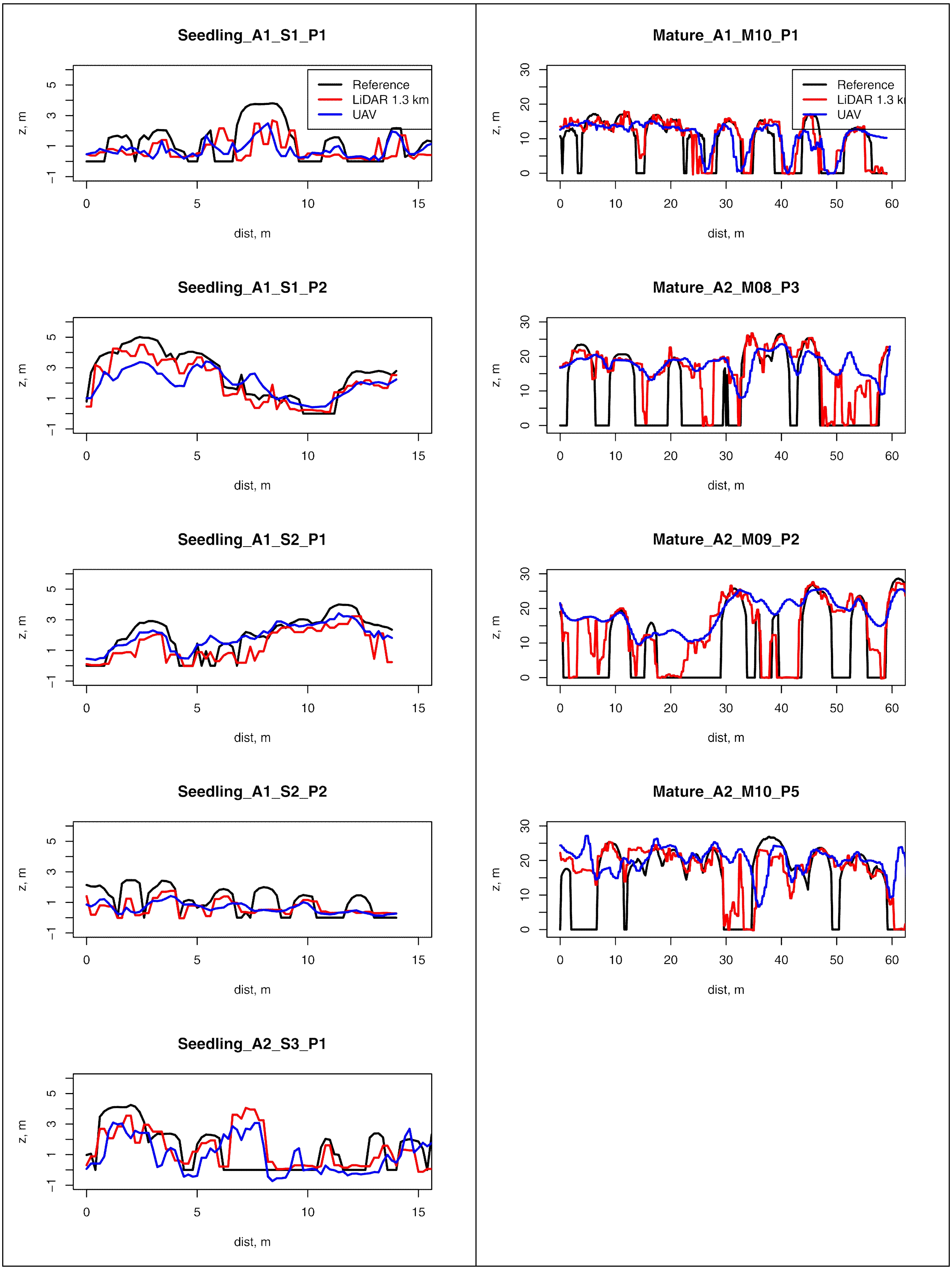

Fig. 4. Vertical profiles from 1) the reference DSM, 2) the LiDAR 1.3 km DSM and 3) the UAV DSM.

3.2 Elevation accuracy at treetops

Elevation accuracy of the LiDAR and UAV based DSMs were assessed by contrasting z-coordinates of the evaluated DSM to the z-coordinates of the reference DSM. Availability of accurate ground elevation information and known XY-locations of the trees enabled performing the evaluation either for whole reference surface area or for the treetop z-coordinates (tree heights) only. Evaluation of tree heights does not reveal the overall performance of the evaluated surface model. Surface model can be accurate at treetops but does not penetrate into canopy gaps, which is especially unfavorable if the surface model is used e.g. in single-tree detection in mature stands. However, treetop z-values were the only variables derived straight from field measurements. Evaluation of tree heights was therefore considered to provide the most reliable measure of the DSM performance.

When evaluating tree height information, it is important to exclude shaded trees because these cannot be seen from aerial images. Visible trees were selected by excluding those trees that had the top inside of a modeled crown envelope of another tree. For each of the visible trees, difference between the z-coordinate of the DSM at tree XY-position and field-measured treetop z-coordinate was calculated. Bias and RMSE of tree heights were derived from these measurements. The analysis was performed for the UAV DSM and for the four different LiDAR DSMs.

Bias and RMSE values for treetop z-coordinates are presented in table 3. All DSMs underestimated tree height, both in seedling and in mature stands. In LiDAR data, RMSE generally increased with increasing flying height (lower pulse density. The lower RMSE values in 3 km data set compared to the 2 km data set can be explained by the higher pulse density of the 3 km data set on some of the plots. In seedling stands, UAV produced more accurate estimates of tree height than any of the LiDAR DSMs on 3 of the 5 study plots. On one plot (Seedling_A1_S1_P2), performance of the UAV was slightly worse than the LiDAR data with highest point density. However, also on this plot, UAV produced more accurate estimates than the 3 LiDAR data sets with lowest point densities. On one plot (Seedling_A2_S3_P1) UAV was clearly more inaccurate than LiDAR and had a great negative bias. On this plot, the stereo cover was not complete, and only part of the plot was covered. It is possible that extraction of the UAV point cloud was not successful. The plot was delineated to exclude those parts where UAV DSM was clearly erroneous in to visual assessment. However, there may still remain errors not seen in visual assessment. Comparison to mean tree heights (Table 4) reveals that relative RMSE values of tree heights are high in seedling stands: 48–82% for LiDAR data sets and 31–96% for the UAV data. Underestimations of tree heights (negative bias) are 23–64% and 10–77% for the LiDAR and UAV data, respectively.

In mature stands, LiDAR produced clearly smaller RMSE values than the UAV. Bias in the UAV data was small on some of the study plots, but it was inconsistent across plots. On one of the plots, UAV surface underestimated the tree height by 4.50 m whereas on one of the plots, UAV produced a 0.81 m overestimation. Bias for the LiDAR DSMs were between -1.43 m and -0.29 m.

Table 3. Bias and RMSE of the tree height data derived from different LiDAR DSMs and the UAV DSM.

	LiDAR_all		**LiDAR_1.3km**		**LiDAR_2km**		**LiDAR_3km**		**UAV**	
	Bias, m	**RMSE, m**	**Bias, m**	**RMSE, m**	**Bias, m**	**RMSE, m**	**Bias, m**	**RMSE, m**	**Bias, m**	**RMSE, m**
Seedling_A1_S1_P1	-0.77	0.91	-0.84	0.95	-0.84	1.09	-0.74	0.99	-0.40	0.64
Seedling_A1_S1_P2	-0.54	0.77	-0.59	0.86	-0.37	0.82	-0.81	1.11	-0.41	0.79
Seedling_A1_S2_P1	-0.67	0.80	-0.84	0.98	-0.81	1.06	-0.54	0.83	-0.16	0.50
Seedling_A1_S2_P2	-0.74	0.91	-0.69	0.85	-0.85	1.09	-0.67	0.99	-0.61	0.81
Seedling_A2_S3_P1	-0.70	0.90	-0.72	0.94	-1.04	1.32	-0.66	1.06	-1.24	1.54
Mature_A1_M10_P1	-0.46	0.82	-0.68	1.06	-0.37	0.78	-1.43	1.87	-3.29	4.28
Mature_A2_M08_P3	-0.72	1.79	-0.80	1.91	-1.22	2.42	-0.85	1.91	-4.50	7.52
Mature_A2_M09_P2	-0.37	2.70	-0.55	2.92	-0.55	3.28	-0.29	3.23	-1.44	5.35
Mature_A2_M10_P5	-0.38	1.57	-0.55	1.34	-0.67	1.88	-0.59	1.93	0.81	5.87

Table 4. Tree height statistics on the study plots.

	Nr of trees	Mean(h), m	Min(h), m	Max(h), m	Stdev(h), m
Seedling_A1_S1_P1	186	1.6	0.4	3.8	0.6
Seedling_A1_S1_P2	105	2.2	0.5	5.2	1.1
Seedling_A1_S2_P1	150	2.2	0.5	4.0	0.8
Seedling_A1_S2_P2	105	1.7	0.4	4.3	0.7
Seedling_A2_S3_P1	77	2.2	0.3	5.2	1.1
Mature_A1_M10_P1	250	16.0	11.0	20.9	1.6
Mature_A2_M08_P3	374	24.5	2.3	32.0	4.8
Mature_A2_M09_P2	381	23.1	2.1	32.9	6.6
Mature_A2_M10_P5	262	20.4	2.5	31.5	6.5

To detect any offsets in XY between the DSM and field reference, the origin of the DSM was moved in a 0.02 m grid in a 2×2 m square around the original location, and the RMSE was calculated for each XY-value in the grid (Fig. 5). The ΔX and ΔY (shifts from the origin) which produced lowest RMSE were determined. The best ΔX and ΔY for each DSM are presented in table 5. Values for ΔX and ΔY were small (<25 cm) in 1.3 km and combined LiDAR data sets. In 2 km and 3 km data sets, values were greater on some of the plots, probably due to bigger pixel size of the 2 km and 3 km LiDAR DSMs. In UAV data, values for ΔX and ΔY were small (<25 cm) on seedling stand plots, whereas on mature stand plots there were obviously greater offsets between UAV and the field reference (up to 64 cm). The bias and RMSE achieved with the best ΔX and ΔY values are presented in table 6. Bias and RMSE were improved a little compared to the original values (Table 3) but the differences between LiDAR and UAV data were not altered significantly.

Table 5. Values for best ΔX and ΔY on the study plots.

	LiDAR_all		LiDAR_1.3km		LiDAR_2km		LiDAR_3km		UAV	
	ΔX, m	ΔY, m	ΔX, m	ΔY, m	ΔX, m	ΔY, m	ΔX, m	ΔY, m	ΔX, m	ΔY, m
See li g_A1_S1_P1	-0.10	-0.04	-0.10	-0.08	0.04	0.12	-0.42	-0.02	-0.10	-0.08
Seedling_A1_S1_P2	0.04	0.12	0.12	0.24	0.16	0.04	0.26	0.00	-0.12	-0.26
Seedling_A1_S2_P1	-0.18	-0.04	-0.08	0.14	-0.18	-0.30	-0.36	0.10	-0.08	-0.20
Seedling_A1_S2_P2	-0.24	-0.12	-0.18	-0.14	-0.04	0.04	-0.18	0.22	-0.04	-0.16
Seedling_A2_S3_P1	-0.14	-0.08	-0.06	0.10	-0.42	-0.40	-0.24	0.02	-0.24	-0.12
Mature_A1_M10_P1	0.04	-0.04	0.06	-0.08	0.02	0.04	-0.06	0.26	0.64	-0.48
Mature_A2_M08_P3	-0.12	0.00	0.04	-0.20	0.22	0.00	-0.04	-0.14	-0.54	0.18
Mature_A2_M09_P2	-0.10	0.08	-0.20	0.22	-0.14	0.08	-0.02	0.28	-0.46	-0.32
Mature_A2_M10_P5	0.20	-0.16	0.02	0.02	0.20	-0.18	0.22	-0.10	0.34	0.62

Table 6. Bias and RMSE achieved with the best ΔX and ΔY values.

	LiDAR_all		LiDAR_1.3km		LiDAR_2km		LiDAR_3km		UAV	
	Bias, m	RMSE, m	Bias, m	RMSE, m	Bias, m	RMSE, m	Bias, m	RMSE, m	Bias, m	RMSE, m
Seedling_A1_S1_P1	-0.73	0.83	-0.81	0.92	-0.81	1.07	-0.73	0.94	-0.34	0.60
Seedling_A1_S1_P2	-0.50	0.72	-0.49	0.78	-0.35	0.77	-0.78	1.04	-0.38	0.69
Seedling_A1_S2_P1	-0.66	0.79	-0.78	0.91	-0.73	0.95	-0.44	0.77	-0.12	0.40
Seedling_A1_S2_P2	-0.66	0.77	-0.61	0.74	-0.82	1.06	-0.67	0.98	-0.57	0.76
Seedling_A2_S3_P1	-0.69	0.82	-0.66	0.83	-0.90	1.14	-0.62	1.02	-1.00	1.21
Mature_A1_M10_P1	-0.44	0.80	-0.63	0.95	-0.38	0.76	-1.33	1.69	-2.80	3.51
Mature_A2_M08_P3	-0.73	1.75	-0.82	1.82	-1.31	2.25	-0.81	1.89	-4.56	7.25
Mature_A2_M09_P2	-0.43	2.49	-0.64	2.48	-0.69	2.96	-0.35	3.09	-1.16	5.13
Mature_A2_M10_P5	-0.69	1.31	-0.58	1.30	-0.70	1.61	-0.60	1.69	0.50	5.78

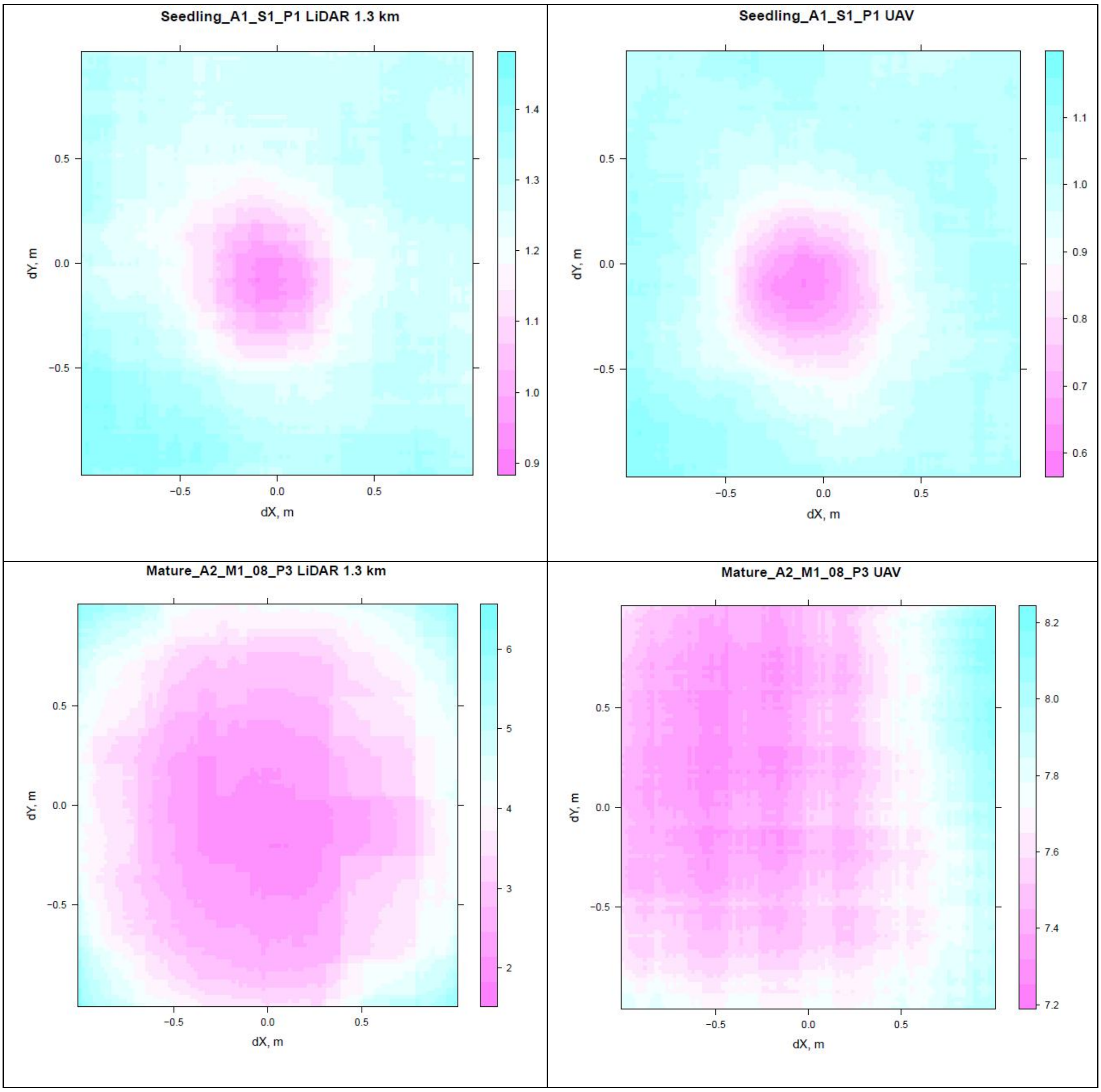

Fig. 5. RMSE of tree heights as a function of shift in ΔX and ΔY in LiDAR 1.3 km DSM (left column) and in UAV DSM (right column) on a seedling stand plot (upper row) and a mature stand plot (lower row). On mature stand plot in UAV data there is a clear ~0.5 m offset between UAV based DSM and field reference data. Same was noticed for all plots.

3.3 Elevation accuracy for the whole reference surface area

Bias and RMSE of Z-coordinates were calculated for the whole reference surface area. Areas with no canopy cover were excluded because no field measurements on understory trees or other vegetation than trees were made.

In seedling stands, RMSE of the UAV DSM was better than any of the LiDAR DSMs on 2 of the 5 study plots (Table 8). On 2 study plots, RMSE for UAV DSMs was similar to LiDAR, and on one plot UAV performance was clearly worse than LiDAR. In mature stands, RMSE values of the UAV were notably higher than those of the LiDAR on all study plots.

Table 7. Bias and RMSE for DSM elevation values (Z-coordinates).

	LiDAR_all		**LiDAR_1.3km**		**LiDAR_2km**		**LiDAR_3km**		**UAV**	
	Bias, m	**RMSE, m**	**Bias, m**	**RMSE, m**	**Bias, m**	**RMSE, m**	**Bias, m**	**RMSE, m**	**Bias, m**	**RMSE, m**
Seedling_A1_S1_P1	-0.94	1.11	-1.00	1.16	-0.98	1.19	-0.76	0.99	-0.73	0.93
Seedling_A1_S1_P2	-0.70	1.00	-0.78	1.07	-0.39	0.87	-1.01	1.30	-0.75	1.07
Seedling_A1_S2_P1	-0.77	0.98	-0.90	1.10	-0.72	1.03	-0.50	0.84	-0.33	0.57
Seedling_A1_S2_P2	-0.89	1.06	-0.86	1.07	-1.02	1.23	-0.79	1.08	-0.91	1.06
Seedling_A2_S3_P1	-0.88	1.23	-0.92	1.30	-1.17	1.57	-0.75	1.32	-1.69	2.07
Mature_A1_M10_P1	-1.42	3.67	-1.88	4.11	-0.39	2.91	-1.33	3.45	-2.31	3.80
Mature_A2_M08_P3	-0.83	4.04	-1.01	4.29	-0.81	4.08	0.47	3.53	-2.58	5.57
Mature_A2_M09_P2	-0.22	4.52	-0.53	4.70	0.23	4.21	1.10	4.10	0.42	4.40
Mature_A2_M10_P5	-0.02	3.89	-0.36	4.11	0.46	3.67	1.12	3.87	1.21	5.09

Difference surfaces calculated by subtracting the reference surface z-coordinates from the evaluated DSM z-coordinates are presented in Fig. 6 and 7. From these figures, the poor performance of the UAV DSMs at near treetops in mature stands can be seen.

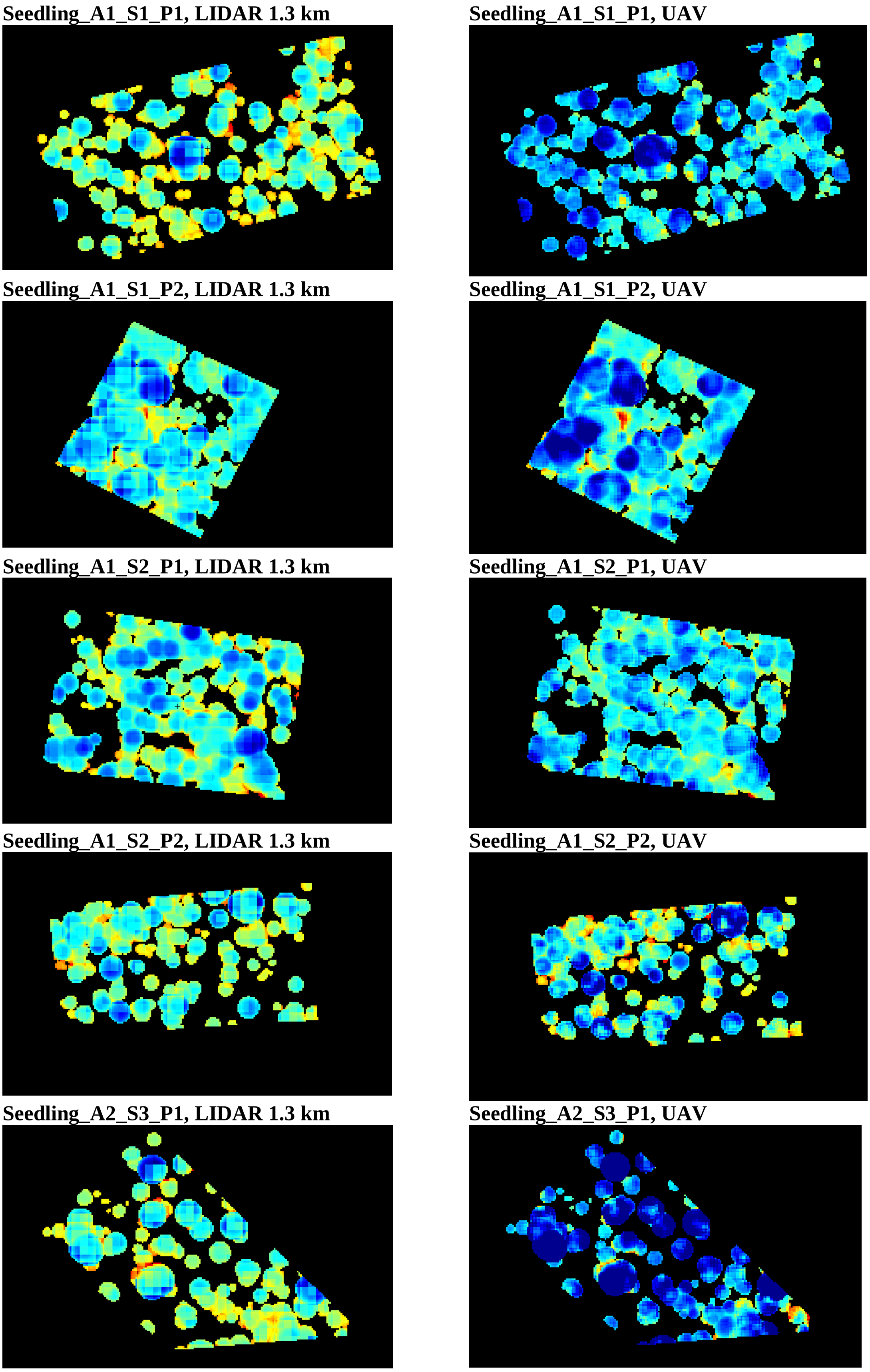

Fig. 6. Difference images calculated for DSMs generated from LiDAR 1.3 km data and for the UAV DSMs in mature stands. HSV colors represent difference between the evaluated DSM and the reference DSM. Scale from -2 to 2 m.

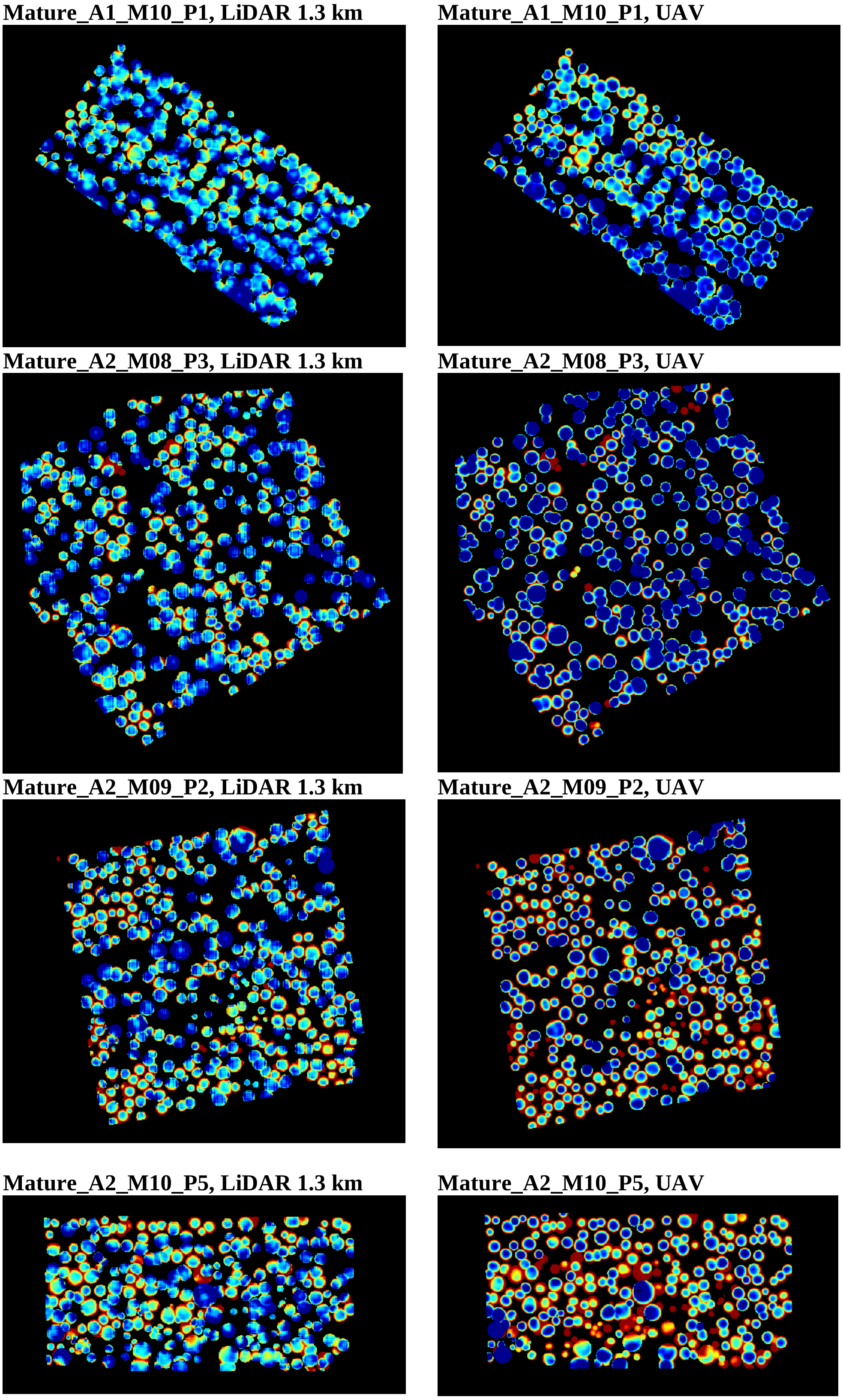

Fig. 7. Difference images calculated for DSMs generated from LiDAR 1.3 km data and for the UAV DSMs in mature stands. HSV colors represent difference between the evaluated DSM and the reference DSM. Scale from -4 to 4 m.

3.4 Crown projection area

To test the performance of the DSMs at different heights in the canopy, crown projection area at 0, 5, 10, … , 100 % relative heights (h/h_{dom}) were calculated for all evaluated DSMs and for the reference DSM. In seedling stands the analyses should be interpreted with caution, because no measurements on the other vegetation than trees were made. However, it can be seen from the crown projection area profiles (Fig. 8) that on seedling stand plots "Seedling_A1_S1_P1" and "Seedling_A1_S2_P1", the crown projection area calculated from UAV DSM is closer to the reference values. It is logical, that on these plots, the UAV produced also lower RMSE values than LiDAR. On plots "Seedling_A1_S1_P2" and "Seedling_A1_S2_P2" UAV and LiDAR are close to each other. On plot "Seedling_A2_S3_P1" UAV DSM results in underestimation of crown projection area. On this plot, there was also large negative bias for tree heights and the crown surfaces.

On mature stand plots "Mature_A1_M10_P1" and "Mature_A2_M08_P3" UAV produces underestimation of the crown projection area near tree tops, and overestimation at the lower heights which could be seen also from the vertical profiles (Fig. 4). The LiDAR follows reference crown projection area at height over 60% of H_{dom} but produces overestimates at lower heights. This could be caused by the lack of field measurements on understory trees. Thus, the reference crown projection area may not be very accurate at low heights. On plots "Mature_A2_M09_P2" and "Mature_A2_M10_P5" UAV does not underestimate projection area near treetops. Thus, there are systematic differences in the UAV DSM elevation between mature stand plots, which were also demonstrated by bias and RMSE observations of tree heights. Bias of individual tree heights in UAV data varied considerably (-4.50–0.81) between mature stand plots.

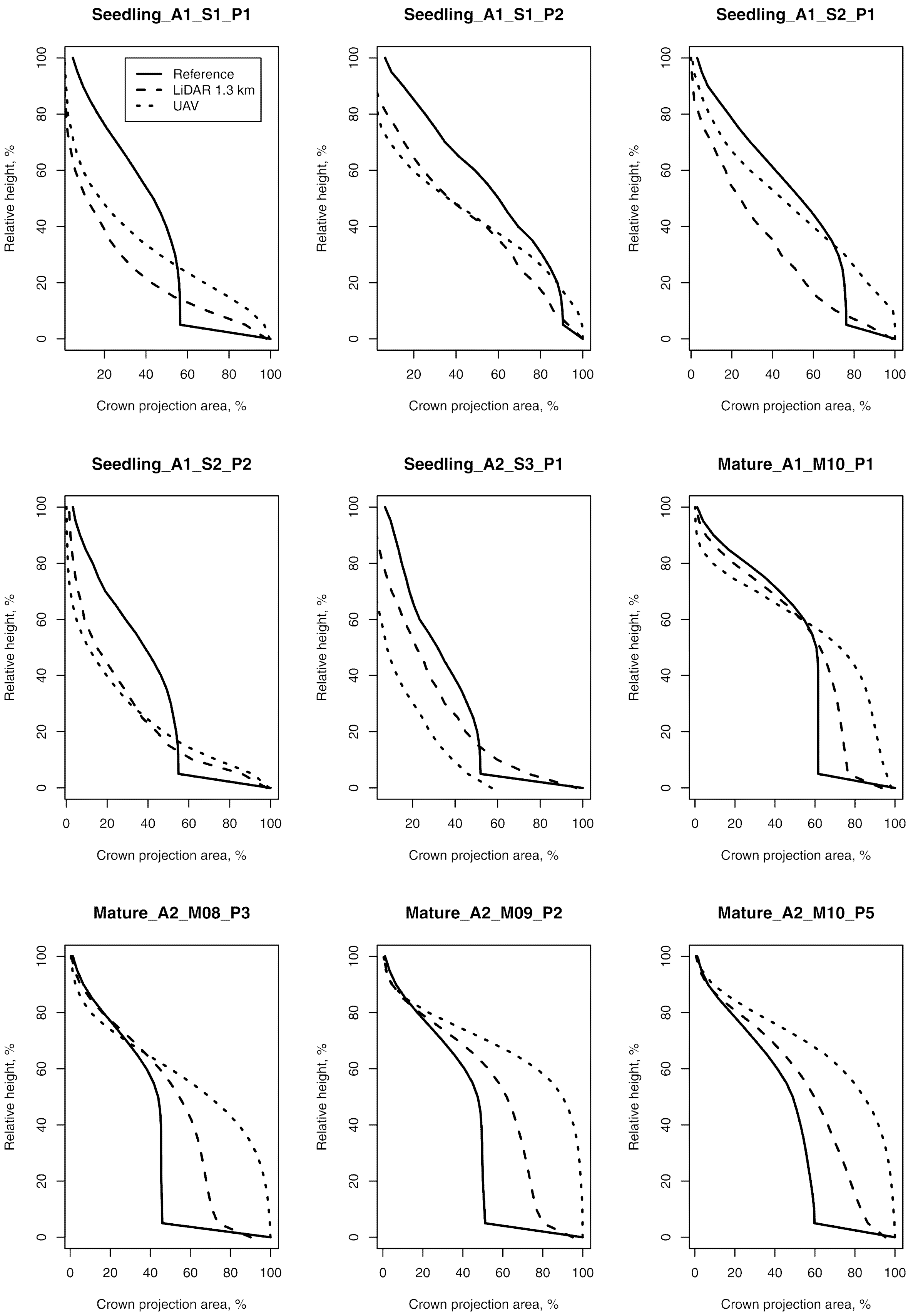

Fig. 8. Crown projection area as a function of relative height (h/h_{dom}) on the study plots.

4. Conclusions

The point cloud extraction procedure for UAV images is accurate in seedling stands. In mature stands, no points are extracted from treetops.

In seedling stands, DSM generated from UAV point clouds produces equal or slightly more accurate estimates for tree heights than LiDAR. For height of the whole canopy, differences are small, and none of these two techniques provides clearly better results.

In mature stands, DSM generated from UAV point clouds does not penetrate to the canopy gaps and on the other hand, does not reach the treetops. There can be very large bias and RMSE in the tree height estimates.

The bias between study plots varies more in UAV than in LiDAR data. This is particularly true for mature stands. Although LiDAR has some bias, it is consistent across the study area and can thus be calibrated and compensated for if tree height information is needed. This is not the case with UAV data. Errors can be due to errors in image orientation or in UAV point cloud extraction procedure.

There are systematic offsets in X and Y coordinates in UAV data in mature stands.