Comparison of UAV- and mowing machine-mounted LiDAR for grassland canopy height estimation

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Abstract: Towards autonomous process monitoring, canopy height estimation in grassland based on data from a mowing machine-mounted LiDAR and a UAV-LiDAR system is compared to manually measured ground truth heights. In a field trial, a LiDAR mounted on the cabin roof of the mowing machine recorded data during the mowing process, while two recording flights before and after the mowing were conducted with a UAV-LiDAR. The data from both systems were processed similarly and parameters such as height estimation method, spatial resolution and percentile filters were systematically varied to investigate their influence on height estimation accuracy. Statistical evaluation showed that canopy height estimates based on the UAV-LiDAR ($R^2 = 0.89$, RMSE = 0.05 m) were more accurate and precise than those based on the mowing machine-mounted LiDAR ($R^2 = 0.51$, RMSE = 0.08 m). The influence of the different investigated parameters varied.

Keywords: LiDAR, UAV, machine-mounted sensors, grassland, canopy height estimation

1 Introduction

Knowledge about the small-structured canopy height distribution of grassland is essential for a differentiated biomass estimation [SKF87]. In addition, canopy height differences may reveal anomalies within a field which could be the basis for a more site-specific crop management or the adjustment of process settings.

Many approaches estimate the canopy height of grassland based on data from UAV-attached cameras and structure-from-motion techniques [Zh18]. Some studies have compared these approaches with estimates from ground-based LiDAR systems [Ob20; GAW21]. Canopy height estimation based on UAV-LiDAR systems has so far only been investigated in other field crops such as wheat [HBK20]. For these crops, there are also studies where LiDAR systems were mounted on real agricultural machines to estimate the crop height [Wa19; LM13]. This study compares the estimation of canopy height in grassland based on data from a mowing machine-mounted LiDAR and a UAV-LiDAR system.

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2 Data Acquisition

A structured experiment was conducted on a 1.6 ha large grassland field in Recke, northwestern Germany. On 10 May 2023, the field was mowed for the first time that year using a high-capacity self-propelled mower conditioner, the Big M 450 from KRONE. The machine's working width divided the field into nine lanes, each approximately 10 meters wide and oriented in a north-south direction.

The height of the grassland was measured manually at 86 systematically arranged plots along the lanes in the morning before the mowing. Two methods were used for ground truth data collection. The first method consists of a ruler which was placed in the canopy. The height was then assessed by comparing the average height of the highest blades of grass in the immediate vicinity with the ruler. The assessment was consistently conducted by a single grassland survey expert, to prevent a variable bias in the measurements. The second method was similar to the Rising Plate Meter used by O'Sullivan et. al [SKF87]. A styrofoam plate measuring 0.5 m × 0.5 m with a center hole for a ruler was placed on top of the canopy and the height was then read off from the ruler. Both methods were applied once after each other on the same position in a plot and the exact location was measured using a RTK-GNSS receiver.

UAV-LiDAR data acquisition took place on two flight dates: one flight on 8 May 2023 before the mowing and one flight on 15 May 2023 after the mowing and collection of the cut grass. The system used was a RIEGL miniVUX-1UAV laser scanner mounted on a DJI Matrice 600 multicopter drone in a nadir down-facing angle. The scanner had a rotation frequency of 29 Hz, a range accuracy of ±1.5 cm and a precision of ±1 cm. A flight altitude of 20 m above ground in combination with a flight speed of 5 km/h and a lateral overlap of 40% between two adjacent flight strips resulted in an average laser shot density of approx. 670 pulses/m². Each shot had a footprint of 3.2 × 1 cm ellipsoid. The flight and scan parameters were kept identical for both flights.

Additionally, data was recorded during the mowing process using a sensor carrier with an Ouster OS1-64 LiDAR attached to the cabin roof of the mowing machine. The LiDAR was mounted 4 m above the ground at a 45° angle relative to the ground level. A measurement area measuring 2 m in length and 6 m in width was defined in front of the machine. The center point of this area was 3.42 m before the sensor mounting position in the driving direction on the central longitudinal axis of the machine. Inside the measurement area, the average point density of the Ouster LiDAR was 325 points/m² with an average footprint of the laser beam being a circle with a diameter of 2.72 cm. The LiDAR sensor had a rotation frequency of 10 Hz, a range accuracy of ±3 cm and a precision of ±1 cm.

The mowing machine operated at a driving speed of 10 km/h and the cutting height was set to approx. 17 cm. All recorded sensor data was georeferenced by RTK-GNSS coordinates.

3 Data Processing

The UAV data was processed according to [Br17]. First, the raw flight trajectory of the drone was corrected by using GNSS reference data recorded from a RTK-referenced base station in the field. The GNSS post-processing resulted in the Smoothed Best Estimate of Trajectory (SBET). Second, this trajectory was subsequently combined with the raw range measurements acquired by the laser scanner and globally registered into one consistent point cloud in the global WGS-84 coordinate reference system. The processing steps were performed using proprietary software associated with the Inertial Measurement Unit (Applanix POSPac UAV) and the scanner (RIEGL's RiPROCESS) of the UAV.

The data from the LiDAR mounted on the mowing machine (MoM) was processed using a Python-based script that utilized the open-source library Open3D. Each individual point cloud was processed for every ground truth measurement position, rather than being globally registered into one large point cloud. First, from the data stream of the sensor carrier, the GNSS message with the spatially closest position information to the respective ground truth point was identified. Next, based on the timestamp of the messages, the temporal closest point cloud message to that GNSS message was determined. This step was necessary because the GNSS sensor on the carrier only operated with 8 Hz. Because of the time difference of the two messages, the position information from the GNSS message was corrected based on the current speed and heading of the machine and transformed to the center point of the measurement area in front of the machine. The raw point cloud itself was cropped to the size of the measurement area after rotating the local sensor coordinate system by 45° to align the z-axis perpendicular to the ground.

The determination of the canopy height using LiDAR in general is done by subtracting the measured distance to the canopy top from the distance to the ground. Therefore, the identification of LiDAR data points that represent the ground is crucial [HBK20]. The generation of a digital terrain model (DTM) from these points is challenging in grassland vegetation due to the high-density coverage, which results in insufficient ground information [Zh18]. As a result, reference measurements were taken at ground level after mowing the field. The LiDAR mounted on the mowing machine maintained a constant distance from the ground, requiring only one reference measurement on a grass-free area of the field. To create the DTM from the UAV data, a second flight was conducted five days after mowing.

The individual point clouds of the MoM-LiDAR and the global point cloud of the UAV were both rasterized into a regular grid. Three different spatial resolutions of 0.2, 0.4 and 0.6 m for the raster fields were tried in order to analyze the effect of raster field size on the estimation accuracy. Based on the reference measurements, the canopy height for each raster field was determined with two different methods. Subtracting the lowest ground point from the highest canopy point was called the minmax-method (mm). The second method was called average-method (avg) where the average height of the ground points got subtracted from the average height of the canopy points. To investigate the influence of outliers a percentile filter was applied. For every spatial resolution and system, the top percentile value was decreased from 100% in 0.5% steps to 50% to identify the best fitting percentile value.

The canopy height estimates from both LiDAR systems, each processed by both methods for every raster resolution with and without percentile filter were statistically compared to both measured ground truth heights. The mean error (BIAS) and the root mean square error (RMSE) between the estimates and the ground truth measurements were calculated to quantify the accuracy while the coefficient of determination (R^2) of a linear regression was calculated to quantify the precision.

4 Results and Discussion

The comparison between the two ground truth measurement methods showed that the plate-based method (GT_plate) delivered slightly lower height values with less variance compared to the ruler-based method (GT_ruler) (Tab. 1). This was reasonable because the weight of the styrofoam plate pushed slightly down the tips of the grass blades.

method	median	mean	standard deviation
GT_ruler	0.72	0.70	0.12
GT_plate	0.71	0.68	0.11

Tab. 1: Ground truth grassland canopy height measurements (all values in meter)

The results of the statistical comparison between the canopy height estimates based on the UAV- and the MoM-LiDAR to the ground truth measurements showed a general trend. Across all settings, the UAV-based estimates were more accurate and more precise (Tab. 2). The detailed analysis showed that the influence of the varied parameters on the estimation quality was different.

The results of the average-method delivered in general more precise (higher R^2), but less accurate (lower RMSE) estimates of the canopy height compared to the minmax-method, but the precision of the minmax-method increased to the same level when the percentile filter was applied. The filter also reduced the BIAS of the minmax-method to nearly zero. Compared to the ground truth measurements, both LiDAR systems showed a higher precision to the plate method than to the ruler method. For both ground truth methods, the accuracy was on the same level for the minmax-method, but for the average-method the accuracy of the ruler method was worse. The influence of the percentile filter was comparable in this case. The spatial resolution of the raster influenced only the precision in case of the average-method. For larger spatial resolutions, the precision improved for the MoM system while it decreased for the UAV system. The accuracy remained at the same level for both systems. In case of the minmax-method, the precision and accuracy decreased for both systems for larger spatial resolutions. The improvement of the estimates by the percentile filter was higher for the larger spatial resolutions. The overall comparison resulted in different best fitting top percentile values depending on the spatial resolution and the LiDAR system (Tab. 2). The percentile values were significantly lower for the MoM-LiDAR than for the UAV-LiDAR. This matched the general observation that the estimates based on the MoM-LiDAR system tended to be higher and scattered more.

Compared to the plate ground truth the best processing method for the UAV-LiDAR system was the 0.2 m minmax-method which results in a R^2 of 0.89 and a RMSE of 0.05 m. The best method for the MoM-LiDAR system was the 0.6 m minmax-method together with a 65.5% top percentile filter which results in a R^2 of only 0.51 and a RMSE of 0.08 m. Both systems were underestimating the ground truth height in these cases.

There are several possible reasons for differences between the systems. Firstly, the angle and the footprint of the two LiDAR systems were different. The much larger footprint of the UAV-LiDAR might have led to an averaging out effect of small grass tips and therefore, to reduced height estimates with less larger outliers. The driving speed of the mowing machine was twice as high as the flight speed of the UAV while the rotation frequency of the MoM-LiDAR was a third compared to the UAV-LiDAR. There were also shock and vibration influences from the machine during the mowing process on the LiDAR, which might have had a negative influence on the measurements. Especially pitch movements of the machine might have changed the distance to the ground compared to the used reference distance. Detailed test trials like those from [Bl20] are needed to further investigate and quantify these influences.

method	**raw data**						**percentile filtered data**					
raster size	0.2		0.4		0.6		0.2		0.4		0.6	
height diff.	mm	avg	mm	avg	mm	avg	mm	avg	mm	avg	mm	avg
GT_ruler_UAV							top perc. 100		top perc. 94.0		top perc. 89.0	
R^2	**0.85**	0.83	0.73	0.76	0.55	0.70	0.85	0.83	0.75	0.77	0.67	0.71
RMSE	**0.06**	0.15	0.06	0.14	0.09	0.13	0.06	0.15	0.06	0.16	0.07	0.15
BIAS	**-0.04**	-0.14	0.01	-0.13	0.05	-0.12	-0.04	-0.14	-0.03	-0.15	-0.02	-0.14
GT_plate_UAV							top perc. 100		top perc. 94.0		top perc. 89.0	
R^2	**0.89**	0.87	0.81	0.84	0.66	0.80	0.89	0.87	0.83	0.84	0.78	0.80
RMSE	**0.05**	0.13	0.06	0.12	0.09	0.11	0.05	0.13	0.05	0.14	0.05	0.14
BIAS	**-0.03**	-0.12	0.03	-0.11	0.07	-0.10	-0.03	-0.12	-0.01	-0.13	-0.01	-0.13
GT_ruler_MoM							top perc. 89.5		top perc. 89.5		top perc. 65.5	
R^2	0.37	0.40	0.31	0.41	0.29	0.44	0.40	0.40	0.37	0.42	**0.44**	0.45
RMSE	0.11	0.16	0.12	0.15	0.13	0.14	0.11	0.16	0.10	0.15	**0.09**	0.17
BIAS	0.01	-0.11	0.05	-0.11	0.08	-0.11	-0.01	-0.12	0.02	-0.12	**-0.01**	-0.14
GT_plate_MoM							top perc. 89.5		top perc. 89.5		top perc. 65.5	
R^2	0.44	0.47	0.39	0.48	0.36	0.50	0.47	0.47	0.44	0.49	**0.51**	0.52
RMSE	0.10	0.14	0.11	0.13	0.14	0.13	0.10	0.14	0.10	0.14	**0.08**	0.15
BIAS	0.02	-0.10	0.07	-0.10	0.10	-0.10	0.01	-0.10	0.03	-0.10	**0.01**	-0.13

Tab. 2: Descriptive statistics of the experiment (all values in meter except R^2, top percentile in %)

5 Conclusion

The comparison of the two LiDAR systems revealed that canopy height estimates based on the UAV-mounted LiDAR were more accurate and precise than those based on the mowing machine-mounted LiDAR. The used minmax-method in combination with a top percentile filter delivered the best estimates for both systems. The effect of the top percentile filter and the spatial resolution of the sampling area was different for the systems.

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Bibliography

[Bl20] Blanquart, J.-E. et al.: Online crop height and density estimation in grain fields using LiDAR. Biosystems Engineering 198, pp. 1-14, 2020.

[Br17] Brede, B. et al.: Comparing RIEGL RiCOPTER UAV LiDAR derived canopy height and DBH with terrestrial LiDAR. Sensors 17/17, pp. 2371:1-2371:16, 2017.

[GAW21] Grüner, E.; Astor, T.; Wachendorf, M.: Prediction of Biomass and N Fixation of Legume-Grass Mixtures Using Sensor Fusion. Frontiers in Plant Science 11, no. 603921, 2021.

[HBK20] ten Harkel, J.; Bartholomeus, H.; Kooistra, L.: Biomass and crop height estimation of different crops using UAV-based LiDAR. Remote Sensing 12/20, pp. 17:1-17:18, 2020.

[LM13] Long, D. S.; McCallum, J. D.: Mapping straw yield using on-combine light detection and ranging (lidar). International Journal of Remote Sensing, vol. 34, no. 17, pp. 6121-6134, 2013.

[Ob20] Obanawa, H. et al.: Portable LiDAR-Based Method for Improvement of Grass Height Measurement Accuracy: Comparison with SfM Methods. Sensors 17/20, no. 4809, 2020.

[SKF87] O'Sullivan, M.; O'Keeffe, W. F.; Flynn, M. J.: The Value of Pasture Height in the Measurement of Dry Matter Yield. Irish Journal of Agricultural Research, vol. 26, no. 1, pp. 63–68, 1987.

[Wa19] Walter, J. D. C. et al.: Estimating Biomass and Canopy Height With LiDAR for Field Crop Breeding. Frontiers in Plant Science 10, no. 1145, 2019.

[Zh18] Zhang, H. et al.: Estimation of grassland canopy height and aboveground biomass at the quadrat scale using unmanned aerial vehicle. Remote Sensing 10/18, pp. 851:1-851:19, 2018.