Optimal Altitude, Overlap, and Weather Conditions for Computer Vision UAV Estimates of Forest Structure
Remote Sensing 2015, 7, 13895–13920

Table S1. List of UAV flight configurations used in the study showing different levels of lighting, altitude, and photographic side overlap as well as UAV track width. The number of replicates actually flown under each set of conditions is also shown. Forward overlap is computed for a UAV traveling at 6 m s^{-1} with the camera taking pictures at 2 frames s^{-1}. GSD is ground sampling distance in centimeters, FOV is field of view in meters.

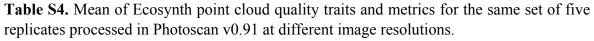| Lighting	Altitude Above Canopy Surface (Meters)	Forward Overlap (Percent)	Side Overlap (Percent)	Track Width (Meters)	Image GSD (cm)	FOV Across Track (meters)	FOV Along Track (Meters)	Mean Number of Images Per Replicate	Number of Replicates
Clear	20	87	80	6	0.84	31	23	2501	4
Clear	40	93	60	25	1.68	62	46	1220	5
Clear	40	93	80	12	1.68	62	46	2506	2
Clear	60	96	60	37	2.51	93	68	1090	5
Clear	60	96	80	25	2.51	93	68	1652	5
Clear	80	97	20	100	3.35	123	91	509	5
Clear	80	97	40	75	3.35	123	91	601	5
Clear	80	97	60	50	3.35	123	91	925	5
Clear	80	97	80	25	3.35	123	91	1219	7
Cloudy	20	87	80	6	0.84	31	23	2478	5
Cloudy	40	93	60	25	1.68	62	46	1222	5
Cloudy	40	93	80	12	1.68	62	46	2659	3
Cloudy	60	96	60	37	2.51	93	68	1093	5
Cloudy	60	96	80	25	2.51	93	68	1780	2
Cloudy	80	97	20	100	3.35	123	91	499	5
Cloudy	80	97	40	75	3.35	123	91	606	5
Cloudy	80	97	60	50	3.35	123	91	930	4
Cloudy	80	97	80	25	3.35	123	91	1213	5
								Total	82

Table S2. Variation in Ecosynth point cloud quality traits and metrics as a function of average wind speed during each flight based on the Beaufort wind force scale.
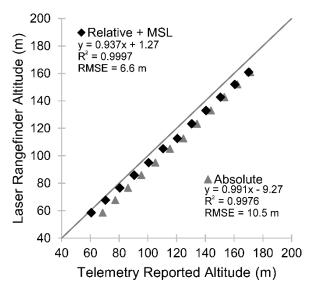
| | Mean Wind Speed during Flight | | | | | | |
| | Beaufort Wind Force (m s⁻¹) | | | | | | |
	1 (0.3 – 1.5)	**2** (1.6 – 3.4)	**3** (3.5 – 5.4)	**4** (5.5 – 7.9)	**R**	**R²**	**F-test**
Path-XY Error RMSE (m)	1.3	1.2	1.6	0.7	−0.48	0.23	NS
Path-Z Error RMSE (m)	0.4	0.4	0.5	0.5	0.99	0.99	p = 0.006
ICP-XY Error RMSE (m)	2.5	1.8	2.2	2.0	−0.52	0.27	NS
ICP-Z Error RMSE (m)	2.5	3.0	2.5	3.4	0.67	0.44	NS
LLED MAD (m)	2.2	3.3	2.0	3.0	0.58	0.34	NS
Ecosynth TCH to Field Height RMSE (m)	4.6	4.1	4.1	5.3	0.48	0.23	NS
Ecosynth TCH to LIDAR TCH RMSE (m)	2.1	2.5	2.8	2.5	0.63	0.40	NS
Average Forest Point Density (points m⁻²)	47	35	36	45	−0.11	0.01	NS
Average Forest Canopy Penetration (% CV)	17	16	18	19	0.89	0.79	NS

Table S3. Mean of Ecosynth point cloud quality traits and metrics for the same set of five replicates processed in Photoscan v0.91 on different computers.
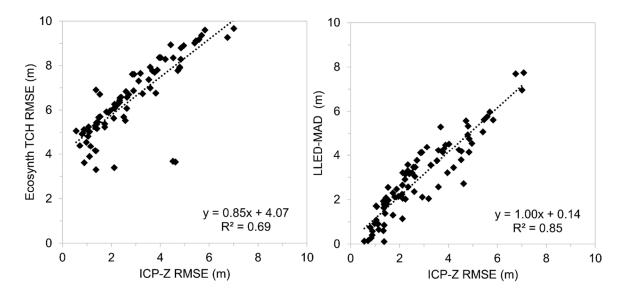
Computer	A	B[a]	C	D	E
CPU	2× Intel Xeon ×5670 2.93 GHz, 6 cores	1× Intel Xeon E5-2670 2.6 GHz, 8 cores	1× Intel i7-950 3.06 GHz, 4 cores	2× Intel Xeon ×5670 2.93 GHz, 6 cores	1× Intel i7-2600 K 3.08 GHz, 4 cores
RAM	192 GB	15 GB	16 GB	48 GB	16 GB
OS	Ubuntu Linux 14.02 64-bit	Windows 7 64-bit	Windows 7 64-bit	Windows 7 64-bit	Windows 7 64-bit
Path-XY Error RMSE (m)	1.2	1.2	1.2	1.2	1.2
Path-Z Error RMSE (m)	0.4	0.4	0.4	0.4	0.4
ICP-XY Error RMSE (m)	1.7	1.7	1.8	1.7	1.6
ICP-Z Error RMSE (m)	1.9	1.8	1.8	1.8	1.9
Launch Location Elevation Difference (m)	1.8	1.8	1.8	1.8	1.8
Ecosynth TCH to Field Height RMSE (m)	4.7	4.7	4.7	4.7	4.7
Ecosynth TCH to LIDAR TCH RMSE (m)	2.0	2.0	2.0	2.0	2.0
Forest Point Cloud Density (points m^{-2})	36	36	36	36	36
Forest Canopy Penetration (% CV)	19	19	18	19	18
Computation Time (hours)	31	48	52	43	45

[a] Same configuration with Ubuntu Linux 14.02 64-bit was run as an Amazon EC2 g2.2xlarge instance for Ecosynther processing.

Table S4. Mean of Ecosynth point cloud quality traits and metrics for the same set of five replicates processed in Photoscan v0.91 at different image resolutions.

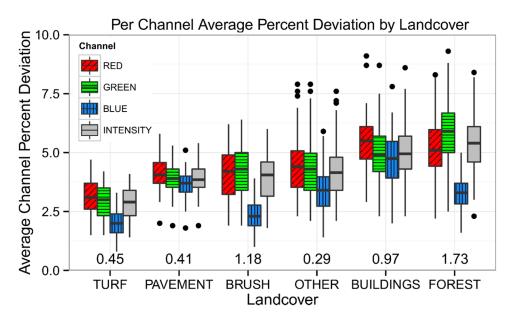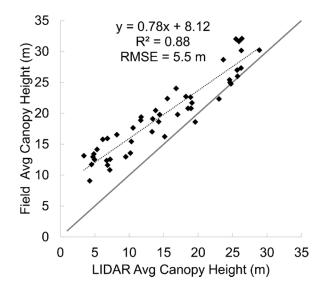| Resolution (Megapixels)	10	7.5	5	2.5	1	0.3
Ground Sampling Distance (GSD) centimeters / pixel	3.4	3.9	4.7	6.7	10.6	19.3
Path-XY Error RMSE (m)	1.3	1.2	1.3	4.5	7.2	7.1
Path-Z Error RMSE (m)	0.4	0.4	0.4	3.4	9.9	10.1
ICP-XY Error RMSE (m)	1.7	1.6	1.7	5.0	16.8	33.7
ICP-Z Error RMSE (m)	1.9	1.8	1.8	11.9	94.5	112
Launch Location Elevation Difference (m)	1.8	1.8	1.6	10.1	92.1	56.2
Ecosynth TCH to Field Height RMSE (m)	4.2	3.7	3.6	9.8	87.2	112
Ecosynth TCH to LIDAR TCH RMSE (m)	2.2	2.1	2.2	11.5	91.1	114
Forest Point Cloud Density (points m^{-2})	30	37	35	37	22	4
Forest Canopy Penetration (% CV)	16	18	18	12	2	0
Computation Time (hours)	36	38	33	45	35	10

Figure S1. Plot showing the difference in mean sea level (MSL) corrected relative and absolute altitude as reported by the UAV telemetry compared to observations of MSL-corrected UAV altitude from a laser rangefinder for the mean of three repeat flights. UAV absolute telemetry is reported in meters above mean sea level while relative altitude is reported in meters above the launch location. MSL-correction involves simply adding the altitude in MSL of the launch location to relative altitude measurements.
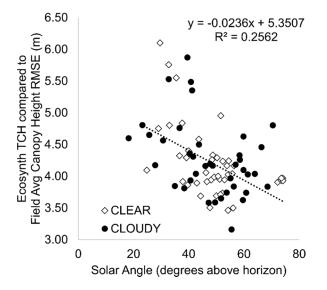
Figure S2. (**Left**) Scatter plots showing the relationship between error in Ecosynth TCH estimates of field height relative to the absolute vertical positioning of the point cloud relative to the LIDAR point cloud (ICP-Z). (**Right**) the relationship between LLED-MAD and ICP-Z. Dashed line is regression line.
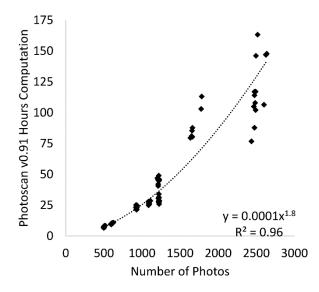

Figure S3. Radiometric precision of Ecosynth point clouds per channel averaged within different landcovers across all main replicates at the Herbert Run site (n = 82). Average channel percent deviation measures variation (standard deviation) in point color within 1 m × 1 m bins, interpreted as a percentage of the maximum potential channel brightness (255). Numbers at bottom axis indicate mean rugosity per land cover in meters which was correlated with average percent deviation in grayscale intensity by landcover ($R^2 = 0.74$).

Figure S4. Plot showing LIDAR estimated average canopy height per plot (TCH) relative to field measured average canopy height at Herbert Run.

Figure S5. Plot of error in Ecosynth TCH compared to field average canopy height (meters RMSE) relative to the solar angle at the time of the UAV flight for all main replicates flown at Herbert Run (n = 82) symbolized by whether the flight was flown on a clear or cloudy day. Linear regression is across all flights, $p < 0.00003$. Solar angles calculated based on date and local time of UAV flight from http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html, accessed 2015-09-05).

Figure S6. Computation time required for SFM processing in Photoscan v0.91 based on the number of photos. Dotted line is polynomial model.