Grapevine volume estimation from UAV-based point clouds using different methods and flight height

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Supplementary Material

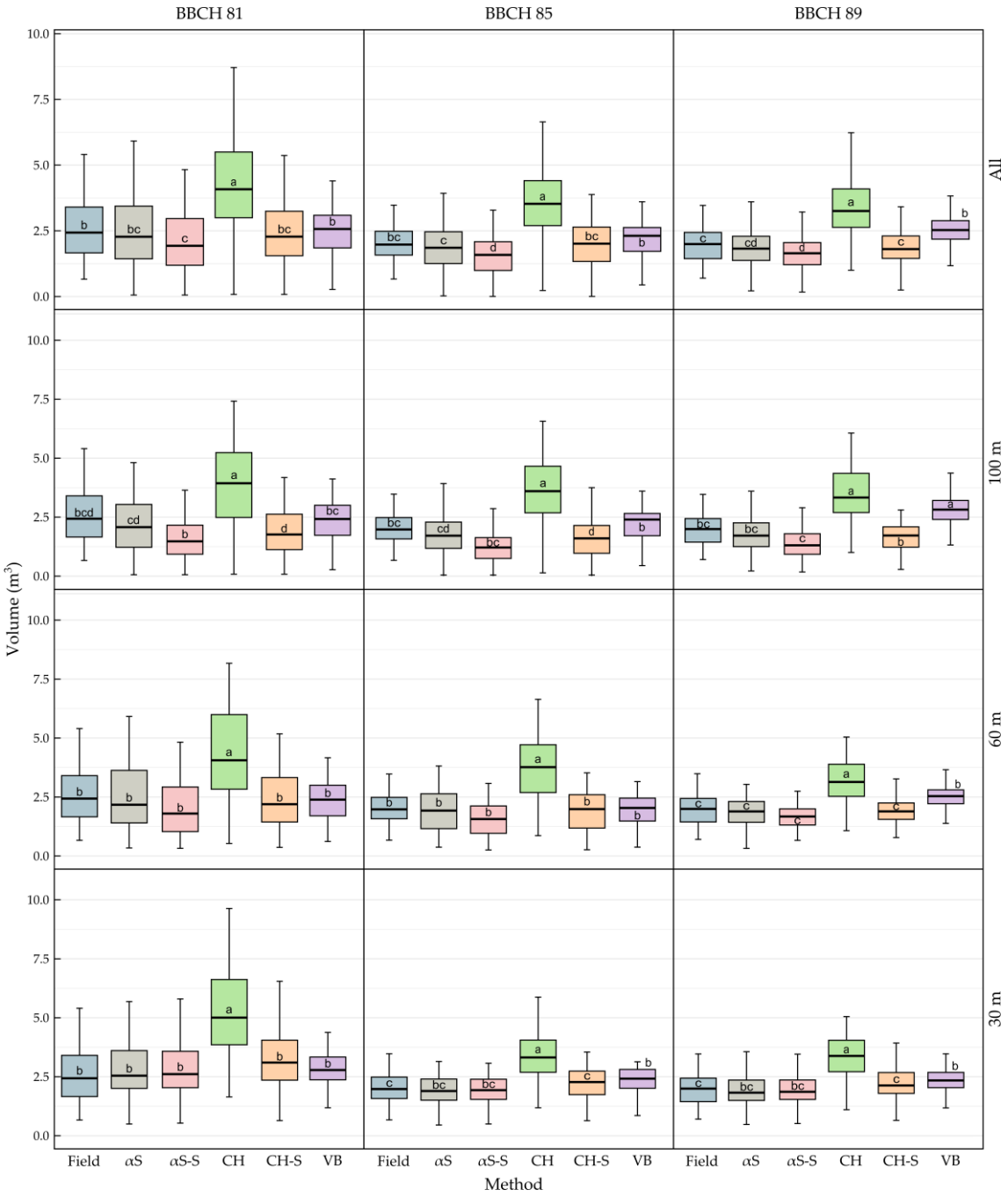


Figure S1. Boxplots of field volume and the evaluated methods at 30, 60, and 100 m flight height by phenological stage. Different letters show significant differences among methods within each flight height at $p < 0.05$.

Table S1. Performance of the different methods using data obtained at 30 meters flight height (n = 216).

Method	Parameter	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
CH	—	1.79	2.11	1.78 [1.62; 1.93]	*	92.15	57.15	0.02	0.02	0.06	0.69	0.32
CH–S	—	0.54	0.77	0.31 [0.22; 0.41]	*	28.08	23.35	0.15	0.30	0.52	0.77	0.72
αS	0.1	1.65	1.86	−1.65 [−1.77; −1.55]	*	72.10	114.14	0.00	0.00	0.00	0.67	0.05
	0.2	0.87	1.09	−0.84 [−0.93; −0.75]	*	36.36	46.80	0.03	0.09	0.19	0.76	0.35
	0.3	0.59	0.78	−0.44 [−0.53; −0.35]	*	26.44	30.40	0.07	0.16	0.40	0.78	0.62
	0.4	0.50	0.68	−0.21 [−0.3; −0.12]	*	23.58	24.75	0.13	0.25	0.52	0.78	0.72
	0.5	0.47	0.67	−0.04 [−0.13; 0.05]	ns	23.03	22.29	0.16	0.33	0.59	0.77	0.75
	0.6	0.48	0.70	0.09 [0; 0.19]	*	24.12	21.84	0.17	0.32	0.57	0.77	0.75
	0.7	0.51	0.74	0.21 [0.12; 0.31]	*	25.81	22.19	0.18	0.34	0.56	0.76	0.73
	0.8	0.55	0.80	0.31 [0.21; 0.41]	*	27.89	23.11	0.18	0.32	0.53	0.76	0.71
	0.9	0.59	0.85	0.39 [0.29; 0.49]	*	30.27	24.44	0.16	0.31	0.50	0.76	0.69
	1.0	0.64	0.90	0.46 [0.36; 0.57]	*	32.63	25.85	0.13	0.26	0.46	0.76	0.67
αS-S	0.1	1.68	1.88	−1.68 [−1.79; −1.56]	*	73.22	116.82	0.00	0.00	0.00	0.67	0.05
	0.2	0.94	1.16	−0.92 [−1.02; −0.83]	*	39.44	51.73	0.03	0.06	0.14	0.75	0.30
	0.3	0.66	0.86	−0.56 [−0.65; −0.48]	*	29.00	34.77	0.07	0.14	0.32	0.78	0.56
	0.4	0.56	0.74	−0.38 [−0.47; −0.29]	*	25.42	28.54	0.10	0.19	0.46	0.78	0.66
	0.5	0.51	0.69	−0.25 [−0.34; −0.17]	*	23.79	25.32	0.12	0.22	0.50	0.78	0.71
	0.6	0.48	0.67	−0.16 [−0.24; −0.07]	*	23.07	23.53	0.12	0.29	0.54	0.78	0.74
	0.7	0.47	0.66	−0.09 [−0.17; 0]	*	22.86	22.52	0.13	0.31	0.60	0.78	0.75
	0.8	0.46	0.66	−0.03 [−0.12; 0.06]	ns	22.84	21.92	0.16	0.33	0.60	0.78	0.75
	0.9	0.46	0.66	0.01 [−0.08; 0.1]	ns	22.97	21.57	0.17	0.33	0.60	0.78	0.75
	1.0	0.46	0.67	0.05 [−0.04; 0.14]	ns	23.18	21.39	0.19	0.33	0.61	0.77	0.75
VB	0.10	0.72	0.98	−0.67 [−0.76; −0.58]	*	28.43	34.44	0.06	0.14	0.31	0.77	0.37
	0.15	0.53	0.70	0.23 [0.14; 0.31]	*	28.17	23.68	0.15	0.30	0.48	0.77	0.64
	0.20	1.12	1.26	1.06 [0.96; 1.15]	*	61.45	43.39	0.05	0.09	0.15	0.78	0.43
	0.25	1.88	2.01	1.86 [1.75; 1.96]	*	100.20	62.62	0.00	0.01	0.04	0.78	0.26
	0.30	2.65	2.77	2.64 [2.53; 2.76]	*	139.29	77.75	0.00	0.00	0.01	0.77	0.18
	0.35	3.38	3.52	3.38 [3.26; 3.51]	*	175.58	89.10	0.00	0.00	0.00	0.77	0.13
	0.40	4.15	4.29	4.15 [4; 4.29]	*	214.55	99.09	0.00	0.00	0.00	0.77	0.10
	0.45	4.98	5.12	4.98 [4.81; 5.13]	*	258.59	108.02	0.00	0.00	0.00	0.73	0.08
	0.50	5.61	5.76	5.61 [5.43; 5.79]	*	289.36	113.80	0.00	0.00	0.00	0.75	0.07

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within 10%: % of estimates within ± 10% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S2. Performance of the different methods using data obtained at 60 meters flight height (n = 216).

Method	Parameter	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
CH	—	1.68	2.05	1.58 [1.41; 1.75]	*	85.49	54.00	0.05	0.05	0.10	0.63	0.29
CH-S	—	0.66	0.94	−0.15 [−0.27; −0.02]	*	31.10	32.36	0.10	0.21	0.42	0.62	0.54
αS	0.1	2.02	2.22	−2.02 [−2.15; −1.89]	*	89.79	164.11	0.00	0.00	0.00	0.22	0.01
	0.2	1.58	1.81	−1.58 [−1.7; −1.46]	*	68.64	108.54	0.00	0.00	0.00	0.39	0.06
	0.3	1.16	1.43	−1.15 [−1.27; −1.04]	*	50.19	72.50	0.02	0.05	0.09	0.51	0.19
	0.4	0.92	1.18	−0.82 [−0.93; −0.71]	*	40.46	54.20	0.03	0.09	0.23	0.58	0.34
	0.5	0.79	1.04	−0.58 [−0.69; −0.46]	*	35.63	44.53	0.08	0.17	0.27	0.61	0.46
	0.6	0.73	0.98	−0.39 [−0.52; −0.27]	*	33.68	39.14	0.06	0.14	0.34	0.62	0.51
	0.7	0.70	0.96	−0.25 [−0.37; −0.13]	*	32.88	35.83	0.06	0.17	0.40	0.62	0.54
	0.8	0.69	0.95	−0.12 [−0.25; 0]	ns	32.67	33.51	0.12	0.19	0.38	0.63	0.56
	0.9	0.69	0.97	−0.01 [−0.14; 0.11]	ns	33.12	32.26	0.11	0.22	0.39	0.63	0.56
	1.0	0.71	0.99	0.08 [−0.05; 0.22]	ns	33.97	31.61	0.13	0.23	0.42	0.63	0.56
αS-S	0.1	2.03	2.23	−2.03 [−2.16; −1.91]	*	90.40	166.05	0.00	0.00	0.00	0.22	0.01
	0.2	1.63	1.86	−1.63 [−1.75; −1.52]	*	71.37	114.64	0.00	0.00	0.00	0.39	0.05
	0.3	1.28	1.53	−1.28 [−1.4; −1.16]	*	55.44	81.94	0.01	0.02	0.05	0.50	0.15
	0.4	1.05	1.31	−1.01 [−1.12; −0.9]	*	45.77	64.23	0.04	0.07	0.13	0.56	0.26
	0.5	0.93	1.18	−0.84 [−0.95; −0.73]	*	40.96	55.07	0.03	0.07	0.22	0.59	0.35
	0.6	0.85	1.10	−0.71 [−0.82; −0.6]	*	37.69	49.03	0.06	0.13	0.26	0.60	0.40
	0.7	0.80	1.06	−0.62 [−0.74; −0.51]	*	35.96	45.49	0.06	0.14	0.28	0.60	0.43
	0.8	0.77	1.03	−0.55 [−0.68; −0.43]	*	34.77	42.92	0.08	0.13	0.30	0.61	0.46
	0.9	0.75	1.01	−0.5 [−0.62; −0.38]	*	33.89	41.06	0.07	0.17	0.31	0.61	0.47
	1.0	0.73	0.99	−0.46 [−0.58; −0.34]	*	33.26	39.59	0.06	0.19	0.31	0.61	0.48
VB	0.10	1.39	1.65	−1.39 [−1.51; −1.27]	*	58.45	86.71	0.00	0.00	0.03	0.37	0.06
	0.15	0.78	1.11	−0.67 [−0.8; −0.56]	*	31.14	39.12	0.08	0.18	0.33	0.44	0.23
	0.20	0.66	0.92	0.07 [−0.06; 0.19]	ns	32.36	29.68	0.13	0.26	0.44	0.48	0.40
	0.25	1.09	1.28	0.83 [0.69; 0.95]	*	58.59	42.82	0.04	0.09	0.18	0.52	0.32
	0.30	1.74	1.92	1.59 [1.44; 1.73]	*	93.02	59.07	0.01	0.02	0.06	0.53	0.21
	0.35	2.44	2.66	2.35 [2.2; 2.51]	*	129.16	72.68	0.01	0.02	0.05	0.53	0.14
	0.40	3.21	3.44	3.16 [2.97; 3.34]	*	168.98	85.29	0.01	0.01	0.04	0.54	0.10
	0.45	3.94	4.20	3.93 [3.73; 4.12]	*	206.83	95.02	0.01	0.02	0.03	0.56	0.08
	0.50	4.69	4.96	4.68 [4.47; 4.9]	*	245.36	103.54	0.00	0.01	0.02	0.54	0.06

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within 10%: % of estimates within ± 10% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S3. Performance of the different methods using data obtained at 100 meters flight height (n = 216).

Method	Parameter	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
CH	—	1.71	2.10	1.49 [1.3; 1.69]	*	87.42	56.87	0.05	0.07	0.14	0.55	0.26
CH-S	—	0.75	1.05	−0.47 [−0.6; −0.35]	*	34.37	43.88	0.09	0.18	0.36	0.57	0.45
αS	0.1	2.16	2.36	−2.16 [−2.29; −2.05]	*	97.16	189.18	0.00	0.00	0.00	0.29	0.00
	0.2	1.90	2.10	−1.9 [−2.02; −1.78]	*	84.32	147.96	0.00	0.00	0.00	0.36	0.02
	0.3	1.59	1.81	−1.59 [−1.71; −1.48]	*	70.22	112.42	0.00	0.00	0.00	0.47	0.08
	0.4	1.28	1.51	−1.28 [−1.39; −1.17]	*	56.47	84.58	0.00	0.01	0.04	0.54	0.18
	0.5	1.03	1.29	−0.99 [−1.1; −0.89]	*	45.66	65.46	0.03	0.07	0.16	0.57	0.30
	0.6	0.87	1.14	−0.75 [−0.88; −0.64]	*	39.44	54.33	0.08	0.14	0.28	0.58	0.40
	0.7	0.81	1.07	−0.57 [−0.69; −0.44]	*	37.37	48.79	0.06	0.13	0.30	0.57	0.45
	0.8	0.78	1.04	−0.43 [−0.56; −0.3]	*	36.39	45.31	0.07	0.16	0.31	0.58	0.49
	0.9	0.77	1.02	−0.3 [−0.45; −0.18]	*	36.22	42.91	0.08	0.18	0.33	0.58	0.51
	1.0	0.76	1.03	−0.2 [−0.34; −0.06]	*	36.30	41.14	0.11	0.17	0.37	0.58	0.52
αS-S	0.1	2.17	2.36	−2.17 [−2.3; −2.05]	*	97.40	190.07	0.00	0.00	0.00	0.29	0.00
	0.2	1.94	2.14	−1.94 [−2.06; −1.82]	*	86.16	153.22	0.00	0.00	0.00	0.35	0.02
	0.3	1.69	1.90	−1.69 [−1.81; −1.58]	*	74.69	122.78	0.00	0.00	0.00	0.45	0.06
	0.4	1.45	1.67	−1.45 [−1.56; −1.35]	*	64.10	99.40	0.00	0.01	0.02	0.53	0.12
	0.5	1.25	1.48	−1.25 [−1.36; −1.14]	*	55.57	83.10	0.01	0.02	0.05	0.56	0.20
	0.6	1.12	1.36	−1.1 [−1.21; −1]	*	49.85	72.86	0.01	0.03	0.10	0.58	0.27
	0.7	1.03	1.29	−0.99 [−1.1; −0.88]	*	46.19	66.37	0.02	0.06	0.17	0.58	0.30
	0.8	0.98	1.24	−0.92 [−1.03; −0.81]	*	43.64	62.00	0.05	0.08	0.20	0.58	0.33
	0.9	0.93	1.21	−0.86 [−0.98; −0.75]	*	41.73	58.75	0.06	0.12	0.23	0.58	0.35
	1.0	0.90	1.18	−0.81 [−0.93; −0.7]	*	40.42	56.44	0.05	0.14	0.25	0.58	0.37
VB	0.10	1.77	1.98	−1.77 [−1.89; −1.65]	*	77.79	129.63	0.00	0.00	0.00	0.38	0.03
	0.15	1.18	1.48	−1.18 [−1.3; −1.06]	*	49.23	70.41	0.02	0.05	0.10	0.40	0.11
	0.20	0.73	1.05	−0.52 [−0.64; −0.4]	*	31.20	37.83	0.08	0.20	0.34	0.44	0.28
	0.25	0.77	1.00	0.18 [0.04; 0.31]	ns	39.01	35.13	0.10	0.19	0.34	0.45	0.37
	0.30	1.21	1.42	0.9 [0.75; 1.04]	*	64.66	46.79	0.03	0.07	0.17	0.46	0.28
	0.35	1.84	2.06	1.66 [1.49; 1.81]	*	97.44	60.60	0.02	0.03	0.11	0.47	0.19
	0.40	2.58	2.85	2.47 [2.29; 2.66]	*	135.90	74.25	0.00	0.02	0.05	0.47	0.12
	0.45	3.28	3.58	3.22 [3; 3.42]	*	170.86	84.66	0.00	0.02	0.05	0.49	0.10
	0.50	4.04	4.38	4 [3.75; 4.22]	*	208.59	94.16	0.00	0.02	0.04	0.48	0.08

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within 10%: % of estimates within ± 10% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S4. Overall Performance of the different methods by flight height for the selected parameters.

Flight height	Method	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
30	CH	1.79	2.11	1.78 [1.62; 1.93]	*	92.15	57.15	0.02	0.02	0.06	0.69	0.32
	CH-S	0.54	0.77	0.31 [0.22; 0.41]	*	28.08	23.35	0.15	0.30	0.52	0.77	0.72
	αS (0.5)	0.47	0.67	−0.04 [−0.13; 0.05]	ns	23.03	22.29	0.16	0.33	0.59	0.77	0.75
	αS-S (0.8)	0.46	0.66	−0.03 [−0.12; 0.06]	ns	22.84	21.92	0.16	0.33	0.60	0.78	0.75
	VB (0.15)	0.53	0.70	0.23 [0.14; 0.31]	*	28.17	23.68	0.15	0.30	0.48	0.77	0.64
60	CH	1.68	2.05	1.58 [1.41; 1.75]	*	85.49	54.00	0.05	0.05	0.10	0.63	0.29
	CH-S	0.66	0.94	−0.15 [−0.27; −0.02]	*	31.10	32.36	0.10	0.21	0.42	0.62	0.54
	αS (0.8)	0.69	0.95	−0.12 [−0.25; 0]	ns	32.67	33.51	0.12	0.19	0.38	0.63	0.56
	αS-S (1.0)	0.73	0.99	−0.46 [−0.58; −0.34]	*	33.26	39.59	0.06	0.19	0.31	0.61	0.48
	VB (0.20)	0.66	0.92	0.07 [−0.06; 0.19]	ns	32.36	29.68	0.13	0.26	0.44	0.48	0.40
100	CH	1.71	2.10	1.49 [1.3; 1.69]	*	87.42	56.87	0.05	0.07	0.14	0.55	0.26
	CH-S	0.75	1.05	−0.47 [−0.6; −0.35]	*	34.37	43.88	0.09	0.18	0.36	0.57	0.45
	αS (0.9)	0.77	1.02	−0.3 [−0.45; −0.18]	*	36.22	42.91	0.08	0.18	0.33	0.58	0.51
	αS-S (1.0)	0.90	1.18	−0.81 [−0.93; −0.7]	*	40.42	56.44	0.05	0.14	0.25	0.58	0.37
	VB (0.25)	0.77	1.00	0.18 [0.04; 0.31]	*	39.01	35.13	0.10	0.19	0.34	0.45	0.37

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within X%: % of estimates within ± X% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S5. Overall performance of the different methods by phenological stage for data acquired at 30 m flight height (n = 72).

Phenological stage	Method	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
BBCH 81	CH	2.50	2.79	2.47 [2.17; 2.78]	*	115.05	66.85	0.00	0.00	0.01	0.73	0.27
	CH-S	0.78	1.07	0.54 [0.32; 0.76]	*	35.04	27.08	0.11	0.15	0.46	0.78	0.66
	αS (0.5)	0.59	0.90	0.09 [−0.12; 0.3]	ns	25.08	21.73	0.24	0.35	0.63	0.78	0.71
	αS-S (0.8)	0.59	0.89	0.1 [−0.1; 0.3]	ns	24.99	21.60	0.19	0.36	0.67	0.78	0.71
	VB (0.15)	0.66	0.90	0.09 [−0.13; 0.29]	ns	29.35	25.57	0.13	0.28	0.44	0.74	0.60
BBCH 85	CH	1.31	1.49	1.31 [1.16; 1.48]	*	75.04	49.70	0.01	0.01	0.10	0.67	0.31
	CH-S	0.42	0.55	0.17 [0.06; 0.3]	*	23.51	20.81	0.18	0.39	0.56	0.76	0.72
	αS (0.5)	0.41	0.53	−0.15 [−0.27; −0.04]	*	21.39	22.41	0.13	0.35	0.56	0.75	0.72
	αS-S (0.8)	0.40	0.52	−0.14 [−0.26; −0.02]	*	21.02	21.77	0.11	0.32	0.56	0.75	0.72
	VB (0.15)	0.49	0.61	0.29 [0.16; 0.41]	*	28.61	23.85	0.14	0.25	0.44	0.73	0.61
BBCH 89	CH	1.56	1.82	1.55 [1.33; 1.78]	*	86.37	54.89	0.04	0.06	0.07	0.55	0.24
	CH-S	0.44	0.57	0.23 [0.12; 0.35]	*	25.69	22.15	0.17	0.35	0.56	0.67	0.69
	αS (0.5)	0.40	0.51	−0.08 [−0.19; 0.04]	ns	22.63	22.73	0.13	0.31	0.60	0.68	0.72
	αS-S (0.8)	0.40	0.49	−0.06 [−0.18; 0.05]	ns	22.50	22.39	0.17	0.31	0.58	0.68	0.73
	VB (0.15)	0.42	0.54	0.3 [0.19; 0.39]	*	26.54	21.63	0.18	0.36	0.54	0.72	0.63

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within X%: % of estimates within ± X% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S6. Overall performance of the different methods by phenological stage for data acquired at 60 m flight height (n = 72).

Phenological stage	Method	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
BBCH 81	CH	1.94	2.39	1.69 [1.32; 2.07]	*	89.03	54.67	0.04	0.04	0.10	0.54	0.26
	CH-S	0.97	1.35	−0.28 [−0.58; 0.02]	ns	39.07	40.45	0.08	0.18	0.29	0.51	0.41
	αS (0.8)	0.99	1.34	−0.18 [−0.49; 0.12]	ns	40.65	40.45	0.10	0.15	0.29	0.54	0.45
	αS-S (1.0)	1.04	1.39	−0.6 [−0.9; −0.32]	*	41.02	48.09	0.04	0.15	0.28	0.52	0.38
	VB (0.20)	0.82	1.24	−0.27 [−0.56; 0]	ns	31.69	32.38	0.11	0.28	0.47	0.42	0.31
BBCH 85	CH	1.72	2.04	1.68 [1.41; 1.96]	*	92.07	56.92	0.06	0.06	0.13	0.58	0.23
	CH-S	0.62	0.76	−0.12 [−0.28; 0.06]	ns	33.19	35.37	0.06	0.17	0.33	0.59	0.56
	αS (0.8)	0.67	0.80	−0.12 [−0.3; 0.06]	ns	35.89	38.23	0.04	0.14	0.28	0.58	0.55
	αS-S (1.0)	0.70	0.84	−0.47 [−0.63; −0.31]	*	35.79	44.53	0.07	0.14	0.21	0.57	0.47
	VB (0.20)	0.54	0.71	−0.05 [−0.22; 0.11]	ns	28.66	27.97	0.18	0.28	0.44	0.47	0.46
BBCH 89	CH	1.39	1.65	1.38 [1.18; 1.59]	*	75.37	50.42	0.04	0.06	0.07	0.63	0.30
	CH-S	0.39	0.49	−0.04 [−0.15; 0.07]	ns	21.06	21.26	0.15	0.29	0.64	0.71	0.75
	αS (0.8)	0.41	0.54	−0.06 [−0.19; 0.07]	ns	21.48	21.83	0.21	0.29	0.58	0.69	0.72
	αS-S (1.0)	0.45	0.55	−0.3 [−0.41; −0.19]	*	22.97	26.14	0.07	0.28	0.46	0.70	0.68
	VB (0.20)	0.61	0.71	0.52 [0.41; 0.63]	*	36.74	28.69	0.08	0.24	0.39	0.63	0.51

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within X%: % of estimates within ± X% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S7. Overall performance of the different methods by phenological stage for data acquired at 100 m flight height (n = 72).

Phenological stage	Method	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
BBCH 81	CH	1.69	2.11	1.25 [0.84; 1.64]	*	76.65	51.61	0.07	0.11	0.22	0.48	0.29
	CH-S	1.03	1.41	−0.75 [−1.02; −0.48]	*	40.86	52.66	0.13	0.17	0.26	0.51	0.36
	αS (0.9)	1.03	1.35	−0.47 [−0.77; −0.17]	*	42.54	49.41	0.07	0.13	0.24	0.52	0.43
	αS-S (1.0)	1.18	1.55	−1.05 [−1.31; −0.79]	*	45.53	63.65	0.04	0.10	0.24	0.52	0.30
	VB (0.25)	0.83	1.20	−0.3 [−0.57; −0.05]	*	32.63	34.02	0.13	0.22	0.39	0.45	0.37
BBCH 85	CH	1.75	2.10	1.57 [1.25; 1.9]	*	96.47	62.62	0.08	0.10	0.13	0.47	0.21
	CH-S	0.72	0.92	−0.45 [−0.64; −0.28]	*	35.36	47.99	0.03	0.13	0.35	0.53	0.42
	αS (0.9)	0.73	0.90	−0.29 [−0.48; −0.1]	*	37.16	46.86	0.04	0.13	0.29	0.53	0.47
	αS-S (1.0)	0.86	1.08	−0.82 [−0.99; −0.66]	*	42.17	61.79	0.04	0.19	0.25	0.56	0.32
	VB (0.25)	0.67	0.81	0.08 [−0.1; 0.26]	ns	37.20	36.70	0.06	0.17	0.35	0.44	0.40
BBCH 89	CH	1.70	2.07	1.65 [1.37; 1.94]	*	89.14	56.39	0.00	0.01	0.07	0.64	0.25
	CH-S	0.51	0.66	−0.22 [−0.36; −0.07]	*	26.88	31.00	0.11	0.25	0.46	0.65	0.64
	αS (0.9)	0.55	0.71	−0.15 [−0.31; 0.02]	ns	28.96	32.46	0.14	0.28	0.46	0.62	0.63
	αS-S (1.0)	0.67	0.80	−0.58 [−0.7; −0.45]	*	33.57	43.87	0.07	0.14	0.26	0.65	0.51
	VB (0.25)	0.80	0.94	0.75 [0.62; 0.89]	*	47.21	34.65	0.13	0.18	0.29	0.60	0.41

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within X%: % of estimates within ± X% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S8. Overall performance of the different methods by grapevine variety for data acquired at 30 m flight height (n = 72).

Grapevine variety	Method	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
Tinta barroca	CH	1.54	1.79	1.51 [1.29; 1.74]	*	76.54	51.42	0.01	0.01	0.07	0.84	0.50
	CH-S	0.44	0.64	−0.02 [−0.17; 0.14]	ns	18.80	18.79	0.18	0.35	0.58	0.89	0.85
	αS (0.5)	0.50	0.74	−0.37 [−0.52; −0.23]	*	20.90	23.98	0.17	0.29	0.56	0.89	0.79
	αS-S (0.8)	0.50	0.73	−0.35 [−0.51; −0.22]	*	20.46	23.27	0.14	0.31	0.56	0.89	0.79
	VB (0.15)	0.54	0.78	−0.11 [−0.3; 0.05]	ns	22.27	21.96	0.10	0.25	0.49	0.87	0.69
Tinto cão	CH	2.42	2.73	2.41 [2.12; 2.73]	*	122.70	67.99	0.01	0.03	0.04	0.40	0.13
	CH-S	0.85	1.09	0.75 [0.58; 0.94]	*	44.54	32.49	0.13	0.19	0.39	0.54	0.43
	αS (0.5)	0.61	0.82	0.37 [0.21; 0.56]	*	32.01	25.75	0.13	0.26	0.47	0.56	0.55
	αS-S (0.8)	0.61	0.81	0.37 [0.21; 0.55]	*	32.10	25.76	0.14	0.26	0.51	0.54	0.55
	VB (0.15)	0.61	0.76	0.48 [0.34; 0.61]	*	34.89	26.84	0.19	0.32	0.47	0.56	0.46
Touriga franca	CH	1.41	1.63	1.4 [1.23; 1.61]	*	77.22	52.04	0.03	0.03	0.07	0.78	0.37
	CH-S	0.34	0.42	0.21 [0.13; 0.29]	*	20.91	18.77	0.15	0.35	0.60	0.87	0.86
	αS (0.5)	0.29	0.35	−0.14 [−0.21; −0.07]	*	16.20	17.13	0.19	0.44	0.75	0.87	0.88
	αS-S (0.8)	0.28	0.34	−0.12 [−0.19; −0.04]	*	15.95	16.75	0.19	0.42	0.74	0.88	0.89
	VB (0.15)	0.43	0.53	0.32 [0.22; 0.41]	*	27.35	22.25	0.15	0.32	0.47	0.86	0.72

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within X%: % of estimates within ± X% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S9. Overall performance of the different methods by grapevine variety for data acquired at 60 m flight height (n = 72).

Grapevine variety	Method	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
Tinta barroca	CH	1.24	1.56	0.96 [0.66; 1.25]	*	58.74	43.74	0.11	0.11	0.18	0.77	0.49
	CH-S	0.87	1.23	−0.67 [−0.92; −0.43]	*	34.96	44.76	0.06	0.14	0.32	0.69	0.46
	αS (0.8)	0.84	1.17	−0.63 [−0.86; −0.4]	*	33.83	42.56	0.13	0.17	0.28	0.75	0.52
	αS-S (1.0)	1.01	1.37	−0.92 [−1.18; −0.71]	*	41.16	56.02	0.06	0.14	0.19	0.69	0.38
	VB (0.20)	0.85	1.26	−0.35 [−0.65; −0.09]	*	33.01	36.78	0.08	0.22	0.38	0.43	0.28
Tinto cão	CH	2.60	2.89	2.6 [2.3; 2.89]	*	131.90	71.44	0.01	0.03	0.04	0.40	0.10
	CH-S	0.75	0.96	0.45 [0.26; 0.64]	*	38.45	30.40	0.11	0.21	0.36	0.44	0.44
	αS (0.8)	0.83	1.07	0.55 [0.35; 0.77]	*	42.24	32.76	0.07	0.18	0.35	0.43	0.41
	αS-S (1.0)	0.63	0.81	0.09 [−0.1; 0.27]	ns	30.31	27.55	0.06	0.24	0.43	0.42	0.51
	VB (0.20)	0.59	0.73	0.36 [0.21; 0.51]	*	33.50	26.22	0.15	0.35	0.50	0.47	0.46
Touriga franca	CH	1.21	1.36	1.19 [1.04; 1.35]	*	65.82	46.83	0.01	0.01	0.07	0.83	0.44
	CH-S	0.36	0.43	−0.21 [−0.3; −0.13]	*	19.91	21.91	0.13	0.29	0.58	0.84	0.83
	αS (0.8)	0.40	0.48	−0.29 [−0.37; −0.2]	*	21.94	25.20	0.15	0.24	0.53	0.81	0.80
	αS-S (1.0)	0.56	0.66	−0.53 [−0.62; −0.43]	*	28.31	35.19	0.07	0.19	0.32	0.80	0.65
	VB (0.20)	0.53	0.65	0.19 [0.04; 0.32]	*	30.57	26.04	0.14	0.22	0.43	0.61	0.58

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within X%: % of estimates within ± X% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.

Table S10. Overall performance of the different methods by grapevine variety for data acquired at 100 m flight height (n = 72).

Grapevine variety	Method	MAE	RMSE	MBE [CI95%]	Sig.	MAPE	SMAPE	Within 5%	Within 10%	Within 20%	ρ	CCC
Tinta barroca	CH	1.34	1.82	0.74 [0.35; 1.13]	*	61.47	50.99	0.06	0.11	0.19	0.63	0.41
	CH-S	1.16	1.52	−0.97 [−1.25; −0.69]	*	48.98	72.31	0.04	0.11	0.18	0.58	0.34
	αS (0.9)	1.09	1.41	−0.81 [−1.07; −0.54]	*	47.17	66.21	0.03	0.06	0.18	0.65	0.41
	αS-S (1.0)	1.29	1.64	−1.22 [−1.49; −0.96]	*	55.24	84.92	0.03	0.07	0.11	0.61	0.28
	VB (0.25)	0.96	1.30	−0.35 [−0.65; −0.08]	*	39.36	45.07	0.08	0.17	0.26	0.44	0.36
Tinto cão	CH	2.58	2.83	2.58 [2.31; 2.85]	*	131.79	71.81	0.03	0.03	0.07	0.39	0.10
	CH-S	0.58	0.73	−0.02 [−0.18; 0.15]	ns	27.32	26.78	0.13	0.24	0.47	0.48	0.57
	αS (0.9)	0.72	0.89	0.28 [0.08; 0.48]	*	34.87	30.48	0.10	0.25	0.39	0.47	0.51
	αS-S (1.0)	0.63	0.82	−0.45 [−0.61; −0.29]	*	26.64	31.53	0.08	0.28	0.47	0.50	0.50
	VB (0.25)	0.67	0.79	0.45 [0.3; 0.59]	*	38.26	29.50	0.14	0.25	0.42	0.48	0.37
Touriga franca	CH	1.21	1.36	1.16 [0.99; 1.33]	*	68.98	47.82	0.07	0.08	0.15	0.79	0.39
	CH-S	0.52	0.66	−0.43 [−0.54; −0.31]	*	26.81	32.55	0.10	0.19	0.42	0.77	0.63
	αS (0.9)	0.50	0.61	−0.38 [−0.49; −0.27]	*	26.63	32.03	0.13	0.22	0.42	0.75	0.69
	αS-S (1.0)	0.79	0.91	−0.78 [−0.88; −0.67]	*	39.38	52.86	0.04	0.08	0.17	0.76	0.43
	VB (0.25)	0.68	0.82	0.44 [0.27; 0.59]	*	39.42	30.80	0.08	0.15	0.35	0.58	0.45

CH: convex-hull; CH-S: convex-hull using 1 m slices; αS: alpha shape, αS-S: alpha shape 1 m slices; VB: voxel-based grid; MAE: mean absolute error; RMSE: root mean square error; MBE: mean bias error and [CI95%]: bias with 95% confidence interval; Sig.: MBE with 95% CI (bootstrap, R=2000). *: significant bias (CI excludes 0); ns: non-significant, MAPE: mean absolute percentage error; SMAPE: symmetric MAPE; Within X%: % of estimates within ± X% of field-measured volume; ρ: Spearman's rank correlation; CCC: Lin's concordance correlation coefficient.