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Supplementary material

Integrating UAV LiDAR and Multispectral Data for Aboveground Biomass Estimation in High-Andean Pastures of Northeastern Peru

Table S1. Vegetation indices (VIs) derived from UAV multispectral imagery, applied to aboveground biomass (AGB) estimation.

Index	Formula	Description	Reference
NDVI	(NIR - Red) / (NIR + Red)	Normalized Difference Vegetation Index. It indicates vegetation vigor or biomass.	[1]
NDRE	(NIR - RedEdge2) / (NIR + RedEdge2)	Normalized Difference Red Edge Index. Sensitive to chlorophyll in moderate to high biomass.	[2]
GNDVI	(NIR - Green) / (NIR + Green)	Green NDVI. Sensitive to chlorophyll content.	[3]
NDGI	(Green - Red) / (Green + Red)	Normalized Difference Green Index. Related to vegetation greenness.	[4]
GCI	(NIR / Green) - 1	Green Chlorophyll Index. Estimates chlorophyll content.	[5]
MCARI	[(Red - Green) - 0.2*(Red - Blue)]*(Red / Green)	Modified Chlorophyll Absorption Ratio Index. Sensitive to chlorophyll.	[6]
SIPI	(NIR - Blue) / (NIR - Red)	Structure Insensitive Pigment Index. Indicates pigment concentration.	[7]
ARI	(1 / Green) - (1 / Red)	Anthocyanin Reflectance Index. Detects anthocyanin pigments.	[8]
VARI	(Green - Red) / (Green + Red - Blue)	Visible Atmospherically Resistant Index. Estimates vegetation greenness.	[9]
EVI	2.5 * ((NIR - Red) / (NIR + 6*Red - 7.5*Blue + 1))	Enhanced Vegetation Index. Reduces atmospheric effects, enhances sensitivity in high biomass areas.	[10]
NDYI	(Yellow - Red) / (Yellow + Red)	Normalized Difference Yellow Index. Sensitive to yellowing due to senescence or stress.	[11]
TGI	-0.5*(190*(Red - Green) - 120*(Red - Blue))	Triangular Greenness Index. Estimates chlorophyll content based on green, red, blue bands.	[12]
CCCI	(NDRE / NDVI)	Canopy Chlorophyll Content Index. Combines NDRE and NDVI to evaluate chlorophyll.	[13]
TCARI	3 * [(Red - Green) - 0.2*(Red - Blue)]*(Red / Green)	Transformed Chlorophyll Absorption Ratio Index. Reduces effects of leaf area and soil background.	[14]
OSAVI	(NIR - Red) / (NIR + Red + 0.16)	Optimized Soil-Adjusted Vegetation Index. Adjusted for soil brightness.	[15]
RECI	(NIR / RedEdge2) - 1	Red Edge Chlorophyll Index. Sensitive to chlorophyll content in canopy.	[16]
RDVI	(NIR - Red) / sqrt(NIR + Red)	Renormalized Difference Vegetation Index. Enhances sensitivity to vegetation.	[17]
SR	NIR / Red	Simple Ratio. Basic index for vegetation density.	[18]

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GDVI	NIR - Green	Generalized Difference Vegetation Index. Measures green vegetation vigor.	[19]
DVI	NIR - Red	Difference Vegetation Index. It indicates amount of vegetation.	[20]

Table S2. LiDAR structural metrics used for AGB estimation, grouped into point count, height, intensity, percentile, and ratio/threshold metrics.

Category	Metric	Description
Point Count Metrics	TOT_ALL	Total number of LiDAR returns (all echoes) within the grid cell.
	TOT_FIRST	Total number of first returns (first echoes).
	ALL_ABV_MIN	Number of all returns above a minimum height threshold (e.g., 0.05 m).
	FIRST_ABV_MIN	Number of first returns above the height threshold.
	RET_1_ABV_MIN	Equivalent to FIRST_ABV_MIN (redundant).
Height Statistics	HMIN	Minimum height (Z) of all returns.
	HMAX	Maximum height (Z) of all returns.
	HMEAN	Mean height.
	HMED	Median height.
	HSD	Standard deviation of height.
	HVAR	Variance of height.
	HCV	Coefficient of variation of height: 100 × (HSD / HMEAN).
	HKUR	Kurtosis of height distribution (peakedness).
	HSKE	Skewness of height distribution (asymmetry).
	CRR	Canopy relief ratio: (HMEAN – HMIN) / (HMAX – HMIN).
Height Percentiles	H01–H99	Percentile metrics of height distribution at 1% intervals (e.g., H01 = 1st percentile, ..., H99 = 99th percentile).
Intensity Statistics	IMIN	Minimum intensity of returns.
	IMAX	Maximum intensity.
	IMEAN	Mean intensity.
	IMED	Median intensity.
	ISD	Standard deviation of intensity.
	IVAR	Variance of intensity.
	ICV	Coefficient of variation of intensity: 100 × (ISD / IMEAN).
	IKUR	Kurtosis of intensity distribution.
	ISKE	Skewness of intensity distribution.
Intensity Percentiles	I01–I99	Percentile metrics of intensity at 1% intervals.
Ratio/Threshold Metrics	PCT_FIRST_MIN	% of first returns above the threshold, relative to all first returns.
	PCT_ALL_MIN	% of all returns above the threshold.
	RATIO_MIN	Ratio of above-threshold returns to total first returns.
	PCT_FIRST_MEAN	% of first returns greater than mean height.
	PCT_ALL_MEAN	% of all returns greater than mean height.
	RATIO_MEAN	Ratio of returns above mean height to total first returns.

Table S3. Plot-level statistics of fresh and dry AGB by month, including sample size (count), mean, standard deviation (SD), and coefficient of variation (CV).

Site	Plot	Month	Type	Count	Mean	SD	CV
Atuen	P10	February	Dry weight	4	6.95	1.25	17.99
Atuen	P10	February	Fresh weight	4	51.83	9.37	18.08
Atuen	P10	March	Dry weight	5	41.20	14.15	34.34
Atuen	P10	March	Fresh weight	5	324.60	105.14	32.39
Atuen	P15	February	Dry weight	5	8.98	3.34	37.20
Atuen	P15	February	Fresh weight	5	60.40	21.15	35.01
Atuen	P15	March	Dry weight	5	43.80	11.14	25.44
Atuen	P15	March	Fresh weight	5	350.40	105.75	30.18
Atuen	P2	February	Dry weight	4	23.45	6.61	28.17
Atuen	P2	February	Fresh weight	4	154.80	16.52	10.67
Atuen	P2	March	Dry weight	5	3.00	0.71	23.57
Atuen	P2	March	Fresh weight	5	19.60	3.65	18.61
Atuen	P4	February	Dry weight	5	24.47	6.00	24.52
Atuen	P4	February	Fresh weight	5	146.82	33.10	22.55
Atuen	P4	March	Dry weight	5	2.40	1.67	69.72
Atuen	P4	March	Fresh weight	5	17.40	10.71	61.58
Atuen	P5	March	Dry weight	5	8.80	5.26	59.81
Atuen	P5	March	Fresh weight	5	60.00	39.29	65.48
Atuen	P7	February	Dry weight	5	19.10	7.85	41.10
Atuen	P7	February	Fresh weight	5	113.74	39.48	34.71
Atuen	P7	March	Dry weight	4	2.25	1.89	84.13
Atuen	P7	March	Fresh weight	4	18.75	21.25	113.34
Molinopampa	P13	April	Dry weight	5	6.80	0.84	12.30
Molinopampa	P13	April	Fresh weight	5	47.80	9.01	18.85
Molinopampa	P13	March	Dry weight	5	3.30	1.35	40.94
Molinopampa	P13	March	Fresh weight	5	22.00	7.68	34.91
Molinopampa	P17	April	Dry weight	5	3.30	1.20	36.49
Molinopampa	P17	April	Fresh weight	5	17.60	3.58	20.33
Molinopampa	P17	March	Dry weight	5	1.90	1.92	100.90
Molinopampa	P17	March	Fresh weight	5	11.00	9.64	87.67
Molinopampa	P19	April	Dry weight	5	9.80	2.39	24.36
Molinopampa	P19	April	Fresh weight	5	56.40	17.17	30.44
Molinopampa	P19	March	Dry weight	5	6.00	2.35	39.09
Molinopampa	P19	March	Fresh weight	5	32.80	11.73	35.78
Molinopampa	P27	April	Dry weight	5	7.60	1.82	23.90
Molinopampa	P27	April	Fresh weight	5	44.00	13.93	31.66
Molinopampa	P27	March	Dry weight	5	3.90	2.97	76.06
Molinopampa	P27	March	Fresh weight	5	20.00	15.25	76.24
Molinopampa	P31	April	Dry weight	5	12.10	5.13	42.38
Molinopampa	P31	April	Fresh weight	5	72.40	31.53	43.55

Molinopampa	P40	April	Dry weight	5	14.80	4.55	30.74
Molinopampa	P40	April	Fresh weight	5	91.20	33.94	37.22
Molinopampa	P40	March	Dry weight	5	8.50	3.28	38.57
Molinopampa	P40	March	Fresh weight	5	64.20	39.91	62.16
Molinopampa	P9	April	Dry weight	5	4.20	5.01	119.23
Molinopampa	P9	April	Fresh weight	5	26.20	31.90	121.76
Molinopampa	P9	March	Dry weight	5	1.28	1.17	91.34
Molinopampa	P9	March	Fresh weight	5	8.00	3.46	43.30

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