remote sensing

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Supplementary Material

An Approach for Foliar Trait Retrieval from Airborne Imaging Spectroscopy of Tropical Forests

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Abstract: Spatial information on forest functional composition is needed to inform management and conservation efforts, yet this information is lacking, particularly in tropical regions. Canopy foliar traits underpin the functional biodiversity of forests, and have been shown to be remotely measurable using airborne 350–2510 nm imaging spectrometers. We used newly acquired imaging spectroscopy data constrained with concurrent light detection and ranging (LiDAR) measurements from the Carnegie Airborne Observatory (CAO), and field measurements, to test the performance of the Spectranomics approach for foliar trait retrieval. The method was previously developed in Neotropical forests, and was tested here in the humid tropical forests of Malaysian Borneo. Multiple foliar chemical traits, as well as leaf mass per area (LMA), were estimated with demonstrable precision and accuracy. The results were similar to those observed for Neotropical forests, suggesting a more general use of the Spectranomics approach for mapping canopy traits in tropical forests. Future mapping studies using this approach can advance scientific investigations and applications based on imaging spectroscopy.

Keywords: Airborne remote sensing; Borneo; Carnegie Airborne Observatory; foliar traits; imaging spectroscopy; Malaysia; PLSR; Sabah; Spectranomics; tropical forest

Table S1. Location (Latitude, Longitude) and forest type for 13 field locations spanning a range of elevation and substrate types across Sabah, Malaysia.

Site	Elevation (m)	Substrate	Latitude	Longitude	Forest Type
Kinabatangan	17	Alluvial	5.56317	117.88886	Lowland alluvial forest
Danum Valley	205	Sedimentary	5.32526	117.43660	Lowland mixed Dipterocarp rainforest
Sepilok					
	135	Heath	5.49618	118.33201	Lowland heath forest (Kerangas)
	73	Sandstone	5.46029	118.34217	Sandstone hill forest
	30	Mudstone	5.46548	118.34733	Lowland alluvial forest
Kinabalu					
	700	Sedimentary	4.22243	118.51857	Hill Dipterocarp rainforest
	1700	Sedimentary	4.06078	118.48249	Lower montane rainforest
	2700	Sedimentary	4.08070	118.51305	Upper montane rainforest
	3100	Granite	4.08686	118.52501	Subalpine rainforest
	700	Ultramafic	4.23313	118.57550	Hill Dipterocarp rainforest
	1700	Ultramafic	4.13763	118.51345	Lower montane rainforest
	2700	Ultramafic	4.08377	118.51753	Upper montane rainforest
	3100	Ultramafic	4.08568	118.52171	Subalpine forest

Table S2. Mean and range of foliar chemical traits and leaf mass per area sampled from collection locations in Kinabatangan, Danum Valley, and Sepilok in western Sabah, Malaysia.

	Kinabatangan	**Danum Valley**		**Sepilok**	
Elevation	15 m	150–215 m	135 m	75 m	30 m
Soil Order	Alluvial	Sedimentary	Heath	Sandstone	Sedimentary
LMA (g m^{-2})	80.0 (41.6–165.8)	91.8 (49.7–145.3)	161.4 (114.1–243.6)	128.4 (88.9–188.2)	102.7 (65.3–138.8)
N (%)	2.22 (1.02–3.84)	2.10 (0.92–4.46)	1.50 (0.85–2.14)	1.72 (1.42–2.71)	1.98 (1.33–2.78)
Water (%)	63.3 (49.4–79.9)	58.1 (46.1–69.5)	53.2 (43.3–60.9)	53.4 (46.6–60.1)	57.8 (46.6–75.8)
Chl ab (mg g^{-1})	6.2 (2.7–10.1)	6.0 (2.7–10.3)	3.6 (2.0–5.7)	4.7 (2.9–6.9)	5.2 (3.0–9.8)
NSC (%)	43.5 (26.7–58.7)	42.0 (24.8–65.0)	47.2 (32.7–60.2)	38.7 (24.6–54.7)	39.5 (23.3–55.9)
δ^{13}C (‰)	–30.9 (–32.9—28.6)	–31.0 (–33.8—27.2)	–29.5 (–31.8—26.7)	–29.9 (–31.9—27.4)	–29.8 (–32.7—26.2)
P (%)	0.14 (0.05–0.32)	0.11 (0.04–0.21)	0.04 (0.02–0.08)	0.06 (0.05–0.09)	0.11 (0.06–0.17)
Ca (%)	1.05 (0.35–1.94)	0.88 (0.24–2.93)	0.25 (0.06–0.36)	0.24 (0.09–0.42)	0.70 (0.26–2.33)
K (%)	0.88 (0.17–2.20)	0.71 (0.20–1.51)	0.49 (0.17–1.02)	0.52 (0.24–0.93)	0.72 (0.36–1.19)
Mg (%)	0.32 (0.09–0.70)	0.24 (0.07–0.70)	0.22 (0.09–0.33)	0.18 (0.10–0.35)	0.20 (0.03–0.58)
B (µg g^{-1})	32.7 (9.7–61.4)	21.8 (5.0–106.1)	24.8 (11.6–38.6)	16.4 (7.2–31.0)	24.8 (9.7–48.1)
Fe (µg g^{-1})	38.8 (18.0–61.9)	52.7 (23.3–189.1)	25.4 (17.3–36.8)	31.1 (22.6–40.8)	42.2 (19.2–114.0)
C (%)	47.3 (43.7–53.0)	48.8 (40.0–53.3)	52.0 (47.1–55.8)	51.3 (47.5–54.4)	48.9 (40.8–53.1)
Lignin (%)	28.8 (0.9–67.2)	27.3 (5.2–55.0)	28.9 (9.3–62.1)	35.6 (20.3–46.5)	30.6 (14.2–57.7)
Cellulose (%)	16.4 (1.1–31.6)	16.7 (1.4–36.9)	14.9 (7.9–20.7)	17.7 (5.7–27.4)	16.9 (3.1–30.9)
Tannins (mg g^{-1})	57.5 (12.8–136.9)	80.8 (23.7–149.1)	66.1 (38.2–100.4)	78.2 (53.8–113.3)	57.2 (16.8–112.6)
Phenols (mg g^{-1})	120.9 (22.6–195.3)	121.6 (26.9–240.2)	132.1 (70.8–184.8)	125.0 (88.8–202.5)	112.3 (24.5–216.6)

Table S2 cont. Mean and range in foliar chemical traits and LMA from collection locations along an elevation gradient on Mt. Kinabalu in Sabah, Malaysia. The upper portion lists traits from sedimentary and granitic substrates. The lower portion lists traits from ultramafic substrates. nd means no data were collected at these sites for these traits.

Elevation	**700 m**	**1700 m**	**2700 m**	**3100 m**
Soil Order		Sedimentary		Granite
LMA (g m^{-2})	85.7 (28.6–156.6)	138.2 (44.7–254.5)	203.2 (136.6–301.3)	215.7 (112.1–306.9)
N (%)	2.19 (1.31–4.02)	1.71 (0.80–3.04)	1.40 (0.90–1.86)	1.13 (0.68–1.90)
Water (%)	60.6 (46.9–80.2)	55.6 (44.0–79.9)	53.9 (45.1–64.5)	55.8 (45.9–68.1)
Chl ab (mg g^{-1})*	nd	nd	nd	nd
NSC (%)	43.4 (28.1–65.4)	45.2 (25.6–75.1)	42.9 (23.1–54.7)	48.3 (38.6–61.8)
δ^{13}C (‰)	–29.3 (–32.3–25.4)	–29.9 (–32.9–26.9)	–28.9 (–30.6—26.4)	–28.0 (–31.4—25.5)
P (%)	0.12 (0.05–0.29)	0.07 (0.03–0.30)	0.05 (0.03–0.08)	0.05 (0.03–0.08)
Ca (%)	0.73 (0.14–1.71)	0.36 (0.12–1.81)	0.18 (0.08–0.44)	0.88 (0.32–2.32)
K (%)	1.03 (0.37–2.51)	0.58 (0.18–1.22)	0.56 (0.27–1.05)	0.43 (0.24–0.88)
Mg (%)	0.24 (0.05–0.54)	0.20 (0.07–0.59)	0.18 (0.04–0.35)	0.21 (0.09–0.36)
B (μg g^{-1})	34.8 (7.3–200.7)	24.6 (10.1–69.5)	13.4 (2.1–27.9)	15.4 (5.4–32.7)
Fe (μg g^{-1})	35.2 (18.2–96.4)	40.3 (16.2–126.6)	31.2 (17.8–116.0)	27.3 (12.5–61.4)
C (%)	47.7 (40.1–52.8)	50.2 (43.0–53.6)	52.9 (50.2–55.7)	50.3 (40.8–55.0)
Lignin (%)	22.9 (5.7–36.5)	24.0 (7.7–44.5)	26.5 (18.7–35.7)	26.4 (10.2–40.7)
Cellulose (%)	17.9 (9.8–29.9)	17.1 (10.1–31.3)	15.5 (5.9–27.2)	15.1 (6.1–24.8)
Tannins (mg g^{-1})*	nd	nd	nd	nd
Phenols (mg g^{-1})*	nd	nd	nd	nd
Elevation	700 m	1700 m	2700 m	3100 m
Soil Order		Ultramafic		
LMA (g m^{-2})	124.7 (86.0–204.5)	255.2 (195.5–309.2)	227.2 (154.8–280.3)	219.5 (184.9–293.0)
N (%)	1.58 (0.60–2.38)	0.95 (0.73–1.22)	1.08 (0.81–1.58)	1.06 (0.66–1.82)
Water (%)	53.5 (44.5–65.7)	51.8 (47.0–58.1)	49.9 (43.1–55.2)	50.5 (38.5–60.1)
Chl ab (mg g^{-1})*	nd	nd	nd	nd
NSC (%)	42.6 (29.0–67.3)	50.5 (42.2–67.9)	43.9 (32.9–56.0)	45.3 (35.3–56.5)
δ^{13}C (‰)	–30.6 (–33.9—28.1)	–28.4 (–30.2—26.9)	–28.9 (–30.7—26.6)	–28.1 (–30.7—24.5)
P (%)	0.06 (0.03–0.12)	0.03 (0.02–0.04)	0.04 (0.03–0.08)	0.03 (0.02–0.06)
Ca (%)	0.27 (0.06–0.75)	0.87 (0.51–1.38)	0.53 (0.06–1.24)	0.56 (0.23–1.46)
K (%)	0.51 (0.15–1.44)	0.27 (0.19–0.41)	0.38 (0.23–0.58)	0.46 (0.17–0.79)
Mg (%)	0.24 (0.07–0.84)	0.19 (0.10–0.41)	0.14 (0.07–0.27)	0.15 (0.08–0.34)
B (μg g^{-1})	23.4 (9.9–63.7)	28.6 (16.5–116.4)	12.8 (5.5–22.7)	17.0 (3.4–33.0)
Fe (μg g^{-1})	30.6 (13.6–99.9)	28.8 (14.4–105.2)	31.7 (13.7–55.7)	34.5 (11.6–116.7)
C (%)	49.6 (41.8–53.8)	51.2 (48.8–53.1)	52.3 (49.4–54.4)	52.5 (49.2–55.3)
Lignin (%)	25.0 (10.8–42.8)	22.3 (11.6–27.4)	27.0 (20.3–38.5)	29.5 (16.6–41.7)
Cellulose (%)	18.7 (9.1–35.9)	15.9 (10.9–24.5)	17.3 (11.7–22.4)	13.3 (2.3–21.3)
Tannins (mg g^{-1})*	nd	nd	nd	nd
Phenols (mg g^{-1})*	nd	nd	nd	nd

Table S3. Principle components analysis results for 14 and 17 foliar traits measured at all locations (n crowns = 424; spectra = 3993) or in the lowlands only (n crowns = 182; spectra = 2430). All components except the final one (shown in italics) were significant in explaining a percentage of the total variation (right column) among the traits (Bartlett's Chi–square test; $p < 0.01$).

All locations			**Lowlands only**		
Number	Eigenvalue	%	Number	Eigenvalue	%
1	4.53	32.39	1	4.99	29.37
2	2.12	15.14	2	2.18	12.81
3	1.24	8.84	3	2.15	12.65
4	1.21	8.65	4	1.26	7.40
5	0.99	7.05	5	1.22	7.17
6	0.81	5.80	6	0.96	5.65
7	0.76	5.43	7	0.77	4.53
8	0.70	4.99	8	0.73	4.28
9	0.47	3.37	9	0.58	3.40
10	0.38	2.71	10	0.48	2.82
11	0.33	2.34	11	0.42	2.49
12	0.20	1.40	12	0.39	2.27
13	0.16	1.17	13	0.32	1.91
14	*0.10*	*0.73*	14	0.21	1.23
			15	0.17	1.01
			16	0.10	0.60
			17	*0.07*	*0.42*

Table S4. Parameters from linear regression analysis between model and lab-measured chemical traits and leaf mass per area (LMA) for crowns used in the canopy model development (70%) and the crowns held out for testing (30%). All models were significant $p < 0.001$, except phenols where the significance value was 0.02. Graphical depictions of results are shown in Figure S4.

	Canopy Model		**Field Test**	
Trait	Slope (RMSE)	Intercept (RMSE)	Slope (RMSE)	Intercept (RMSE)
		Light capture and growth		
LMA (g m^{-2})	1.00 (0.04)	–0.19 (5.14)	1.09 (0.05)	–10.29 (6.36)
N (%)	0.96 (0.06)	0.06 (0.11)	1.09 (0.09)	–0.14 (0.17)
Water (%)	0.91 (0.08)	4.67 (4.39)	1.06 (0.12)	–3.82 (6.77)
Chl ab (mg g^{-1})*	0.81 (0.17)	1.11 (0.96)	1.24 (0.34)	–1.31 (1.97)
NSC (%)	0.80 (0.11)	8.57 (4.55)	0.94 (0.16)	2.65 (7.13)
$\delta^{13}C$ (‰)	0.83 (0.10)	–5.12 (3.05)	1.21 (0.14)	6.44 (4.23)
		Rock-derived nutrients		
P (%)	0.95 (0.06)	0.00 (0.01)	0.98 (0.07)	0.00 (0.01)
Ca (%)	0.98 (0.07)	0.03 (0.05)	0.96 (0.09)	–0.02 (0.06)
K (%)	0.93 (0.09)	0.04 (0.06)	0.89 (0.10)	0.05 (0.07)
Mg (%)	0.90 (0.12)	0.02 (0.03)	1.18 (0.18)	–0.02 (0.04)
B (μg g^{-1})	0.71 (0.11)	6.49 (2.62)	1.58 (0.26)	–10.66 (6.58)
Fe (μg g^{-1})	0.82 (0.12)	6.54 (4.59)	1.45 (0.23)	–14.65 (8.70)
		Structure and defense		
C (%)	0.99 (0.06)	0.33 (2.98)	0.89 (0.10)	5.71 (4.84)
Lignin (%)	0.87 (0.12)	3.37 (3.15)	0.89 (0.15)	3.37 (4.10)
Cellulose (%)	0.62 (0.15)	6.46 (2.50)	1.26 (0.25)	–4.60 (4.28)
Tannins (mg g^{-1})*	0.87 (0.15)	9.33 (10.38)	1.15 (0.20)	–12.39 (14.33)
Phenols (mg g^{-1})*	0.46 (0.20)	66.81 (24.30)	1.23 (0.36)	–31.86 (44.54)

* indicates chemical traits measured from flash-frozen samples. These were only available from a subset of sites (Danum Valley, Kinibatagan, and Sepilok).

Table S5. Correlation values (top half of table) among 14 foliar traits measured in 424 tree crowns in Sabah, Malaysia. Significance values are shown in italics in the lower portion of the table.

	LMA	**N**	**Water**	**NSC**	**$\delta^{13}C$**	**P**	**Ca**	**K**	**Mg**	**B**	**Fe**	**C**	**Lignin**	**Cellulose**
LMA	----	-0.71	-0.55	0.10	0.34	-0.68	-0.27	-0.51	-0.21	-0.24	-0.31	0.52	0.04	-0.05
N	*<0.01*	----	0.52	-0.21	-0.11	0.78	0.27	0.57	0.19	0.20	0.40	-0.37	-0.06	0.11
Water	*<0.01*	*<0.01*	----	0.08	0.01	0.64	0.27	0.61	0.36	0.20	0.10	-0.37	-0.08	-0.08
NSC	*0.05*	*<0.01*	*0.10*	----	0.30	-0.15	0.09	-0.07	0.09	0.11	-0.03	-0.10	-0.61	-0.50
$\delta^{13}C$	*<0.01*	*0.03*	*0.92*	*<0.01*	----	-0.09	-0.08	-0.02	-0.04	0.03	-0.17	0.04	-0.24	-0.20
P	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*0.08*	----	0.37	0.69	0.30	0.26	0.30	-0.45	-0.01	0.05
Ca	*<0.01*	*<0.01*	*<0.01*	*0.07*	*0.10*	*<0.01*	----	0.21	0.32	0.31	0.29	-0.49	-0.11	-0.09
K	*<0.01*	*<0.01*	*<0.01*	*0.16*	*0.76*	*<0.01*	*<0.01*	----	0.36	0.25	0.20	-0.35	-0.08	0.03
Mg	*<0.01*	*<0.01*	*<0.01*	*0.07*	*0.38*	*<0.01*	*<0.01*	*<0.01*	----	0.36	0.25	-0.34	-0.16	-0.03
B	*<0.01*	*<0.01*	*<0.01*	*0.03*	*0.60*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	----	0.12	-0.25	-0.09	-0.08
Fe	*<0.01*	*<0.01*	*0.04*	*0.49*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*0.01*	----	-0.24	-0.06	-0.04
C	*<0.01*	*<0.01*	*<0.01*	*0.05*	*0.45*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	----	0.29	-0.08
Lignin	*0.47*	*0.27*	*0.13*	*<0.01*	*<0.01*	*0.77*	*0.03*	*0.11*	*<0.01*	*0.07*	*0.26*	*<0.01*	----	-0.16
Cellulose	*0.34*	*0.02*	*0.13*	*<0.01*	*<0.01*	*0.36*	*0.06*	*0.56*	*0.58*	*0.11*	*0.46*	*0.13*	*<0.01*	----

Table S6. Correlation values (top half of table) among weighting coefficients for 14 foliar traits retrieved from airborne spectroscopic measurements of 182 crowns in Sabah, Malaysia. Significance values are shown in italics in the lower portion of the table.

	LMA	**N**	**Water**	**NSC**	**⚜^{13}C**	**P**	**Ca**	**K**	**Mg**	**B**	**Fe**	**C**	**Lignin**	**Cellulose**
LMA	----	-0.40	-0.52	-0.11	0.32	-0.46	0.00	-0.42	-0.19	-0.04	-0.04	0.24	0.03	0.20
N	*<0.01*	----	0.32	-0.03	0.07	0.77	0.19	0.75	0.10	0.09	0.13	-0.13	-0.04	0.06
Water	*<0.01*	*<0.01*	----	0.27	0.11	0.50	0.34	0.57	0.48	0.37	0.06	-0.31	-0.02	-0.47
NSC	*0.16*	*0.70*	*<0.01*	----	0.52	-0.04	0.42	-0.06	0.29	0.44	0.12	-0.63	-0.76	-0.68
◎^{13}C	*<0.01*	*0.39*	*0.17*	*<0.01*	----	0.10	0.32	0.13	0.05	0.38	-0.08	-0.44	-0.49	-0.28
P	*<0.01*	*<0.01*	*<0.01*	*0.60*	*0.23*	----	0.36	0.78	0.24	0.20	0.12	-0.25	0.03	-0.06
Ca	*0.99*	*0.02*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	----	0.19	0.38	0.46	0.33	-0.56	-0.23	-0.43
K	*<0.01*	*<0.01*	*<0.01*	*0.48*	*0.11*	*<0.01*	*0.02*	----	0.27	0.23	0.01	-0.13	0.05	-0.01
Mg	*0.02*	*0.23*	*<0.01*	*<0.01*	*0.55*	*<0.01*	*<0.01*	*<0.01*	----	0.49	0.25	-0.30	-0.22	-0.39
B	*0.66*	*0.25*	*<0.01*	*<0.01*	*<0.01*	*0.01*	*<0.01*	*<0.01*	*<0.01*	----	0.14	-0.25	-0.18	-0.46
Fe	*0.59*	*0.10*	*0.45*	*0.13*	*0.34*	*0.12*	*<0.01*	*0.93*	*<0.01*	*0.08*	----	-0.09	-0.08	-0.16
C	*<0.01*	*0.11*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*0.09*	*<0.01*	*<0.01*	*0.25*	----	0.64	0.36
Lignin	*0.70*	*0.60*	*0.76*	*<0.01*	*<0.01*	*0.70*	*<0.01*	*0.54*	*<0.01*	*0.03*	*0.29*	*<0.01*	----	0.17
Cellulose	*0.01*	*0.46*	*<0.01*	*<0.01*	*<0.01*	*0.47*	*<0.01*	*0.90*	*<0.01*	*<0.01*	*0.04*	*<0.01*	*0.03*	----

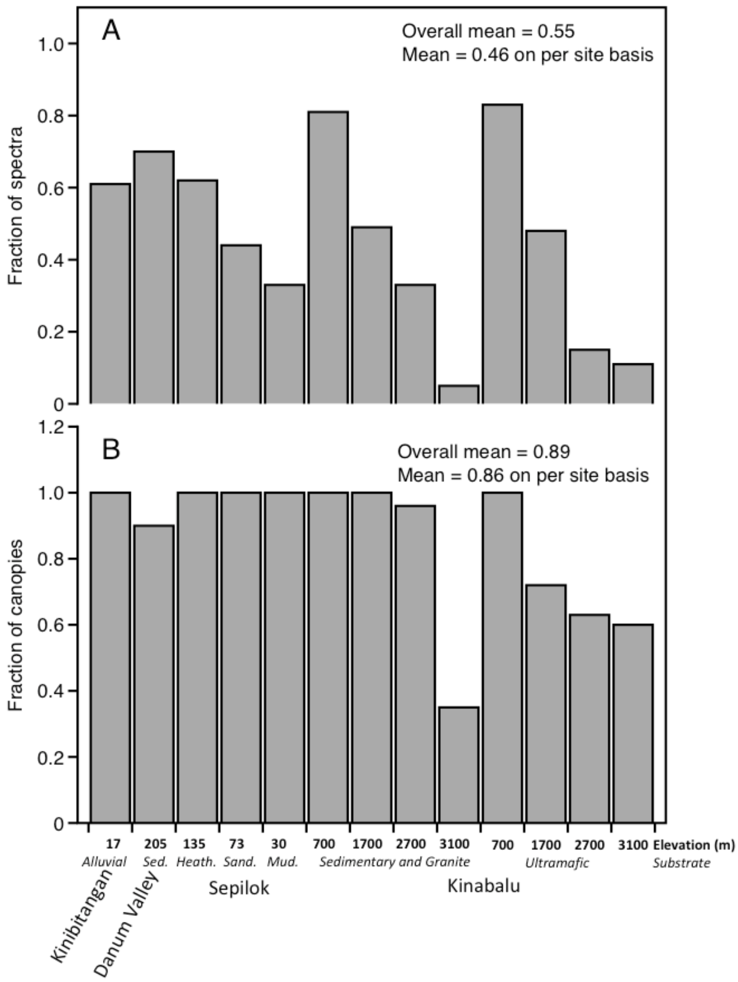

Figure S1. Histograms showing (A) the fraction of 4 m CAO VSWIR pixels within delineated crowns that passed through prescreening criteria in each collection site in Sabah, and (B) the fraction of tree crowns at each site that had suitable pixels following prescreening.

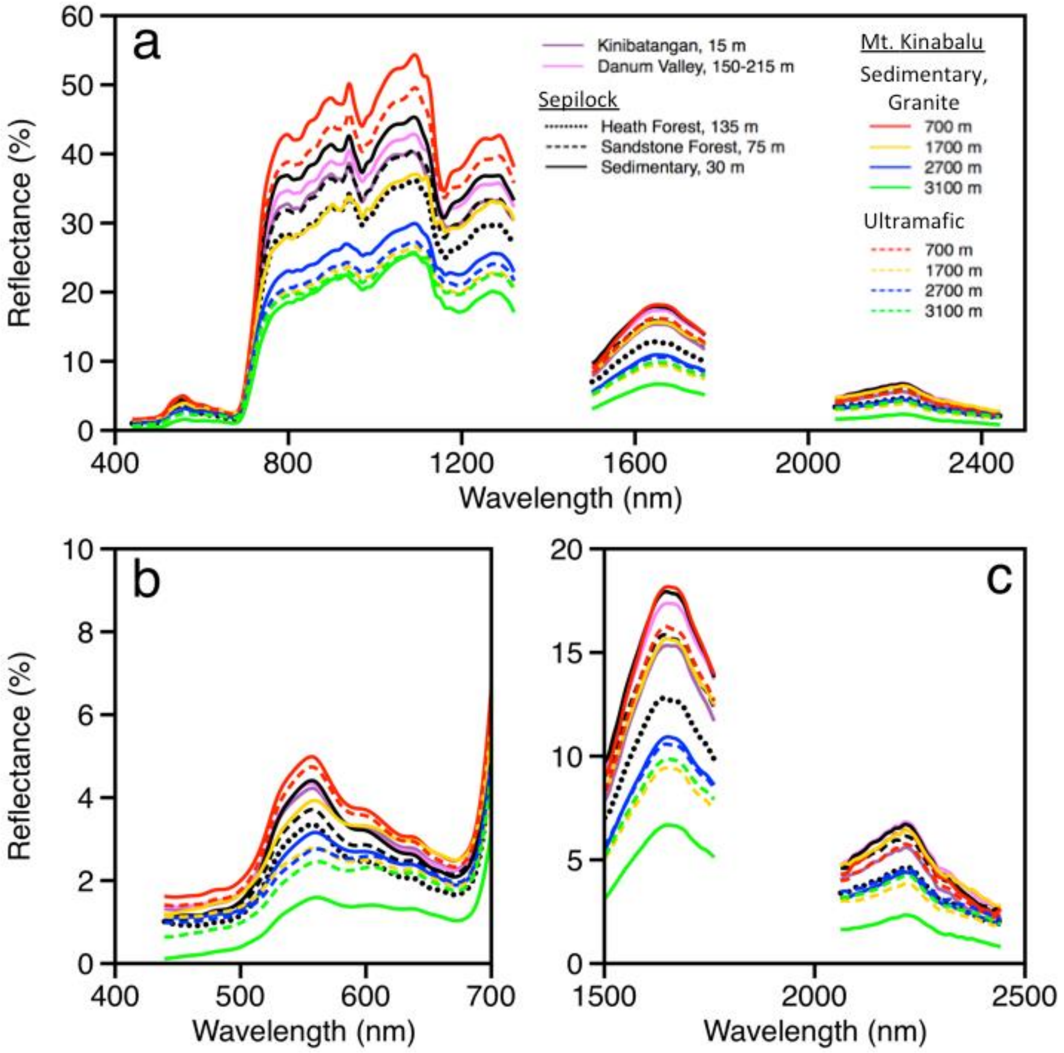

Figure S2. (a) Examples of crown reflectance spectra derived from the mean number of pixels at each site suitable for chemometric analysis (Table 1) following prescreening within each collection location. Zoom images of spectra are provided for (b) visible and (c) shortwave infrared regions to reveal subtle features associated with varying chemical.

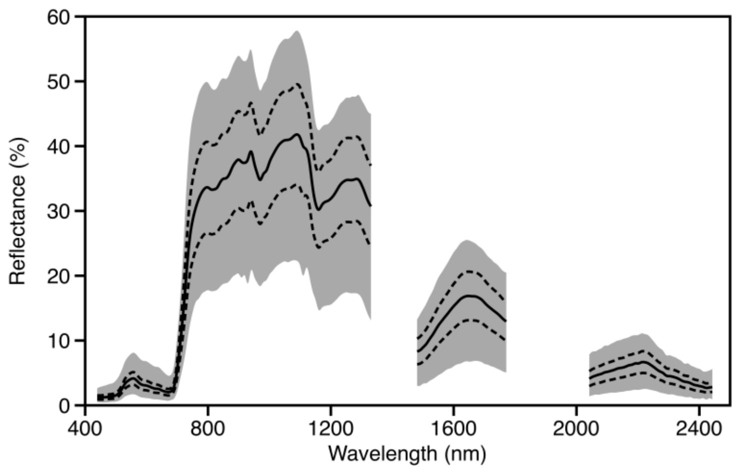

Figure S3. Mean (solid line), standard deviation (dashed lines), and total range (gray area) of the CAO visible-to-shortwave infrared (VSWIR) crown spectra that passed the prescreening step (see Figure 3) for a collection site (Danum Valley; Table 1).

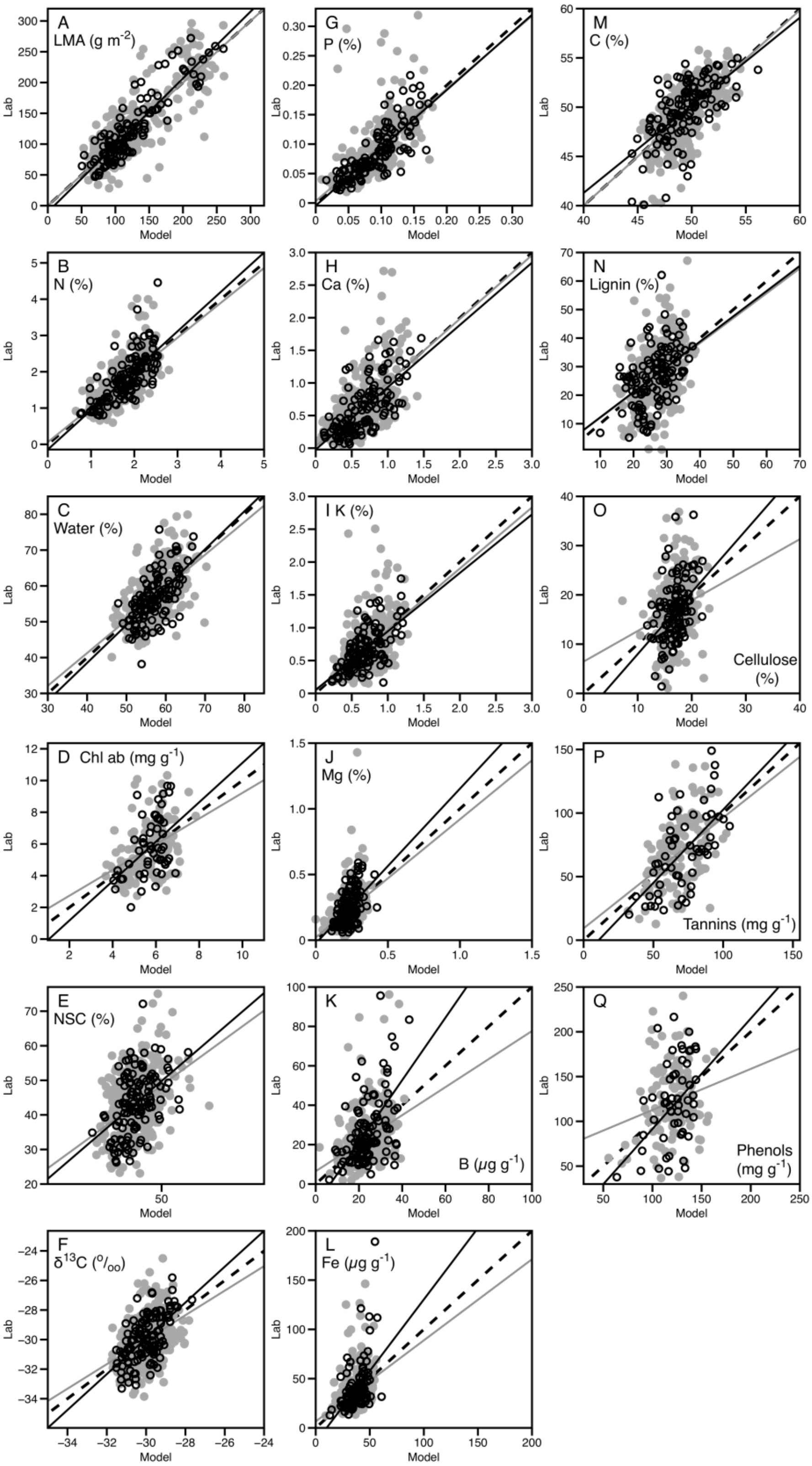

Figure S4. Linear regression analysis between model and lab-measured chemical traits and leaf mass per area (LMA) for crowns used in the canopy calibration model (70%), shown in grey, and the canopies held out for testing (30%), shown in black. The dashed line is the 1:1 line. Regression parameters are given in Table S4. Subfigures show (a) leaf mass per area (LMA), (b) nitrogen, (c) leaf water, (d) chlorophyll ab, (e) nonstructural carbohydrates (NSC), (f) δ^{13}C, (g) phosphorous, (h) calcium, (i) potassium, (j) magnesium, (k) boron, (l) iron, (m) total carbon, (n) lignin, (o) cellulose, (p) tannins, and (q) phenols.

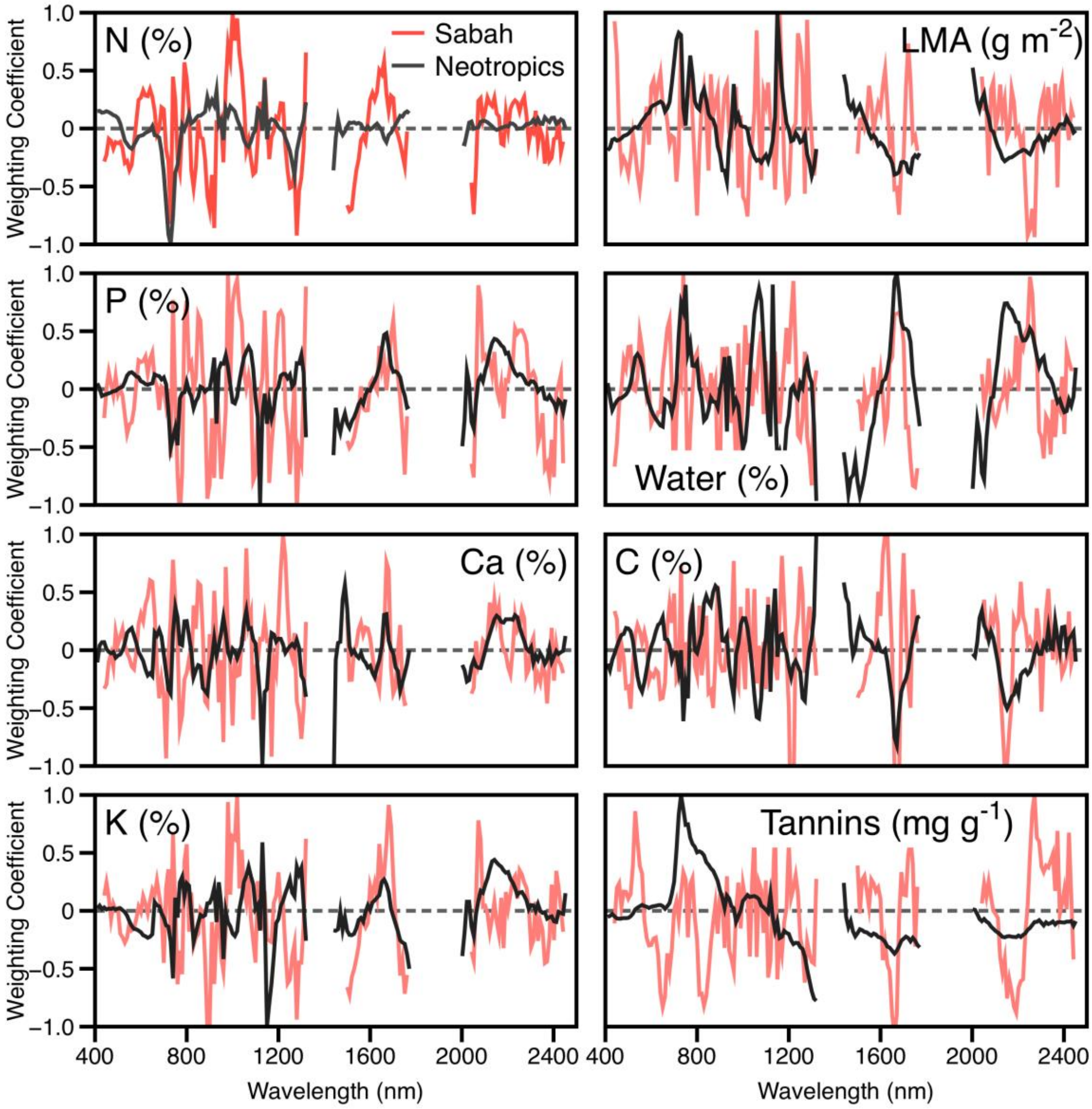

Figure S5. Comparison of selected PLSR weighting coefficients from the study in Sabah, Malaysia (red lines) and Peru in the Neotropics (black lines). Lighter colored lines show the modeled coefficients.

Code S1. Location of code used for foliar trait retrieval.

The code, which draws on elements of the autoPLS package from R, was created to develop and manage results of multiple individual PLSR models in a more computationally efficient way. The code can be found in a public github repository at https://github.com/pgbrodrick/ensemblePLSR.git . The code requires an input csv file of coupled chemistry and spectral data from multiple crowns, as well as a settings file. Example can be found in the repository.