Drone-based hyperspectral and thermal imagery for quantifying upland rice productivity and water use efficiency after biochar application

Supplementary Material

1. Estimation of canopy gap fraction and hemispherical transmittance

The directional gap fraction $b(\theta)$ is the directional upward transmittance through the canopy to the camera in field measurement, writing as

$$b(\theta) = e^{-\frac{G}{cos\theta}LAI}, \quad \text{(S1)}$$

in which G is a geometric function of leaf angular distribution, being estimated from an ellipsoidal leaf angular distribution model [1]:

$$G = \frac{\sqrt{\chi^2 cos^2\theta + sin^2\theta}}{\chi + 1.77(\chi + 1.182)^{-0.733}}, \quad \text{(S2)}$$

where χ is the ratio of semi-axes of the ellipsoidal distribution model, estimated as $\chi = 0.409$ using relation in Wang, *et al.* [2] and discrete measurement of rice leaf angle distribution ($\bar{\theta}_L = 73.1^{\circ}$) from Zhang, *et al.* [3]:

$$\chi = -3 + (\frac{\bar{\theta}_L}{9.65})^{-0.6061}. \quad \text{(S3)}$$

σ_f is called shading factor and $1 - \sigma_f$ is the hemispherical transmittance, estimated from $b(\theta)$:

$$1 - \sigma_f = \frac{1}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-\frac{G}{cos\theta}\cdot LAI} d\theta. \quad \text{(S4)}$$

The estimated G = 0.245 for nadir direction and a χ of 0.409. The integral of Eq. (S4) has no analytical expression, instead, it can be approximated by $1 - \sigma_f = e^{-0.423\cdot LAI}$ using Matlab numerical integration and curve fitting toolbox (Matlab R2015b, MathWorks, USA).

2. Variation propagation for estimating variations in GPP and water use efficiency

The Gross primary productivity (GPP) can be modeled using a simple light use efficiency concept [4] and considering the proportion of APAR absorbed by chlorophyll instead of whole canopy [5]:

$$GPP = \varepsilon \cdot fAPAR \cdot CCC \cdot PAR, \quad \text{(S5)}$$

where ε is light use efficiency, fAPAR is the fraction of photosynthetically active radiation (PAR) absorbed by canopy. *PAR* is the incoming PAR radiation in the spectrum range of 400nm to 700nm. *CCC* is the canopy chlorophyll content.

Since fAPAR has a linear relationship to normalized difference vegetation index NDVI [6]:

$$fAPAR = k \cdot NDVI, \quad \text{(S6)},$$

where k is a constant slope in the linear relationship between fAPAR and NDVI. It is assumed that zero fAPAR for NDVI = 0.

From Eq. (S1) and (S2), GPP is then written as:

$$GPP = \varepsilon \cdot k \cdot PAR \cdot CCC \cdot NDVI. \quad \text{(S7)}$$

Using variation propagation [7], the GPP change changes induced by NDVI and CCC variations is obtained using first-order difference and ignoring other minimal effects on light use efficiency parameters:

$$\Delta GPP = \varepsilon \cdot k \cdot PAR \cdot (CCC \cdot \Delta NDVI + NDVI \cdot \Delta CCC). \quad \text{(S8)}$$

And the relative GPP variation is obtained by dividing GPP from both sides of Eq. (S8):

$$\frac{\Delta GPP}{GPP} = \frac{\Delta NDVI}{NDVI} + \frac{\Delta CCC}{CCC}. \quad \text{(S9)}$$

The standard error of the relative variation ($\Delta GPP/GPP$) is:

$$SE_{\Delta GPP/GPP} = \sqrt{(SE_{\Delta NDVI/NDVI})^2 + (SE_{\Delta CCC/CCC})^2}. \quad \text{(S10)}$$

The relative NDVI variation between biochar group NDVI ($NDVI_{BC}$) and the control group NDVI ($NDVI_C$) is:

$$\frac{\Delta NDVI}{NDVI} = \frac{NDVI_{BC} - NDVI_C}{NDVI_C}. \quad \text{(S11)}$$

The standard error (SE) of the variation is estimated from the SE of $NDVI_{BC}$ and $NDVI_C$:

$$SE_{\Delta NDVI/NDVI} = \sqrt{{SE_{NDVI_{BC}}}^2 + {SE_{NDVI_C}}^2}/NDVI_C. \quad \text{(S12)}$$

And similarly the relative changes in CCC and the SE are written as:

$$\frac{\Delta CCC}{CCC} = \frac{CCC_{BC} - CCC_C}{CCC_C}. \quad \text{(S13)}$$

$$SE_{\Delta CCC/CCC} = \sqrt{{SE_{CCC_{BC}}}^2 + {SE_{CCC_C}}^2}/CCC_C. \quad \text{(S14)}$$

The significance level of the variation can be given from the Student's t distribution. The variations and the SE of other variables were estimated similarly.

The water use efficiency (WUE) can be simply defined as the ratio of GPP to evapotranspiration (ET) water loss:

$$WUE = \frac{GPP}{ET}. \quad \text{(S15)}$$

The variation in WUE from both GPP and ET variations is obtained using first-order difference:

$$\Delta WUE = \frac{1}{ET}\Delta GPP - \frac{GPP}{ET^2}\Delta ET. \quad \text{(S16)}$$

The relative WUE variation is obtained by dividing WUE from both sides of Eq. (S16):

$$\frac{\Delta WUE}{WUE} = \frac{1}{ET \cdot WUE}\Delta GPP - \frac{GPP}{ET^2 \cdot WUE}\Delta ET = \frac{\Delta GPP}{GPP} - \frac{\Delta ET}{ET}. \quad \text{(S17)}$$

The standard error of the relative variation is:

$$SE_{\Delta WUE/WUE} = \sqrt{(SE_{\Delta GPP/GPP})^2 + (SE_{\Delta ET/ET})^2}. \quad \text{(S18)}$$

Table S1. Statistics for variables of the biochar experiment

Variables		C	BC1	Δ_{BC1-C} / C		BC2	Δ_{BC2-C} / C		Standard error (SE)	SE / C
		Mean	Mean	%	*p*-value	Mean	%	*p*-value		%
Soil properties	θ_UAV (m^3/m^3)	0.203	0.239	**17.7**	**<0.001**	0.225	**10.8**	**<0.001**	0.0001	0.1
	θ_*in situ* (m^3/m^3)	0.193	0.210	8.8	0.396	0.208	7.8	0.522	0.007	5.1
	ψ_UAV (MPa)	-0.172	-0.095	**44.8**	**<0.001**	-0.289	**– 66.9**	**<0.001**	0.001	0.7
	ψ_*in situ* (MPa)	-0.401	-0.500	– 24.7	0.672	-0.871	– 117.2	0.233	0.156	55.0
	Soil N content (%)	0.153	0.147	– 3.9	0.392	0.157	2.6	0.786	0.003	2..8
	Soil albedo (-)	0.216	0.217	**0.5**	**0.003**	0.219	**1.4**	**<0.001**	0.000	0.1
	Soil LST (°C)	36.59	36.34	**– 0.7**	**0.004**	36.09	**– 1.4**	**<0.001**	0.047	0.2
Leaf properties	Leaf water content (g/g)	0.567	0.623	9.9	0.143	0.552	– 2.6	0.866	0.020	5.0
	Leaf N content (%)	0.593	0.788	**32.9**	0.035	0.554	– 6.6	0.857	0.052	12.4
	Leaf P content (%)	0.218	0.228	4.6	0.607	0.218	0.0	1.000	0.007	4.5
	Leaf K content (%)	0.092	0.143	**55.4**	0.027	0.159	**72.8**	0.003	0.013	20.0
Canopy properties	CCC (g/m^2 ground)	0.604	0.797	**32.0**	<0.001	0.665	**10.1**	0.012	0.013	3.0
	NDVI (-)	0.502	0.552	**9.96**	<0.001	0.539	**7.4**	<0.001	0.005	1.4
	GPP ($gC/m^2/day$)	-	-	**41.9**	0.003	-	**17.5**	0.018	-	3.4
	WUE (gC/kg H_2O)	-	-	**40.8**	0.004	-	**13.4**	0.031	-	3.5
	f_c (-)	0.288	0.303	**5.2**	<0.001	0.277	**– 3.8**	0.007	0.002	1.0
	LAI (m^2/m^2)	1.462	1.550	**6.0**	<0.001	1.391	**– 4.9**	0.004	0.013	1.3
	Canopy albedo (-)	0.292	0.294	0.7	0.523	0.283	**– 3.1**	<0.001	0.001	0.5
	Canopy LST (°C)	32.33	32.14	**– 0.6**	0.004	32.53	**0.6**	0.003	0.035	0.2
Land surface energy components	Rn (W/m^2)	205.7	205.3	– 0.2	0.838	210.3	**2.3**	<0.001	0.460	0.3
	AE (W/m^2)	156.4	156.9	0.3	0.445	159.3	**1.9**	<0.001	0.304	0.3
	EF (-)	0.434	0.450	**3.7**	0.002	0.433	– 0.2	0.951	0.003	1.0
	λET (W/m^2)	79.61	80.47	1.1	0.544	82.83	**4.0**	0.002	0.567	1.0
	H (W/m^2)	76.82	76.50	– 0.4	0.812	76.48	– 0.4	0.832	0.387	0.7
	G (W/m^2)	49.33	48.42	**– 1.8**	0.011	51.05	**3.5**	<0.001	0.195	0.6

Note: Standard error (SE) of the marginal mean is the same for all three groups. Red numbers show negative changes and green numbers positive changes in biochar groups compared with the control. Bold font indicates significant changes at p <0.05.

BC1: local bamboo biochar group, BC2: Taiwan sugarcane biochar group; C: control group

AE: available energy, Rn-G, or λET+H
CCC: canopy chlorophyll content
ET: evapotranspiration
EF: evaporative fraction, λET/AE
f_c: fractional vegetation cover
G: ground heat flux
GPP: gross primary productivity
H: sensible heat flux
LAI: leaf area index
LST: land surface temperature
NDVI: normalized difference vegetation index
N, P, and K: nitrogen, phosphorous, and potassium
Rn: net radiation
SMP: soil matric potential
WUE: water use efficiency
θ: soil moisture content
λET: latent heat flux (energy form for ET)

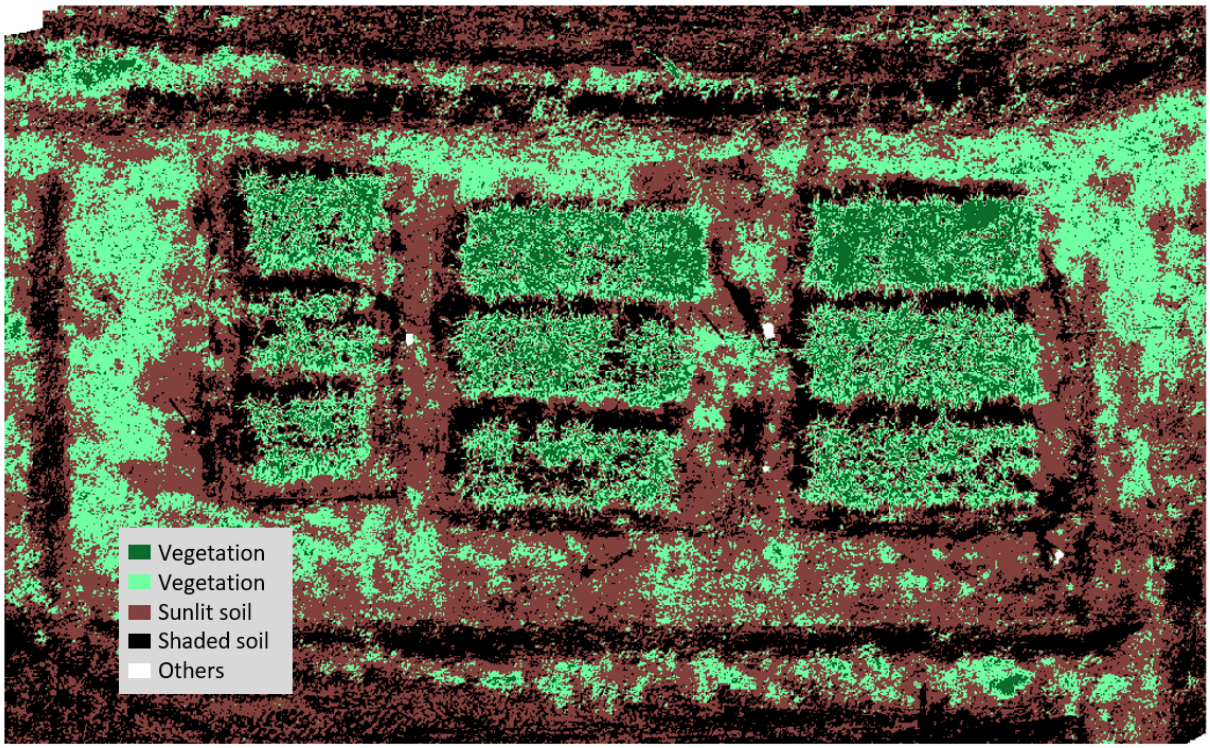

Figure S1. Unsupervised classification using k-means clustering method. Sunlit soil pixels are separated from others for albedo analysis.

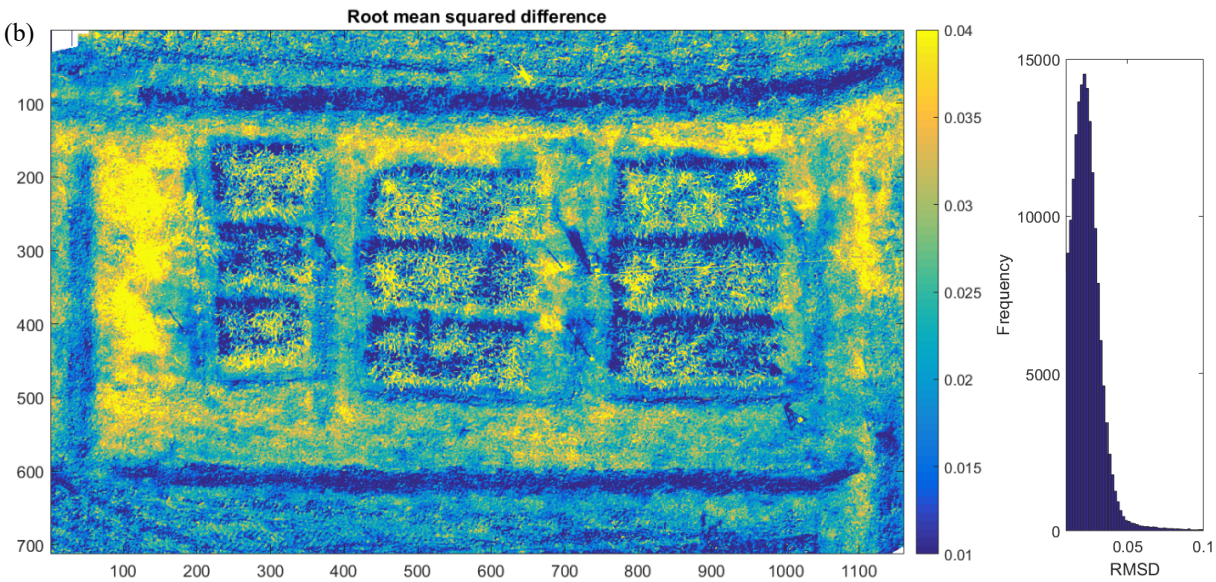

Figure S2. (a) R^2 and (b) root mean squared difference (RMSD) between the UAV-measured and the Pro4SAIL-modeled hyperspectral reflectance using the parameters from the model inversion outputs. Histograms show the frequencies of these values over three groups of rice canopy.

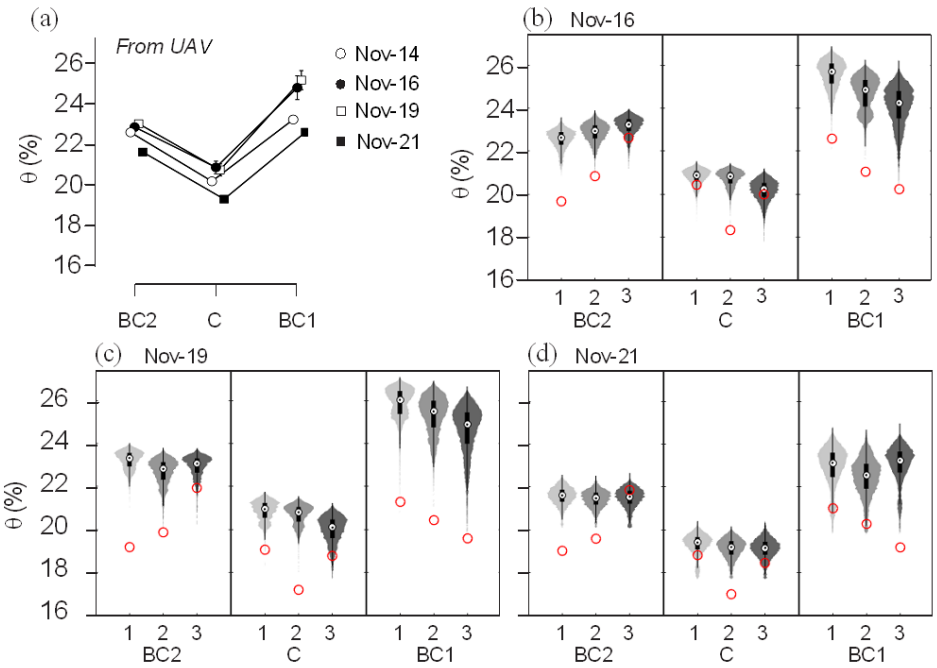

Figure S3. (a) The comparison of plot-averaged soil moisture content (θ) in three groups BC1, BC2, and C from UAV over the period Nov 14 to 21, 2018 and during the four UAV campaigns. Whiskers denote the 95 % confidence interval of each group on each day. Violin plots of θ from UAV in each plot and each treatment on (b) Nov16, (c) Nov 19, and (d) Nov-21. The shaded areas of the violin plot denote distribution of the day's measurement, the white dots denote the median values, and the bottom and top edges of the black bars denote the 25th and 75th percentiles respectively. The red circle '○' denotes sensor measurements during flight

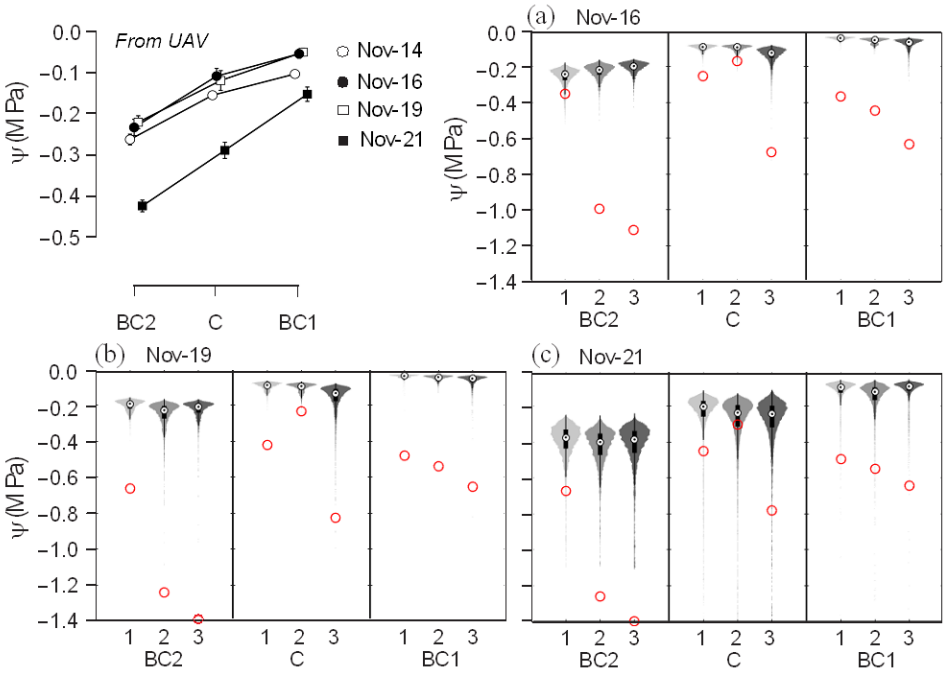

Figure S4. (a) The comparison of plot-averaged soil matric potential (ψ) in three groups BC1, BC2, and C from UAV over the period Nov 14 to 21, 2018 and during the four UAV campaigns. Whiskers denote the 95 % confidence interval of each group on each day. Violin plots of ψ from UAV in each plot and each treatment on (b) Nov16, (c) Nov 19, and (d) Nov-21. The shaded areas of the violin plot denote the distribution of the day's measurement, the white dots denote the median values, and the bottom and top edges of the black bars denote the 25th and 75th percentiles respectively. The red circle '○' denotes sensor measurements during flight

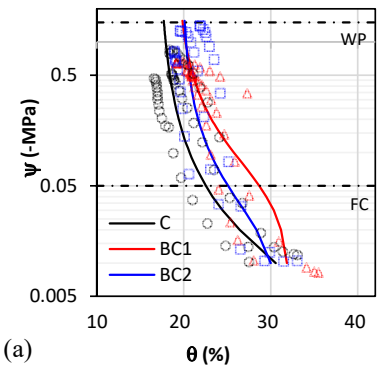

Figure S5. Water retention curves estimated from field-measured soil matric potential (ψ) and soil moisture content using Van Genuchten model. Dot-dash line denotes field capacity (FC) at -0.05MPa. The wilting point (-1.5 MPa) is out of the x-axis range.

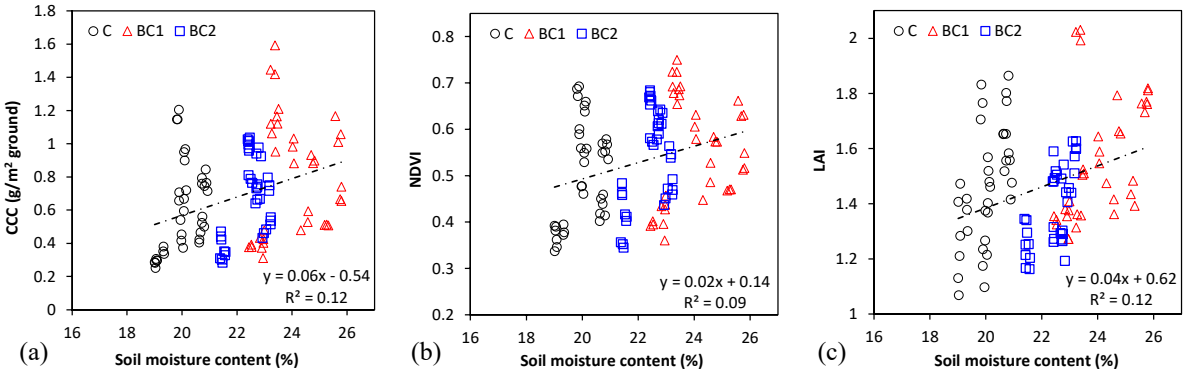

Figure S6. Overall relationships of (a) canopy chlorophyll content (CCC), (b) NDVI, and (c) LAI to soil moisture content in three groups BC1, BC2 and C.

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