Hailun Experiment for LAI Measurement (HELM 2016)

Field Report

Version 1.0

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1. Overview

Quantitative retrieval of vegetation structural parameters based on remote sensing has been widely conducted. However, the validation of these products based on ground measurement is still insufficient. Accurate estimation of vegetation structural parameters, such as leaf area index (LAI), is important for its proper use of the ecological, hydrological, and biogeochemical models, and helps to understand and quantify the model uncertainties.

Several field LAI collection campaigns have been carried out in the paddy rice fields over an entire growing season (Fang et al. 2014b; Sun et al. 2017), which provide an independent and valuable dataset for the producers of remote sensing products and model researchers. We further emphasize the necessity to carry out similar work in other farmland ecosystems.

A field campaign was conducted at the Hailun cropland in northeast China from mid-June to late September 2016. The objective of the field experiment is to collect consistent structural parameters of farmland ecosystem for the validation of remote sensing products. Five plots (A-E) from maize, soybean, and sorghum fields) were selected. A variety of observing instruments were used.

2. Materials and methods

2.1. Study area and sampling design

The study area is located in the western suburb of Hailun city (46°58′-47°52′N, 126°14′-127°45′E), northeast China. The city is mainly surrounded by farmland (Wang et al. 2016). Maize and soybean are the most widely planted crops. The crops are harvested once a year. The area has a cold temperate continental climate dominated by the East Asian monsoon. The annual mean temperature is 2°C, with extreme temperature ranging from −39.5°C to 37°C (Liu et al. 2013). Precipitation concentrates from May to September, with the annual total precipitation ranges from 500 to 600 mm. The main soil types are Luvic Phaeozem and Haplic Phaeozem (FAO classification) (Li et al. 2016). The water and soil in this area are completely frozen from late October to mid-May.

Five plots were chosen for repeated measurements (Fig. 1). Nine different

instruments were used, including three conventional optical instruments (LAI-2200 plant canopy analyzer (PCA), digital hemispheric photography (DHP) and AccuPAR ceptometer), three smartphone applications (APPs) (PocketLAI, LAISmart and SmartLAI), one destructive instrument (LI-3100C leaf area meter), and two Automatic observation instruments (Pai Autonomous System from Transmittance Sensors (PASTIS-57) and LAIPhoto) (Table 1).

Table 2 shows the detailed information about crop type, location and instruments used in each plot. Fig. 2 shows a diagram of instruments. Fig. 3 shows the pictures for different growing stages.

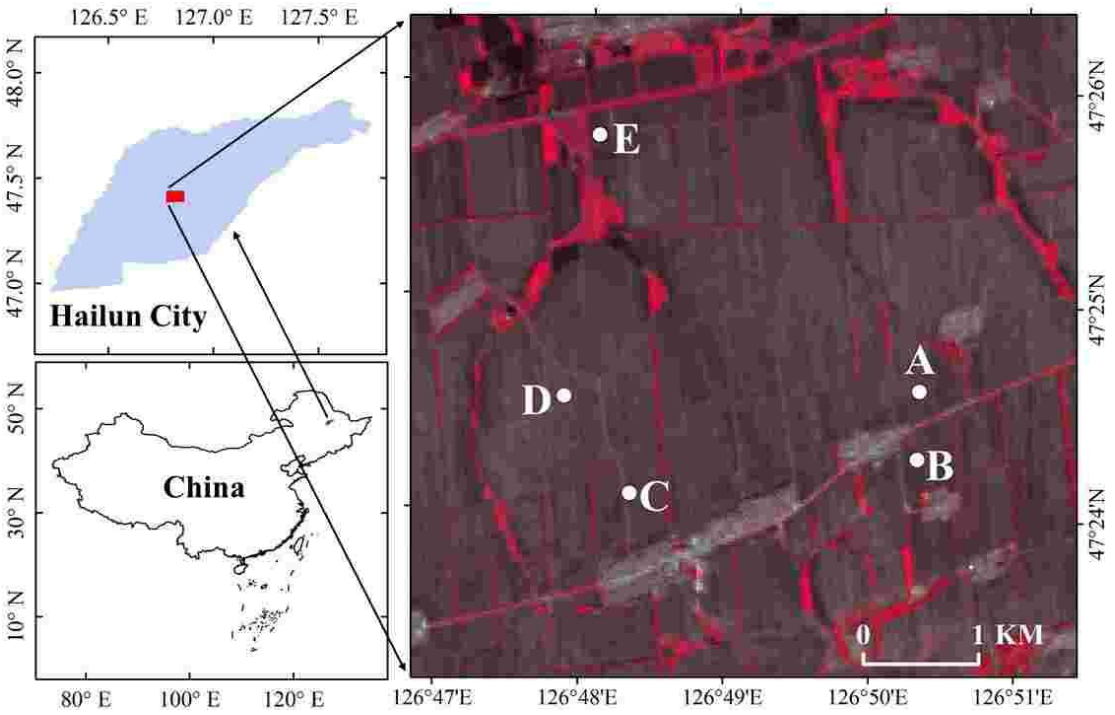


Fig. 1 Location of the study area l in the western suburb of the Hailun city, northeast China. The right picture shows the position of five plots in a false color composite of a Landsat 8 image (path 118, row 027, Jun 2, 2016). Five plots (A-E) are marked. The crop was maize at plot A and D, soybean at plot B and C, sorghum at plot E.

Table 1. Structural variables derived from different instruments

Parameters	LAI-2200	DHP	AccuPAR	PocketLAI	LAISmart	SmartLAI	LI-3000C	PASTIS-57	LAIPhoto
Leaf area index (LAI)							√		
Effective plant area index (PAIeff)	√	√	√	√	√	√		√	√
Angular gap fraction	√	√							
Integrated gap fraction	√	√	√						
Fraction of vegetation cover (fCover)	√	√							√
Clumping index (CI)	√	√							
Apparent clumping factor (ACF)	√								
Average leaf angle (ALA)	√	√							
Fraction of absorbed photosynthetically active radiation (fPAR)								√	

DHP: Digital Hemispheric Photography; PASTIS-57: Pai Autonomous System from Transmittance Sensors

Table 2. The crop type, location and instruments in each plot.

Plot	Crop	Location	LAI-2200	DHP	AccuPAR	PocketLAI	LAISmart	SmartLAI	LI-3000C	PASTIS-57	LAIPhoto
A	Maize	126.838°E, 47.410°N	√	√	√	√	√	√	√	√	√
B	Soybean	126.838°E, 47.405°N	√	√	√	√	√	√	√	√	√
C	Soybean	126.805°E, 47.401°N	√	√	√	√	√	√			
D	Maize	126.798°E, 47.409°N	√	√	√	√	√	√			
E	Sorghum	126.801°E, 47.429°N	√	√	√	√	√	√			



Fig. 2 An illustration of all instruments used in the field campaign. (a) LAI-2200; (b) LI-3000C (c) DHP; (d) AccuPAR; (e) PocketLAI; (f) SmartLAI; (g) LAISmart; (h) LAIPhoto; (i) PASTIS-57.

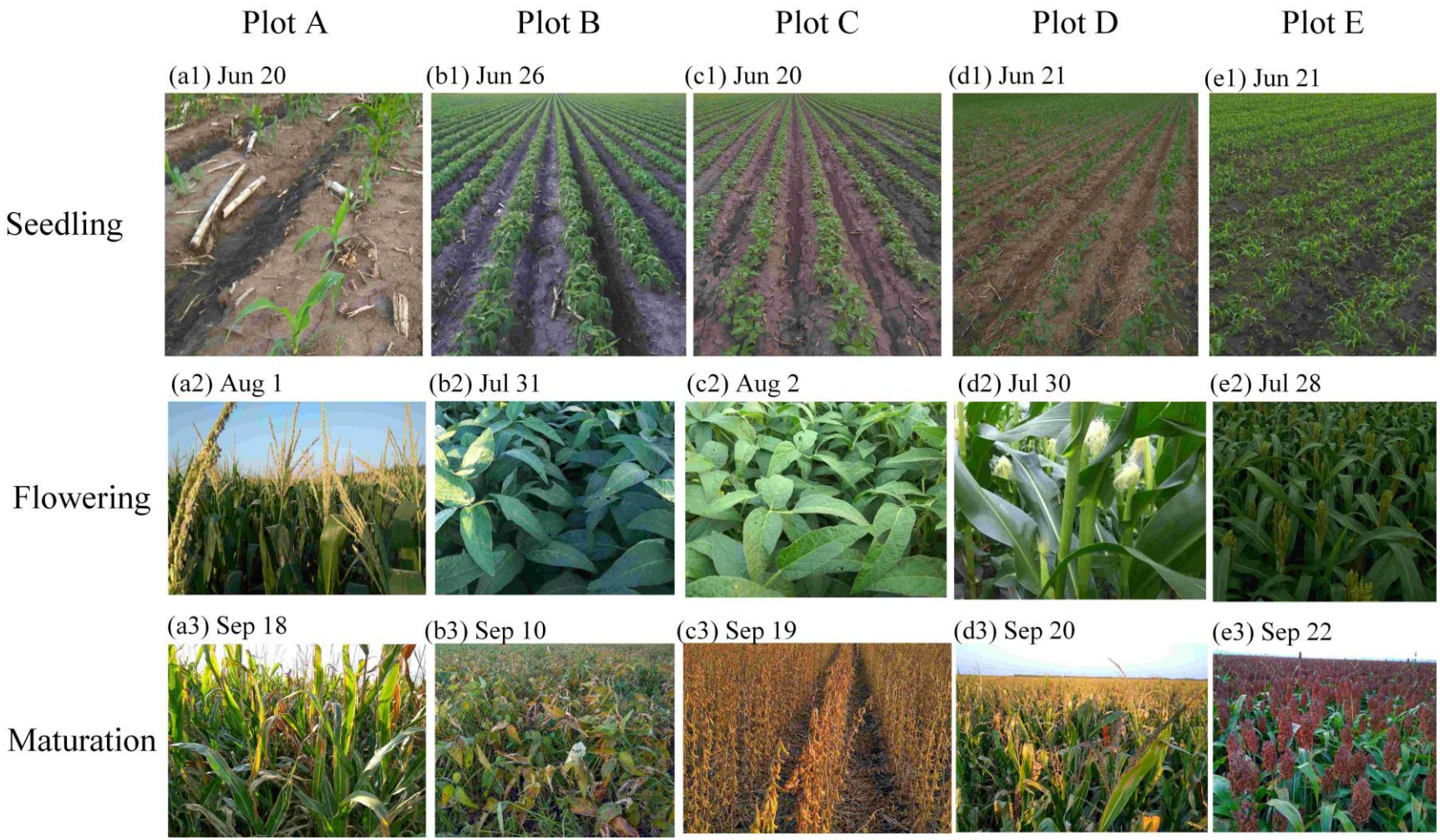


Fig. 3 Different crop growing stages in plots A to E (left to right) for seedling (top row), flowering (middle row) and maturity (bottom row) stages in 2016. .

The plots are flat and homogeneous and more than 100 × 500 m^2 in size. Three 20 × 20m Elementary Sampling Units (ESUs) were set within each plot. ESUs at the same plot located in one row (plot A, B and C) or at the three vertices of a triangle (plot D and E). ESUs were at least 5 m away from the field borders. ESU-level sampling was performed uniform (DHP and smartphone APPs) or at the four corners and one at the center (AccuPAR and LAI-2200) (Fig. 4). Two PASTIS-57 systems apiece were deployed in plots A and B within two ESUs separately (Fig. 5). The PASTIS-57 sensors were oriented toward the northat 57.5° view zenith angle.

Ground LAI measurements were continuously carried out from June 20 (day of year (DOY) 172) to September 22 (DOY 266), 2016. Each plot was measured at approximate 1-week interval. The interval was adjusted in rainy day. To diminish the retrieval errors caused by direct light, the measurements were mainly carried out close to sunset or sunrise or under overcast conditions (Fang et al. 2014a).

The traditional optical instruments and smartphone Apps were used at all five plots. LI-3100C and two automatic observation instruments were used only at plots A and B. Five plants were randomly selected in an ESU and cut off the ground for destructive measurement each week. Three ESUs were chosen sequentially for destructive measurement in order to reduce the impact of damage on other measurements. Plant height and diameter at about 5 cm above the ground were recorded with a tape and vernier caliper before harvesting (Fig. 6). Because the maize stem is close to a elliptic cylinder, both the long and short axis diameters were measured. Two PASTIS-57 systems and one LAIPhoto were set at plot A and B respectively. The PASTIS-57 systems were located at two different ESUs. The LAIPhoto and one of the PASTIS-57 were in the same ESU.

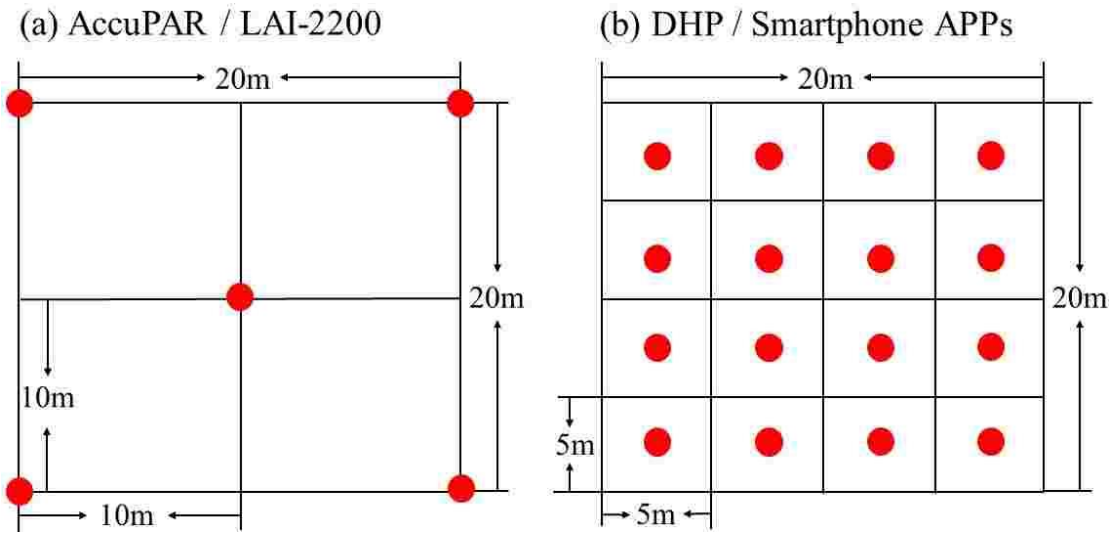


Fig. 4 Diagram of sampling strategies in each 20×20 m Elementary Sampling Units (ESU). (a) AccuPAR and LAI-2200 were used at the four corners and the center. (b) Regular sampling for DHP and PocketLAI, LAIsmart and SmartLAI, totally 16 sample points.

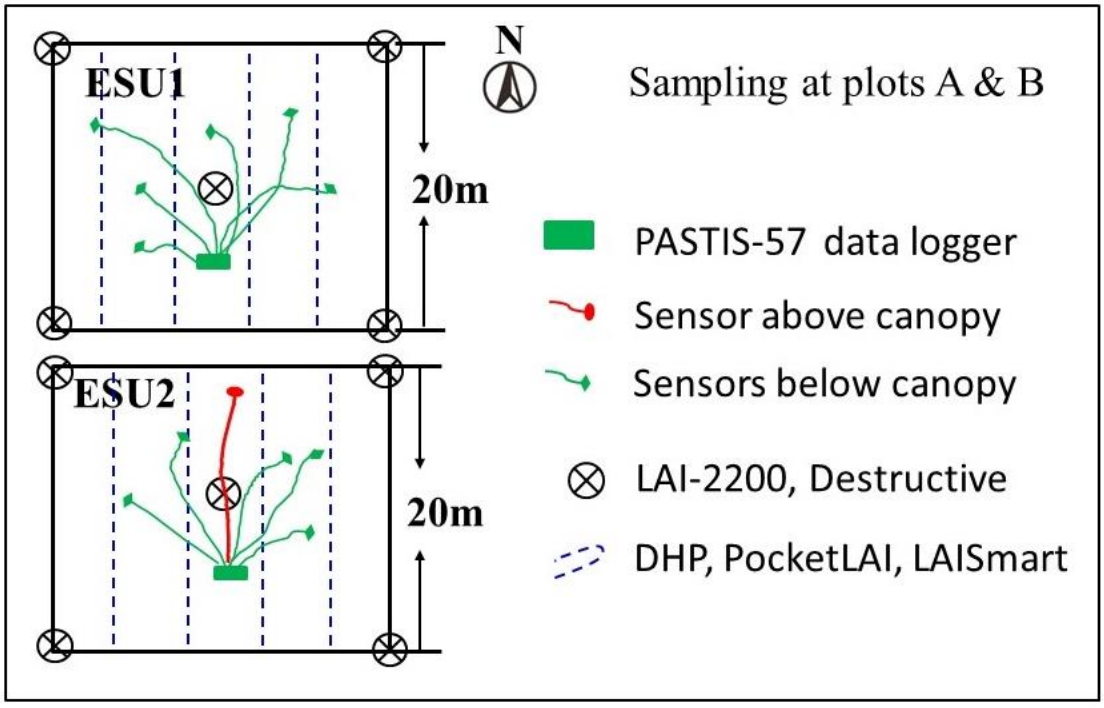


Fig. 5 PASTIS-57 systems deployed in plots A and B. Two PASTIS-57 systems were deployed similarly at plot A and B, respectively, with sensors toward north at 57.5° view zenith angle.

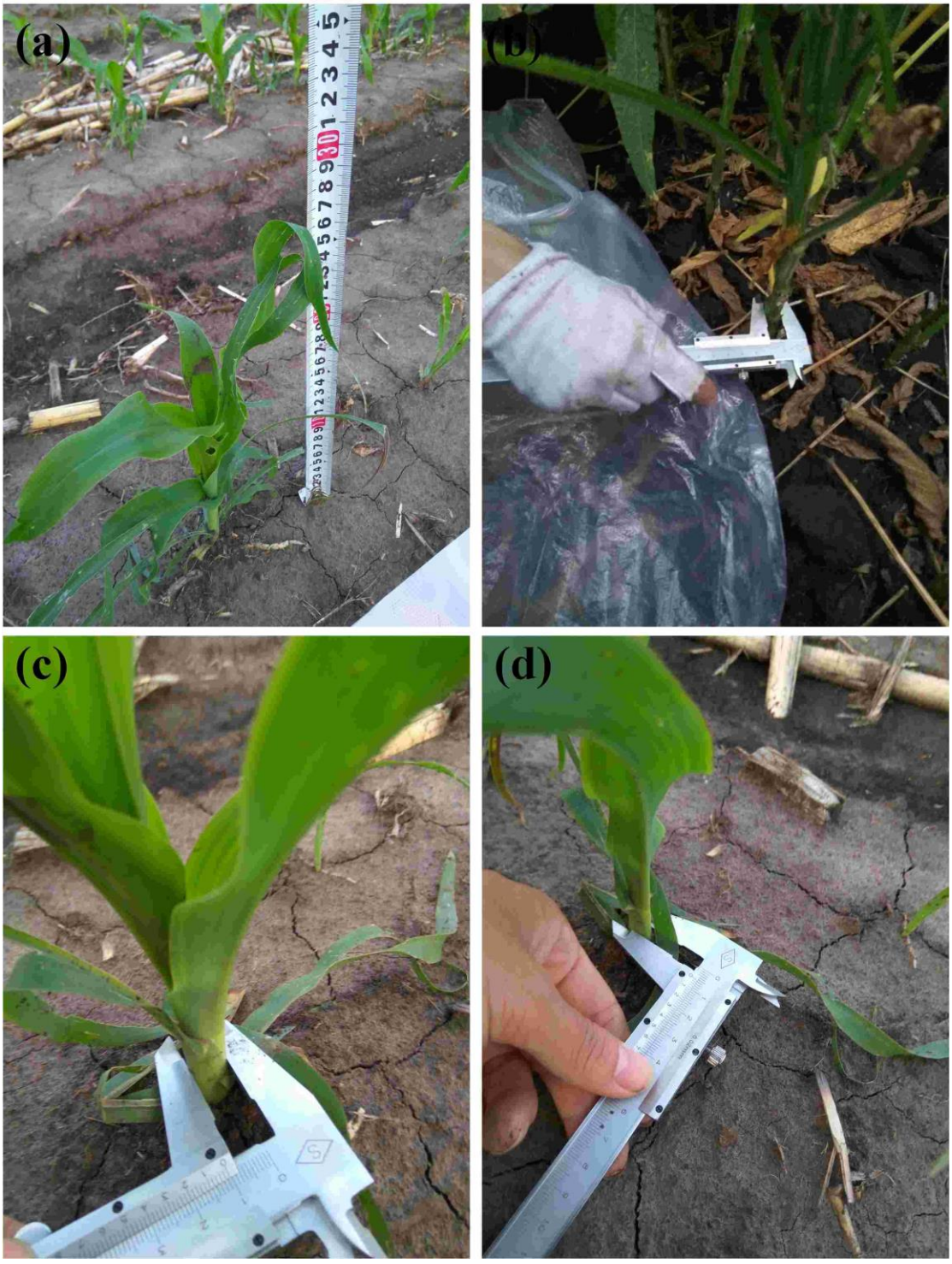


Fig. 6 Plant height (a) and diameter (b-c) measurement. For soybean, only one number was read (b). Both long (c) and short (d) axes were read for maize.

2.2. LAI-2200 plant canopy analyzer

LAI-2200 estimates the canopy plant area index (PAI) because all parts of the plant including green leaves, yellow leaves, stems and seeds contribute to the light

transmittance process in the canopy (Fang et al. 2014b). Ground measurements follow the LAI-2200 instruction manual for row crops (LI-COR 2012). Two repeats were taken for each sampling point with one above and four below canopy readings. Before the seedling stage, significant gaps exist and a 90° view cap was used to minimize the measurement errors. After July 1 (DOY 183), large gaps between rows had disappeared. A 270° view cap was used to shield the sensor from the operator (Fang et al. 2014b). When the maize canopy was high enough, a ladder was used for the above readings. The ladder has 6 layers and the top layer is 1.7 m beyond the ground (Fig. 7). The optical sensor was about 5 cm above ground for the below canopy readings.



Fig. 7 The ladder used for LAI-2200, AccuPAR and SmartLAI measurement in the maize plots.

2.3. Digital hemispherical photography (DHP)

The DHP images were taken by a Nikon D5100 camera with a 4.5 mm F2.8 EX DC circular fisheye convertor. An ultraviolet cap was covered on the lens to prevent dust and water. The total height of the camera and lens was about 16.5 cm. Two bubble

levels were attached to the camera to keep it horizontal for both downward and upward viewing. The DHP camera was calibrated according to the CAN_EYE manual (version 6.313) (Weiss and Baret 2014).

Sixteen pictures were captured in each ESU. Before the seedling stage, photos were taken downward (Fig. 8). The distance between crop canopy and the camera was kept greater than 50 cm to ensure a large enough field of view. After July 1 (DOY 183), all the photos were taken upward. At that time, the soybean and sorghum are higher than 30 cm, while the maize is higher than 70 cm. The camera was close to the ground at the soybean and sorghum plots. At the maize plots, the distance between the ground and camera was gradually increased as the maize grows higher with the maximum distance no more than 30 cm. The camera was carefully operated to minimize the operator impact.

The aperture size and shutter speed were manually adjusted according to the illumination conditions. All the DHP photos were taken in a fixed azimuth angle to the row directions, which allowed us to examine the impact of viewing angle on the clumping index (CI) (Fang et al. 2014b; Weiss et al. 2004). The Photos were stored in the JPEG format at a resolution of 3264 x 4928 pixels. All valid photos for each ESU were processed by the CAN_EYE software (version 6.3.13) to obtain the structural parameters of crops. The resolutions of zenith and azimuth angle were both set at 2.5°. One operator performed all the classification procedures to minimize the subjective errors.

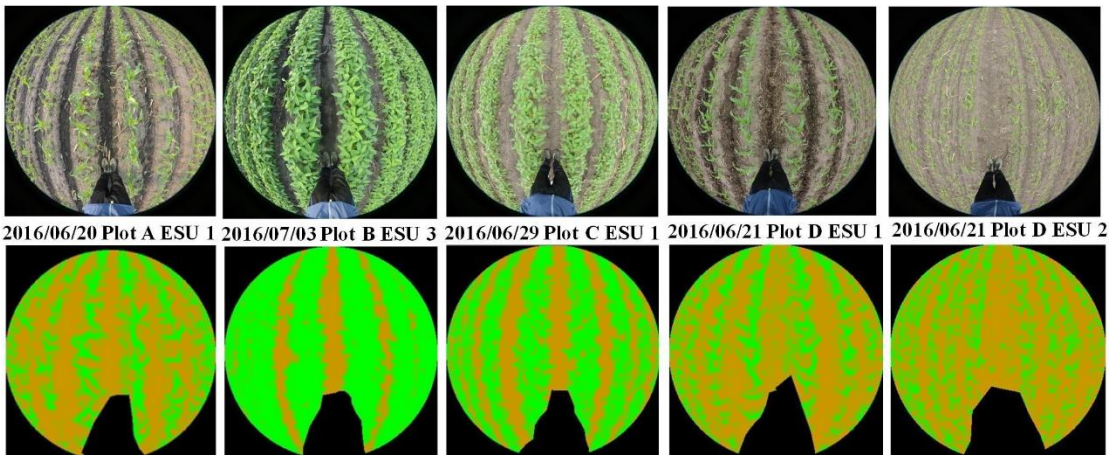


Fig. 8 Sample DHP downward images (upper panels) and the classified results by CAN_EYE (lower panel) at the seedling stage at each plot. Green and brown colors are for the plant and the soil, respectively.

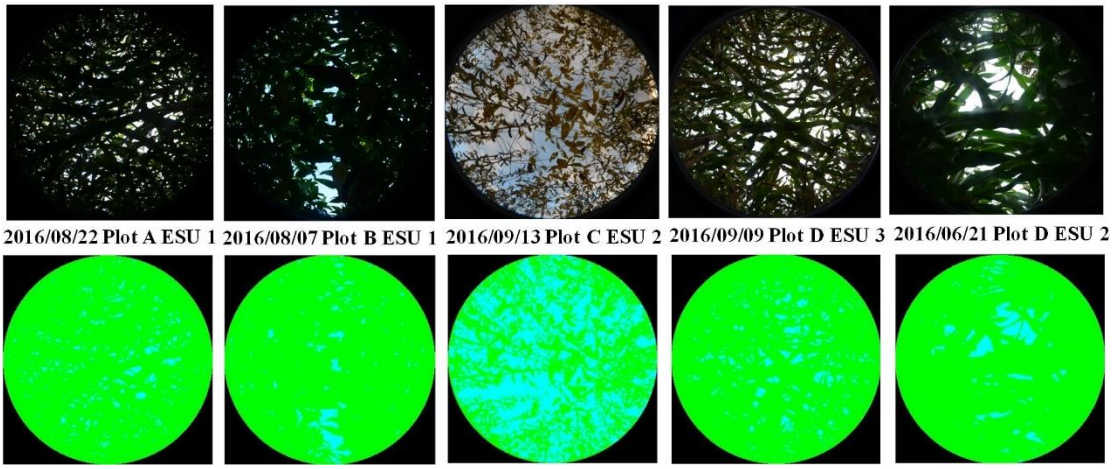


Fig. 9 Sample DHP images (upper panel) and the classification results (lower panles). Green and cyan colors show the plant and the sky, respectively.

2.4. AccuPAR ceptometer

AccuPAR (Decagon Devices, Inc., model LP-80 PAR/LAI ceptometer) measures photosynthetically absorbed radiation (PAR). It uses 80 individual sensors on its probe with a 180° field of view. It measures the radiation by locating the probe above and beneath the canopy and then calculate the percentage of transmittance. Before measurement, AccuPAR was calibrated according to the instruction manual (Decagon Devices 2016).

At each sampling point, AccuPAR was designed to measure the canopy reflectance, canopy transmittance, and soil reflectance continually. For the canopy transmittance measurement, one above reading and four below readings were recorded with the probe always towards the sky. For the four beneath readings, the probe was placed at about 5 cm above the ground in four different directions subsequently. The probe directions were 45° to the row direction to minimize the row effects according to the manual (Decagon Devices 2016). For the canopy reflectance measurement, the four beneath readings were replaced with readings at canopy level but with probe against the sky, that is towards the top of canopy. For the soil reflectance measurement, the four beneath readings were recorded with the probe towards the soil.

Additionally, we repeated the AccuPAR measurements at plots A and B in direct light condition. These measurements were carried out from 10 AM to 4 PM on clear days. When the maize canopy was high enough, a ladder was used for the above readings.

2.5. PocketLAI

PocketLAI is a smartphone APP developed for estimating LAI. Its algorithm is a simplified light transmittance model based on the assumption of a random spatial distribution of infinitely small leaves (Confalonieri et al. 2013). The gap fraction $P_0(\theta_v, \varphi_v)$ can be estimated as:

$$P_0(\theta_v, \varphi_v) = \exp\left[-G(\theta_v, \varphi_v) \frac{LAI}{\cos(\theta_v)} \right]$$

where θ_v is the zenith angle, φ_v is the azimuth angle, and $G(\theta_v, \varphi_v)$ is the projection function. The mean projection of a unit foliage area in the direction (θ_v, φ_v) depends on the leaf angle distribution of the canopy. However, the G-function can be considered as almost independent for leaf inclination (G ≦ 0.5) for a view angle of 57.5° (Weiss et al. 2004). So the LAI can be obtained from the gap fraction measured at 57.5°.

$$LAI = -\left(\frac{\cos(57.5^\circ)}{0.5} \right) \log(P_0(57.5^\circ))$$

The specific PocketLAI instructions have been well documented (Confalonieri et al. 2013). In this field work, PocketLAI was installed on a Redmi Note 3, with a Hexa-Core 1.8GHz processor and 3 GB RAM. The images taken by the smartphone were set to standard quality with a resolution of 1920 x 1080 pixels. The output LAI value is an average of a number of four shots. Fig. 10 shows the images taken by PocketLAI for maize, soybean and sorghum at different growing stages. The images are blurred during the camera tilting process. We held the smartphone vertically with the bottom main axis about 5 cm above the ground and the rear camera 10 cm to the plant, then rotated the device along its main axis starting with the display orientated downward until the angle between the vertical and the normal to the screen reaches 57.5°. The distance between ground and the bottom main axis of the smartphone was gradually increased as the crops grow higher. But the maximum distance was no more than 20 cm for soybean and sorghum and 30 cm for maize.



Fig. 10 PocketLAI images for maize (a-c), soybean (d-f) and sorghum (g-i) at different growing stages.

2.6. LAISamrt

LAISmart is developed to estimate the LAI based on the Beer gap fraction model under the hypothesis of random distribution of leaves (Qu et al. 2016). Canopy gap P(θ) can be estimated by:

$$P(\theta) = e^{-G(\theta)LAI/\cos\theta}$$

Then,

$$LAI = -\ln P(\theta)\cos\theta / G(\theta)$$

where θ is the zenith angle, G(θ) is the projection of the unit foliage area on the plane perpendicular to the view angle.

The distribution function of the leaf angle could be approximated by a spherical distribution, and the G(θ) (≦ 0.5) is independent to the viewing angle of the sensor in such situations. Taken this assumption, LAI can be calculated by:

$$LAI = -2\ln P(\theta)\cos\theta$$

where θ can be read from the gyro attitude sensor. P(θ) is equal to the proportion of background pixels in the image.

LAISmart was installed on the same smartphone as PocketLAI. The software is developed by Beijing Normal University, China. The system language is only Chinese

currently. Similar to PocketLAI, LAISmart, saves the photos in the cellphone memory and gives the estimated LAI values. At the seedling stage, photos were taken downward through the rear camera with a resolution of 1920 x 1080 pixels. The image segmentation feature was set to greenness index (GI) to segment the vegetation and soil. The distance between crop canopy and the smartphone was kept greater than 50 cm to ensure a large enough field of view. In order to reduce the sampling error, the cellphone was placed regularly above the ridge, the left side of the ridge, the right side of the ridge, the middle of two ridges and vertical to the ridge (Fig. 11).

After July 1 (DOY 183), photos were taken upward at the maize plots by the front camera with a resolution of 960 x 540 pixels. The image segmentation feature was set to the blue band to segment the vegetation and sky. After July 6 (DOY 188), the upward looking model was used for all the five plots. The smartphone was about 5 cm above the ground at the soybean and sorghum plots. At the maize plots, the distance between ground and smartphone was gradually increased as the maize grows higher. But the maximum distance was no more than 30 cm. To reduce the sampling error, the cellphone was placed regularly at the left side of the ridge, the middle of two ridges and the right side of the ridge (Fig. 12). However, no significant difference was observed from the photos.

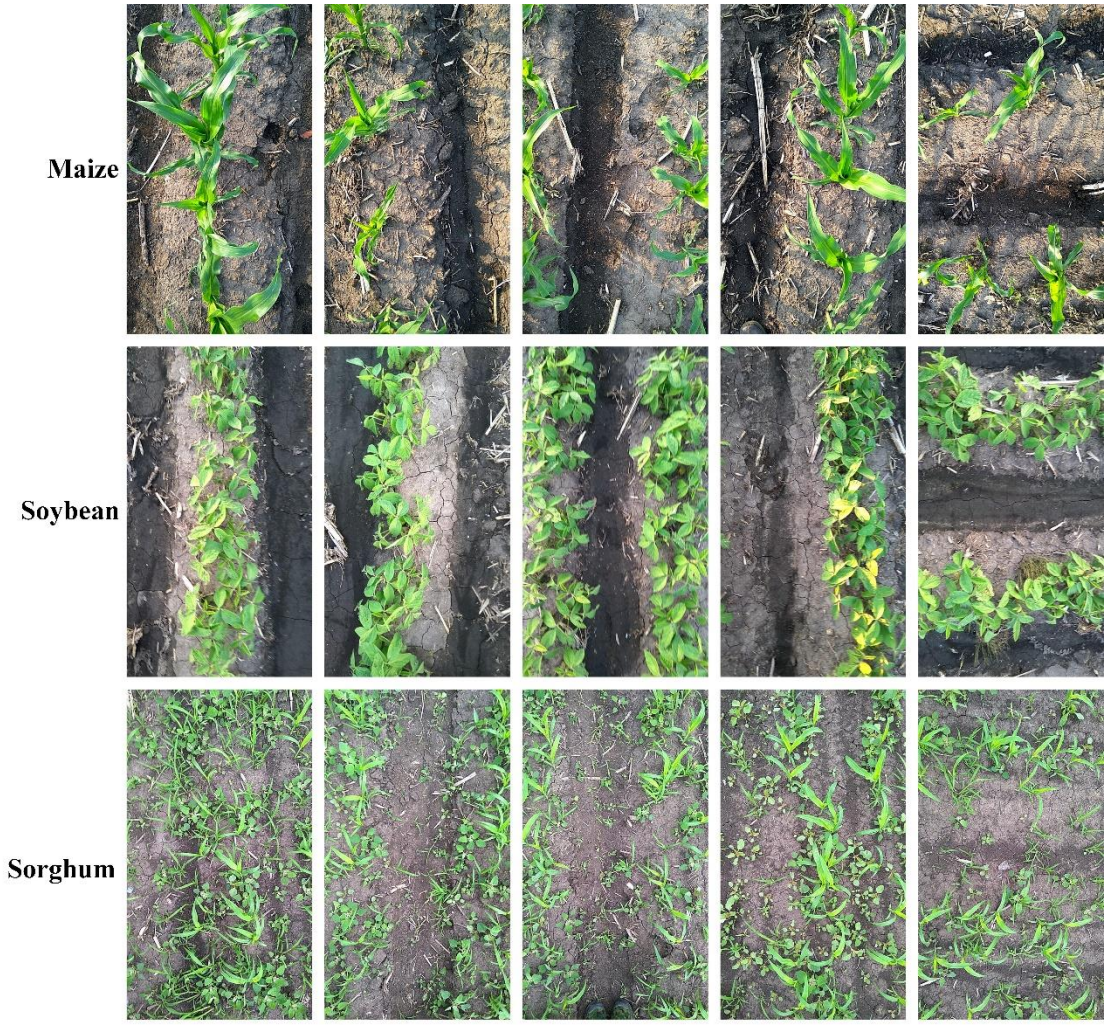


Fig. 11 Sample LAISmart downward looking images by the rear camera at the seedling stage for maize, sorghum and sorghumt. The smartphone was placed regularly above the ridge, the left side of the ridge, the right side of the ridge, the middle of two ridges and vertical to the ridge (from left to right).



Fig. 12 LAISmart upward looking images by the front camera for maize, sorghum and sorghum. The smartphone was placed regularly at the left side of the ridge, the middle of two ridges and the right side of the ridge.

2.7. SmartLAI

SmartLAI is still in the development stage. The system language is only French currently. SmartLAI was designed to estimate the wheat LAI. The pictures were taken perpendicular to the row direction at a zenith angle of 45° (Fig. 13). The distance between crop canopy and the smartphone was kept greater than 50 cm to ensure a large enough field of view. The pictures were not stored in the smartphone but sent to a remote developer server for LAI calculation. Four successive pictures were combined to obtain one LAI value.

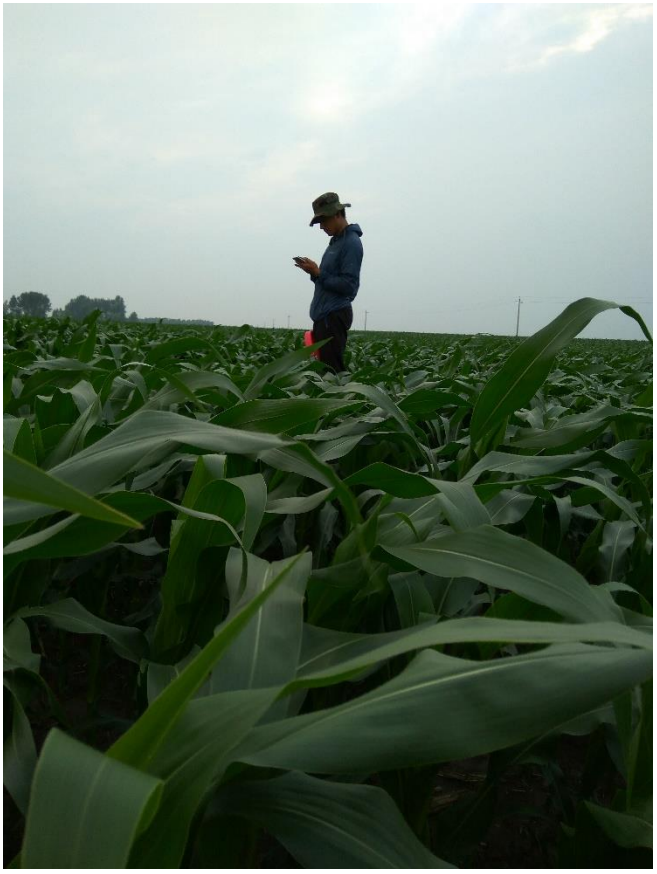


Fig. 13 Measuring LAI using SmartLAI at the maize plot. A ladder was used to reach the top of the canopy. The angle between the smartphone camera and the horizontal plane was 45°

2.8. LI-3100C leaf area meter

Five plants were randomly harvested in a plot. All the five plants were cut from one ESU. The three ESUs were taken turn in harvest. The plants were cut off, put in a plastic bag and taken to laboratory. Branches and yellow leaves were not measured. Only green leaves were scanned by LI-3100C leaf area meter (LI-COR: Lincoln, Nebraska, U.S.). The scanning work was usually completed within three hours after the harvest. If the yellow parts in a leaf were mixed with green parts and difficult to separate, the proportion of the yellow portion to the single leaf area was estimated.

Plant height and stem diameter at about 5 cm above the ground were measured before harvesting. The cross section of the maize stem is considered as an oval and both the short and long axes were measured. The cross section of the soybean stem is treated as a circle and the diameter was recorded. The maize and soybean were considered as a cone and a cylinder respectively. The mean value of short and long axes was regarded as the diameter of the bottom surface.

The stem area of maize was estimated as:

$$s = \pi \cdot \frac{a+b}{2} \cdot \sqrt{h^2 + \left(\frac{a+b}{2}\right)^2}$$

S is the area of plant stem side area (cm^2), a and b is the length of the long and short axes (cm), and h is the plant height (cm).

The stem area of soybean wass estimated as:

$$s = \pi \cdot d \cdot h$$

S is the area of plant steam area (cm^2), and h is the plant height (cm).

The plant density was estimated after measuring the distance between rows and plants (Fig. 14). The row space was estimated by the average distance of a preset number of rows. The plant space was estimated by the average distance of a preset number of plants for maize or a preset distance divided by the number of plants for soybean. The distances between rows and plants were measured five times randomly within each ESU. LAI was calculated as the leaf area per plant divided by the ground area it occupied.



Fig. 14 Measurement of the space between rows (a) and plants (b).

2.9. PASTIS-57

The PASTIS-57 system is composed of a data logger (2GB memory, 2LR20 batteries) and 6 sensors connected with wires (Fig. 15). The data logger is based on the LOG6200 main board designed and manufactured by YBdesign. The system is operated with 2 LR20 1.5V batteries ensuring about 8 months autonomy. A maximum of 174000 measurements for each sensor, ensuring 3 months autonomy with a 1 minute frequency. The main board is set up in a waterproof box. The system may be connected to a PC

under windows with a USB port for programming the acquisition or downloading the data. The clock is synchronized with that of the PC, with a programmable shift. The frequency of acquisition is 1, 5 or 10 minutes.

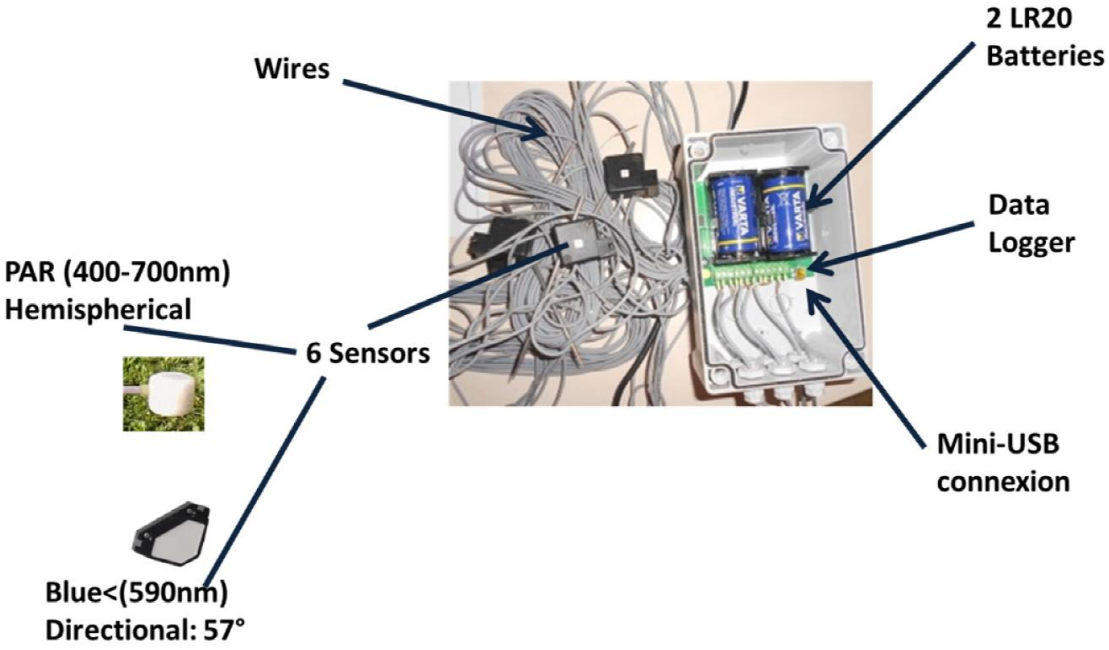


Fig. 15 The PASTIS-57 system. The picture was extracted from PASTIS-57 User Guide V2.0.

The sensors are based on LEDs sensitive to the blue spectral domain, allowing to minimize the effect of the illuminations conditions. As a matter of fact, the sky is relatively bright in the blue domain because of the Rayleigh and aerosol scattering. Conversely, vegetation elements show very low values of reflectance and transmittance in this spectral domain where absorption by pigments and several molecules is very high. The contrast between the sky and the vegetation elements will be therefore maximal in this domain. The field of views of the LEDs are restricted to ±22° at HWHM (Hal Width at Half Maximum) to avoid signals from below the horizon. The sensors are oriented at 57.5° towards the north, which allows to minimize the effect of the illumination conditions (the sun never enters the field of view of the sensor), as well as the effect of leaf angle distribution and clumping. The sensors are equipped with a nail allowing fixing it directly in the soil.

The PASTIS-57 systems allow monitoring the canopy fraction of fPAR and PAI. Two systems were deployed at plots A and B, respectively. Eleven sensors were fixed directly in the soil, and the other one was set up at the top of an iron pipe attached with a solar panel. The solar panel provided power to LAIPhoto. All the sensors were towards north to avoid the direct sunlight. The sensors fixed on the ground were

distributed regularly among rows. The angle between two sensors and the host is about 30 degrees. Fig. 15 shows the layout of the PASTIS-57.

The frequency of measurements was set to 10 minutes. All the systems were set up with the same PC, allowing for synchronous measurements (Fig. 17). However, some slight shift of the clocks of the systems may be observed and should be corrected for.

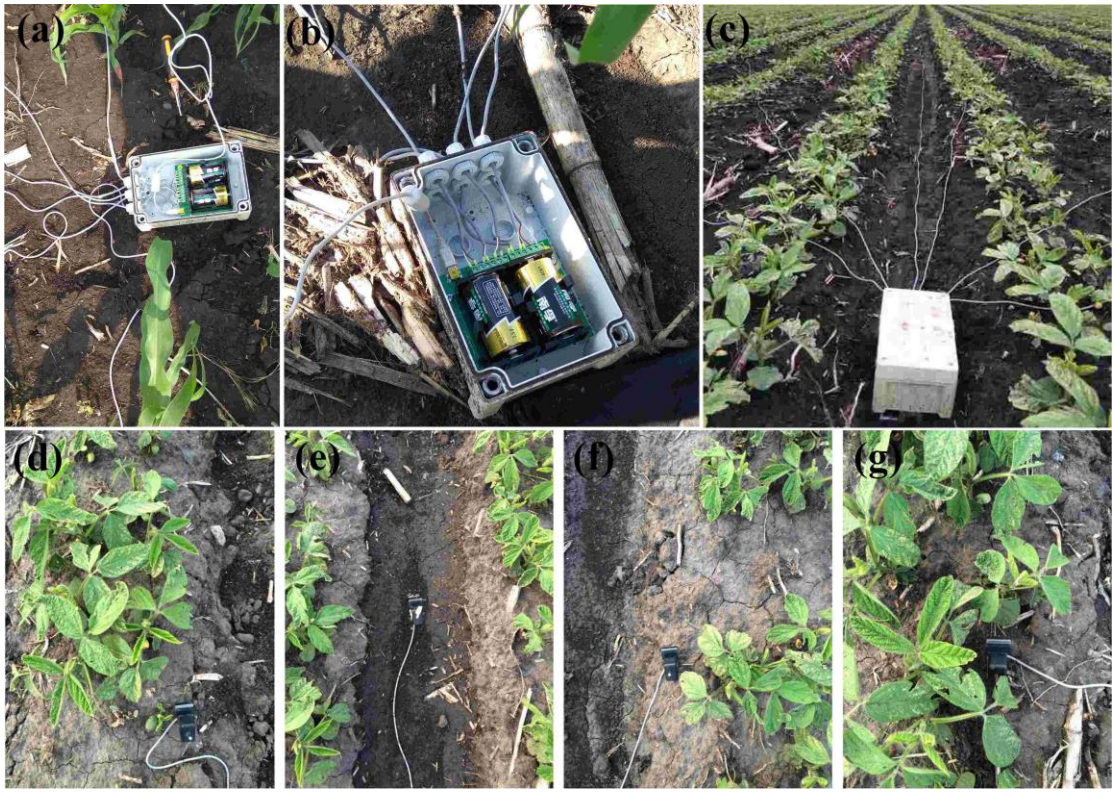


Fig. 16 The composition of PASTIS-57 and the sensors layout. The data loggerwith two LR20 1.5V batteries (a) and a mini-USB port (b). The angle between two sensors and the data logger is about 30 degrees (c). The sensors fixed on the ground were distributed in the left, the right, and the middle of a ridge or the middle of two rows.



Fig. 17 PASTIS-57 data collection with a personal laptop through the micro-USB connection (a) and the main interface of the data collection software (b).

2.10. LAIPhoto

LAIPhoto was still in the development stage. LAIPhoto is developed to monitor the vegetation growth continuously by taking pictures every 30 minutes. LAIPhoto is composed of an imaging system and a data transmission system. The imaging system is like a waterproof RGB camera . The quality of the picture taken by the camera is 640 x 480 pixels. The data transmission system sends the data to the remote server over the wireless network. The LAIPhoto is powered by 220 V alternating current. In order to use the LAIPhoto in the field, it was connected to a solar panel (Fig. 18). The downward looking camera was attached on the top of an iron pipe. The pipe was about 3.5 m and 2.5 high at the maize and soybean plots, respectively. Although some images were transferred back to the laboratory, most of the data was lost and unusable due to unknown reasons.

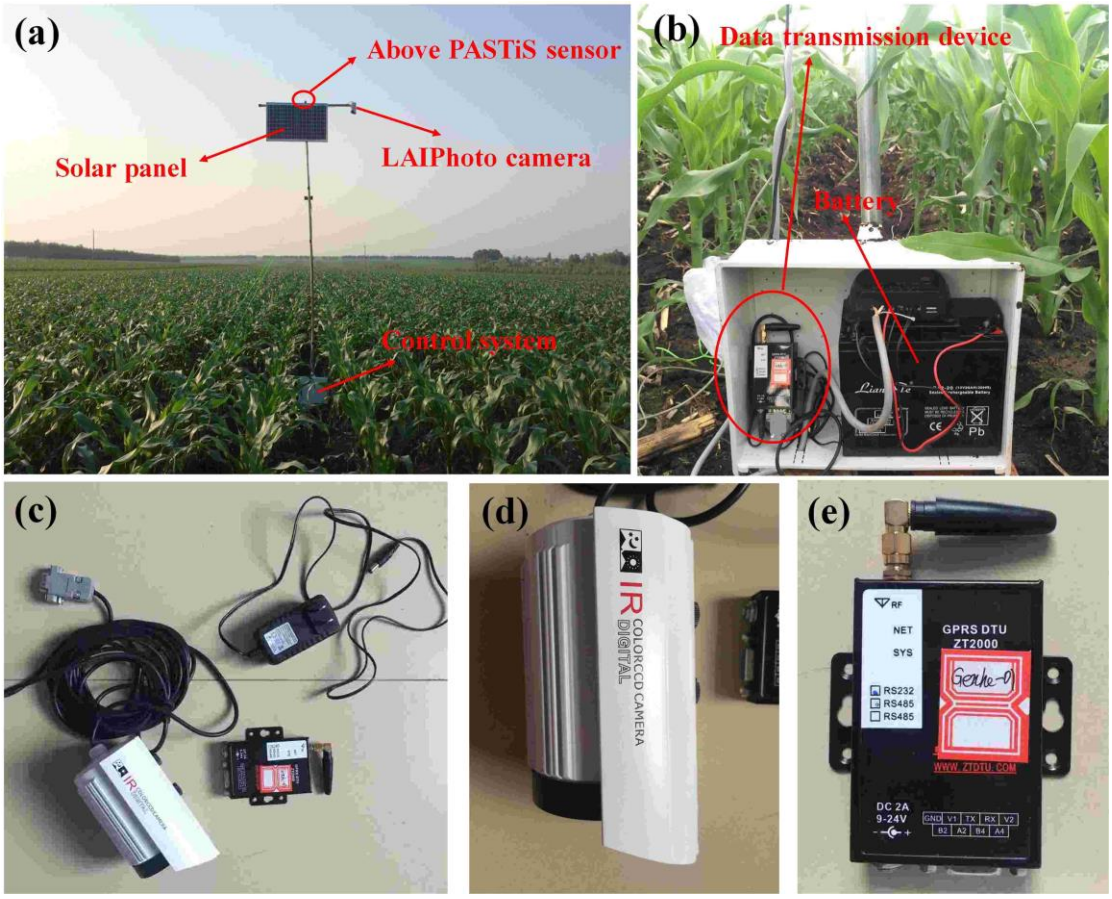


Fig. 18 The modified (a, b) and original (c-e) LAIPhoto. A solar panel connected to the LAIPhoto provides the power. The camera was attached above the crops (a). The data transmitting device and the battery were stored in a waterproof box (b).

3. Quality assurance

The plots are homogeneous and more than 100×500 m^2 in size. Each plot is located away from the road and ditches. Because the five pieces of farmland belong to different owners, the crop varieties and field management may be different. Though the crop types were both maize at plots A and D, the maize at plot A was half a meter higher than that at plot D. No chemical fertilizers and pesticides were applied at the sorghum fields (plot E).

The measurements were usually carried out once a week. Although efforts were tried to ensure the completeness and reliability of the measurement, there were some data gaps and uncontrollable errors. In general, the data qualities of LAI-2200, DHP, AccuPAR, PocketLAI, LAISmart, LI-3100C, and PASTIS-57 are more reliable than those of the SmartLAI and LAIPhoto.

3.1. LAI-2200

A 90° view cap was generally used before July 1 and a 270° view cap was used after that day. Five repeats were made in each ESU. Several data gaps occurred due to cap missing or battery die out (Table 3).

Table 3. Notes about LAI-2200 field measurements.

Date	Plot	Crop	Notes
Jul, 1	D	Maize	Only four repeats were made in ESU 2.
Jul, 30	D	Maize	The last two data in ESU 3 were deleted because of weak illumination after sunset.
Aug, 15	A	Maize	Only ESU 1 were measured due to the data logger failure for other ESUs.
Aug, 22	A	Maize	Four repeats were made in ESU 2 but no measurement in ESU 3 due to cap missing.
Aug, 30	A	Maize	No cap used in the fifth record in ESU 3 due to cap missing.
Sep, 20	D	Maize	A 180° view cap was used due to the missing of the 270° view cap

3.2. DHP

Sixteen pictures were generally taken in each ESU. Photos were taken downward before July 1 and upward after that. The blue color of sky light is similar with the green color of leaves, which increases the classification difficulty. Other notes are shown in Table 4.

Table 4. Additional notes about DHP measurements in the field campaign

Date	Plot	Crop	Notes
Jun, 26	B	Soybean	Illumination was darker than normal.
Jun, 28	A	Maize	Some pictures were slightly blurry.
Jul, 4	A	Maize	Pictures were blurry because of suboptimalfocal length.
Jul, 18	A	Maize	Fifteen pictures were taken in ESU 1.
Jul, 30	D	Maize	The illumination of the pictures in ESU 3 were darker.
Aug, 5	D	Maize	Pictures had water shadows due to the rain.
Aug, 31	C	Soybean	Twelve pictures were taken in each ESU.

3.3. AccuPAR

Five repetitions were made in each ESU. At each sampling point, we measured the canopy reflectance, canopy transmittance, and soil reflectance subsequently. Under

diffuse light condition, the illumination intensity maybe too weak for soil reflectance measurement. TThe moving clouds also bring unstable light conditions, although we tried to avoid the situation as far as possible.

All measurements were made with one above and four below readings, except for some unusual conditions (Table 5).

Table 5. Additional notes about the AccuPAR measurements in the field campaign

Date	Plot	Crop	Notes
Diffuse light condition			
Jun, 21	D	Maize	One above and five bellow readings were recorded when the third soil reflectance was measured in the ESU 1.
Jul, 1	D	Maize	After the first ESU measurement, the light was not stable.
Jul, 8	E	Sorghum	One above and three bellow readings were recorded when the first soil reflectance was measured in the ESU 1. The light is not stable.
Jul, 30	D	Maize	The reading is lower, especially in ESU 3, because the measurement started too late.
Sep, 15	D	Maize	One above and two bellow readings were recorded when the first canopy reflectance was measured in the ESU 3. One above and three bellow readings were recorded when the fifth canopy reflectance was measured in the ESU 3.
Sep, 20	D	Maize	One above and three bellow readings were recorded when the third and fifth canopy reflectance was measured in the ESU 3.
Direct light condition			
Jul, 21	A	Maize	Cloudy with unstable light condition.
Jul, 21	B	Soybean	Cloudy with unstable light condition.
Jul, 26	A	Maize	One above and five bellow readings were recorded when the first soil reflectance was measured in the ESU 2.

3.4. PocketLAI

Sixteen repetitions were made in each ESU. The essential factors influencing the LAI value are the crop density and distance between the camera and the crop plant. We kept the rear camera 10 cm to the plant in measurements.

3.5. LAISmart

Sixteen repetitions were made in each ESU. Photos were taken downward before July 1 and upward after that at the maize plots. After July 6, the upward model was chosen at all plots. In the upward model, the camera position may influence the LAI

value. The smartphone was sequentially put in the 1/2 and 1/4 positions between two rows or in the middle of the rows to minimize the error. In several times, the camera failed, possibly due to software bug, and only gave a pure green picture. Table 6 shows the dates on which the camera failed.

Table 6. Additional notes about the LAISmart measurements in the field campaign

Date	Plot	Crop	Notes
Aug, 25	E	Sorghum	One repeat measurement in ESU 2 failed.
Sep, 3	E	Sorghum	One repeat measurement in ESU 2 failed.
Sep, 9	D	Maize	One repeat measurement in ESU 3 failed.

3.6. SmartLAI

The SmartLAI requires a 45° angle between the smartphone display and the zenith, which means only downward model can be used when taking pictures. As the crops grow, the gaps between the rows become smaller. Taking pictures downwards increases the classification difficulty. Additional, it is very difficult to measure tall vegetation. At plot A, when the maize height was close to 3 m (after Jul, 25), the measurements were made by standing on a 1.7 m ladder. In this case, the distance between crop top and the smartphone may be less than the required 50 cm.

Unfortunately, the SmartLAI data must be sent to the developer server to calculate LAI calculation. Four repeats were made in each ESU during the measurement. However, many data were lost permanently due to the data uploading failure,.

3.7. LI-3100C

Green leaves were scanned by LI-3000C, without branch and yellow leaves. The scanning work was done within three hours after the crops being cut off in order to avoid the occurring of leaf area shrinking caused by tissue water loss.

3.8. PASTIS-57

Although the data recorded by PASTIS-57 were high frequency and continuous, we only kept the time span during which the measurements were carried out. It means that other instruments (LAI-2200, DHP, PocketLAI, and LAISmart) were used simultaneously. However, the manual measurements were not done daily. We retained the PASTIS-57 data recorded on the dates which there were no other measurements.

We selected exactly the same time if the manual measurements were carried out on that day. If not, we filtered the date which was the closest to it. If multiple plots were measured on one day, only the time of measurements carried out before sunset was kept on. If there were two days with the same time interval of the selected date, we chose the day on which the start time of measurements was later.

The readings were calibrated using the sensor calibration parameters supplied by the developer (Table 7). More than 500 samplings of each sensor were taken for the calibration. The results of calibration are shown in Fig. 19 (R^2 = 1, RMSE = 5.23).

Although the PASTIS-57 has a waterproof box, water can still penetrates from the wire outlet in heavy rains. The mini-USB connecions are located inside the box, not convenient for computer connection. The inner clock of the PASTIS-57 also had a little shift.

At the soybean plot, fallen leaves occurred during the entire growing season, especially from the flowering stage to the senescence stage. Dense leaves may occasionally cover the sensors (Fig. 20).

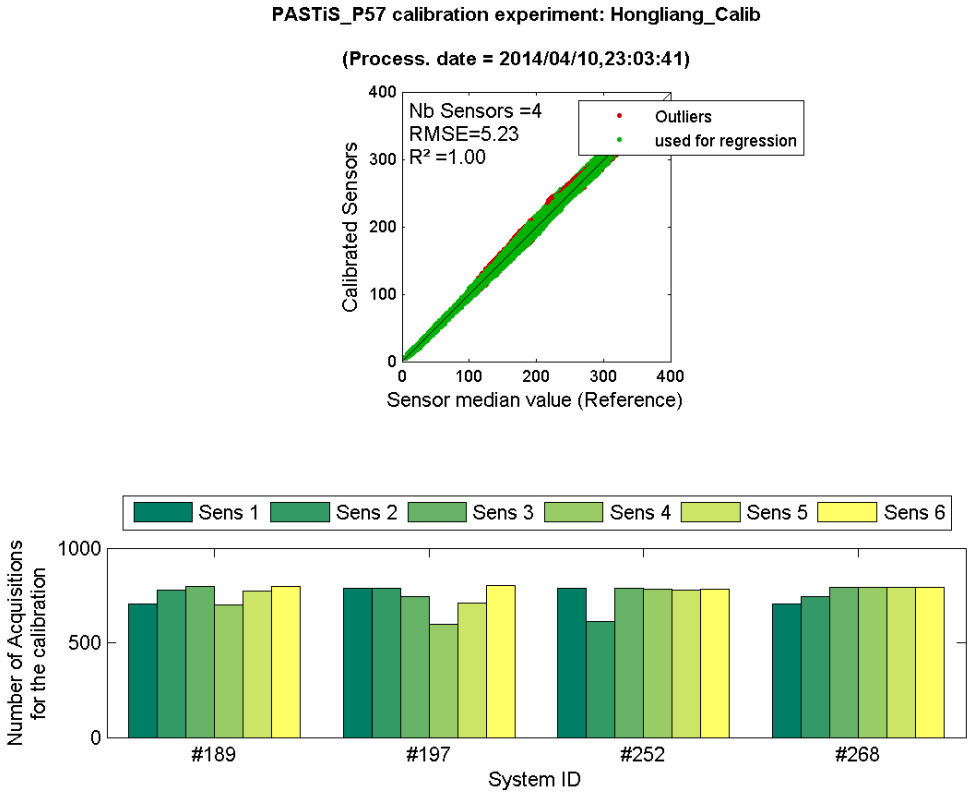


Fig. 19 Calibration of the PASTIS-57 sensors. More than 500 samplings of each sensor were taken for calibration.

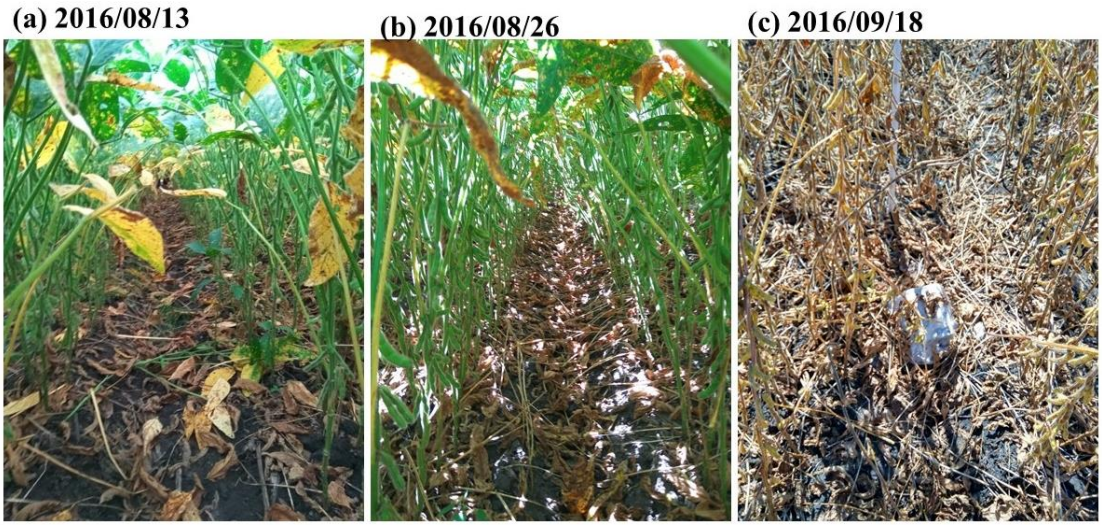


Fig. 20 Fallen leaves covering the ground at the soybean field (plot B). The PASTIS-57 sensors may be covered by fallen leaves. The PASTIS-57 data logger was covered with a white waterproof plastic bag (c).

Table 7. PASTIS-57 calibration coefficients

ID	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6
189	0.8293	0.8614	0.9146	1.1557	0.8740	0.4926
197	1.1478	1.3647	1.0346	1.0148	0.9946	0.4903
252	1.0441	0.9899	1.2885	1.3266	1.5548	0.5498
268	0.9323	0.8978	1.0026	1.0812	1.4170	0.7234

3.9. LAIPhoto

The LAIPhoto was fixed on a pipe top and powered by a solar panel. The position of the camera may shift under strong wind.

The picture was supposed to be sent back to the lab every 30 minutes. However, most data were lost due to the instability of the network and the server failure.

4. Results

4.1. Seasonal variation of ALA calculated from LAI-2200 and DHP

Fig. 21 shows the seasonal variation of average leaf angle (ALA) derived from LAI-2200 and DHP. The LAI-2200 ALA is derived a polynomial regression method.

The DHP ALA is retrieved from the Beer-Lambert equation assuming an ellipsoidal distribution of the leaf inclination using the LUT technique (CAN_EYE, V6.1).

The ALA values vary slightly over the season. The maize and sorghum values vary around 50º–65º and 50º–70º, respectively. The soybean values are around 50º–60º before DOY 240 (August 27, 2016), but increases by about 20º after that. In general, the DHP ALA values are higher than those of the LAI-2200, especially for maize and sorghum (Table 8). The true ALA values are higher than the effective values for soybean and sorghum, but both true and effective ALA values are similar for maize.

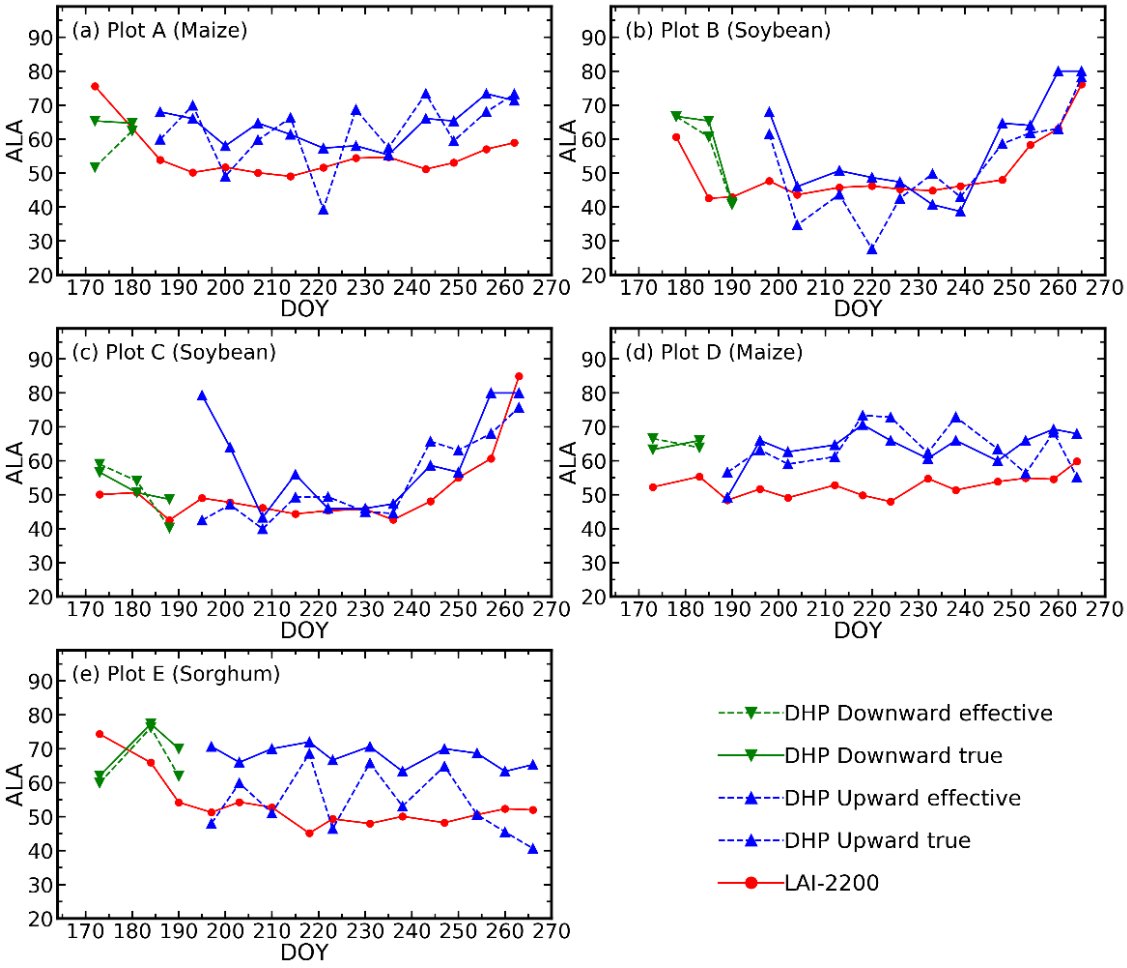


Fig. 21 Seasonal variation of ALA calculated from LAI-2200, downward DHP and upward DHP. Solid and dashes lines represent true and effective ALAs retrieved from DHPs, respectively.

Table 8. Field ALA derived from LAI-2200 and DHP over different periods. The number in the bracket in the standard deviations.

Maize (plots A & D)			
	169–200	201–240	241–264
LAI-2200	54.5 (10.4)	52.1 (9.2)	53.2 (9.3)
DHP (true)	63.3 (12.8)	63.6 (12.7)	65.3 (12.9)
DHP (effective)	61.6 (16.4)	64.1 (16.4)	65.0 (16.0)
Soybean (plots B & C)			
	169–205	206–245	246–265
LAI-2200	50.0 (10.1)	49.3 (8.9)	53.2 (12.2)
DHP (true)	58.0 (14.9)	55.6 (13.3)	61.2 (13.8)
DHP (effective)	51.3 (17.7)	50.3 (17.3)	55.9 (16.5)
Sorghum (plot E)			
	173–195	196–245	246–266
LAI-2200	64.8 (16.5)	50.4 (4.2)	50.8 (3.2)
DHP (true)	69.8 (7.0)	68.5 (4.0)	66.8 (3.5)
DHP (effective)	66.0 (8.5)	56.1 (15.7)	50.4 (15.4)
Overall			
	169–200	201–245	246–266
LAI-2200	53.8 (10.4)	48.7 (9.6)	58.5 (9.6)
DHP (true)	63.7 (8.4)	57.5 (9.5)	69.5 (6.4)
DHP (effective)	57.8 (9.1)	54.4 (12.3)	62.6 (9.5)

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