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|  | **Technical Handbooks of FRM4VEG Instrumentation**  **(TR-1): LI-COR LAI-2200C Plant Canopy Analyser**  version 1.0  National Physical Laboratory  University of Southampton  EOLAB  28 May 2020 |
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##### Acronyms

|  |  |
| --- | --- |
| **Abbreviation** | **Stands for** |
| BNC | Bayonet Neill-Concelman |
| CEP | Circular error probability |
| EEPROM | Electronically erasable programmable read only memory |
| ESA | European Space Agency |
| FAPAR | Fraction of absorbed photosynthetically active radiation |
| FAT16 | File allocation table 16 |
| FIPAR | Fraction of intercepted photosynthetically active radiation |
| FOV | Field-of-view |
| FRM4VEG | Fiducial Reference Measurements for Vegetation |
| GPS | Global positioning system |
| LAI | Leaf area index |
| LCD | Liquid crystal display |
| NiMH | Nickel-metal hydride |
| PAI | Plant area index |
| RF | Radio frequency |
| TIFF | Time to first fix |

# Introduction

## Purpose and Scope

This document forms part of deliverable D-60 of the European Space Agency (ESA) project ‘Fiducial Reference Measurements for Vegetation (FRM4VEG)’ and it should be used as a guide to operating the LI-COR LAI-2200C Plant Canopy Analyser.

Its purpose is to provide an instrument technical description, together with information about maintenance and calibration history, pre-deployment uncertainties estimates, and steps required to achieve the FRM status.

The document is organized into 7 key sections:

* **Section 1** provides a summary of the document.
* **Section 2** overviews the technical characteristics of the instrument together with a description of its functioning.
* **Section 3** refers to the-deployment calibration carried out at the LI-COR calibration facility in Lincoln, Nebraska.
* **Section 4** describes all the procedures that need to be followed when using the instrument, both in the field and during the data processing.
* **Section 5** lists useful advices for care and storage of the camera as provided by the manufacturer.
* **Section 6** lists the reasons for and solutions to common problems with the use of the camera.
* **Appendix A** provides the calibration results mentioned in Section 3.

# Technical Description

## Overview

The LI-COR LAI-2200C Plant Canopy Analyser is an instrument designed to calculate leaf area index (LAI) and other canopy attributes from multi-angular measurements of light interception. It makes use of an optical sensor with a 148° field-of-view (FOV). Technical characteristics of the instrument provided by the manufacturer are detailed in Table 1. Technical characteristics of the LAI-2270C control unit are detailed in Table 2, whilst those of the LAI-2250 optical sensor are detailed in Table 3.

Table 1: Technical characteristics of the LI-COR LAI-2200C Plant Canopy Analyser [1].

|  |  |
| --- | --- |
| **Characteristic** | **Details** |
| Operating temperature | - 20° C to 50 °C (-4° F to 122° F) |
| Humidity range | 0% to 95% relative humidity (RH), non-condensing conditions |
| Storage temperature range | - 40° C to 65° C (-40° F to 149° F) |

Table 2: Technical characteristics of the LI-COR LAI-2270C control unit [1].

|  |  |
| --- | --- |
| **Characteristic** | **Details** |
| Sensor inputs | 2 bulkhead connectors (6-pin) for LAI-2250 optical sensors; 2 Bayonet Neill-Concelman (BNC) bulkhead connectors for LI-COR quantum sensors |
| Data storage capacity | 128 MB of file allocation table (FAT16) memory |
| Keypad | 22 button tactile response keypad; 10 key numeric keypad with full alphabetic capabilities with 9 function/control keys |
| Display | 128 x 64 graphics liquid crystal display (LCD) |
| GPS | GPS RADIONOVA radio frequency (RF) antenna module, horizontal position accuracy: 2.5 m (50% circular error probability (CEP), open-sky, 24 hour static, good view of the sky); maximum position update rate: 1 Hz; GPS receiver sensitivity, autonomous acquisition: - 148 dBm; time to first fix (TIFF), hot start: 1 s, TIFF, warm start: 6 s (typical), TIFF, cold start (with good view of the sky): 37 s at 90% probability. |
| Clock | Year, month, day, hour, second ± 3 minutes per month |
| Power requirements | 4 AA batteries (alkaline, nickel metal-hydride (NiMH), lithium) |
| Battery life | 90 hours with 4 AA batteries without optical sensor attached; 60 hours with 4 AA batteries with one optical sensor attached and without GPS enabled; 40 hours with 4 AA batteries without optical sensor attached and with GPS enabled |
| Low battery warning | Display indicated when power is < 15% |
| Size | 20.9 cm x 9.8 cm x 3.5 cm (8.2 “ x 3.9 “ x 1.4 “) |
| Weight | 0.454 kg (1.0 lb) with batteries |

Table 3: Technical characteristics of the LI-COR LAI-2250 optical sensor [1].

|  |  |
| --- | --- |
| Characteristic | Details |
| Sensor inputs | 16-pin bulkhead connector for control unit interface |
| Memory | 1 MB flash memory for record storage, 1 KB electronically erasable programmable read only memory (EEPROM) for calibration and configuration storage |
| Keypad | 2 button, tactile response keypad |
| Clock | Year, month, day, hour, second ± 3 minutes per month; can be synced with control unit clock when joined with a data cable |
| Power requirements | 2 AA batteries (alkaline, NiMH, lithium) |
| Battery life | 180 hours of typical operation (with 2 alkaline batteries) |
| Optics | 1.00° maximum decentring error as measures from centre mass of ring. 0.50° maximum magnification error as measured from the centre mass of ring 4. |
| Wavelength range | 340 nm to 490 nm |
| Nominal angular coverage | Ring 1: 0.0° to 12.3° Ring 2: 16.7° to 28.6 Ring 3: 32.4° to 43.4°  Ring 4: 47.3° to 58.1°  Ring 5: 62.3° to 74.1° |
| Lens coating | MgF2 for improved transmission at oblique angles (external and internal lenses) |
| View caps | Provide azimuthal masking of view into quadrants of: 0°, 10°, 45°, 90°, 180° and 270° |
| Size | 63.8 cm L x 2.9 cm W x 2.9 cm D (25.1 “ x 1.125 C x 1.125 “) |
| Drilled cap | Used to measure leaf optical properties |
| Weight | 0.845 kg (1.86 lbs) with batteries |

## Theory of Operation

The LAI-2200C consists of an optical sensor that facilitates the measurement of canopy transmittance in the blue region of the electromagnetic spectrum (320 to 490 nm) at five zenith angles simultaneously. The optical sensor projects the image of its 148° FOV onto five detectors, which are arranged in concentric rings. An optical filter is used to reject electromagnetic radiation at wavelengths of greater than 490 nm in order to minimise the effects of within-canopy multiple scattering.

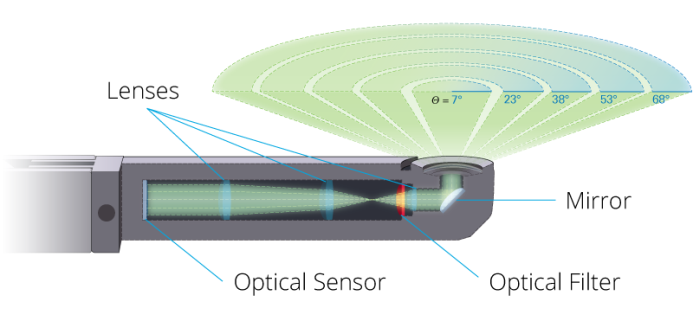


Figure 1: Breakdown of the optical sensor of the LAI-2200C [2].

Using the LAI-2200C, LAI is derived according to the theory proposed by [3], which states that

where is the gap fraction (which considered nearly equivalent to transmittance due to strong absorption by photosynthetic pigments) at zenith angle . By making measurements above and below the canopy, canopy transmittance can be determined at a range of zenith angles, which can then be used to solve a discretised version of this integral according to [4].

Because the LAI-2200C cannot discriminate between interception by leaves and other canopy elements such as stems and branches, it cannot strictly be considered to measure LAI itself, and instead the term plant area index (PAI) may be preferred. Additionally, the following assumptions are made [1]:

* The foliage is black (i.e. completely absorbing). Below-canopy readings are assumed not to include light reflected or transmitted by foliage. Because the instrument rejects radiation at wavelengths greater than 490 nm, violations of this assumption are minimised (there is strong absorption by photosynthetic pigments in the blue region of the electromagnetic spectrum). Additionally, a scattering correction can be applied if additional above canopy measurements are made with the aid of a diffuser cap (the ‘4A’ measurement sequence). The scattering correction should be applied if measurements are performed in direct sunlight, as errors due to scattering are highest under these conditions, but can be applied to all data.
* The foliage is randomly distributed within foliage-containing envelopes (i.e. parallel tubes for row crops, a single ellipsoid in the case of an isolated plant, an infinite box for grass, or an infinite box with holes for a deciduous forest with gaps).
* Compared to the area viewed by each ring, the foliage elements are small. The instrument should be no closer to the nearest leaf than four times the leaf’s width (and this distance should be increased if a view-restricting cap is used).
* The foliage has a random azimuthal orientation (i.e. foliage inclination does not matter provided that all leaves are not facing in the same compass direction). The importance of this assumption is reduce when measurements are made in a wide range of compass directions or without a view-restricting cap.

In addition to LAI, the LAI-2200C can also be used to approximate the fraction of intercepted photosynthetically active radiation (FIPAR), a quantity closely related to the fraction of absorbed photosynthetically active radiation (FAPAR). In this case, angular variations in canopy transmittance can be used to reconstruct diurnal variation in FIPAR.

# Calibration History and Uncertainty Budget

## Calibration History

Pre-deployment calibration of instrument #PCH3987 was carried out by LI-COR at their calibration facility in Lincoln, Nebraska on 12/05/2014. The associated calibration certificate can be found in Appendix A.1.

# Instrument Operation

The following instrument operation instructions are adopted from those provided by the manufacturer [1]:

## Instrument Setup

1. Although the optical sensor can be operated independently of the control unit, operation with the control unit is recommended to more easily manage the recoded data files. In this case, the optical sensor need not have its own batteries installed.
   1. Before turning the instrument on, the optical sensor should be connected to the control unit using the supplied cable. The 6-pin bulkhead connector must be carefully aligned using the red dots and pressed straight in.
2. Turn the control unit on and ensure the date and time are set correctly.
   1. Press the ‘MENU’ button, then select ‘Console Setup’ from the available options using the arrow buttons and press the ‘OK’ button.
   2. Select ‘Set Time’ from the available options using the arrow buttons and press the ‘OK’ button.
   3. Enter the date and time using the alphanumeric keypad, then press the ‘OK’ button.
3. Ensure global positioning system (GPS) logging is enabled.
   1. Press the ‘MENU’ button, then select ‘Log Setup’ from the available options using the arrow buttons and press the ‘OK’ button.
   2. Select ‘GPS’ from the available options using the arrow buttons and press the ‘OK’ button.
   3. Ensure that ‘GPS’ is set to ‘On’, ‘Log GPS’ to ‘Yes’ and ‘When’ to ‘Any’, then press the ‘EXIT’ button.
4. Define the desired transmittance computation settings.
   1. Press the ‘MENU’ button, then select ‘Log Setup’ from the available options using the arrow buttons and press the ‘OK’ button.
   2. Select ‘Transcomp’ from the available options using the arrow buttons and press the ‘OK’ button.
   3. Select the desired ‘Define above’ setting using the arrow buttons. A or B measurements can be treated as above canopy measurements, or the control unit can compare the measurements and decide this automatically.
   4. Select the desired ‘Determine above’ setting using the arrow buttons. Either the previous or closest in time above canopy measurement can be used, or temporal interpolation between above canopy measurements can be adopted.
   5. Select the desired ‘Bad readings’ setting using the arrow buttons. Bad readings can be skipped or clipped (i.e. the transmission is clipped to one if a higher value is recorded).
   6. Press the ‘OK’ button, then the ‘EXIT’ button.
5. Press the ‘START/STOP’ button. Select ‘NEW FILE’ and press the ‘OK’ button. Enter the desired filename using the alphanumeric keypad and press the ‘OK’ button again. Press the ‘OK’ button once more to accept the default values.
   1. The display will show ‘READY’.
6. Remove the opaque lens cap from the optical sensor. A view-restricting cap should be installed if:
   1. The sun will be in the instrument’s FOV.
   2. The operator will be within the instrument’s FOV (no view-restricting cap is required if the operator is careful to block the same part of the FOV, but it is simpler to use one).
   3. The sky is very non-uniform.
   4. There are substantial gaps or clumps in the canopy.
   5. The required plot size needs to be reduced.
   6. Above-canopy measurements need to be made in a small clearing.

## Dealing with Different Illumination Conditions

1. The best illumination conditions for performing measurements with the LAI-2200C are single layer uniform overcast skies, or clear blue skies with the sun below the horizon or blocked by a cloud.
   1. Stable conditions will enable a longer period between above and below canopy measurements, whilst uniformity will make maintaining the same direction for each measurement less important.
2. Good measurements can also be made on a clear blue sky day during sunlight hours.
   1. Under such conditions, interpolating between above canopy measurements works well, making tall canopies such as forests easier to measure with a single optical sensor.
   2. A view-restricting cap should be used to mask the sun from the instrument’s FOV.
   3. Although direct sunlight will increase errors due to scattering, these can be accounted for by applying the scattering correction. The ‘4A’ measurement sequence should be performed this case.
3. The worst illumination conditions are broken and non-uniform clouds. Under these conditions, the time between above and below canopy measurements must be minimised and the direction of each measurement must be carefully maintained to ensure the same section of the sky is viewed.
   1. To minimise the time between above and below canopy measurements, perform an above canopy measurement before every below canopy measurement.

## Performing an Above Canopy Measurement (Single Optical Sensor)

Above canopy measurements should be performed before a series of below canopy measurements, and at regular intervals if illumination conditions are variable. If measurements are to be made in a tall canopy such as a forest using a single optical sensor, it is good practice to perform above canopy measurements both before and after the below canopy measurements. Temporal interpolation can then be carried out in post-processing.

1. Above canopy measurements should be performed using the same view-restricting cap and at the same direction as the below canopy measurements.
   1. Ensure the instrument is in ‘ABOVE’ mode. This is indicated by the blue light on the optical sensor. If the blue light is not lit, press the ‘A/B’ button on the optical sensor.
   2. Holding the instrument level, press the ‘LOG’ button on the optical sensor to perform a measurement.
   3. A series of beeps will sound to indicate the measurement was stored, and the display will show ‘A:1’ to indicate a single above canopy measurement has been performed. This number will update with subsequent measurements.
2. If measurements are being conducted under direct sunlight, a ‘4A’ measurement sequence should be performed to enable scattering correction to be applied in post-processing.
   1. Place the diffuser cap on the optical sensor, and ensuring the instrument is in ‘ABOVE’ mode, perform a measurement whilst holding the instrument in the sun.
   2. Perform a second measurement, shading the diffuser cap with your body.
   3. Remove the diffuser cap, and perform a third measurement, again shading the instrument with your body but with a small a shadow as possible (alternatively use the 270° view-restricting cap).
   4. The final ‘4A’ measurement should be performed using the same view-restricting cap and at the same direction as the below canopy measurements (i.e. a standard above canopy measurement)

## Performing Automatic Above Canopy Measurements (Two Optical Sensors)

1. In tall canopies such a forests, it is often difficult or impossible to perform regular above canopy measurements, particularly if no clearings are present. It is best to use two optical sensors in this case, with one in a clearing or above the canopy logging data automatically. The above canopy records can then be combined with the below canopy records.
   1. If two optical sensors will be used, they first should be matched. Attach both optical sensors to the control unit, and place them next to each other so they view the same section of blue, cloudless sky.
   2. Press the ‘MENU’ button, then select ‘Wand Setup’ from the available options using the arrow buttons and press the ‘OK’ button. Select the optical sensor that will be used for below canopy readings and press the ‘OK’ button.
   3. Select ‘Match Values’ and press the ‘OK’ button, then select ‘Calculate’ and press the ‘OK’ button again.
   4. The optical sensors will now be matched. Press the ‘OK’ button.
   5. To reset the original calibration values, select ‘View/Set’ and press the ‘OK’ button. Then press the ‘LOG’ button to reset the values, followed by the ‘OK’ button.
2. To set up automatic logging on an optical sensor that will then be disconnected from the control unit, ensure the optical sensor has its batteries fitted and connect it to the control unit. Press the ‘MENU’ button, then select ‘Wand Setup’ from the available options using the arrow buttons and press the ‘OK’ button. Select the desired optical sensor and press the ‘OK’ button again.
   1. Before logging, the time of the optical sensor should be synchronised to that of the control unit.
      1. Select ‘Clock’ from the available options using the arrow buttons and press the ‘OK’ button, then select ‘Sync Time’ and press the ‘OK’ button, followed by the ‘OK’ button again to confirm the selection.
      2. The new optical sensor time will be displayed. Press the ‘OK’ button, followed by the back arrow button.
   2. Auto logging can now be set up by selecting ‘Auto Log’ and pressing the ‘OK’ button.
      1. Select ‘Start Time’, press the ‘OK’ button, and enter the desired start time and date using the alphanumeric keypad. Press the ‘OK’ button to save the settings.
      2. Do the same for ‘Stop Time’ and ‘Frequency’, which can be set to a multiple of 5 s (between 5 s and 3600 s).
      3. Finally, select ‘On/Off’ and press the ‘OK’ button. Ensure ‘Auto Log Enable’ is set to ‘ON’, then press the ‘OK’ button again. The optical sensor will now log automatically.
   3. In the run up to automatic logging, the ‘LOG’ light on the optical sensor will blink every 2.5 s. When logging, it will blink every 1 s, and beep at the beginning and end of each log.
   4. If measurements are being performed under direct sunlight, a ‘4A’ measurement sequence will be required (see Section 4.3). If the logging interval is long enough, normal above canopy records can be manually interspersed with this measurement sequence.
   5. After logging, the above canopy measurements need to be moved from the optical sensor to a file on the control unit.
      1. Press the ‘MENU’ button, and select ‘Data’ from the available options using the arrow buttons and press the ‘OK’ button. Then select ‘Wand’ and press the ‘OK’ button again.
      2. Select ‘Download’, then press the ‘OK’ button, then select the desired optical sensor and press the ‘OK’ button again.
      3. You may now either select the file with the below canopy measurements in, or specify a new file if you wish to merge the measurements later in post-processing. Select the desired file and press the ‘OK’ button.
   6. To delete measurements from the optical sensor, press the ‘MENU’ button, and select ‘Data’ from the available options using the arrow buttons and press the ‘OK’ button. Then select ‘Wand’ and press the ‘OK’ button again.
      1. Select ‘Purge’, then press the ‘OK’ button, then select the desired optical sensor and press the ‘OK’ button again.
3. Automatic logging may also be achieved using an optical sensor connected to a control unit. In this case, press the ‘MENU’ button, then select ‘Log Setup’ from the available options using the arrow buttons and press the ‘OK’ button.
   1. Select ‘Console AutoLog’ and press the ‘OK’ button, then ensure ‘Active’ is set to ‘On’ and ‘Period’ to the desired logging frequency (a multiple of 5 s between 5 s and 3600 s). Press the ‘OK’ button.
   2. When a file is open and automatic logging is active, ‘AUTO’ will be shown on the display, in addition to a countdown to the next log. All attached optical sensors will be logged to the file.
4. To import above canopy observations from one file into another file containing below canopy records, press the ‘MENU’ button, and select ‘Data’ from the available options using the arrow buttons and press the ‘OK’ button. Then select ‘Console’ and press the ‘OK’ button again.
   1. Select the file containing the below canopy observations and press the ‘OK’ button, then select ‘Edit’ and press the ‘OK’ button again.
   2. Select ‘Import Observations’ and press the ‘OK’ button, before selecting the file containing the above canopy observations and pressing the ‘OK’ button again.
   3. LAI values will be recomputed automatically using the newly imported above canopy records.

## Performing a Below Canopy Measurement

1. Below canopy measurements should be performed using the same view-restricting cap and at the same direction as the associated above canopy measurements.
   1. Ensure the instrument is not in ‘ABOVE’ mode. This is indicated by the blue light on the optical sensor. If the blue light is lit, press the ‘A/B’ button on the optical sensor.
   2. Holding the instrument level, press the ‘LOG’ button on the optical sensor to perform a measurement.
   3. A series of beeps will sound to indicate the measurement was stored, and the display will show ‘B:1’ to indicate a single above canopy measurement has been performed. This number will update with subsequent measurements, and the display will also show the current LAI and standard error values. Different variables can be selected using the arrow buttons.
2. When measurements are complete, press the ‘START/STOP’ button on the instrument control unit.

## Viewing, Editing and Recomputing Data on the Control Unit

1. Collected data can be subsequently viewed, edited and recomputed on the control unit. and select ‘Data’ from the available options using the arrow buttons and press the ‘OK’ button. Then select ‘Console’ and press the ‘OK’ button again.
   1. Select the desired file, then press the ‘OK’ button.
   2. To view a summary, select ‘Quick View’ and press the ‘OK’ button.
   3. To edit the transmittance computation settings used to compute the file, select ‘Edit’ and press the ‘OK’ button. Select ‘Edit Transcomp’ and press the ‘OK’ button again.
      1. Select the desired settings (see Section 4.1) and press the ‘OK’ button.
      2. Once edited, the file needs to be recomputed. Press the back arrow button, then select ‘Recompute’ and press the ‘OK button. Press the ‘OK’ button again to confirm the selection.
   4. Other settings can be edited in the same way, including renaming/deleting the file or masking one or more of the instrument’s rings.

## Downloading Data

1. Data are stored as text files on the LAI-2200C, which are ready for further analysis. To download them, connect the control unit to a computer using the supplied cable, and copy the text files to the desired location as you would a normal mass storage device.
2. The freely available FV2000C software may be used for more advanced processing, including scattering correction, mapping LAI using GPS data recorded by the instrument, and recomputation of LAI with alternative settings (e.g. different transmittance models, masking rings) or after stripping erroneous observations.

# Care and Storage

The following care and storage advice is adapted from that provided by the manufacturer [1]:

* The optical sensor lens should be kept free of dust and dirt. Use the opaque lens cap when the instrument is not in use to help keep the lens clean.
* The lens can be cleaned with distilled water or the lens cleaning kit included with the instrument. Care must be taken to ensure the MgF2 coating on the lens is not scratched, and paper products should be avoided. Never wipe the lens when it is dry.
* The instrument display and keypads can be cleaned with a moistened non-abrasive cloth.
* Before storing the LAI-2200C, remove the batteries to prevent leakage and corrosion, and install the bulkhead connector caps and opaque lens cap.
* When changing batteries, ensure they are installed with the correct polarity.

# Troubleshooting

Reasons for and solutions to common problems with the LAI-2200C are provided by the manufacturer [1], and are listed in Table 4.

Table 4: Reasons and solutions to common problems with the LAI-2200C [1].

|  |  |  |
| --- | --- | --- |
| **Problem** | **Reason** | **Solution** |
| Control unit will not power up | Low battery power, locked processor or short in optical sensor | Try removing batteries for a few seconds, disconnecting all sensors, and replacing batteries with new ones |
| Cannot match sensors | Both sensors do not see the same diffuse view, the optical sensor match values are not set to their default values, the sensors see direct sunlight or artificial light | Ensure both sensors see the same diffuse view and that both want match values are set to their default values before performing a match; if they are not set to their defaults there is a chance that the match will fail; if this fails, reset the match values to those given on the calibration sheet |
| Instrument will not turn off | A data file is open or the instrument is reading data from memory | Wait a few moments for the data transfer to finish, close any open data files; if the instrument continues to be unresponsive, press and hold the power button for 5 seconds (open data files may be lost); if the instrument is still unresponsive, remove the batteries for a moment |
| Instrument (optical sensor or control unit) locks up |  | Remove and reinstall the batteries |
| Optical sensor not recognised or does not respond to light | Cables are not properly connected or short in optical sensor | Disconnect and reconnect the optical sensor |
| LAI = 0 |  | Check that there are both A and B readings in the file, that the relative magnitudes seem correct, and the number of samples used; set the transcomp settings to APC and recompute the file |
| Data will not read to memory or transfer to a computer | The internal memory card has fallen out of place | Power off the instrument, remove the batteries, and open its case; if the memory card is touching the side, it is disconnected; disconnect the light sensor and power cable connectors from the main board, and using a small Philips screwdriver, remove the main board from the case enabling the memory card to be pushed back into place, then replace the main board and connectors, reassemble the case, and reinstall the batteries |

# Applicable and Reference Documents

[1] LI-COR, *LAI-2200C Plant Canopy Analyser Instruction Manual*. Lincoln, Nebraska, United States: LI-COR, 2013.

[2] LI-COR, “LAI-2200C Optical Sensor,” 2017. [Online]. Available: https://www.licor.com/env/products/leaf\_area/LAI-2200C/optical-sensor.html. [Accessed: 10-May-2017].

[3] J. Miller, “A formula for average foliage density,” *Aust. J. Bot.*, vol. 15, no. 1, pp. 141–144, Apr. 1967.

[4] J. M. Welles and J. M. Norman, “Instrument for Indirect Measurement of Canopy Architecture,” *Agron. J.*, vol. 83, no. 5, pp. 818–825, 1991.

###### Appendix

Calibration Certificate

