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USE OF SMARTPHONE TO DERIVE THE LEAF AREA INDEX

Masih Rajaei Najafabadi

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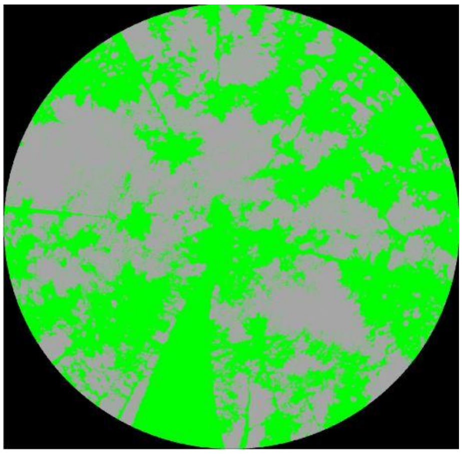

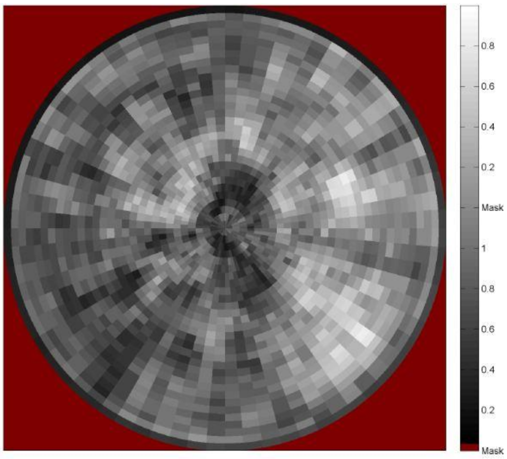

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Use of Smartphone to Derive the Leaf Area Index

Masih Rajaei Najafabadi

Registration number 900829679100

Supervises:

Arun Pratihast

Dr. ir. Jan Verbesselt

A minor thesis submitted in partial fulfillment of the degree of Master of Geoinformation Science at Wageningen University and Research Centre, The Netherlands.

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Laboratory of Geo-Information Science and Remote Sensing

CERTIFCATE

This is to certify that the project work entitled, *"Use of smartphone to derive leaf area index"* submitted to Laboratory of Geo-Information Science and Remote Sensing, Wageningen University during the year 2014, has been carried by **Mr. Masih Rajaei Najafabadi** under the supervision of Arun Pratihast and Dr. ir. Jan Verbesselt, Laboratory of Geo-Information Science and Remote Sensing , Wageningen University, the Netherland for the partial fulfillment of the degree of Master of Geoinformation Science.

Date: 11th of February 2014

Place: Wageningen, Netherland

(Arun Pratihast)

Laboratory of Geo-Information

Science and Remote Sensing,
Wageningen University
Wageningen , Netherland

(Dr. ir. Jan Verbesselt)

Laboratory of Geo-Information

Science and Remote Sensing,
Wageningen University
Wageningen , Netherland

DECLARATION

I, Mr. Masih Rajaei Najafabadi declare that the dissertation "Use of smartphone to derive leaf area index "is submitted to the University of Pune. In the partial fulfillment of the requirements for the award of the degree of the degree of Master of Geoinformation Science, is original work carried out by me and has not been previously submitted for the obtaining degree of any other university.

Masih Rajaei Najafabadi

Date: 11th of February 2014

Place: Wageningen, Netherland

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Masih Rajaei Najafabadi

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Abstract

Leaf Area Index (LAI) is a crucial parameter in environmental, ecological and agronomic because of its importance for quantitative analysis of biophysical process. In particular, it can be an important parameter related to climate, carbon cycle and hydrological modeling studies at different spatial scale. Direct methods for LAI estimation are very accurate, but they are destructive and time consuming and hardly applicable for forest ecosystem. Therefore, it let to development of different fast and non-destructive indirect methods (e.g. LAI-2000 PCA, hemispherical photography and other methods of ceptometers). On the other hand, these instruments are expensive, low portability and in case of damage require long and expensive services. Nowadays, smartphones are become ubiquitous and their advance properties (high camera quality, GPS, and high memory capacity) have made them suitable candidate for indirect methods.

The main objective of this study was to test the Pocket LAI app developed by CSIRO for LAI estimation based on the use of sensors and processing power normally present in most of the modern mobile phones. For testing the app we need to find suitable smartphone, proper height for smartphone to capture images, evaluation and check whether there is any improvement in LAI estimation by increasing number of smartphone's measurements.

After checking and testing the app on over ten locally present smartphone, the result shown Samsung Galaxy S4 mini is a suitable smartphone. The comparison of the LAI of hemispherical photography and smartphone at three heights (0.5m, 1m, and 1.5m) indicates that 0.5 meter (R2=0.7776) is the most suitable height for smartphone to capture images and indicates their comparable performance. There is no improvement in the result of LAI estimation of smartphone at 1 meter with 13 measurements in compare with 5 measurements.

The comparison of the LAI of LAI-2000 PCA and smartphone at three heights for evaluation indicates that there is not significant correlation at any heights and same result between hemispherical photography and LAI-2000 PCA (R2=0.0134) . The comparison of LAI from LAI-2000 PCA and other two approaches indicates that LAI-2000 PCA underestimate the LAI. A possible reason for this can be caused by sensor position, canopy height and user error.

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Abbreviations and Acronyms

ALA	Average Leaf Inclination Angle
CLW forest	CSIRO Land and Water forest
fCover	Fractional cover
LAI	Leaf Area Index
LUT	Look Up Table
NDVI	Normalized Difference Vegetation Index
PAR	Photosynthetically Active Radiation
PCA	Plant Canopy Analyzer
PGAP	Predict Gap Probability
RMSE	Root Mean Square Error
SR	Simple Ratio
VGI	Volunteered geographic information
VI	Vegetation Indices

CHAPTER 1

INTRODUCTION

1. Introduction

1.1. Background

The majority of world vegetation which is complex and widely distributed ecosystem on the Earth, affecting the life of most humans daily, either as an economic good or an environmental regulator is naturally occurring in remote and inaccessible area in wide variety and extent of range(Gosa 2006). Nowadays the need for timely and accurate information on the status and functioning of forest biomes, for a variety of purposes, is increasing. While traditionally forest information was gathered using in-situ methods, the role of remote sensing is becoming more and more central because of the need to the spatial and temporal variability of the key forest processes(Mengesha 2005).

To study the characteristics of vegetation, remote sensing techniques are useful because they provide spatially explicit information and access to remote locations. These techniques allow scientists to examine properties and processes of ecosystems and their inter-annual variability at multiple scales because remote sensing observations can be obtained over large areas of interest with high re-visitation frequencies(Mengesha 2005, Gosa 2006).

Leaf area index (LAI) is one of most used and essential vegetation parameter for numerous studies of atmosphere- vegetation interaction, as it is very often a fundamental parameter for quantitative analysis of many physical and biological processes related to vegetation dynamics and its effects (Confalonieri, Foi et al. 2013) which is defined as the projected one-sided leaf area per unit ground area(Chen and Black 1992, Fassnacht, Gower et al. 1997, Gosa 2006, Khosravi, Namiranian et al. 2012, Confalonieri, Foi et al. 2013). In particular, it has crucial contribution in studies such as: climate, carbon cycle, hydrological modeling, biogeochemistry, ecological, ecophysiological and sit and global ecosystem productivity modeling. This parameter has been routinely estimated from remote sensing measurements (Kucharik, M Norman et al. 1998, Chen, Pavlic et al. 2002, Myneni, Hoffman et al. 2002, Gosa 2006, Pekin and Macfarlane 2009).

Consequently, within the last one and half decades extensive research has been done on the estimation of forest LAI from remote sensing data and most of the studies on forest are based on the relation of LAI with vegetation indices (VIs), such as simple ratio (SR) or the normalized difference vegetation index (NDVI) (Brown, Chen et al. 2000, Chen, Pavlic et al. 2002, Hall, Davidson et al. 2003, Stenberg, Rautiainen et al. 2004, Wang, Woodcock et al. 2004, Gosa 2006). However, the application of such relationships to large areas or at different seasons is limited by being site and sensor specific and the sensitivity of VIs to changes in LAI is often not dynamic enough to allow accurate estimation of LAI(Manninen, Stenberg et al. 2005, Gosa 2006).

The derived LAI products can be validated using a bottom-up approach, i.e. from local field level measurements to global comparison with satellite derived LAI products (for example LAI products of MODIS, AVHRR, and Landsat TM)(Morisette, Baret et al. 2006). LAI databases and validation become significantly important for users to determine the most appropriate product, or combination of products, to use for their applications.

There are several techniques of LAI estimation, generally categorized as direct or allometric methods and indirect methods (Bréda 2003, Jonckheere, Fleck et al. 2004, Weiss, Baret et al. 2004). Direct methods are including harvesting, litter collection and allometry equations (Khosravi, Namiranian et al. 2012) or by non-harvesting litter traps during autumn leaf-fall period in deciduous forests (Jonckheere, Fleck et al. 2004, Gosa 2006). Direct methods are the most accurate, but they are destructive, labor and time consuming (Fuentes, De Bei et al. 2012, Khosravi, Namiranian et al. 2012, Confalonieri, Foi et al. 2013) and hardly applicable in case of forest ecosystems and small leaves species (Confalonieri, Foi et al. 2013). Then, it can be said that direct methods are not suitable for long-term monitoring.

These reasons led to the development of different indirect methods, based on models for light transmission into the canopy and implemented into dedicated commercial instruments (e.g. LAI-2000 Plant Canopy Analyzer (PCA),LAI-2200, Accu- PAR ceptometer , hemispherical photography and CI-100 plant canopy analyzer; (Fuentes, De Bei et al. 2012, Confalonieri, Foi et al. 2013) which this method is known as the gap fraction method(Chen, Rich et al. 1997, Weiss, Baret et al. 2004, Gosa 2006).

Advantages of indirect methods includes fast and easy sampling for a large spatial area (Jonckheere, Fleck et al. 2004, Fuentes, Palmer et al. 2008, Garrigues, Shabanov et al. 2008, Pekin and Macfarlane 2009) . Digital cover image analysis is the most easy-to-use method. This method only requires a common digital camera and its result is highly comparable with more established techniques (Fuentes, De Bei et al. 2012, Gong, Wu et al. 2013). By the advancement in smartphone devices and its accessary such as camera, accelerometer, GPS and increasing memory and processing power has made them suitable for indirect methods (Fuentes, De Bei et al. 2012, Confalonieri, Foi et al. 2013) for LAI estimation. Software packages designed to run on smartphones, in short ''apps'', are expanding fast, and already include scientific applications (e.g.,(D'Elia and Paciello 2012, Fuentes, De Bei et al. 2012, Weng, Sun et al. 2012, Confalonieri, Foi et al. 2013)). Therefore, it has enabled researcher to estimate LAI in an efficient and cost effective way

1.2.Problem definition

LAI is a critical parameter of vegetation (Confalonieri, Foi et al. 2013). The current problems of LAI estimations are:

- ✓ Expensive LAI devices (LAI-2000,LAI-2200 and Accu- PAR ceptometer);
- ✓ Complex measurement technique ;
- ✓ Difficult to implement with local community, citizen science or VGI.

On the other hand, mobile devices are cheap, easy to use and local people can easily use. Mobile devices are becoming ubiquitous and by improvement in their technology and capability, they have become suitable option to use them as a sensor for LAI estimation. Therefore, some researchers have designed software packages to run on smartphones, in short "apps" to estimate LAI (e.g.(D'Elia and Paciello 2012, Fuentes, De Bei et al. 2012, Confalonieri, Foi et al. 2013, Francone, Pagani et al. 2013, Gong, Wu et al. 2013)).

However, the use of smart phone based LAI data is limited due to a lack of confidence in data collection procedures. Moreover, the quality of such data set is often unknown and the data may not be usually consistent because the user may be independent and can collect data independent of each other. This can further result into a problem of oversampling, incomplete data collection and under representation. Thus, there is a need for systematically test the application, method and quality control mechanisms.

Before making smart phone as a key element of LAI estimation, the following research gaps are essential to be explored:

1. What are the technical requirements a smartphone needs to run these apps perfectly? These applications to run perfectly on smartphones need a specific type of operation system and version, but nowadays with different operation systems and different versions, it has become very difficult. While, there are smartphones with different operation systems and versions, which many of them have low quality. It has become very difficult to choose which smartphone can perfectly run such applications. The suitable requirement for Pocket LAI application will be checked in this study.

2. Are the results of these apps accurate enough?

3. How many Image and in which pattern do we need to take image to measure LAI accurately?

4. Are these apps can keep up with development of different operator systems and different versions of smartphones? Every day many more of such questions are adding to this list regarding these applications. To understand and solve these questions, this type of study must be carried out.

Therefore, this study investigates the Pocket LAI application and proves if this application can be an alternative to the available commercial instrument. It includes setting up an experiment to test the application and compare it with LAI-2000 and hemispherical photography method.

1.3. Research objectives and questions

Research objectives and questions of this study are shown in table below

Main Objective ➢ To test the Pocket LAI application	
Sub Objectives	**Research questions**
1. To test the smartphone (Pocket LAI) as tool to for estimating leaf area index.	✓ What are the technical (software and hardware) and external equipment to run the pocket LAI application on smartphone? ✓ What is the best height for smartphone to derive LAI?
2. To evaluate accuracy and effectiveness of smartphone (Pocket LAI) in comparison with expert field measurements (e.g.LAI-2000 PCA).	✓ What is the accuracy of the Pocket LAI application's data compared with LAI-2000 PCA? ✓ Will be any changes in the result of LAI by acquiring more images with smartphone?

Table 1.1.Research objectives and questions

1.4. Structure of the Report

Chapter one of this report comprises an introduction about the general background, overview of the context, definition of the topic and the importance of leaf area index as a key biophysical parameter. Description and definition of the problem is also main part of this chapter. The objectives of this study and research questions are covered in this chapter, as well. Chapter two deals with review of the relevant literature and discusses similar studies conducted in the field of the study area. The third chapter describes the methodologies followed in order to achieve the research objectives. The results of this study are presented and discussed in chapter four. Conclusion and recommendations are given in the fifth chapter.

CHAPTER 2

Literature Review

2. Literature Review

This chapter deals with relevant literatures and studies conducted in similar areas of interest. It also gives an insight about the theoretical background about this research topic by discussing related works.

2.1.Definition of Leaf Area Index (LAI)

The definition of LAI was given by different authors and they vary according to the interest of the individuals. Here are some of the definitions about LAI from the literature. LAI was first defined by Watson (1947) as the total one-sided area of photosynthetic tissue per unit ground surface area(Watson 1947, Jonckheere, Fleck et al. 2004). For broad- leaved trees with flat leaves, this definition is applicable because both sides of a leaf have the same surface area. However, if foliage elements are not flat, but wrinkled, bent or rolled, the one-sided area is not clearly defined. Similar problems exist for coniferous trees, as needles may be cylindrical or hemi-cylindrical (Chen and Black 1992). Therefore, Chen and Black (1992), and Lang (1991), proposed that half the total interception area per unit ground surface area would be a more suitable definition of LAI for non-flat leaves than the projected leaf area which is valid regardless of the vegetation element shape(Lang, McMurtrie et al. 1991, Chen and Black 1992, Jonckheere, Fleck et al. 2004, Weiss, Baret et al. 2004, Mengesha 2005, Gosa 2006).

Some authors consequently defined LAI as the maximum projected leaf area per unit ground surface area (Smith, Sampson et al. 1991, Myneni, Ramakrishna et al. 1997, Jonckheere, Fleck et al. 2004). Within the context of the computation of the total radiation interception area of plant elements, and based on calculations of the mean projection coefficients of several convex and concave objects of different angular distributions. The theoretical reasoning behind abandoning the projection concept was that the latter has neither physical nor biological significance, whereas the total intercepting area has a physical meaning and the total area has a biological connotation (Jonckheere, Fleck et al. 2004). Following current literature and also in this study, LAI is defined as one half the total leaf areas per unit ground surface area (Chen and Black 1992, Fassnacht, Gower et al. 1997, Jonckheere, Fleck et al. 2004, Gosa 2006). Still other definitions of LAI have been proposed. These vary depending on the technique used to measure the LAI. It is therefore important to note that the choice of the LAI definition can result in significant differences between calculated LAI values.

2.2. Methods for LAI estimation

There are two main categories of LAI estimation: direct or allometric and indirect methods (Bréda 2003, Jonckheere, Fleck et al. 2004, Weiss, Baret et al. 2004).

2.2.1. Direct methods

Direct methods are including area harvest, litterfall collection and allometry equations(Jonckheere, Fleck et al. 2004, Khosravi, Namiranian et al. 2012) which they are summarized by Scurlock et al. (2001) as follow:

1. "destructive harvesting and direct determination of one-sided leaf area, using squared grid paper, weighing of paper replicates, or an optically based automatic area measurement system;
2. collection and weighing of total leaf litterfall, converted to leaf area by determining specific leaf area (leaf area/leaf mass) for sub-samples; and
3. allometry (based on simple physical dimensions, such as stem diameter at breast height), using species-specific or stand-specific relationships based on detailed destructive measurement of a sub-sample of leaves, branches, or whole individuals."(Scurlock, Asner et al. 2001, Mengesha 2005, Gosa 2006).

These methods are the most accurate, but they are destructive and extremely time consuming spatially with tall canopies such as those in forest. In this case accuracy problems are result from the definition of LAI, the up scaling methods, or from the error accumulation due to frequently repeated measurements(Jonckheere, Fleck et al. 2004, Gosa 2006). Therefore, these methods are not really compatible for the long term monitoring of spatial and temporal dynamics of leaf area developments. However, direct methods can be considered as calibration methods. These reasons led to the development of different indirect methods.

2.2.2. Indirect methods

Many indirect methods determine LAI from gap fraction over a range of zenith angles. Gap fraction defined as the fraction of sky seen from below the canopy, which can be easily transformed in to effective LAI values(Jonckheere, Fleck et al. 2004, Weiss, Baret et al. 2004, Garrigues, Shabanov et al. 2008, Confalonieri, Foi et al. 2013). Many companies implemented this technique into dedicated commercial instruments. Of all the instruments available for measuring gap fractions, the LAI-2000 plant canopy analyzer and hemispherical photography are attractive because these sensors can measure the canopy gap fraction from several different zenith angles simultaneously(Thimonier, Sedivy et al. 2010).

In general, instruments for indirect LAI estimation proved to be a suitable alternative to directs methods. These instruments are allowing researchers to save time, but on the other hand these instruments are expensive, low portability, and long repairing time in case of damage (Kovacs, Flores-Verdugo et al. 2004, Fuentes, Palmer et al. 2008, Yilmaz, Hunt Jr et al. 2008, Thimonier, Sedivy et al. 2010).

Since all the methods for indirect LAI estimates depend on models for light transmittance into the canopy and these models are strongly affected by canopy architecture (Weiss, Baret et al. 2004, Gosa 2006, Stroppiana, Boschetti et al. 2006) ,testing these methods on canopies with different structures is mandatory.

Nowadays, smartphones are become ubiquitous. Smartphones computation power and storage capabilities are ever growing and with increasing in quality of accelerometer, camera, microphone, GPS, Wi-Fi and gyroscope have made them suitable for indirect methods for LAI estimation. On the other hand, these methods are generally requiring a careful post-processing phase to provide LAI estimates (Confalonieri, Foi et al. 2013).

2.3. Optical field instrument for LAI estimation

The most widely used LAI measuring instruments are also discussed in the following section.

2.3.1. LAI-2000 Plant Canopy Analyzer

The LAI-2000 calculates leaf area index (LAI) and other canopy structure attributes from radiation measurements made with a "fish-eye" optical sensor (LAI-2000, 2005). This instrument is a portable, but it can provide LAI estimates, measuring simultaneously diffuse radiation by means of a fisheye light sensor in five distinct angular bands, with various configurable central zenith angles(Jonckheere, Fleck et al. 2004). These results can be provided without any additional data acquisition and processing(Gosa 2006). LAI-2000 measures the transmitted blue sky light (400-490 nm) under the canopy in five concentric rings from 0º to 75º, from which to calculate the gap fraction for five zenith angle ranges(Chen, Rich et al. 1997).

The LAI-2000 internal software is based on the following assumptions (Mengesha 2005, Gosa 2006, Garrigues, Shabanov et al. 2008):

1. black body assumption(foliage elements are absolutely absorbing);
2. foliage elements are randomly distributed within certain foliage containing envelopes and without their azimuthal orientation is uniform;
3. foliage elements are small compared to the area spanned by each ring.

All computation and stores measurements and results are performed on-board. This instrument has been used to estimate LAI in continuous and homogeneous canopies with success(Levy and Jarvis 1999), but in discontinuous and heterogeneous canopies, there is a general tendency towards underestimating LAI(Chason, Baldocchi et al. 1991, Gosa 2006). Impact of external factors (illumination conditions and boundary effects) can be minimized by means of a 270º view cap (Nackaerts, Coppin et al. 2000). To achieve best results, two LAI-2000 devices must be used; one in open space, and the other in the canopy(Mengesha 2005) , but during an overcast sky or perfect diffuse conditions, one LAI-2000 instrument can be used.

2.3.2. Hemispherical Canopy Photography

Hemispherical canopy photography is a technique used to measure sub-canopy light conditions (Roxburgh and Kelly 1995, Mengesha 2005, Gosa 2006) and it also defined explicitly by Jonckheere et al. (2004a) as a technique for studying plant canopies via photographs acquired through a hemispherical fisheye lens from beneath the canopy (oriented upwards) or placed above the canopy looking downward. Hemispherical photographs provide a 180º field of view. Moreover, it provides a permanent record which is a valuable information source for position, size, density, distribution of canopy gaps, and clumpiness through the gap size distribution (Chen and Cihlar 1995, Gosa 2006).

Hemispherical photography is more flexible in more variable illumination conditions, particularly when looking upwards in compare with other instrument such as the LAI-2000. On the other hand, with the advent of affordable digital technologies, standard graphic image formats, and more powerful desktop computing, digital image analysis techniques have been used increasingly to examine hemispherical canopy photographs (Rich 1990, Mengesha 2005).

In hemispherical photography method for determination of LAI, the selection of the optimal brightness threshold in order to distinguish leaf area from sky area thus producing a binary image is one of the main problems cited in the literature , while with a high resolution digital camera, the choice of the threshold level would be less critical, because the frequency of mixed pixels is reduced in comparison to the aggregation of pixels in cameras with lower resolution(Leblanc, Chen et al. 2005, Zhang, Chen et al. 2005, Gosa 2006). A series of software packages for hemispherical images processing have been developed, Hemiview (Delta-T Device), SCANOPY GLA (Forest Renewal BC) and CAN_EYE (http://www6.paca.inra.fr/can-eye) (Weiss, Baret et al. 2004, Baret, Weiss et al. 2005, Gosa 2006). Hemispherical photography has already proven over the last decade to be a powerful indirect method for measuring various components of canopy structure and under story light regime and also a technique that is markedly cheaper than alternatives.

CHAPTER 3

METHODOLOGY

3. Methodology

3.1. Study area

The study area for the use of smartphone to derive the leaf area index is conducted at Pine segment of Oostereng, Netherlands. Oostereng is the name for a number forest fragments between Wageningen and Bennekom (Fig. 3.1). It is situated at 51.6º N and 5.42º E and it covers approximately an area of 19 km^{2}.

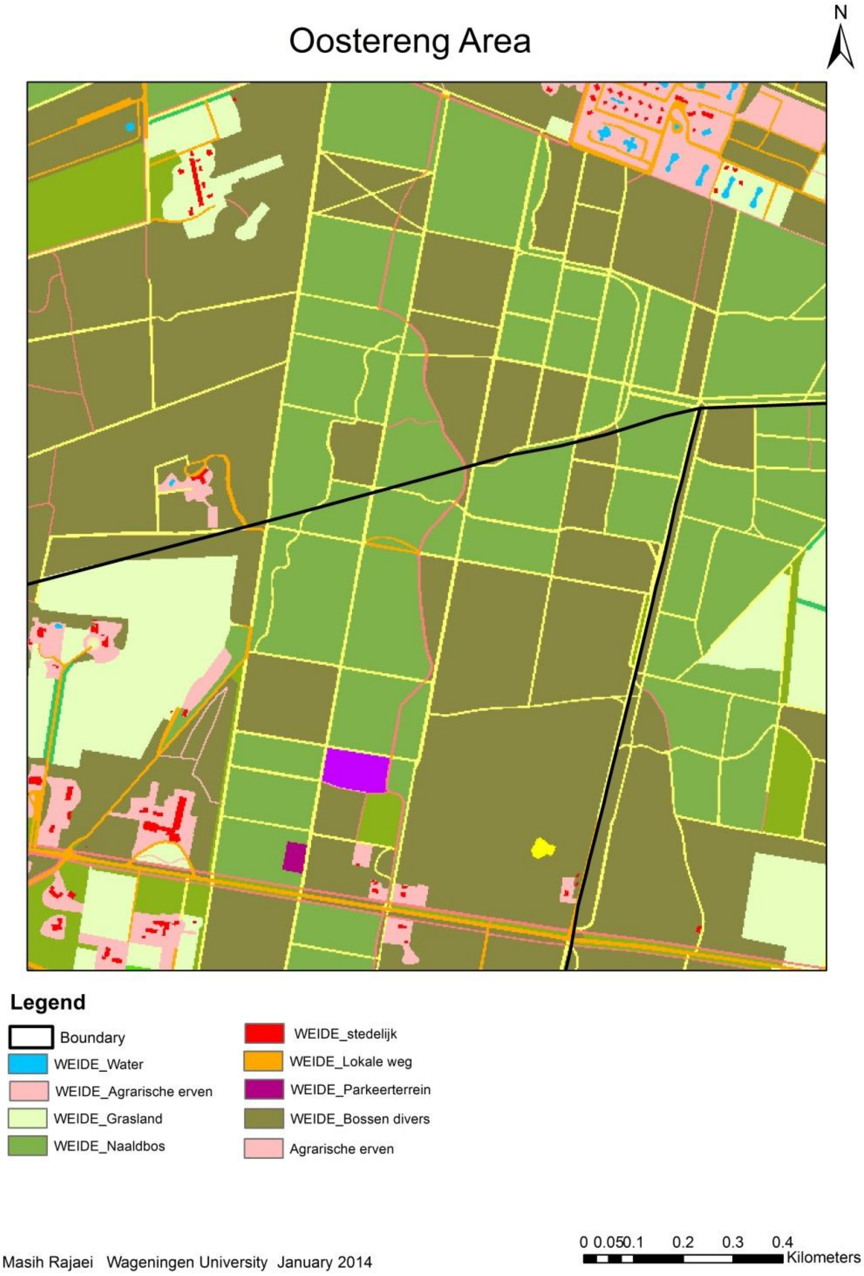

Fig. 3.1 Location of the study area

This forest consists of plantations of conifers (Pinus, Pseudotsuga, Larix) (Fig. 3.2), and there are also various deciduous trees (Quercus, Betula) and a lane with old beech trees (Fagus).

Fig. 3.2 Pine segment of Oostereng forest

3.2.Methodological Conceptual Model

The general working methodology of this study followed the schema indicated by a conceptual model in Fig. 3.3. There are generally three input data sets: LAI2000; hemispherical photographs and smartphone. The ground measurements of LAI2000 were used for finding the best height. Finally, the output was compared with hemispherical photographs for evaluation the result.

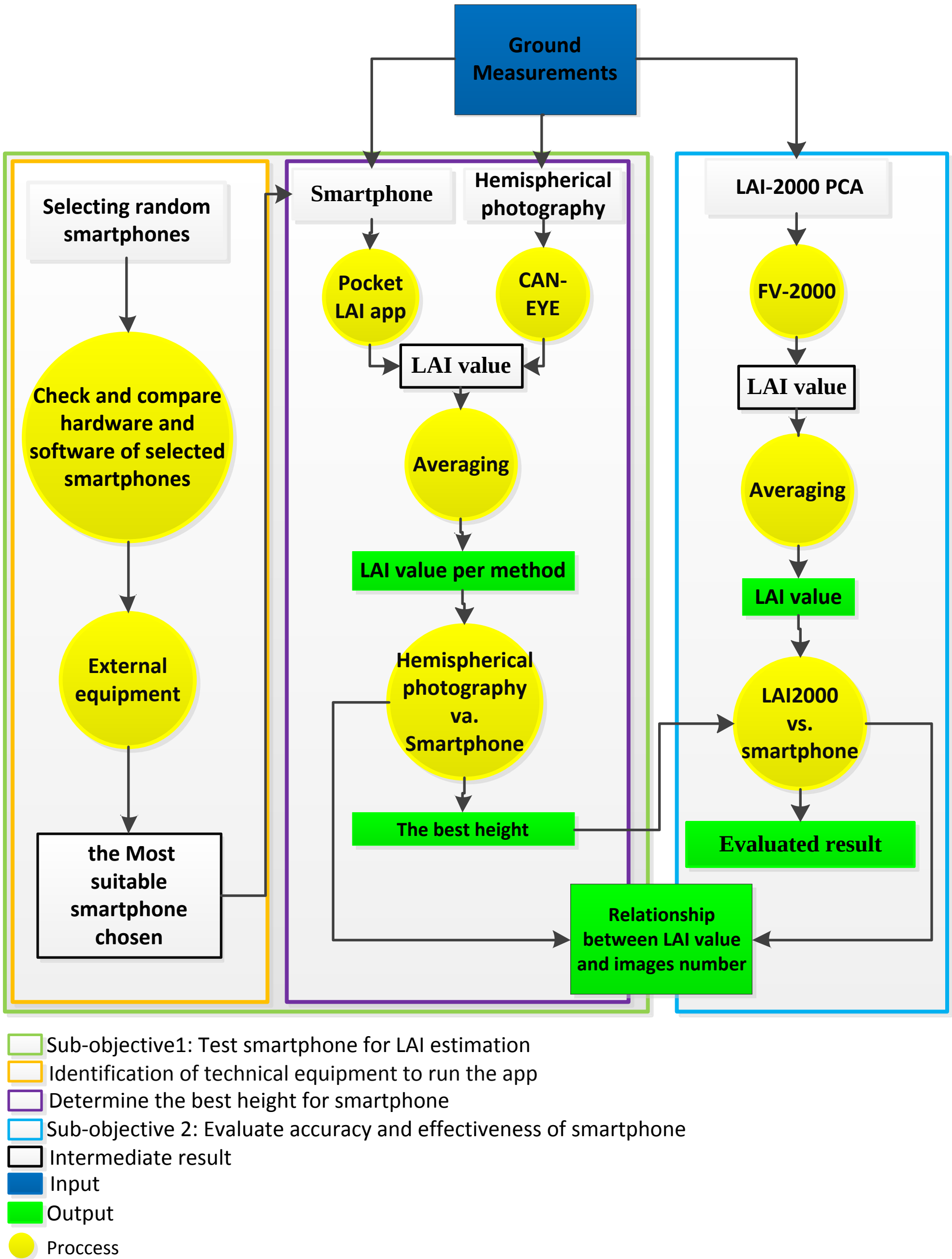

Fig.3.3 Flow chart of working scheme to use of smartphone to derive leaf area index

3.3. Ground Measurement Sampling Technique

This is a cross-sectional study and all data were collected in November 2013 at Pine segment of Oostereng forest. 25 plots were measured on a straight line with 45° angle in 100 m distance from each other up to 300 m which each plot covers 100m^2 (Fig. 3.4).

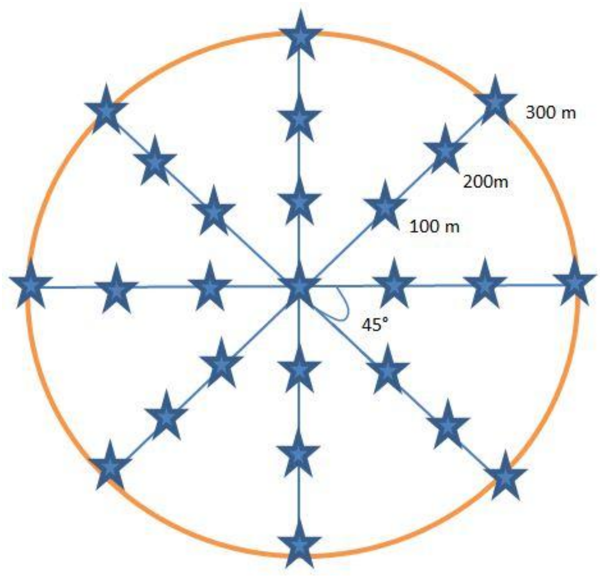

Fig. 3.4 Sampling Technique

Therefore, for achieving more accurate LAI estimation; at each plot five times LAI were measured (Fig. 3.5) and later the average was derived from these five measurements. The sampling technique is same for all three instruments. Few parameters like canopy height, plot dimensions, site topography, height of sensors from ground, and spatial integration of sensors are causing variation in LAI estimation (Nilson 1971, Kucharik, M Norman et al. 1998, Bréda 2003, Weiss, Baret et al. 2004). Therefore, many researchers (Morrison 1991, Jonckheere, Fleck et al. 2004) stated that at 1m above ground, LAI can be determining with good accuracy.

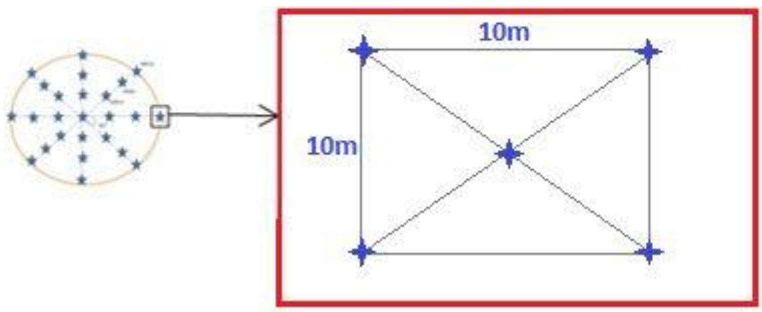

Fig. 3.5 Measurements at each plot

A total 825 measurements were included in this study which with each instruments (LAI-2000 and Hemispherical photography (Nikon D700 hemispherical digital camera with fisheye lens)) 125 measurements and with smartphone 575 measurements (at three heights (0.5m, 1m and 1.5 m)) each 125 measurements and also 200 extra measurements were collected at 1m height (at each plot 8 extra measurements) (Fig. 3.6).

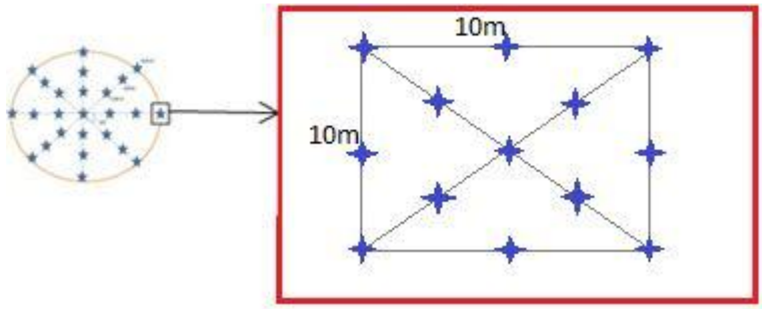

Fig. 3.6 Extra measurements at 1m height

The location of each measurement was determined using Garmin 60CSx, which has an accuracy of about ±3m and smartphone itself. In case of sunny and bright day, an azimuth mask of 180° view caps will be used on LAI-2000 sensor to block the bright sky near the sun's direction and to eliminate the shadowing effect of instrument operators (Gosa 2006).

3.4. Smartphone selection

Smartphones are becoming ubiquitous; this section is dealing with identification of proper hardware and software present at local area in a common smartphone and external requirement to use the Pocket LAI application run on it perfectly. For better understanding the Pocket LAI application, a contact was made with the developer of the application Mr. Anders Siggins (Anders.Siggins@csiro.au) at CSIRO, Australia and few suggestions about the external requirement for smartphone to analyze properly were made.

Randomly 10 common smartphones such as: Samsung galaxy young, Motorola DEFY XT556, Sony experia E, Samsung Corby S3850, Samsung galaxy S2, Samsung galaxy S4 mini, IPhone 4, Samsung galaxy star, HTC Vivid, and Samsung galaxy S5301 were chosen to run the application on. All of the properties (hardware and software) of these smartphones were checked and later the application was installed on all smartphone to run a test with proper external requirement. After the test, the most suitable smartphone was chosen based on its properties and performance.

3.5. LAI estimation from Optical field instruments

3.5.1. Smartphone

The Pocket LAI application is designed to capture images straight upwards, adjust mask manually, calculate LAI, PGAP, and finally save results with coordinate of the location in a file on smartphone memory (Fig.3.7). In this study, all measurements were made in uniform overcast cloud condition to reduce the effect of scattered blue light in the canopy and to have diffuse radiation from all directions in the hemisphere.

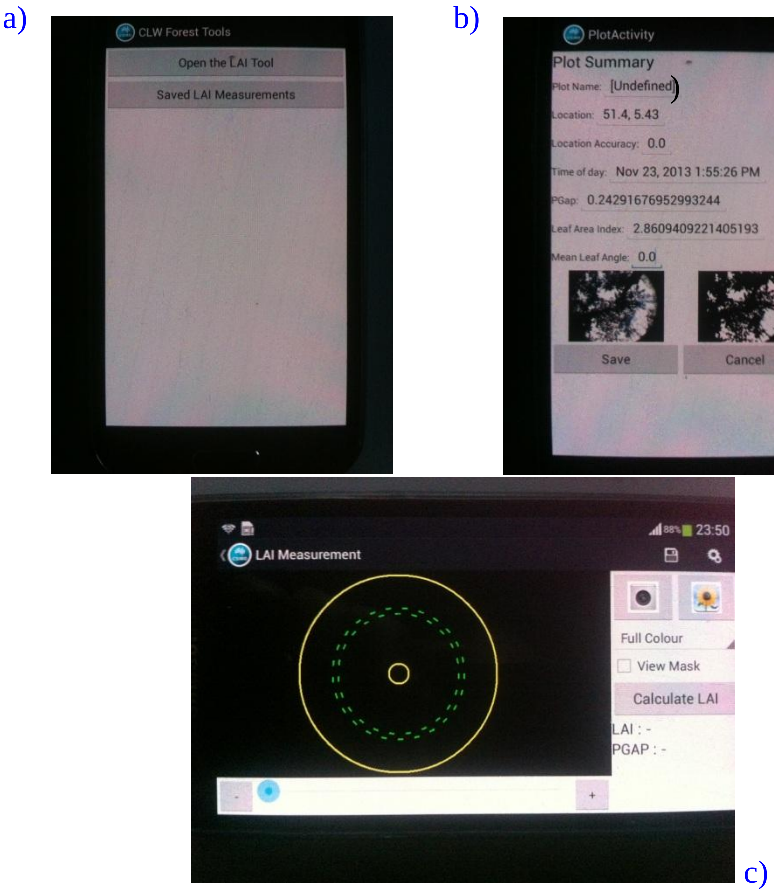

Fig. 3.7 An overview of the application

3.5.1.1. Image collection

Before starting with capturing images, the fisheye clip lens was adjusted on smartphone's camera and GPS was enabled.

Fig. 3.8 Captured image at 0º zenith

To start capturing images, the following procedures were taken:

1. Run the Pocket LAI application (CWL forest tools);
2. Click on the Open LAI tool's bottom;
3. Click on the camera logo on top right side (Fig. 3.7c);
4. To capture images upwards exactly at 0º zenith, the dot must be exactly in the crosshairs when an image is captured (Fig. 3.8);
5. The captured image is saved automatically in a folder in photo gallery of the smartphone for further analysis.

For this study three sets of images at three different heights were captured. Therefore, to captured these images at exact height; a pole with marked heights was used.

3.5.1.2. LAI estimation and save data

After capturing images, this is time for analyzing images for LAI estimation and save data in application's folder.

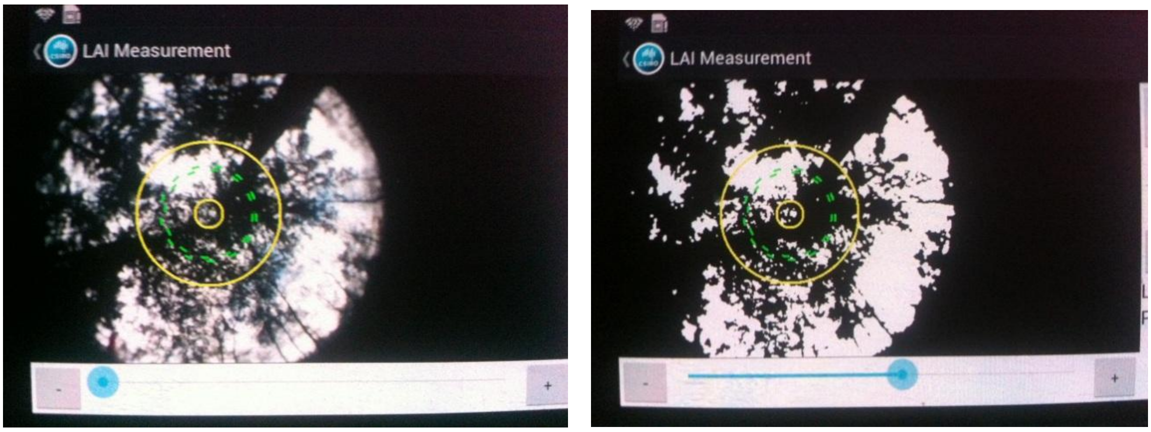

Fig. 3.9 An image with properly adjusted mask

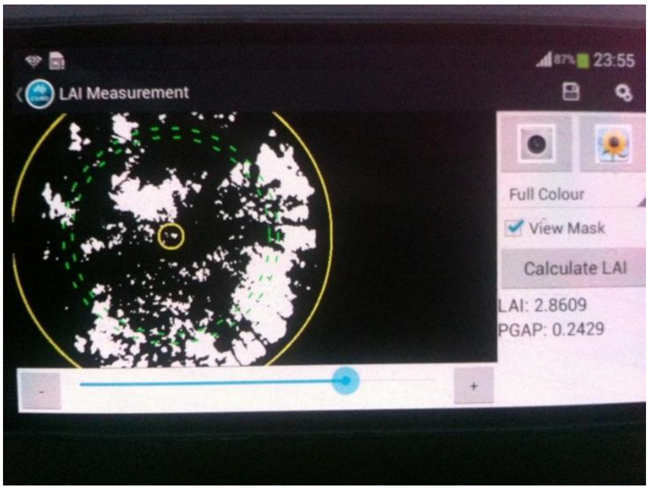

Fig. 3.10 Expanded green rings up to the edges of the image

To start this part, the following procedures were taken:

1. Select an image from phone's gallery by clicking on the second button on top;
2. Manually adjust proper mask for image at the bottom of the page (Fig. 3.9);
3. There are three sets of rings present in application (Fig. 3.7c). The inner yellow ring is simply a guide for the center of the image and outer yellow ring is a selection ring for image processing. There should be two other rings – dashed green ones. These show the 'magic angle' or hinge point zone. These rings must be expanded until it

matches the edges of the image before calculation of LAI (Fig.3.10).

4. Click the Calculate LAI button;
5. LAI and PGAP values are appeared (Fig. 3.10);
6. To save the results, a save button on top right side of this page (Fig. 3.7c) must be clicked. A page with Plot Summary name on top is opened (Fig. 3.7b). In this page all the information of the image are filled automatically, but plot name must entered manually.
7. These information can be accessed either by clicking on the Saved LAI measurements button (Fig. 3.7a) or from desktop for further analysis.

As it already mentioned in section 3.3, there were five measurements for every height at each plot. There were also eight extra measurements at 1m height (total eighteen measurements). Finally, measurements at every height (0.5m, 1m, and 1.5m) were averaged per plot to get more accurate plot level LAI and also average of eighteen measurements at 1m height were taken (Appendix 2).

3.5.2. LAI-2000 Plant Canopy Analyzer

The LAI-2000 plant canopy analyzer is designed to be used in diffuse light conditions with either no cloud or complete cloud cover. An azimuth mask of 180º view caps was used on LAI-2000 sensor all the time to block the bright sky near the sun's direction and to eliminate the shadowing effect of instrument operators.

A plan was designed for the LAI-2000 to record seven measurements by holding the LAI-2000's sensor 1 meter above ground surface. Five records were made within canopy for each plot and two reference recorded were made outside canopy in the open area, one before entering in canopy and one at end. All measurements were extracted using FV2000 software (http://envsupport.licor.com/index.jsp?menu=Area_Meters&spec=LAI-2000). Finally, measurements were averaged per plot.

3.5.3. Hemispherical Photography

Hemispherical photographs were acquired as same time as LAI-2000 and smartphone. The photographs were captured by the use of Nikon D700 hemispherical digital camera at 0° zenith. For capturing images at 0° zenith, a 3D

Fig 3.11 3D level for hemispherical photographs

level was used (Fig. 3.11). The images captured were arranged in similar orders in a folder to be processed by software developed for this specific purpose. Accordingly, the images in one elementary sample unit were arranged in folders named UP and Down for upward and downward photos (Fig. 3.12) for the processing purpose.

These procedures are implemented on the photographs arranged in folders according to the direction and the plot from which they are taken based on CAN- EYE software (http://www6.paca.inra.fr/can-eye/). The dedicated software, CAN_EYE, which was developed to process the color hemispherical photographs with special emphasis on green element, was used to do the classification and processing of a series of five photographs at a time. The software processes with optimal performances a large number of photographs to derive canopy characteristics. This neural network system based CAN_EYE version 6.3 software was used to compute the LAI value and gap fraction.

Fig 3.12 Upward looking hemispherical photographs of plot 23

As compared to currently existing software available for processing hemispherical images, CAN_EYE has a set of specific features that improves its efficiency, accuracy, flexibility, portability and traceability (Jonckheere, Fleck et al. 2004, Weiss, Baret et al. 2004, Gosa 2006).

3.5.3.1. Calibration of the CAN-EYE software

Before any image processing, the CAN-EYE software must to be calibrated and this process is done manually. The software calibrate requires few training images and for this study, eleven training images were captured (Figs 3.13 and Appendix 4).

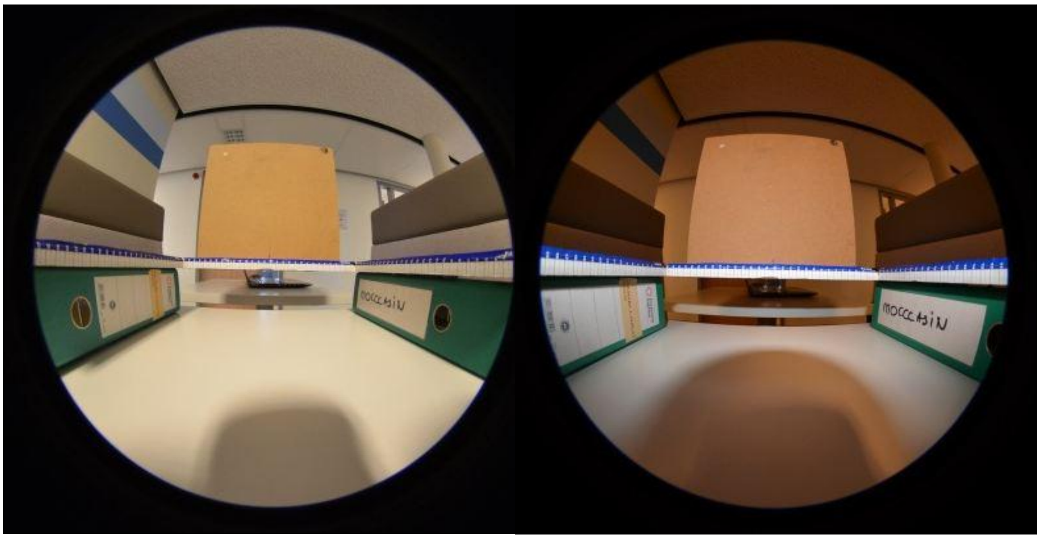

Fig 3.13 First set of calibration Images (Images at two different distances)

To calibrate the software the following procedures were taken:

1. Open the Calib_Panasonic_DMC_FZ8 excel file;
2. In the Start page, enter X -Y resolution of training images;
3. In the Optical Center page, fill X –Y coordinates of the 3 holes for each image in order (Appendix 4);
4. In the Projection Function page, fill value (cm) of given fixed pixels from fig. 3.13 and save the file;
5. Open CAN-EYE software, go to Calibration and click on the optical center; select the excel file which prepared in step 4 and wait until it is calibrated;
6. Repeat the same procedure for the projection function and wait until it is calibrated (Fig. 3.14).
7. The result of calibration is saved in the result page of the excel file.

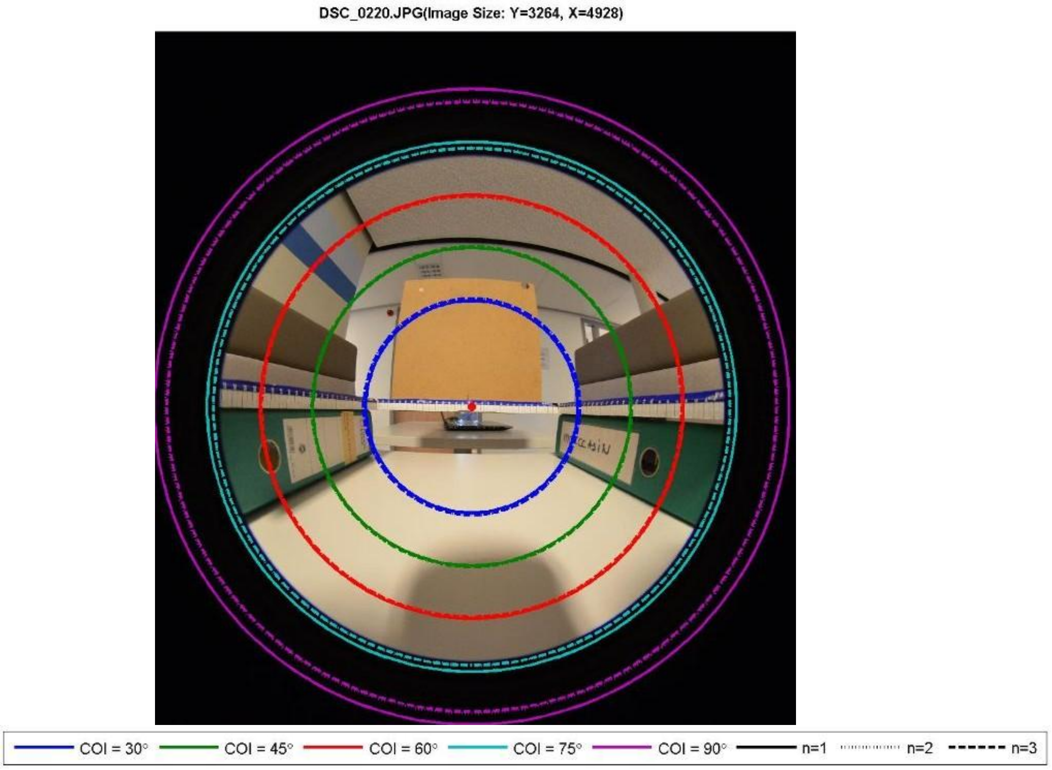

Fig. 3.14 Calibration result

3.5.3.2. Image processing the CAN-EYE software

After calibration, the following procedures were taken for image processing:

1. Go to Hemispherical Images, RGB Images and click on Upward. Select the folder contains images;
2. Parameterization page opens. In this page all the parameters for image processing are defined and saved. In this study all the photographs were processed using the following calibration parameters and angular resolution of the CAN_EYE software in table 3.1.
3. The Raw image pages opens, in this page very basic setting can be changed;
4. The Masking pages opens, in this page a threshold can be set and press ;

Table 3.1 Calibration parameters

Calibration Parameters	value
Image size (lines)	4928
Image size (rows)	3264
Optical center (lines)	1641
Optical center (rows)	2466
Horizon (pixel)	4928
Radius (°)	90
Sub-sampling factor	2
Circle of interest (°)	75
Zenith angular resolution (°)	2.5
Azimuth Angular Resolution (°)	5
fCover max zenith angle (°)	10
Latitude (°)	52

5. The classification page opens, in this page a method can be chosen between mixed-pixel and no-mixed method for image classification. In this study all images were classified by mixed method.
6. The next page is the result page. It may take long time to compute (Fig. 3.15).

7. The result is saved in a excel file in the selected image folder. In this study, measurements were averaged per plot.

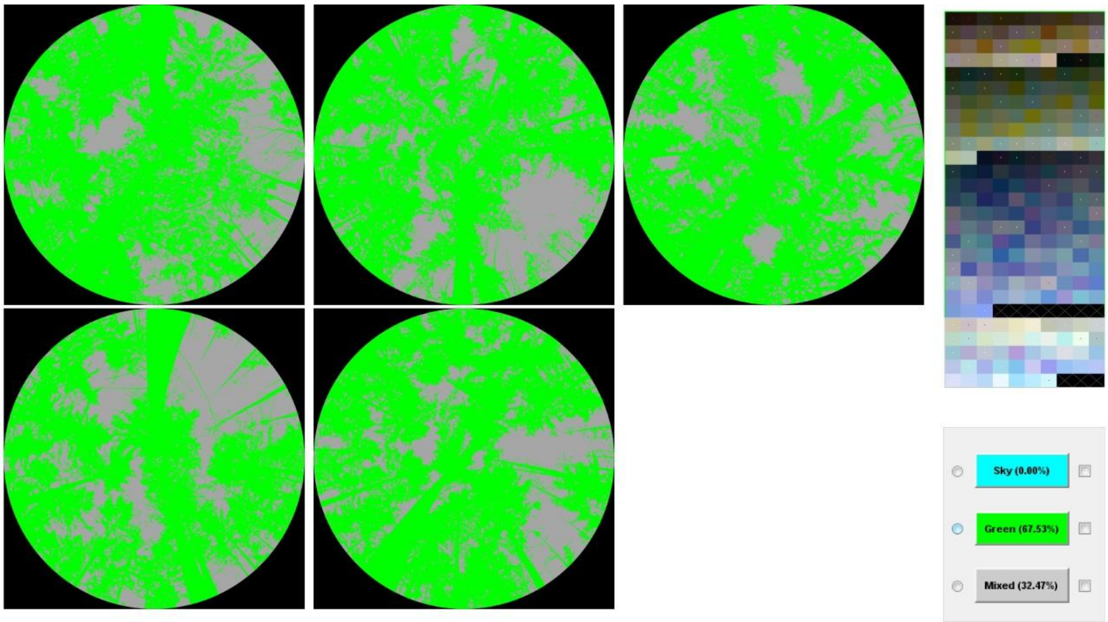

Fig 3.15 The result page of plot 1

All the calibration parameters determined by the extent of the photographs i.e., size in pixel and field of view of the hemispherical camera used. The calibration parameters, the angular and, circle of interest were obtained manually and were used for image processing.

The photographs were computed at 75° circle of interest. The gamma factor was used to increase the brightness of the image or darkening the image to provide better visual discrimination between the vegetation elements and the background. At the end of preprocessing, the colors are reduced to a sufficient number to get good discrimination capacities. The classification step differentiates the leaf and the non-leaf areas in to different classes. Then after, the gap fraction is computed to derive LAI. The technique to derive the canopy architecture variables leaf area index (LAI) and average leaf inclination (ALA) using CAN_EYE is based on the use of a look-up-table (LUT), i.e. a reference table composed of gap fraction value in different view zenith angles and the corresponding LAI and ALA parameters (Jonckheere, Fleck et al. 2004, Weiss, Baret et al. 2004, Gosa 2006).

CHAPTER 4

RESULTS AND DISCUSSION

4. Results and Discussion

4.1. Smartphone selection

It is not possible to find the best smartphone to run the Pocket LAI application due to presence of vast number of smartphones with different feature properties. Therefore, this study was checked ten common smartphones present in local area. The most suitable smartphone for this study was Samsung Galaxy S4 mini. This smartphone in comparison with other ones has very high camera quality, high processor and enough storage capacity. Other smartphones like Samsung Galaxy S2 and HTC Vivid had high camera quality and processor, but their versions of OS were low and the application was not able to run. Summary of checking smartphone's properties were given in Appendix 1. For smartphone to capture image properly, a universal fish eye clip lens was used (Fig. 4.1). This was the only external requirement identified.

Fig. 4.1 Fish eye clip lens

4.2. Comparison of LAI results from optical field instruments

4.2.1. Best height for smartphone

Estimation of leaf area index using smartphone was made at three heights for 25 plots with Pocket LAI application. Summary of smartphone measurement results are given in Appendix 2. The results of the analysis of averaged LAI value ranges from 3.02 – 6.79 m2/m2, 3.95 – 6.77 m2/m2 and 3.46 – 6.47 m2/m2 at 0.5 meter, 1meter and 1.5 meters, respectively (Table 4.1).

Table 4.1 Summary of averaged LAI (m^2/m^2) at three heights as estimated using smartphone

Plot number	Smartphone		
	0.5 m	**1m**	**1.5m**
plot 1	3.5504	4.018	4.06
plot 2	3.0186	3.957	3.463
plot 3	3.7898	4.632	3.6934
plot 4	4.1448	4.7142	3.862
plot 5	5.2623	5.425	4.7496
plot 6	5.4076	6.225	4.825
plot 7	5.0728	5.1356	5.0556
plot 8	4.4362	5.0442	4.3958
plot 9	4.7998	5.387	4.475
plot 10	4.4612	4.7156	5.145
plot 11	4.9426	5.0158	5.0498
plot 12	5.1142	5.3636	4.9278
plot 13	5.5974	5.31616	4.6366
plot 14	5.8624	6.2488	5.4478
plot 15	6.0204	6.385	5.9846
plot 16	5.9584	6.1216	6.1568
plot 17	5.7536	6.6352	5.9816
plot 18	4.9972	5.614	5.4738
plot 19	4.6016	5.0482	4.9026
plot 20	4.7644	5.2766	4.8444
plot 21	5.046	5.481	5.2747
plot 22	4.7792	5.5308	5.0772
plot 23	6.791	6.7736	6.4762
plot 24	5.613	6.2404	5.7866
plot 25	6.393	6.6412	6.0692

The hemispherical images were processed using the CAN_EYE software (version 6.3) to derive leaf area index and all images were acquired upward. The result of the analysis of averaged LAI value ranging from 3.77 – 6.39 m^2/m^2 (Table 4.2). The result reveals that plot 2 is the most dense (vegetation% = 72.07) and plot 11 is the lowest dense (vegetation% = 36.95) (Appendix 3).

Table 4.2 Averaged LAI (m^2/m^2) as estimated by hemispherical photography

Plot number	LAI
Point 1	3.95
Point 2	6.77
Point 3	4.31
Point 4	4.40
Point 5	4.90
Point 6	5.16
Point 7	4.46
Point 8	4.98
Point 9	4.62
Point 10	4.36
Point 11	3.78
Point 12	5.09
Point 13	5.43
Point 14	5.27
Point 15	5.14
Point 16	5.11
Point 17	5.27
Point 18	4.60
Point 19	4.38
Point 20	5.25
Point 21	4.94
Point 22	5.00
Point 23	6.36
Point 24	5.92
Point 25	6.09

White et al. (2000) concluded that hemispherical photography is the most accurate and efficient way, as compared to LAI-2000 for long term monitoring of arid ecosystems. This was in good agreement with the recent results of Leblanc et al. (2002c), who concluded that hemispherical photographs in a grid offer a good potential to replace LAI-2000 devices for canopy structure measurement (Gosa 2006).

Much care has been made to avoid the errors (Rich 1990, Gosa 2006) during different processing steps of hemispherical photographs using CAN_EYE software. Some error can be made during image capturing such as the moisture on the lens(Gosa 2006) and distortion. Rich et al., (1988) discussed the problems and summarized it as an error in the case of image acquisition, which includes camera positioning, horizontal/ vertical positioning, exposure, evenness of sky lighting, evenness foliage lighting (reflections), direct sunlight, and optical distortion.

The other possibility of committing an error according to him is classified as during image analysis while distinguishing foliage from canopy openings, assumed direct sunlight distribution, assumed diffuse skylight distribution, assumed surface of interception, image editing/enhancement, consideration of missing areas and finally in the case of violation of model assumptions like assessment of G- function variations, leaf angle variability and consideration of clumping factors (Rich 1988, Rich 1990, Gosa 2006).

The availability and use of the color plates in the latest version of CAN_EYE (i.e. CAN_EYE Version 6.3) during the classification process gives a better chance to accurately assign the leaves, and sky, in the proper classes based on the percentage of the availability of each class in the input image.

To find the best height for smartphone to capture images was to compare its result with other instrument's result like hemispherical photographs. These two instruments are using same technique, but different approaches to estimate LAI. The results of relationship between hemispherical photography and smartphone were shown in Figs 4.2 – 4.4.

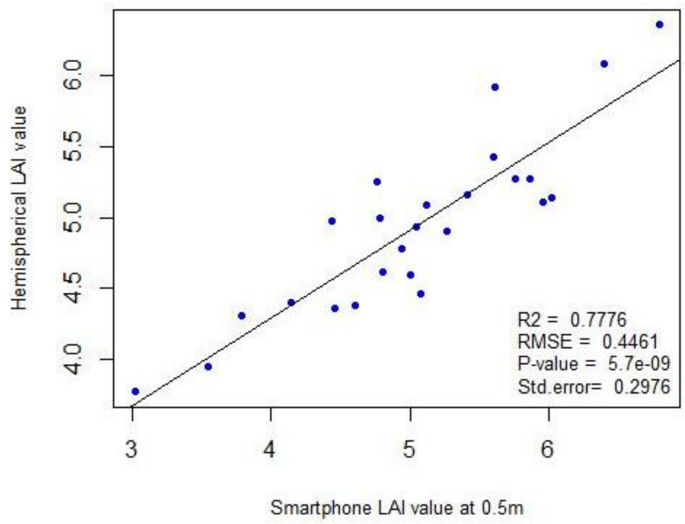

Fig 4.2 Relationship between LAI value (m^2/m^2) using hemispherical photography and smartphone at 0.5 meter

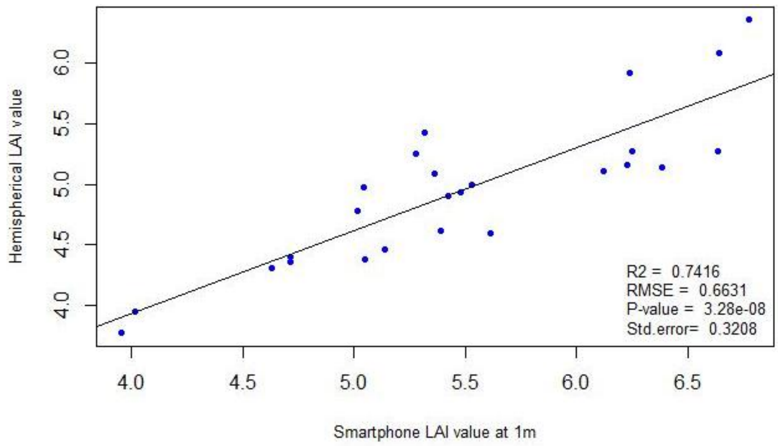

Fig 4.3 Relationship between LAI value (m^2/m^2) using hemispherical photography and smartphone at 1 meter

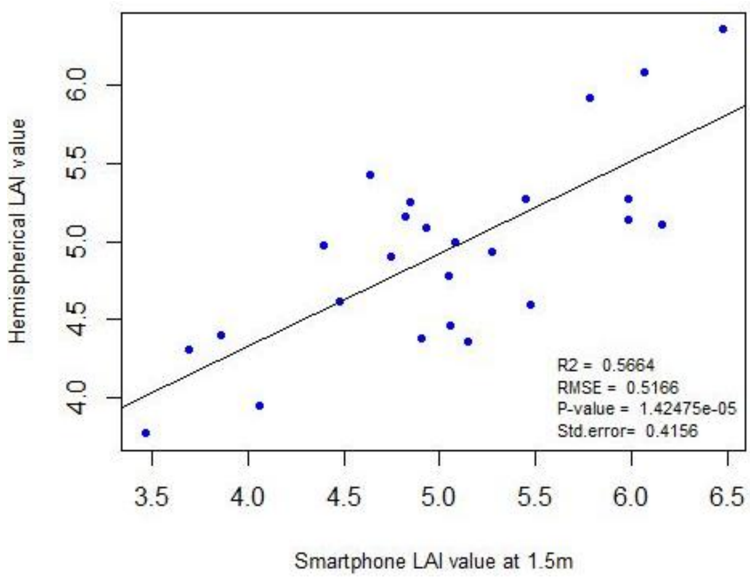

Fig 4.4 Relationship between LAI value (m^2/m^2) using hemispherical photography and smartphone at 1.5 meters

The results above are represented that as height increases, correlation decreases. Therefore, there is high correlation between hemispherical photographs and smartphone LAI at 0.5 meter (R^2=0.7776 and RMSE= 0.4461) and low correlation at 1.5 meters (R^2=0.5664 and RMSE= 0.5166) (Appendix 5). Thus, the best height for smartphone to capture and analyses images is 0.5 meter. The area smartphone can captures, decreases as height increases. Then, there is a larger area for smartphone to analyses and obtains LAI. On the other hand, many other parameters can affect LAI such as: canopy density, smartphone position, direct sunlight, moisture and height of canopy. The other possibility of an error can be in LAI computation, because masking process is manually user must to decide whether use mask or not and how much. However, no explanations for these parameters are evident, and there remains a need for further testing.

4.2.2. The relationship between LAI values of LAI-2000 PCA and smartphone to find how accurate is smartphone's result

The results of the analysis of averaged LAI value using LAI-2000 PCA ranges from 3.22 – 6.57 (m^2/m^2) (Table 4.3) and the results of smartphone's LAI value are shown in table 4.1.

Table 4.3 Averaged LAI (m^2/m^2) as estimated by LAI-2000 PCA

Plot number	LAI
plot 1	6.57
plot 2	5.58
plot 3	3.63
plot 4	4.02
plot 5	4.32
plot 6	4.86
plot 7	3.47
plot 8	3.22
plot 9	4.74
plot 10	3.83
plot 11	3.76
plot 12	3.69
plot 13	6.53
plot 14	4.48
plot 15	4.46

plot 16	5.37
plot 17	4.62
plot 18	4.73
plot 19	5.05
plot 20	4.09
plot 21	4.38
plot 22	5.52
plot 23	3.94
plot 24	4.08
plot 25	5.08

Figs 4.5 – 4.6 are shown the correlation between LAI-2000 PCA and smartphone at three heights. All three results (smartphone at 0.5meter, 1meter, and 1.5 meters) are shown very low correlation (R^2 =0.0064, R^2=0.0094, and R^2=0.0084) (Appendix 5), which their values are almost zero and very high RMSE. These results are opposite to the result hemispherical photographs and smartphone.

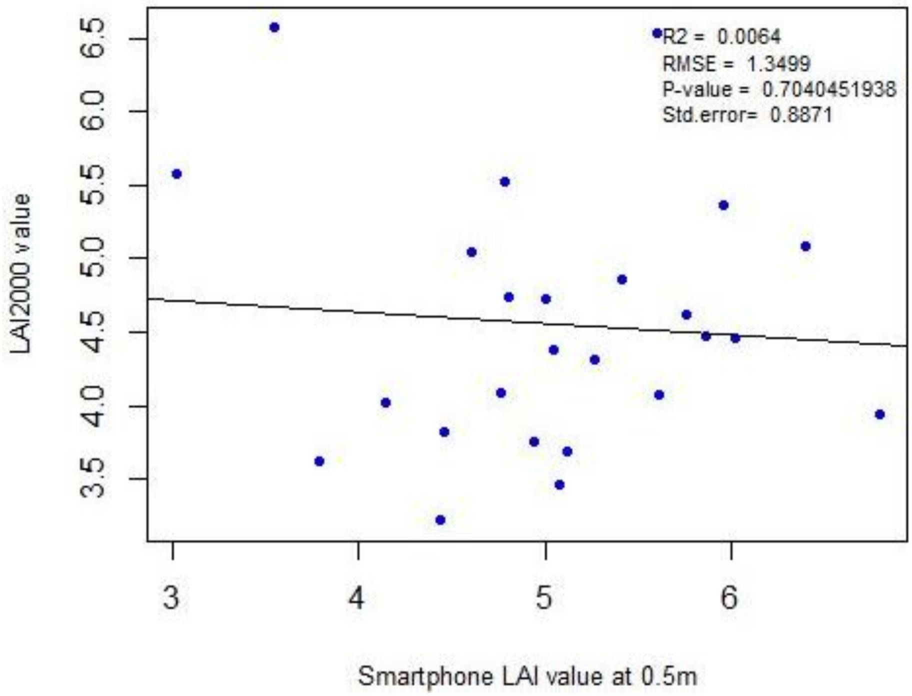

Fig 4.5 Relationship between LAI value (m^2/m^2) using LAI-2000 PCA and smartphone at 0.5 meter

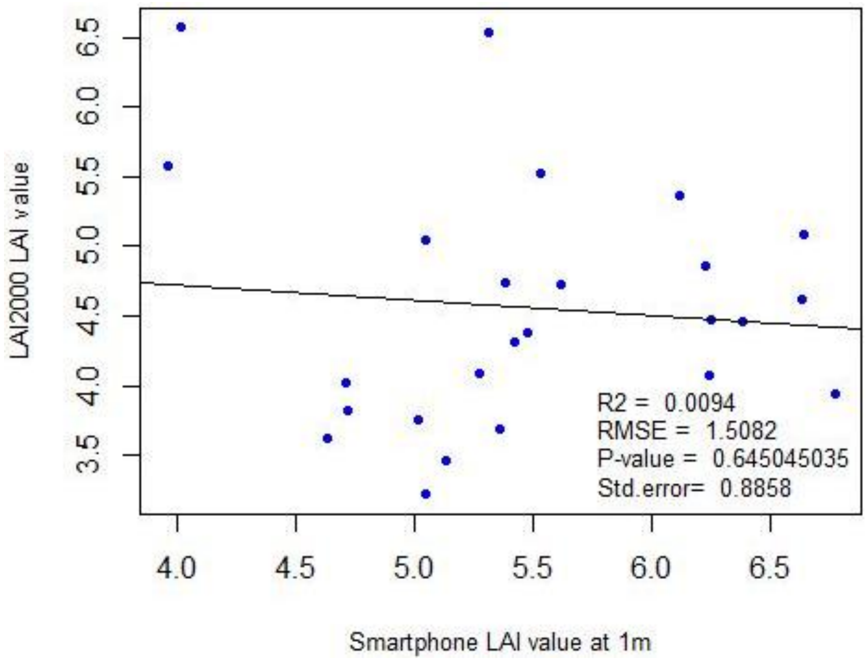

Fig 4.6 Relationship between LAI value (m^2/m^2) using LAI-2000 PCA and smartphone at 1 meter

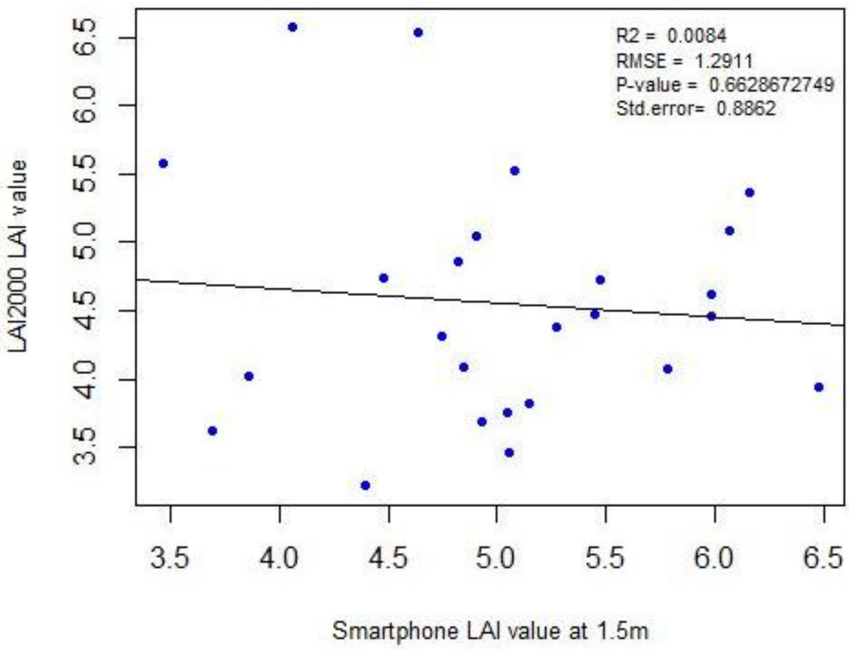

Fig 4.7 Relationship between LAI value (m^2/m^2) using LAI-2000 PCA and smartphone at 1.5 meters

Also hemispherical photographs and LAI-2000 PCA was shown no correlation (R^2 = 0.0134 and RMSE = 1.166) same as smartphone (Fig 4.8). Jonckheere et al. (2004a) mentioned the possibility of errors as with any remote sensing technique, at any stage of image acquisition, analysis or violation of model assumption (Gosa 2006).

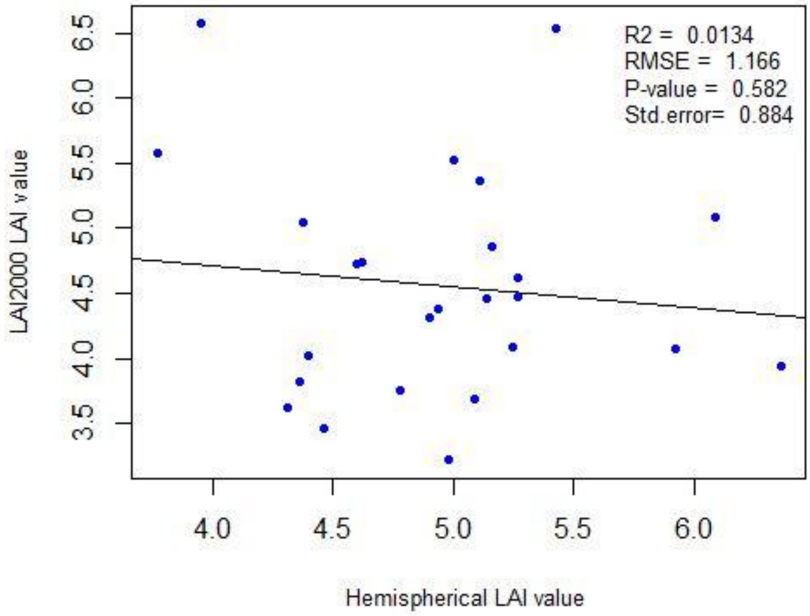

Fig 4.8 Relationship between LAI value (m^2/m^2) of hemispherical photographs and LAI-2000 PCA

These results are represented that the LAI-2000 PCA is not suitable instrument for validation. The comparison of LAI from LAI-2000 PCA with other two instruments represented that LAI-2000 PCA underestimate the LAI (Appendix 5). On the other hand, in some studies (Nackaerts, Coppin et al. 2000, Jonckheere, Fleck et al. 2004, Weiss, Baret et al. 2004, Gosa 2006, Garrigues, Shabanov et al. 2008) it mentioned that the LAI-2000 PCA is one of the accurate instruments, but in order to get an accurate LAI estimation the LAI-2000 PCA needs an above canopy reference reading (Welles 1990, Jonckheere, Fleck et al. 2004). These abnormal results can be caused by user error, direct sunlight, sky lighting, sensor position, and moisture. However, there remains a need for further testing.

4.2.3. The effect of high number of measurements at 1 meter height on LAI value from smartphone

The results of the analysis of averaged LAI value of 13 measurements using smartphone at 1 meter height ranges from 3.62 – 6.65 (m^2/m^2) (Table 4.4) (Appendix 2).

Table 4.4 Averaged LAI (m^2/m^2) of 13 measurements at 1 meter height as estimated using smartphone

Plot number	**Smartphone 13 measurements**
	1 meter
plot 1	4.148
plot 2	3.616
plot 3	3.841
plot 4	4.174
plot 5	5.070
plot 6	5.286
plot 7	5.028
plot 8	4.626
plot 9	4.928
plot 10	4.803
plot 11	5.209
plot 12	5.373
plot 13	5.496
plot 14	6.231
plot 15	6.224
plot 16	6.130
plot 17	6.186
plot 18	5.527
plot 19	4.883
plot 20	4.986
plot 21	5.224
plot 22	5.037
plot 23	6.656
plot 24	5.968
plot 25	6.472

The relationships between smartphone at 1meter with 13 measurements and hemispherical photographs and LAI-2000 PCA are shown that how high number of images(13 measurements) effected LAI value in comparison with normal number of images (5 measurements) (sub-sections 4.2.1 and 4.2.2) (Figs 4.9-4.10).

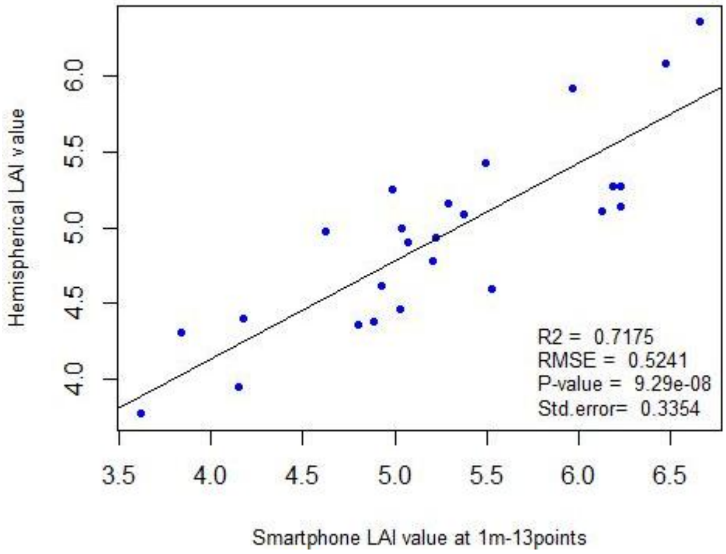

Fig 4.9 Relationship between LAI value (m^2/m^2) of hemispherical photographs and smartphone at 1meter with 13 measurements

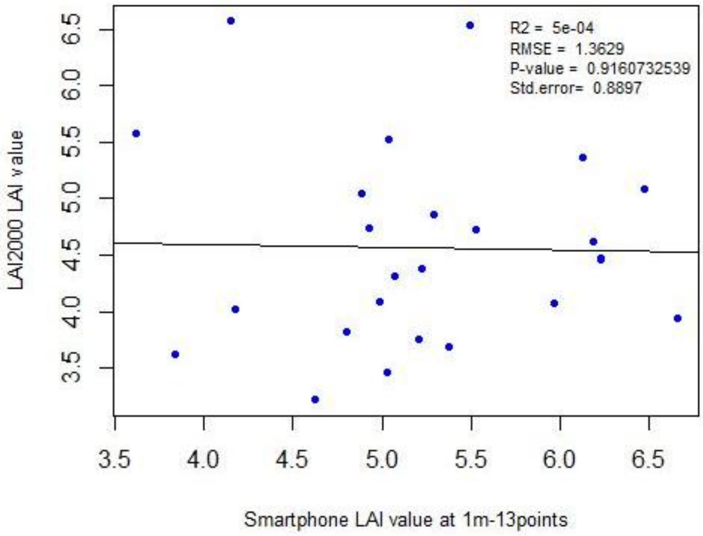

Fig 4.10 Relationship between LAI value (m^2/m^2) of LAI-2000 PCA and smartphone at 1meter with 13 measurements

There is high correlation between LAI of hemispherical photographs and smartphone at 1 meter with 13 measurements (R^2=0.7175), but it is lower correlation with smartphone at 1 meter (5 measurements) (R^2=0.7416) (Fig. 4.3). There is negative correlation between LAI of LAI-2000 PCA and smartphone at 1 meter with 13 measurements (R^2= 5e-04), which in comparison with smartphone at 1 meter (5 measurements) (R^2= 0.0094) (Fig. 4.6) has lower correlation.

These results show that the accuracy of smartphone's LAI values decreases by increasing the number of images for both methods. It means that the accuracy of estimates LAI has not increased. This test was carried out for one height only and it is not possible to say strictly the accuracy will not increase. There is a need for further testing in different situations and height.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5. Conclusions and Recommendations

5.1. Conclusions

The present study shows that in the studied Oostereng pine segment of the Netherlands, many methods can be used to estimate LAI. The Pocket LAI application was designed to run on OS version 4 or higher. However, many smartphones had suitable feature properties (camera, storage capacity and CPU), but Samsung Galaxy S4 mini had satisfactory OS version and camera quality. Because of time constraints, it was not possible to completely check and analyze those smartphone with poor camera quality and compare the results and also update the android version of OS for some smartphone (HTC Vivid and Galaxy S2). To estimate accurate LAI with the Pocket LAI application, selection of smartphone was half of the process. The other half was to use proper lens to capture hemispherical images, which universal fisheye clip lese was used.

The comparison of LAI from Hemispherical photographs and smartphones at three heights shows that LAI from smartphone at 0.5 meter (R^2=0.7776) is the most suitable height for image capturing. There are many parameters which were not included; therefore it is very difficult to conclude 0.5 meter is the best height. Because of a problem with connection of the Pocket LAI application to GPS, the coordinates were not saved in the application. On the other hand, Garmin recorded plots location with very low accuracy.

Regarding the evaluation of smartphone's results with LAI-2000 PCA, a small test was done to check the correlation between hemispherical photographs as one of the best methods for LAI estimation and LAI-2000 PCA. The result was unexpected and no correlation was found. The comparison of LAI from LAI-2000 PCA and smartphones at three heights also shows there are no relationships. On the other hand, LAI-2000 PCA demonstrated underestimates the LAI in compare with hemispherical photography and smartphone (Appendix 5). The height of foliage element to the sensor, position of sensor, and light condition could affect the LAI result from LAI-2000 PCA.

However, the comparison of hemispherical photographs and smartphone at 1 meter with 13 measurements, demonstrated lower correlation in compare with smartphone at 1 meter with 5 measurements (R^2=0.7175) and also no correlation with LAI-2000 PCA. By acquiring more images and at other heights, it could leads to different result. Additional work at the study site investigating direct methods could provide more of an unbiased estimate in the future.

This study demonstrates that smartphones have strengths and potential to be used in bigger and more important projects such as detection of deforestation and can provide significant additional information that can be important for ecological modeling. A key advantage of all of these estimation methods especially smartphone's is that observations can be collected in a short period of time in contrast to weeks, months or even years required for direct estimation (e.g. litterfall or harvest), which is a major benefit, particularly for remote sensing investigations, where timely ground reference data collection of adequate size and spatial distribution is often a constraint.

5.2. Recommendation

Based on the present study, the following points are mentioned to be considered for future studies.

In future study, field measurements have to be well documented and have to be checked for the quality before the end of field days so that the missing or poor quality data can be re-measured in time. There is a need for further studies on the validation of smartphone's results. In this study, the evaluation results were not significant.

The Pocket LAI application is only run on android OS, but it is important in the future to develop a version of application that runs on ISO operation system. Because the second most available OS is ISO. The masking step in the application is a manual process, which can cause error in computation. Therefore, if this process becomes automated in future; it would prevent many errors. The new version of the application has a problem to use GPS data during data saving. It is important to solve this problem in the next version

Additionally, it is reasonable to say on the basis of these results that exploring the applicability of leaf area index alongside investigation of gap fraction and gap size distribution and also integration with Lidar data remains an important field of research.

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Appendix

Appendix 1. Smartphones properties

Names	Camera (MP)	Memory (MB)			Battery (h)	Application Test
		Internal	External	RAM		
Sony Xperia E	3.15	4000	32000	512	6	Tested
Samsung Galaxy S5301	2	4000	32000	512	14	Tested
Motorola XT556	5	512	32000	1000	5	Not tested
Samsung Galaxy S6310	3.12	4000	64000	768	6	Tested
Samsung Corby	2	50	8000	--	9	Not tested
HTC Vivid	8	16000	32000	1000	8	Not tested
Samsung Galaxy S7260	2	4000	32000	512	15	Tested
Samsung Galaxy S2	8	16000	32000	1000	7	Not tested
IPhone 4	5	16000	--	512	14	Not tested
Samsung Galaxy 19190 S4 mini	8	8000	64000	1500	12	Tested

Names	Features			
	OS	Version	CPU	GPS
Sony Xperia E	Android	4.1	1 GHz	Yes
Samsung Galaxy S5301	Android	4	850 MHz	Yes
Motorola XT556	Android	2.3	1 GHz	Yes
Samsung Galaxy S6310	Android	4.1.2	1 GHz	Yes
Samsung Corby	JAVA	2	--	No
HTC Vivid	Android	2.3.4	1.2 GHz	Yes
Samsung Galaxy S7260	Android	4.1.2	1 GHz	No
Samsung Galaxy S2	Android	2.3.5	1.5 GHz	Yes
IPhone 4	ISO	4	1 GHz	Yes
Samsung Galaxy 19190 S4 mini	Android	4.2.2	1.7 GHz	Yes

Names	Comments
Sony Xperia E	Low camera quality and slow processing
Samsung Galaxy S5301	Very low camera quality and slow processing
Motorola XT556	Unable to install application due to low OS version and low internal memory, but good camera quality
Samsung Galaxy S6310	Low camera quality
Samsung Corby	Unable to install application due to low OS version
HTC Vivid	Unable to install application due to low OS version, but with very high camera quality
Samsung Galaxy S7260	Low camera quality, slow processing, and unable to find coordinates
Samsung Galaxy S2	Unable to install application due to low OS version, but with very high camera quality
IPhone 4	Unable to install application due to different OS
Samsung Galaxy 19190 S4 mini	Suitable OS version and high camera quality

Appendix 2. Summary of smartphone measurements analyzed by the pocket LAI application at 0.5 meter, 1 meter, and 1.5 meters

Plot name	**LAI Measurements at 0.5 meter**					**Averaged LAI**
	1	**2**	**3**	**4**	**5**	
Plot 1	3.102	3.515	3.919	3.120	4.096	3.5504
Plot 2	2.761	3.125	2.676	3.345	3.186	3.0186
Plot 3	3.572	4.028	3.887	4.201	3.261	3.7898
Plot 4	4.678	5.052	3.810	3.166	4.018	4.1448
Plot 5	5.677	6.598	5.498	4.383	4.155	5.2623
Plot 6	7.218	5.710	4.438	5.188	4.484	5.4076
Plot 7	5.028	4.400	6.345	5.510	4.081	5.0728
Plot 8	3.961	5.540	4.350	4.285	4.045	4.4362
Plot 9	4.456	4.533	4.444	5.110	5.456	4.7998
Plot 10	4.566	5.095	4.956	4.344	3.345	4.4612
Plot 11	4.030	4.978	6.089	4.266	5.350	4.9426
Plot 12	4.800	4.975	4.678	5.118	6.000	5.1142
Plot 13	4.468	5.778	6.538	6.018	5.185	5.5974
Plot 14	6.068	6.965	5.128	5.298	5.853	5.8624
Plot 15	4.028	5.784	6.568	7.278	6.444	6.0204
Plot 16	6.250	5.666	7.198	5.378	5.300	5.9584
Plot 17	5.648	4.718	6.367	6.635	5.400	5.7536
Plot 18	4.738	5.523	5.090	4.385	5.250	4.9972
Plot 19	4.277	5.000	4.600	4.333	4.798	4.6016
Plot 20	4.158	4.259	5.178	5.142	5.085	4.7644
Plot 21	5.447	5.245	5.090	5.370	4.078	5.0460
Plot 22	5.228	4.182	5.500	4.228	4.758	4.7792
Plot 23	6.888	5.987	7.183	6.358	7.539	6.7910
Plot 24	6.085	6.108	5.552	5.152	5.168	5.6130
Plot 25	5.955	7.565	5.738	5.852	6.855	6.3930

Plot name	LAI Measurements at 1 meter					Averaged LAI
	1	2	3	4	5	
Plot 1	3.178	4.128	3.530	3.798	5.456	4.0180
Plot 2	3.676	3.967	4.667	3.488	3.987	3.9570
Plot 3	3.879	4.966	4.443	4.982	4.890	4.6320
Plot 4	3.648	4.885	5.428	4.528	5.082	4.7142
Plot 5	6.616	5.650	5.498	4.823	4.538	5.4250
Plot 6	5.252	5.830	5.371	7.851	6.821	6.2250
Plot 7	5.182	5.221	4.871	5.822	4.582	5.1356
Plot 8	5.935	4.721	3.944	5.216	5.405	5.0442
Plot 9	4.319	5.015	5.378	7.578	4.645	5.3870
Plot 10	4.458	5.666	5.348	4.156	3.950	4.7156
Plot 11	4.097	5.468	3.682	5.999	5.833	5.0158
Plot 12	5.785	4.800	5.570	4.905	5.758	5.3636
Plot 13	4.871	6.187	4.953	5.6528	4.917	5.3161
Plot 14	6.448	7.103	6.503	5.005	6.185	6.2488
Plot 15	5.198	6.719	7.100	6.908	6.000	6.3850
Plot 16	6.965	5.111	7.288	5.478	5.766	6.1216
Plot 17	5.498	6.785	6.468	7.965	6.460	6.6352
Plot 18	5.328	5.944	4.781	5.628	6.389	5.6140
Plot 19	4.922	5.622	5.127	4.985	4.585	5.0482
Plot 20	4.760	5.110	6.158	5.578	4.777	5.2766
Plot 21	6.068	5.600	5.620	5.785	4.332	5.4810
Plot 22	5.566	4.875	6.102	5.000	6.111	5.5308
Plot 23	6.185	6.354	7.484	5.855	7.990	6.7736
Plot 24	6.700	6.111	6.508	5.883	6.000	6.2404
Plot 25	6.515	8.010	6.985	5.440	6.256	6.6412

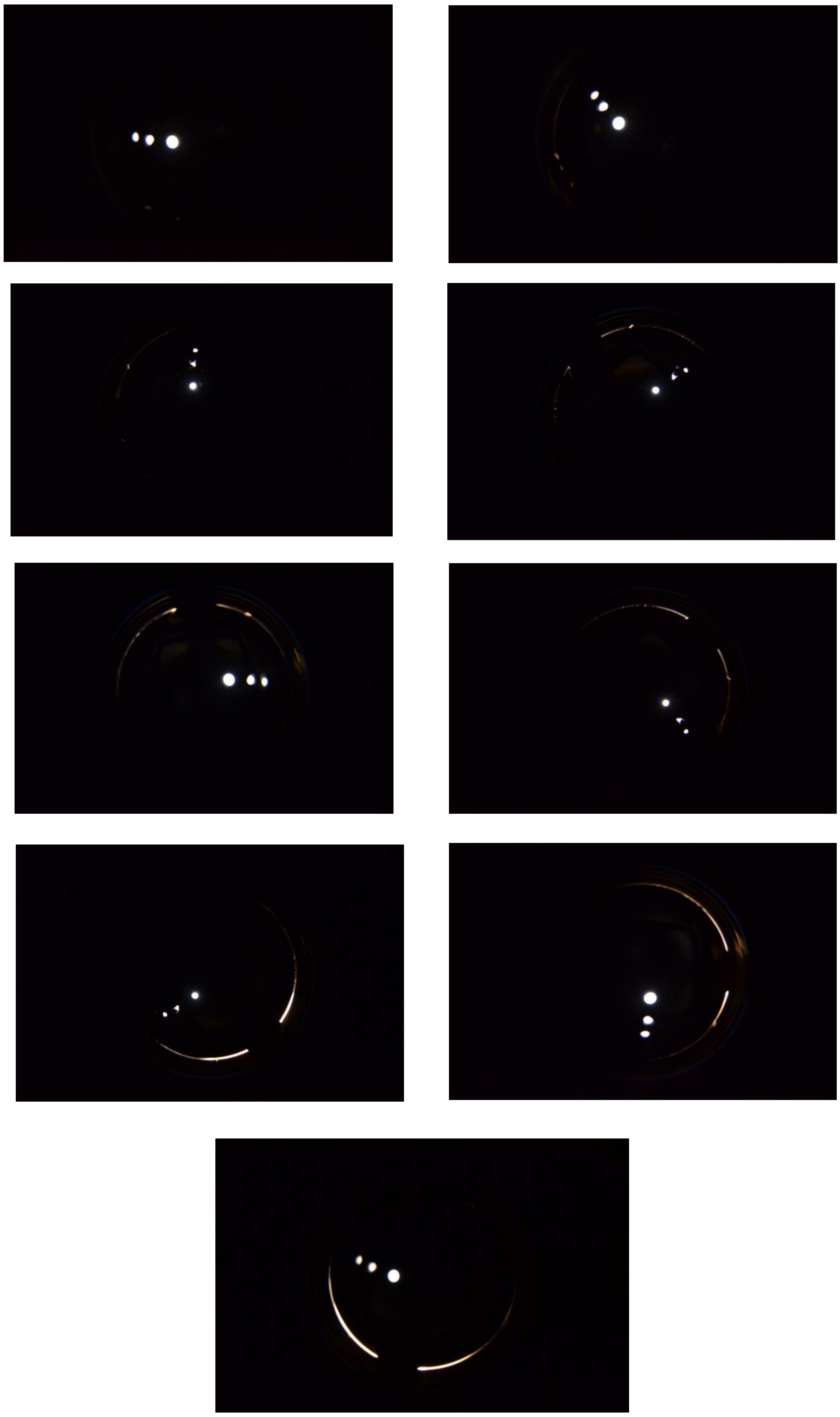
Plot name	LAI Measurements at 1.5 meters					Averaged LAI
	1	2	3	4	5	
Plot 1	3.311	3.541	3.981	4.196	5.271	4.0600
Plot 2	3.181	3.571	3.188	4.041	3.334	3.4630
Plot 3	3.952	3.280	3.258	4.333	3.644	3.6934
Plot 4	3.832	3.367	4.355	3.628	4.128	3.8620
Plot 5	4.982	5.219	4.837	4.128	4.582	4.7496
Plot 6	4.490	4.414	4.382	5.821	5.018	4.8250
Plot 7	5.381	4.888	4.588	4.981	5.440	5.0556
Plot 8	5.078	4.485	3.658	4.000	4.758	4.3958
Plot 9	5.45 0	4.500	4.404	4.465	3.556	4.4750
Plot 10	8.155	4.982	3.928	5.000	3.660	5.1450
Plot 11	4.185	4.360	5.638	4.916	6.150	5.0498
Plot 12	5.200	4.985	4.268	5.005	5.181	4.9278
Plot 13	4.755	5.860	4.400	4.000	4.168	4.6366
Plot 14	3.978	5.368	6.181	5.497	6.215	5.4478
Plot 15	5.267	5.615	6.778	6.718	5.545	5.9846
Plot 16	6.128	5.785	6.985	5.785	6.101	6.1568
Plot 17	5.400	5.215	7.100	6.638	5.555	5.9816
Plot 18	5.448	5.148	4.411	6.000	6.361	5.4738
Plot 19	4.978	5.565	5.800	4.165	4.005	4.9026
Plot 20	4.992	4.640	4.485	5.105	5.000	4.8444
Plot 21	5.700	5.910	5.000	5.380	4.383	5.2747
Plot 22	5.344	4.977	5.185	4.880	5.000	5.0772
Plot 23	6.865	5.185	7.000	5.776	7.555	6.4762
Plot 24	6.185	6.008	5.885	5.000	5.855	5.7866
Plot 25	5.995	7.500	6.000	5.666	5.185	6.0692

Plot name	LAI Measurements at 1 meters													Averaged LAI
	1	2	3	4	5	6	7	8	9	10	11	12	13	
Plot 1	3.178	4.128	3.53	3.798	5.456	3.328	4.910	5.091	4.283	3.931	5.223	3.882	5.524	4.148
Plot 2	3.676	3.967	4.667	3.488	3.987	4.327	3.878	4.018	3.878	3.771	4.687	3.535	3.823	3.616
Plot 3	3.879	4.966	4.443	4.982	4.89	3.095	4.028	3.887	3.548	4.100	4.212	3.300	4.821	3.841
Plot 4	3.648	4.885	5.428	4.528	5.082	5.950	3.560	4.128	3.418	4.430	3.900	4.050	4.112	4.174
Plot 5	6.616	5.650	5.498	4.823	4.538	5.201	4.821	5.778	6.051	3.872	4.230	4.785	4.872	5.070
Plot 6	5.252	5.830	5.371	7.851	6.821	5.258	5.018	6.100	4.860	5.182	5.028	5.500	4.744	5.286
Plot 7	5.182	5.221	4.871	5.822	4.582	4.458	5.248	5.815	4.644	4.371	6.221	4.718	4.530	5.028
Plot 8	5.935	4.721	3.944	5.216	5.405	5.240	6.125	4.438	5.630	4.800	3.388	4.050	4.290	4.626
Plot 9	4.319	5.015	5.378	7.578	4.645	4.540	4.045	4.778	5.250	6.212	5.010	5.250	4.989	4.928
Plot 10	4.458	5.666	5.348	4.156	3.95	5.982	4.048	4.740	6.200	4.682	5.168	5.500	3.821	4.803
Plot 11	4.097	5.468	3.682	5.999	5.833	5.396	4.916	4.078	4.391	6.578	5.111	5.616	6.918	5.209
Plot 12	5.785	4.800	5.570	4.905	5.758	4.660	6.118	4.485	5.468	4.677	6.700	6.300	5.875	5.373
Plot 13	4.871	6.187	4.953	5.6528	4.917	6.499	4.345	5.485	5.938	4.650	6.385	4.930	5.238	5.496
Plot 14	6.448	7.103	6.503	5.005	6.185	4.895	6.070	6.782	5.970	7.138	7.534	7.012	6.290	6.231
Plot 15	5.198	6.719	7.100	6.908	6.000	5.518	6.095	7.878	5.250	7.785	6.575	4.289	7.422	6.224
Plot 16	6.965	5.111	7.288	5.478	5.766	5.848	6.855	6.611	6.618	5.185	6.633	5.348	6.800	6.130
Plot 17	5.498	6.785	6.468	7.965	6.46	5.785	6.662	6.990	6.900	6.585	5.498	5.500	7.733	6.186
Plot 18	5.328	5.944	4.781	5.628	6.389	5.778	6.155	6.918	5.555	5.088	5.988	5.385	6.000	5.527
Plot 19	4.922	5.622	5.127	4.985	4.585	5.690	5.280	4.115	4.335	5.000	4.858	5.185	6.015	4.883
Plot 20	4.760	5.110	6.158	5.578	4.777	4.185	5.365	5.655	4.855	5.690	5.478	4.585	5.185	4.986
Plot 21	6.068	5.600	5.620	5.785	4.332	5.185	5.851	5.565	4.925	5.495	6.111	5.038	4.518	5.224
Plot 22	5.566	4.875	6.102	5.000	6.111	5.455	5.098	5.333	5.855	4.258	6.148	4.444	5.000	5.037
Plot 23	6.185	6.354	7.484	5.855	7.990	6.738	6.345	5.928	6.645	7.528	6.185	5.858	7.352	6.656
Plot 24	6.700	6.111	6.508	5.883	6.000	5.390	6.060	7.200	5.185	6.438	7.085	6.285	5.888	5.968
Plot 25	6.515	8.010	6.985	5.440	6.256	8.300	6.188	5.818	6.000	7.332	5.440	5.989	7.112	6.472

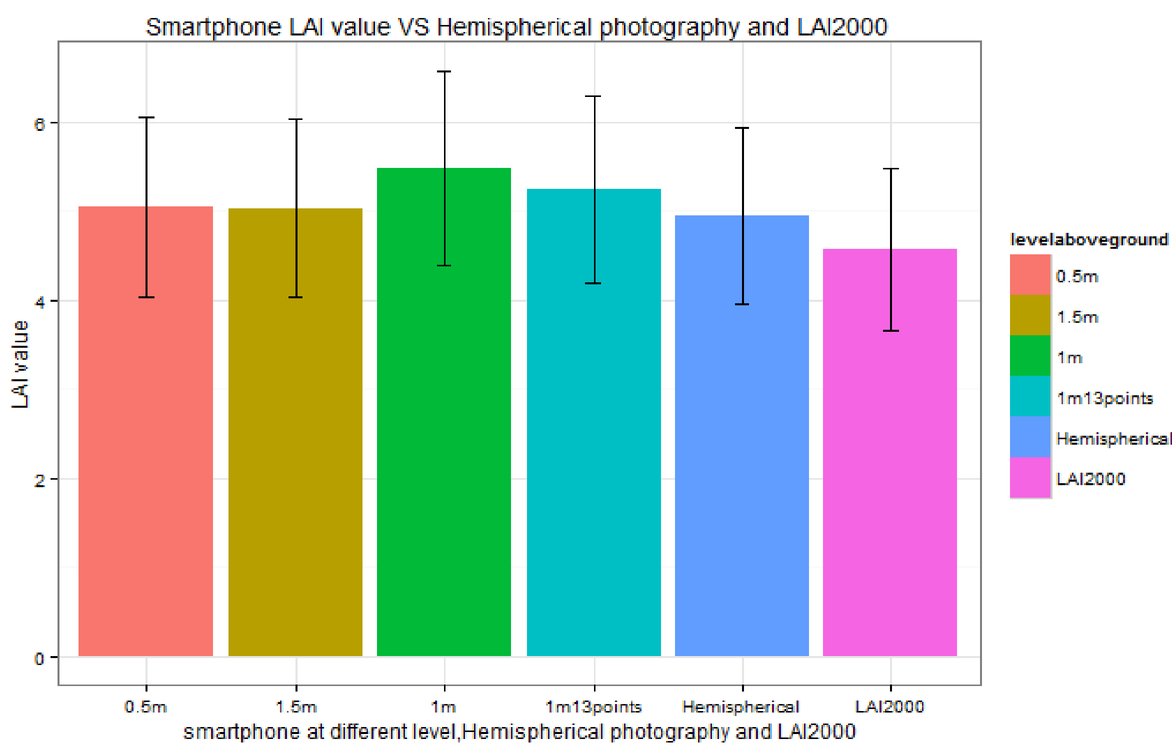
Appendix 3. Summary of hemispherical photographs measurements analyzed by CAN-EYE software

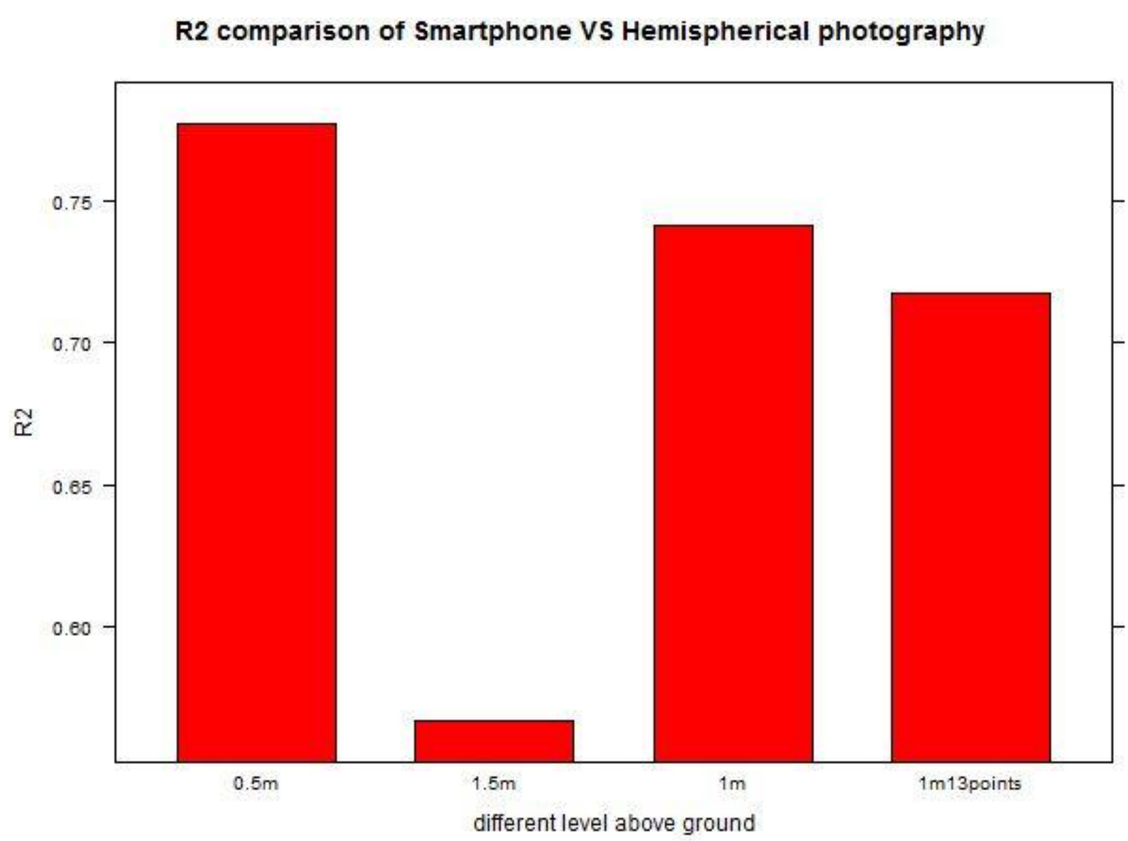
Plot number	Vegetation (%)	Sky/Mixed (%)	Averaged LAI
Plot 1	67.53	32.47	3.95
Plot 2	72.07	27.93	6.77
Plot 3	57.96	42.04	4.31
Plot 4	55.40	44.60	4.40
Plot 5	52.77	47.23	4.90
Plot 6	58.50	41.50	5.16
Plot 7	63.27	36.73	4.46
Plot 8	62.81	37.19	4.98
Plot 9	48.74	51.26	4.62
Plot 10	59.36	40.64	4.36
Plot 11	36.95	63.05	3.78
Plot 12	44.48	55.52	5.09
Plot 13	55.41	44.59	5.43
Plot 14	54.16	45.84	5.27
Plot 15	54.87	45.13	5.14
Plot 16	53.37	46.63	5.11
Plot 17	53.40	46.60	5.27
Plot 18	70.72	29.28	4.60
Plot 19	55.32	44.68	4.38
Plot 20	61.68	38.32	5.25
Plot 21	44.62	55.38	4.94
Plot 22	52.96	47.04	5.00
Plot 23	68.94	31.06	6.36
Plot 24	67.57	32.43	5.92
Plot 25	62.35	37.65	6.09

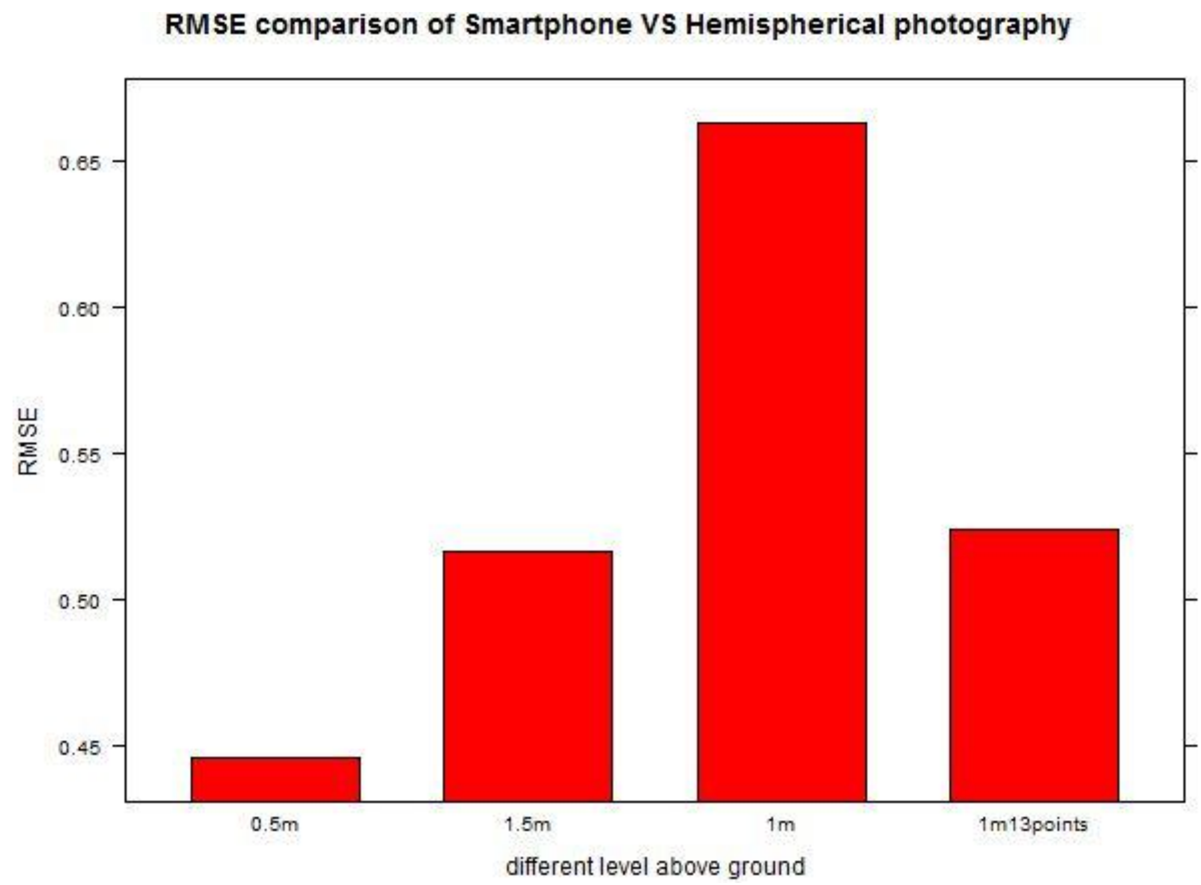
Appendix 4. Calibration images for CAN-EYE software

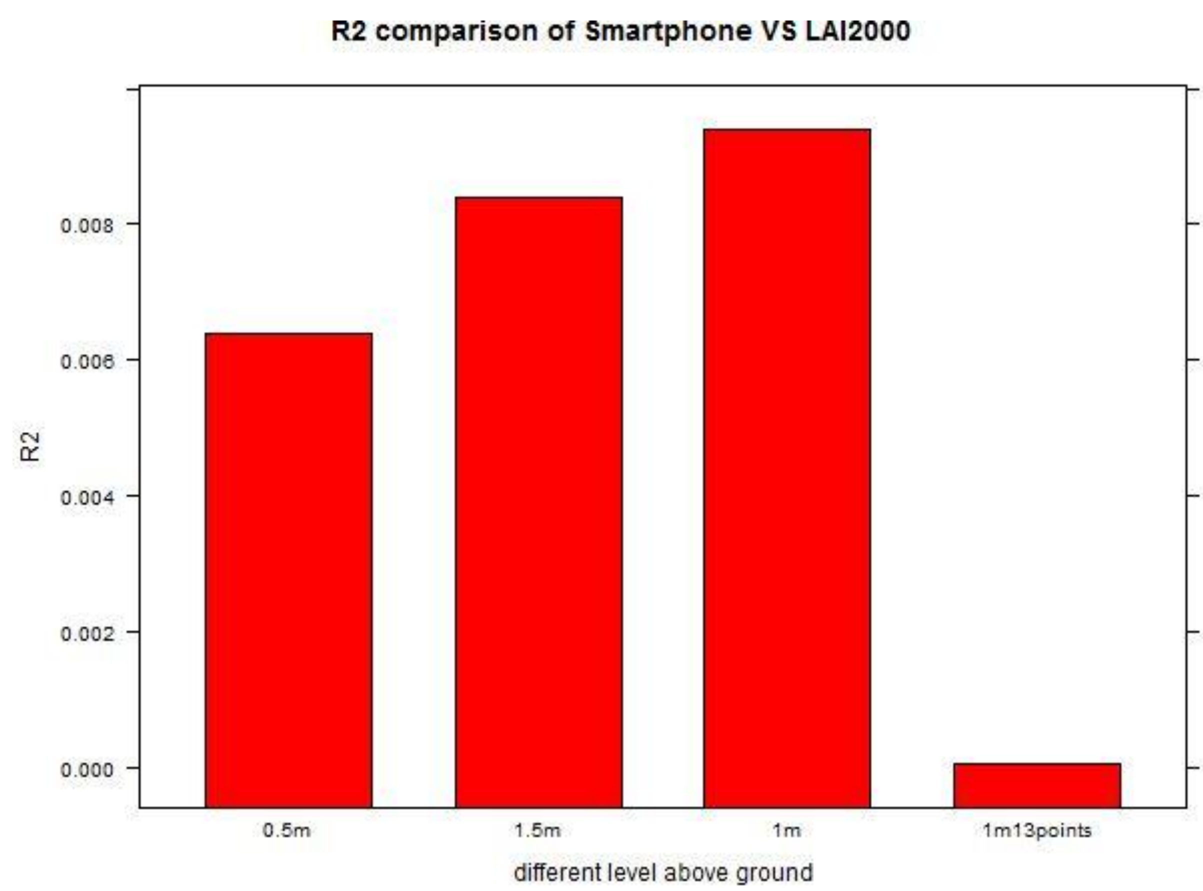


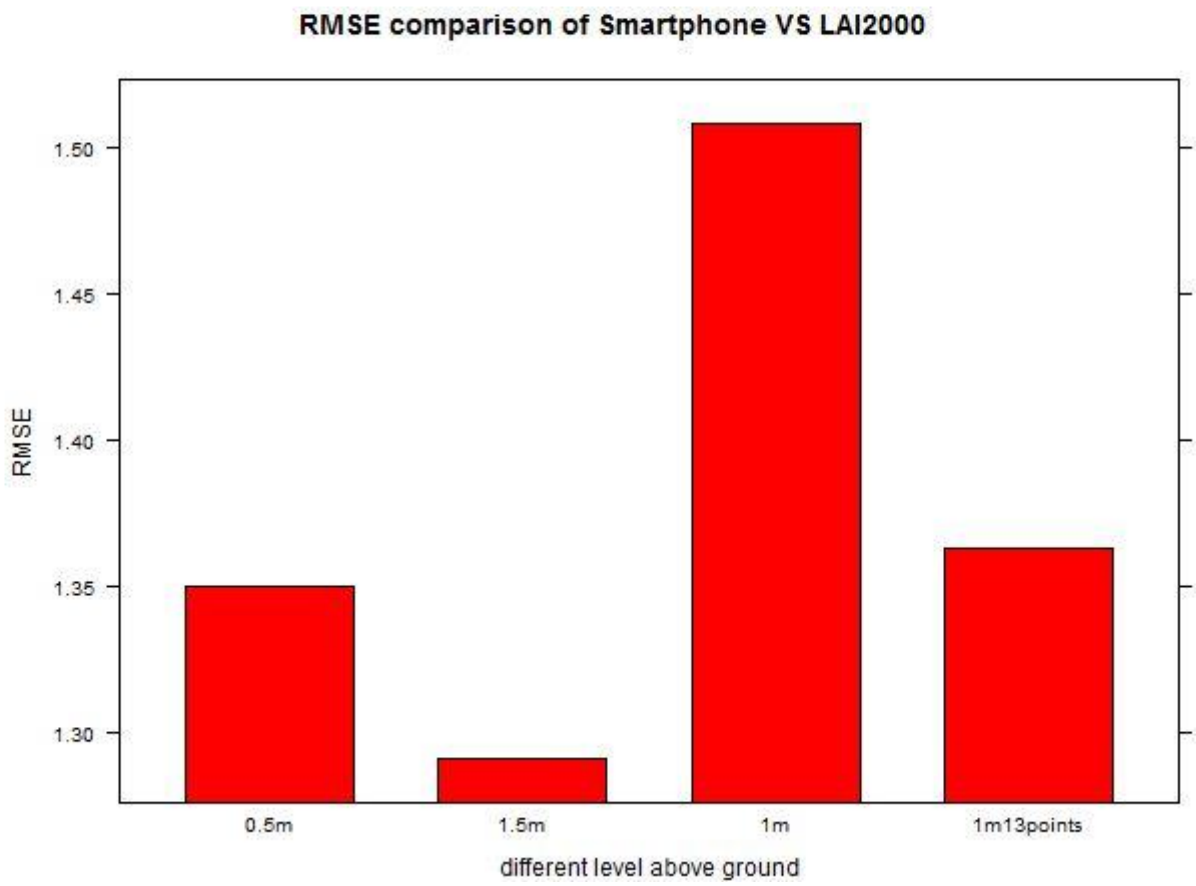
Appendix 5. Summary of analysis






RMSE comparison of Smartphone VS Hemispherical photography
RMSE
0.65
0.60
0.55
0.50
0.45
0.5m
1.5m
1m
1m13points
different level above ground


R2 comparison of Smartphone VS LAI2000
R2
0.008
0.006
0.004
0.002
0.000
0.5m
1.5m
1m
1m13points
different level above ground


RMSE comparison of Smartphone VS LAI2000
RMSE
1.50
1.45
1.40
1.35
1.30
0.5m
1.5m
1m
1m13points
different level above ground