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Searching for the Optimal Sampling Design for Measuring LAI in an Upland Rainforest

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Abstract

Leaf Area Index (LAI) and vegetation cover are important metrics for deriving structural information of forest ecosystems across multiple scales. Ground-based measurements of LAI are necessary for up-scaling to coarse resolution satellite products as well as for calibrating and validating such products derived from airborne and satellite remote sensing datasets, which are increasingly being used for forestry and ecosystem health applications across the globe. A crucial consideration when gathering field measurements is determining a suitable sampling design, which ensures the collection of representative measurements. In this study, we address this question by obtaining LAI measurements across the Terrestrial Ecosystem Research Network (TERN) 25ha Robson Creek Supersite, which is representative of upland rainforests in Far North Queensland. The Robson Creek supersite contains over 200 species of woody vegetation and has one of the highest levels of biomass found in forest ecosystems globally. A variety of ad hoc and established sampling designs such as the State wide Land cover and Trees Survey (SLATS) and the Validation of Land European Remote Sensing Instruments (VALERI) cross elementary sampling unit protocol were applied across the site. Measurements obtained from the ground-based sampling designs were then compared to measurements derived from satellite imagery (i.e., Landsat). Preliminary results indicate the measurements obtained from between-plot sampling designs were highly correlated and comparable. On the other hand, there was disagreement between the ground-based measurements and values estimated from the Foliage Projective Cover (FPC) satellite product. The study suggests that at least in dense canopy forests, different sampling designs will yield similar results. Consequently, the sampling strategy should ultimately be driven according to the desired spatial resolution of the final product.

Key Words: validation, LAI, fC, FPC, satellite, sampling strategy

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1.0 Introduction

Leaf Area Index or LAI, defined as one half the total surface area of green leaves per unit of ground area (Myneni *et al.*, 1997), is an essential climate variable (ECV) used in studies of climate, ecosystem productivity, agrometeorology, biogeochemistry, hydrology, and ecology (e.g., Gobron, 1997; Garrigues *et al.*, 2008b; GCOS, 2010). When quantified at scales larger than the individual leaf, it becomes an integral component of the structure and functioning of vegetation, thus making LAI a basic descriptor of vegetation condition (Asner *et al.*, 1998; Garrigues *et al.*, 2008a).

LAI can be derived across large areas using remotely sensed imagery. Historically, there have been many studies and campaigns for calibrating and validating LAI products derived from coarse resolution sensors such as MODIS LAI and CYCLOPES, and some of these are still ongoing (Hill *et al.*, 2006; Morisette *et al.*, 2006; Sea *et al.*, 2011; Fang *et al.*, 2012). These studies rely on the collection of accurate and representative ground-based measurements of LAI. Morisette (2006) outlined two main approaches for validating LAI products using ground-based measurements. The first is direct validation, where the ground measurements are directly compared to the LAI product. This approach has successfully been used to validate MODIS collection 4 and 5 LAI in Australia, predominantly using ground-based estimates of LAI derived from hemispherical cameras (Hill *et al.*, 2006; Sea *et al.*, 2011). The second approach is to relate the ground-based measurements to an intermediate high-resolution remote sensing dataset, in a technique known as up-scaling. Up-scaling allows the ground-based measurements to be extrapolated across a larger area, where the mapped values are then used for product validation.

Ground-based measurements of LAI can be obtained directly or indirectly. Direct measurement consists of techniques like destructive sampling, litter-fall collection, and point contact sampling. Indirect methods, on the other hand, derive LAI from other variables taken through observations such as the proportion of sky obscured from vegetation, or the implementation of allometric relationships from tree height and diameter at breast height or DBH (Gower *et al.*, 1999). Direct methods are generally regarded as more accurate than indirect methods due to their independence of the influence of confounding factors such as leaf angle distribution, foliage clumping, variable sample size, and woody vegetation components (Jonckheere *et al.*, 2004; Weiss *et al.*, 2004). However, they are inefficient and infeasible in some forest environments when compared with indirect methods due to their time-, labor-intensive, and destructive nature (Bréda, 2003; Jonckheere *et al.*, 2004). In the absence of direct measurements or allometric equations accurately relating structural metrics to LAI, indirect non-contact measurements are the most suitable alternative for validating LAI across large areas (Jonckheere *et al.*, 2004).

The more frequently used indirect ground-based methods include optical instruments such as cameras (with standard or fisheye lenses); the LAI-2200 Plant Canopy Analyser (Li-Cor Inc.); the Canopy Imager-110 (CI-110, CID Inc.); the DEMON (CSIRO, Canberra, Aus), and the TRAC instrument (Tracing Radiation and Architecture of Canopies, 3rd Wave Engineering) (Bréda, 2003; Jonckheere *et al.*, 2004; Keane *et al.*, 2005). More recently, terrestrial laser scanning (TLS) is also being used to derive LAI indirectly (Lovell *et al.*, 2003). These instruments are used to record information on LAI according to a sampling strategy, which comprises of a number of measurements to be collected along a defined spatial arrangement (extent and location).

Presently, there is no consensus amongst the scientific community for best practice methods and optimal sampling strategy through which to derive LAI at the ground scale (Gobron and Verstraete, 2009). The sampling strategy should ultimately be tailored to the validation approach (single or multi-stage) and the resolution of the product being validated (Morisette *et al.*, 2006). Published studies which aim to validate LAI employ varying sampling strategies. In large area validation (greater than 9km^2), ground-based measurements are generally aggregated into plots, where a number of plots are required to characterise the site. For example, the Validation of Land European Remote Sensing Instruments (VALERI) project's validation approach uses a multi-stage methodology to up-scale their 0.2ha (n = 12) sample plots to high-resolution SPOT imagery (Baret *et al.*, 2008). Within Australia, the Statewide Landcover and Tree Study (SLATS) start transect method was developed to map woody vegetation cover or Foliage Projective Cover (FPC) (Kuhnell *et al.*, 1998). FPC is the percentage of ground area occupied by the vertical projection of foliage (Specht and Morgan, 1981). A modified plot design for validating LAI based on the original SLATS validation approach was developed using ground-based optical instruments such as hemispherical photography and the LAI-2200 (TERN, 2012b). The SLATS plot design characterises a 1ha (n = 13) area. Through upscaling, these plots are used to validate concurrently flown small-footprint airborne LiDAR used to estimate LAI (Armston *et al.*, 2012).

This study aims to investigate and quantify the differences obtained when applying three sampling designs to derive plot scale values of LAI in a representative rainforest in Queensland, Australia. The three designs compared are the VALERI cross, the SLATS Digital Hemispherical Photography (DHP) protocol, and a one hectare grid sampled every 20-m (1 ha, n = 36; Figure 5). Specifically, the within measurement, within plot, and between plot variability is examined. In addition, the plot scale assessments of fractional cover (fC) and FPC derived on the ground across the sampled plots is compared against results obtained from an FPC satellite product (Armston *et al.*, 2009) - where fC is the proportion of an area that is covered by a specific land cover type (Scanlon *et al.*, 2002), which in this case is rainforest.

2.0 Study Area

The study took place within the 25km^2 Robson Creek Supersite (Figure 1), an upland rainforest on the Atherton Tableland of Far North Queensland (FNQ). Robson Creek is located in Danbulla National Park within the Wet Tropics World Heritage Area.

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The forest present (forest type is Simple Notophyll Vine Forest) has one of the highest rates of biodiversity in all of Australia. In addition, it has some of the highest biomass per hectare ratios found in the world (TERN, 2012c; TERN, 2012d). The mean yearly rainfall and temperature average is approximately 2300 mm and 19° C respectively, and the canopy height ranges from around 26 m to 40 m (TERN, 2012a).

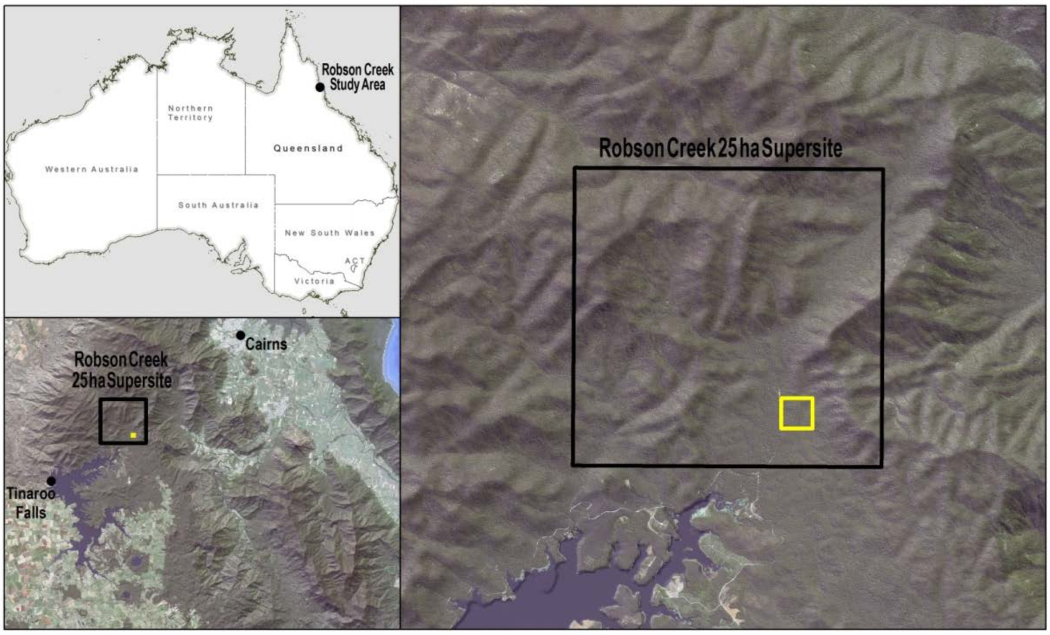

Figure 1. Robson Creek study area location. Bottom-left shows the location of the 5 km x 5 km study area (outlined in black) with regards to Cairns and Lake Tinaroo. The study area is expanded in the right and the 25ha permanent monitoring plot is outlined in yellow. A SPOT image is used in the background.

The study site is part of the Terrestrial Ecosystem Research Network's (TERN) FNQ Rainforest Biodiversity Node. It specifically sits within the Australian Supersite Network which comprises 10 supersites throughout Australia that are intensively studied to gain knowledge regarding how Australian ecosystems respond to environmental change. It is currently managed by CSIRO, who began working here in 2009, even though the first 0.5 ha monitoring plot was established in 1972 (TERN, 2012a). A permanent 25 ha plot was established within the supersite (Figure 1), with steel markers placed every 100m. In addition, the permanent plot was further subdivided every 20 m with 20 mm poly pipe. This plot includes an extensive and comprehensive database of all the woody vegetated species that fall within it. Over 25,000 trees have been marked, geolocated, identified to the species level and measured (e.g., tree height, DBH). More than 200 woody vegetation species have been identified within the 25ha plot.

3.0 Methods

Various sampling designs that are commonly used amongst the remote sensing calibration/validation community to collect LAI measurements from the ground were tested in a rainforest context. LAI was collected using several instruments. The ground-based measurements were collected between 10th September and 15th September, 2012, during a TERN AusCover field-airborne campaign. The following section details the steps followed in this study.

3.1 Sampling design

Three different sampling designs were investigated: VALERI 'cross', the SLATS DHP protocol, and a grid sample design. Each of these represents a different spatial extent and arrangement, and is associated with the collection of different numbers of measurements.

In total, measurements were collected across 14 plots (4 SLATS DHP, 9 VALERI cross plots; and one grid); with a total of 186 individual measurements. The spatial location of each of the plots within the study site is shown in Figure 2. As can be noticed, some of these are placed outside the permanent plot (5 VALERI cross and 1 SLATS DHP) whereas others are located within the permanent plot (3 SLATS DHP, 4 VALERI cross, and the grid).

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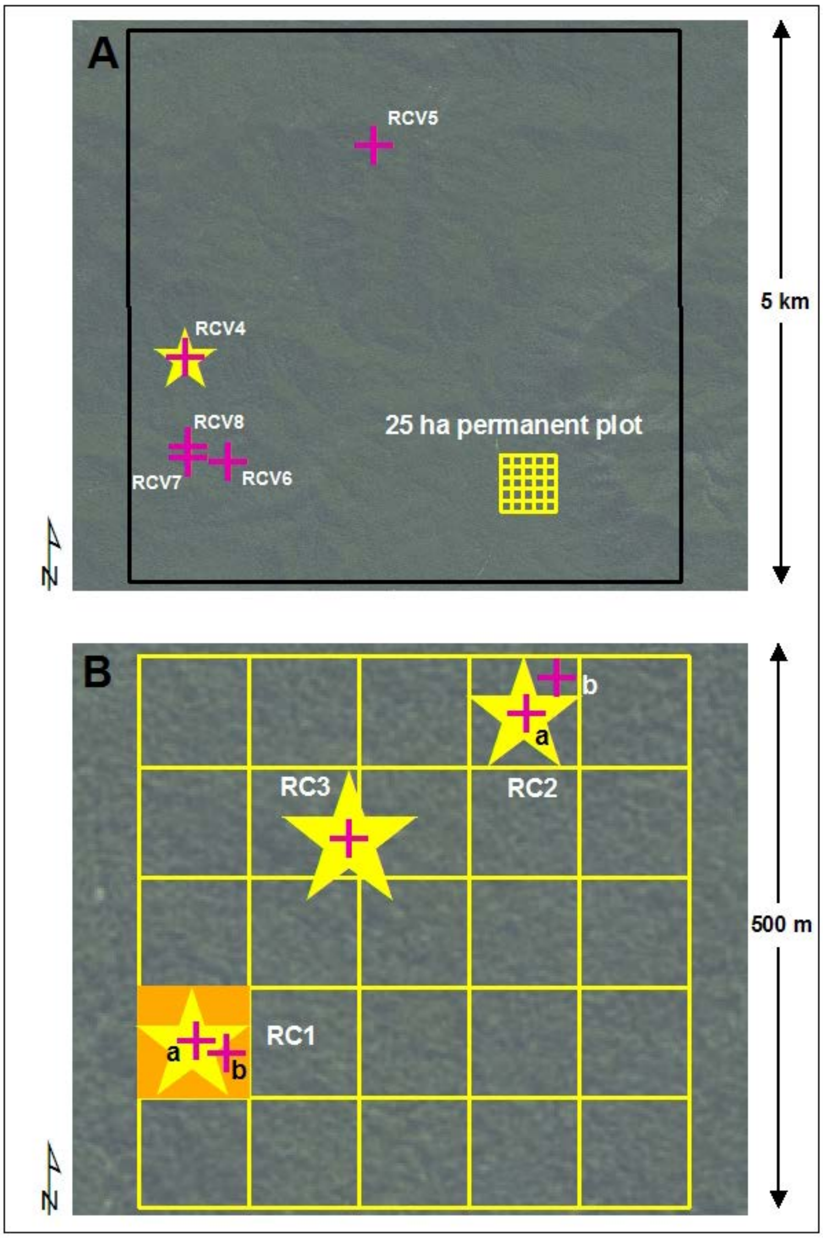

*Figure 2**(a):** Robson Creek 25 km^2 study area with plot locations overlayed on a SPOT image (not to scale). The black square represents the outline of the 5 km x 5 km Robson Creek study area; the yellow cells show the 100 m grid markings for the 25 ha permanent plot (see Figure 2(b) for a close-up); the yellow star represents the only SLATS plot (RC4) completed outside the 25 ha permanent plot; the purple crosses show VALERI plot locations. **(b):** close up of 25ha permanent plot with location of plots completed in this study overlayed on a SPOT image (to scale). The yellow cells show the 100 m grid markings; the yellow stars are the SLATS plots RC1, RC2, and RC3; the purple shows VALERI plot locations, and the orange square represents the 1 ha grid.*

3.1.1 VALERI 'cross'

Two VALERI plot designs were considered in this study (Figure 3). These are the 'square' and 'cross' design, both of which are suited to locally continuous vegetated areas (Baret *et al.*, 2008). Each plot aims to characterise a 20m x 20m area with 12 measurements using either the LAI-2000/2200 (Li-Cor. Inc.) or DHP methods. The performance of the 'square' design is similar to the 'cross' design (Baret *et al.*, 2008). However, only the 'cross' design was used in this study due to the increased efficiency in establishing the measurement locations.

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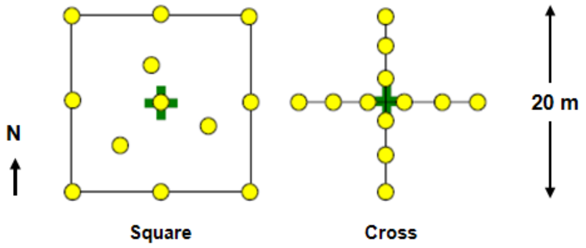

Figure 3. The 'square' and 'cross' VALERI plot designs. The yellow circles show where measurements are collected. The green cross represents the centre of the plot, which also has a GPS or known location associated with it.

3.1.2 SLATS DHP Protocol

The DHP protocol is based on a modified SLATS protocol established for the collection of field data for calibrating and validating fractional cover products in Australia (Kuhnell *et al.*, 1998; Muir *et al.*, 2011). Three 100 metre measuring tapes or transects are laid in a star shape (Figure 4). The first is oriented north to south, and the second and third at 60 and 120 degrees from north, respectively. Measurements are captured in the centre of the plot, at the 25m interval and at the end of each transect, totalling 13 measurements per plot.

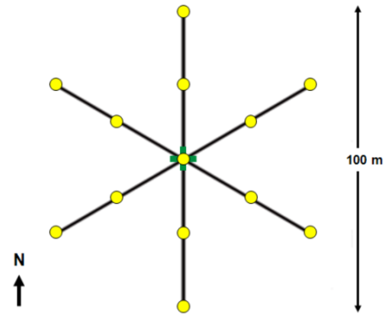

Figure 4. The SLATS sampling design. The yellow circles show the sampling points. The green cross represents the centre of the plot, which is associated with a GPS or known location.

3.1.3 Grid Plot design

The grid sampling design employs a regular systematic sampling pattern to characterise a 100 m x 100 m area (Figure 5). Each cell of the grid represents a 20 m x 20 m area, where one measurement is captured at each of the cell corners, totalling 36 measurements. The four corners of the grid were surveyed using a handheld GPS in combination with a differential GPS providing an accuracy of 2.3 m ± 1.8 SD. The remaining measurement locations were surveyed in via sighting and a tape measure, using the four corner points as control. Each of these points within the hectare is considered to have an accuracy of ±1 m.

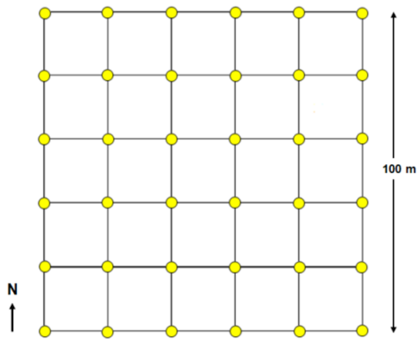

Figure 5. The Grid plot design, with yellow circles indicating sampling point locations. Each cell is 20 x 20m.

3.2 Instruments Used

Two instruments were used to collect LAI measurements: CI-110 and DHP. The CI-110 (CID Inc.) is a passive self-levelling imaging sensor. It has a 180° instantaneous field of view (IFOV) and a 24 sensor Photosynthetically Active Radiation (PAR) wand used to measure the amount of incident solar radiation in the visible spectrum. The imaging device is restricted to a resolution of 0.4 mega pixels (MP), which is much lower than the current commercially available digital cameras.

DHP is a passive sensing technology that provides a large IFOV image at the point of capture. The DHP setup used in this study comprised a Canon EOS 50D Digital SLR camera with a Sigma 8mm EX 180° fisheye lens. The resolution of the camera was 15 MP.

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Due to field limitations, at three VALERI plot locations (RC1 and RC8) the CI-110 could not be used and instead, the results obtained using DHP are presented. The root mean square relative error for effective LAI (LAI_{eff}) and clumping (Ω) (*see section 3.4 for explanation*) for 6 plots measured concurrently with both instruments at Robson Creek was 0.32 and 0.07 respectively (results not presented in this paper).

3.3 Data Collection

Field data was collected with both instruments in accordance with the TERN/AusCover Hemispherical Photography Protocol (TERN, 2012b) during mid September, 2012. Measurements were taken after levelling the instrument in diffuse lighting conditions in day-time hours, when cloud cover was uniform. Furthermore, measurements were collected at approximately 1.6m above ground, ensuring that the foliage elements remained small compared with the IFOV of the instrument.

3.4 Theory and Data Processing

The data was analysed using *CanEye v6.39*. CanEye is an actively maintained free software developed at the French National Institute of Agricultural Research (INRA). The CanEye software uses supervised classification to derive gap fraction (P_{gap}: the proportion of sky obscured by foliage and plant elements), which can then be used to derive canopy structural variables such as LAI, foliage inclination angle (*G*), and the degree of foliage clumping (*Ω*) (Equations 1 and 2). Since no distinction is made between foliage and non-foliage elements (e.g., tree stems and branches are not distinguished from green vegetation in the classification process), the variable derived is plant area index (PAI). However, for consistency in nomenclature it will be referred to as LAI. As will be discussed below, several formulas were used to derive LAI.

3.4.1 General LAI formula relating P_{gap} to LAI

Equation 1 follows the Poisson model which assumes a random distribution of leaves within a canopy.

$$P_{gap}(\theta,h) = e^{\frac{-G(h,\theta)LAI_e(h)}{\cos(\theta)}}$$

$$P_{gap}(\theta,h) = e^{\frac{-G(h,\theta)LAI(h)}{\cos(\theta)}}$$

(1)

Nilson (1971) demonstrated that LAI can be expressed as a function of Pgap, even if the assumptions of a Poisson model are not met. The addition of a clumping factor (*Ω*) corrects for this assumption (Equation 2), in this way converting effective LAI (LAI_e) into true LAI (LAI_t) (Equation 3).

$$P_{gap}(\theta,h) = e^{\frac{-G(h,\theta)\Omega(\theta)LAI_t(h)}{\cos(\theta)}}$$

$$P_{gap}(\theta,h) = e^{\frac{-G(h,\theta)\Omega(\theta)LAI(h)}{\cos(\theta)}}$$

(2)

Where;

$$LAI_m = LAI_t \, . \, \Omega \tag{3}$$

3.4.2 CanEye LAI

LAI estimation in the CAN-EYE software is performed by model inversion. LAI and average leaf angle (ALA) are directly retrieved by inverting Equation 1 in CanEye assuming an ellipsoidal distribution of the leaf inclination using look-up-table techniques (Knyazikhin *et al.*, 1998; Weiss *et al.*, 2000). CanEye determines foliage clumping over zenith view angle based on Lang and Yueqin's (1986) formula and applies the correction to the image to convert LAI_e to LAI_t. Both LAI_e and LAI_t values are reported in this study since clumping has been identified as the factor with most potential to introduce error when estimating LAI in an indirect way Jonckheere *et al.* (2004).

Within each plot, the images were batch processed to produce one set of values per plot. The 0-60 degrees IFOV of the images were analysed to minimise the influence of mixed pixels at larger zenith angles (Weiss *et al.*, 2004).

3.4.3 Miller LAI

Welles and Norman (1991) proposed a practical method to derive LAI from gap fraction measurements in several directions based on a formula of Miller (1967). Miller (1967) assumes that P_{gap} depends only on view zenith angle. Welles and Norman's (1991) method assumes a horizontally homogenous canopy, as the view zenith angles further away from zenith are weighted more heavily, thus reflecting the longer path length through a canopy. The P_{gap} results from CanEye were used to compute LAI_m for each image (Equation 4). The 0-60 degree view zenith angle range was analysed for consistency with the CanEye LAI values.

$$LAI_m = 2\int_0^{\frac{\pi}{2}} -\ln P_{gap}(\theta).\cos(\theta).\sin(\theta).d(\theta) \tag{4}$$

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3.5 Foliage cover: ground based measurement and satellite product comparison

Ground-based measurements of fC and FPC were directly compared with values derived from an FPC satellite product (2010 FPC map of the Cairns region). The FPC mapping product is based on an automated decision tree classification technique applied to dry season (May to October) Landsat 5 TM imagery for the period 1986-2010 (Armston *et al.*, 2009). The Landsat scenes were resampled to 25m pixels, which range from 0-100% FPC. For comparison in this study, FPC values from the product were averaged over each of the four 1ha SLATS plots (RC1, 2, 3 and 4), by selecting the 16 closest overlapping pixels.

On the ground measurements of fC were derived from the IFOV (30°) angles close to zenith, which can be treated as the near-vertical projection of foliage cover. Because fC derived from the CI-110 does not distinguish between foliage and non-foliage components, images derived with this instrument were classified in CanEye using a supervised classification. Furthermore, the ground-based assessment of FPC was conducted following the protocol developed for the validation of the FPC product (TERN, 2012e). To maintain consistency, FPC values were recorded following the CI-110 methodology (overstory greater than 2m above ground was considered).

4.0 Results

This study compared LAI and fC results obtained by applying three different sampling strategies in a rainforest environment. The values obtained for LAI and fC across the different plots throughout the Robson Creek study area are summarized in Table 1. Both LAI_e and LAI_t results are presented given clumping has been known to be the greatest error influence of indirect estimation of LAI (Jonckheere *et al.*, 2004). It is important to note that the LAI_e and LAI_m measurements obtained produce an $R^2 = 0.70$ ($p < 0.01$) when including only the plots measured with the CI-110, thus indicating the methods are significantly correlated.

Table 1. Summary table of LAI and fC values for each plot. Plots have been grouped into the 1ha area they fall within. The Sampling Design column denotes the sampling design used: G = grid, S = SLATS, V = VALERI (a indicates plots that also align with the centre of a SLATS plot and * *shows plots where the DHP method was used). The additional columns indicate the algorithm used to derive LAI: LAI_e and LAI_t values from CanEye; LAI_m (SD) values from Miller formula; fractional cover (SD) values over a 30° IFOV.*

Plot Area	Sampling Design	Plot ID	LAI_e	LAI_t	LAI_m (SD)		fC (SD)	
RC1	G	rc1g	4.81	7.16	5.81	(0.64)	94.56	(7.63)
	S	rc1s	4.63	6.72	5.58	(0.35)	96.49	(3.16)
	V	rc1v*a**	4.23	7.11	6.54	(0.20)	96.03	(3.06)
	V	rc1v*b**	4.88	7.06	5.33	(0.23)	94.62	(10.76)
RC2	S	rc2s	4.44	6.54	5.07	(0.44)	94.02	(7.82)
	V	rc2v*a*	4.18	5.88	5.19	(0.35)	94.28	(5.62)
	V	rc2v*b*	4.88	7.06	5.35	(0.35)	92.60	(11.35)
RC3	S	rc3s	4.20	6.21	5.27	(0.59)	95.84	(5.20)
	V	rc3v	5.04	7.18	5.69	(0.46)	97.46	(4.88)
RC4	S	rc4s	4.64	6.96	5.17	(0.65)	91.18	(12.64)
	V	rc4v	5.16	7.11	5.56	(0.48)	95.45	(4.97)
RC5	V	rc5v	5.53	7.67	6.11	(0.73)	96.47	(5.90)
RC6	V	rc6v	5.48	8.00	6.60	(0.35)	92.35	(19.34)
RC7	V	rc7v	5.16	7.55	6.11	(0.52)	97.22	(6.49)
RC8	V	rc8v*	4.49	7.16	5.82	(0.21)	97.50	(1.10)

Table 2 compares averaged FPC values obtained from the satellite product against oversotry FPC (greater than 2m above ground) and fC values obtained from the ground-based methods for the four 1ha SLATS plots. The FPC values from the satellite product vary by up to 8% (min = 76.25%, max = 84.44%), whereas the fC and FPC from the ground-based methods vary by up to 5% (min = 91.18, max = 96.49) and 4% (min = 89%, max = 93%) respectively.

Table 2. Comparison of averaged FPC (SD) values. obtained from the satellite 2010 FPC product against overstory FPC (> 2m above ground) and fC values (obtained from the ground) for each of the 1ha plot areas

Plot Area	FPC from Satellite	fC from SLATS plots	FPC field values
RC1	80.13	96.49	89.00
RC2	77.56	94.02	91.00
RC3	76.25	95.84	93.00
RC4	84.44	91.18	90.50

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Figure 6 shows the proportion of gap or P_{gap} per plot, as a function of view zenith angle. The four plots shown are those where multiple coincident sampling designs were implemented. Except for RC1, where SLATS; VALERI; and the grid plot coincide, the plots show results for VALERI cross and SLATS. Within each plot, the VALERI method co-aligns with the centre of a SLATS plot. Figure 6 suggests that the different sampling strategies implemented to record gap fraction record quite variable results at low zenith angles. However, the variability amongst the different sampling strategies implemented appears to decrease with increasing zenith angles and eventually stabilizes near complete canopy closure between 50 to 55 degrees.

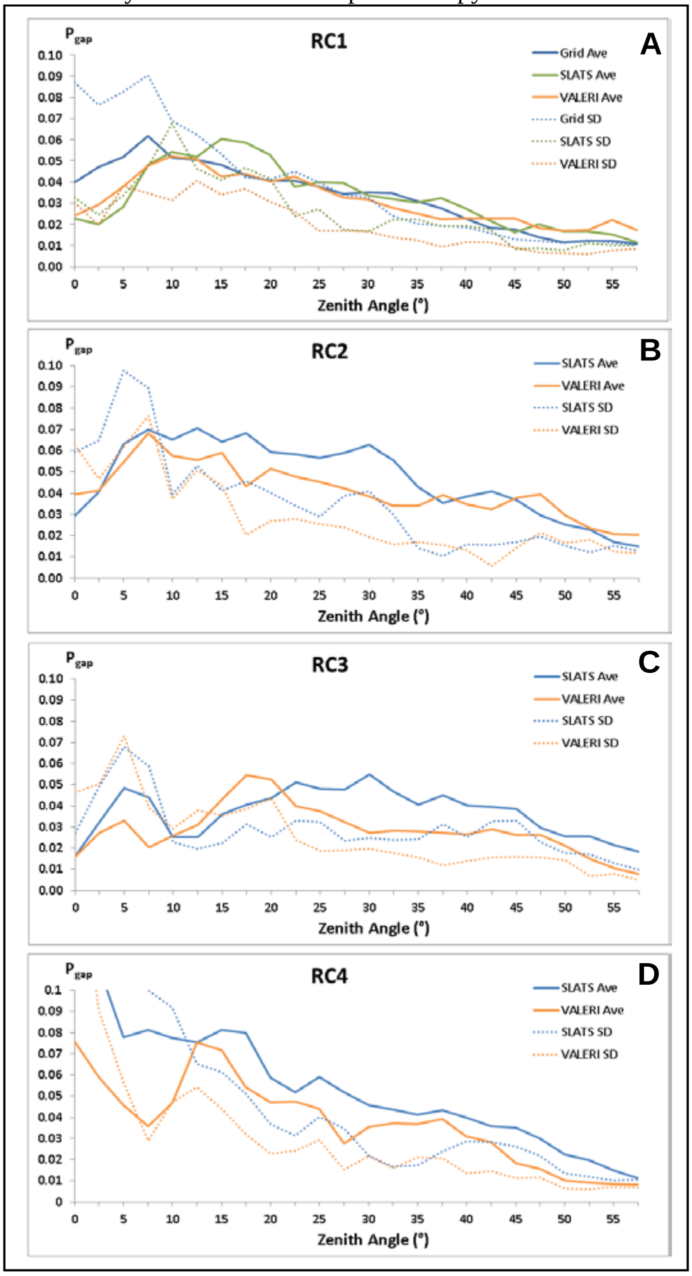

Figure 6. Proportion of gap or gap probability (P_{gap}) for each plot as a function of view zenith angle. ***A)*** *P_{gap} as a function of zenith angle for RC1 using the Grid, SLATS, and VALERI plot designs.* ***B)*** *P_{gap} as a function of zenith angle for RC2 using the SLATS and VALERI plot designs.* ***C)*** *P_{gap} as a function of zenith angle for RC3 using the SLATS and VALERI plot designs.* ***D)*** *P_{gap} as a function of zenith angle for RC4 using the SLATS and VALERI plot designs.*

5.0 Discussion

In this study, three sampling strategies commonly used to measure LAI were compared in a rainforest environment. On average, the standard deviation for LAI of all plots and plot types closely approximated the variability of LAI found within each plot – indicating the study area is relatively homogenous. Furthermore, the LAI results obtained in this study (i.e., LAI_e range 4.18 – 5.53, $\mu = 4.78$ [0.44]; LAI_t range 5.88 – 8, $\mu = 7.03$ [0.54]; LAI_m range 5.07 – 6.60, $\mu = 5.68$ [0.49]) are consistent with results obtained in other rainforests in Australia and other countries (see Nightingale *et al.*, 2008 for a review of these).

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5.1 Within measurement variability

The results obtained demonstrate high variability in P_{gap} for low zenith angles (less than 30 degrees) in each of the plots, which is also consistent with other studies (i.e., Leblanc *et al.*,2005). Furthermore, at these low zenith angles, the standard deviation is greater than the mean P_{gap}, which highlights the high variability present in these environments at the low zenith angles. This has implications for fC, which is derived using low zenith angles (0-15 degrees). Due to the high level of variability present at low zenith angles, a sufficient sample size must be collected in order to derive a value that is representative of the plot mean. Results indicate that fC values derived from the CI-110 images closely match the ground-based FPC values, where the FPC method has determined an optimal sample size per plot (n = 300) to characterise the FPC value.

5.2 Within plot variability

It was noted that the standard deviation of P_{gap} at zenith angles greater than 30 degrees was consistently lower with the VALERI designs than the SLATS design, and then again with the VALERI and SLATS compared to the grid plot design. Furthermore, the standard deviation for each plot type from Miller's formula decreased proportionally with the area of the plot and number of measurements. Both of these findings are consistent with Tobler's (1970) first law of geography, also known as the concept of spatial dependence (Atkinson and Curran, 1995; Atkinson, 2000). Spatial dependence (or auto correlation) suggests that measurements close together are more highly correlated than those that are further apart. Accordingly, the findings of the standard deviation of each plot type increasing with the spatial coverage of the plot are consistent with this concept.

5.3 Sampling design comparison

An important factor to consider in any sampling design for validation purposes is the target resolution or scale of the product for validation or up-scaling. Both the grid and SLATS plot designs aim to characterise a 1 ha area with a different spatial arrangement and number of measurements. Results in Table 1 indicate that both managed to produce similar values of LAI, where LAI_e and LAI_m from each design were matching within 4%. When comparing the coincident VALERI plots with the SLATS plots, LAI_e and LAI_m differences ranged by up to 16% and 17% respectively. These differences suggest that the plot area of 0.2 ha and 1 ha has a large effect on the derived LAI values from both plot designs within the study area, where the number of samples for both methods was comparable.

5.4 Comparison of ground-based assessments of fC and FPC to the satellite FPC product

There was a minimum 10% difference when comparing foliage cover values derived from the FPC satellite product to those derived on the ground. However, it is important to note that direct comparisons of satellite products and on-the-ground based measurements is difficult at small scales given factors such as geo-location uncertainty (between 20-50 m for the FPC product and 5-10 m for the plot centres). Other aspects such as woody to non-woody correction factors (none made in this study) also have the potential to compound these differences. Nevertheless, it was noted that mean fC derived from the CI-110 matched more closely with the FPC values derived following the field SLATS transect protocol.

6.0 Conclusion

This paper investigated the impact of plot and site scale variability of LAI and foliage cover metrics in a representative rainforest. Three ground-based sampling designs were tested in the field to derive LAI and fC, and then related to an FPC satellite product over the same area. The key distinguishing factors between the three sampling designs (VALERI, SLATS, and Grid) were their number of measurements (12, 13, and 36); spatial representation (cross, star transect, and grid); and plot area (0.2 ha, 1 ha, and 1 ha).

The LAI results obtained are consistent with those found in the literature for tropical rainforests. In addition, the following summarizes findings in terms of within study area variability, within plot variability, and within measurement variability. In terms of within study area variability and according to the sampled plots (each of which represents an area that ranges between 0.2 ha to 1 ha), the study area was found to be relatively homogenous since the standard deviation of LAI values obtained amongst the plots was on average consistent with the standard deviation found within each plot. Within plots, it was found that plot size is proportional to LAI variability. Despite the number of measurements taken, LAI variability increases as plot size increases. This agrees with Tobler's first law of geography and the spatial auto-correlation of objects. A recommendation is then to choose a plot size which is most relevant to the purpose of use, such as a resolution comparable to the medium satellite product to be validated. When looking at the individual LAI measurements collected, the variability of gap fraction was also noted. High variability was detected at low zenith angles, whereas the opposite occurred and even appeared to stabilize with increasing zenith angles. Finally, the ground-based vegetation cover estimates from the fC and FPC methods matched closely with each other, but not to the same degree with the FPC satellite product.

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