



Evaluation of easily measured stand inventory parameters as predictors of PAR transmittance for use in poplar silvopastoral management

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ABSTRACT

This study compares the ability of several poplar (*Populus* spp.) stand parameters to predict photosynthetically active radiation (PAR) transmission through the overstorey canopy in a silvopastoral system. As an indirect measure of PAR transmission, diffuse non-intercepted radiation (DIFN) levels underneath fully foliated poplar stands were measured in two climatically contrasting regions of the North Island of New Zealand. The ability of several easily measured stand inventory parameters to predict understorey DIFN was then evaluated using regression analysis. Pasture net herbage accumulation (NHA) was also measured below the fully foliated trees and related to understorey DIFN. A directly inverse relationship between DIFN in the gap between tree crowns and stand canopy closure measured with a standard digital camera was found to be the simplest, most accurate and robust of the stand parameters examined. In comparison, there were site differences in the relationship for this understorey environment for all of the stand parameters based on individual tree metrics. Site differences in the relationship for DIFN directly underneath the tree-crowns were also apparent for both the stand parameters based on individual tree metrics and digital photographs. Inter-site variation in these relationships was attributed to unaccounted differences in stand leaf area. There was a strong straight-line relationship between DIFN and understorey pasture NHA.

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1. Introduction

In New Zealand poplar (*Populus* spp.) are mainly planted on farmland and are used for a wide variety of purposes (Wall et al., 1997; McGregor et al., 1999). Over the last 60 years more than six million poplar trees have been planted in New Zealand (NZPC, 1995). This genus is especially valued on North Island hill pastures for soil conservation (Hathaway, 1986; Thompson and Luckman, 1993). The ability to establish from large (2–3.5 m tall) unrooted poles, combined with a fast growth rate make poplars very useful for attaining rapid hillside stabilisation, while having minimal impact on pasture management (Miller et al., 1996; Wilkinson, 1999). Stands are usually small in size, compared to farm woodlots and commercial forestry, with trees normally strategically planted on only erosion-prone landscape units (Wall et al., 1997). Many stands also receive little silviculture (NZPC, 1995; Cameron, 2003). The resulting low volume and wood quality of these trees, com-

bined with often poor site access for logging, limits their direct economic value, beyond use on farm. This explains in part the limited silviculture, but does not explain the lack of action by land owners to limit tree shading effects on understorey pasture mass grazed by domestic livestock, which remains the sole source of income on these landscapes (Wilkinson, 1999).

Reduced levels of photosynthetically active radiation (PAR, 400–700 nm) caused by tree-shading have a significant effect on the botanical species composition, morphology, and productive capacity of understorey pastures. In temperate tree-pasture systems, as PAR transmission is reduced understorey pastures become less dense through reduced tillering or branching, plants become etiolated, shade-tolerant species become more prevalent, and overall biomass production decreases (Devkota et al., 1998; Peri et al., 2007). Young poplar trees have little impact on the productive capacity of North Island hill pastures, but as their crown's develop in size and increasingly reduce the level of PAR transmitted to the understorey this changes (Gilchrist et al., 1993; Douglas et al., 2006; Wall et al., 2006; Guevara-Escobar et al., 2007). A measure of PAR transmission below poplar trees would be a useful tool that land owners could use to manage the density of a stand to ensure an acceptable level of understorey pasture production is sustained.

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Table 1
General characteristics of poplar stands.

Site	Kiwitea	Ballantrae	Hautope 1	Hautope 2
Location (district)	Manawatu	Tararua	Hautope	Hautope
Latitude longitude	40.08°S 175.47°E	40.18°S 175.50°E	39.58°S 176.43°E	39.58°S 176.44°E
Hill slope	20–36°	5–10°	15–27°	23–28°
Aspect	North	North-east	South-east	North-west
Elevation (m a.s.l.)	320	135	160	220
Annual rainfall (mm)	1062	1200	800	800
Mean air temp (°C)	12.1	12.2	12.5	12.5
Poplar hybrid	I45/51, I78, I214, and I488	NZ559	I78 and I214	I214
Age (years)	>30	5	>25	>25
No. of sample plots	14	21	12	6
Density (stems ha ⁻¹)	10–119	50–750	29–374	30–291
Basal area (m ² ha ⁻¹)	4–43	0.3–4.4	6–36	2–13
Top height (m)	21–39	6–9	19–28	10–15
Height ratio ^a	0.06–0.17	0.43–0.54	0.09–0.34	0.14–0.23

^a Height ratio = live-crown base height/live-crown top height.

Several methods are available for directly measuring PAR transmission (Wünsche et al., 1995; Gendron et al., 1998; Loeffers et al., 1999). To account for high spatial and temporal variation in light amongst trees, these methods normally use integrated arrays of quantum sensors, placed simultaneously below, outside or above a stand (Sibbald and Griffiths, 1992), or alternatively fewer sensors are moved to various sampling positions with repeated readings taken over time (Chen et al., 1997; Hassika and Berbigier, 1998). While direct measurements provide the most accurate estimates of PAR transmission, their practicality for widespread and routine sampling of large numbers of small sized stands, is limited (Engelbrecht and Herz, 2001; Bellow and Nair, 2003). Also, it is difficult to link direct measures of PAR transmission to specific stand management prescriptions and marking guidelines for silvicultural operations (Buckley et al., 1999; Lhotka and Loewenstein, 2006). PAR transmittance models based on easily measured stand parameters (structural metrics), commonly taken as part of normal agroforestry or forestry inventories, would be more applicable (Balandier et al., 2006; Lhotka and Loewenstein, 2006). However, there are a wide range of stand parameters that could potentially serve as good predictors of PAR transmittance, all of which require calibration (Jenkins and Chambers, 1989; Bellow and Nair, 2003; Comeau and Heineman, 2003; Lhotka and Loewenstein, 2006). This study assesses several individual stand parameters as indirect measures of PAR transmission. These stand parameters are compared, using best-fit empirical models, to evaluate the utility of each for predicting PAR transmittance.

2. Materials and methods

2.1. Site descriptions

Study sites were four sheep and cattle farms in New Zealand's Southern North Island hill country (Table 1). Kiwitea and Ballantrae farm sites were located in Western Manawatu and Central Tararua districts of the North Island, respectively, while Hautope 1 and 2 were adjacent farm sites in the East Coast District of Waipawa. These sites spanned climatically contrasting regions of the North Island. Main axial mountain ranges stretching across the North Island act as a barrier to weather systems moving eastwards (Burgess, 1983). With westerly airstreams being predominant in late spring and summer, east coast districts such as Waipawa experience highly variable rainfall during this period and often evapotranspiration rates are high enough to cause drought conditions (Thompson, 1987). Annual rainfall ranges between 800 mm and 1200 mm. Annual mean air temperature ranges between 12.1 °C and 12.5 °C (Table 1).

All four farm sites had *P. × euramericana* (Dode) Guinier black hybrid clones (Table 1). Kiwitea, Hautope 1 and 2 were planted with Italian bred hybrids I45/51, I78, I214, and I488. These stands consisted of mature (>25-years-old) untended trees planted up to stocking rates of 400 stems per hectare (stems ha⁻¹), depending on the extent and severity of soil erosion present (Table 1). In contrast, Ballantrae had young (5-year-old) New Zealand bred hybrid 'Tasman' (NZ559) poplars. These trees had received an initial lower-branch pruning and were planted in a systematic-spacing 'Nelder' experimental design (Nelder, 1962). The stocking rate for the trees at this site ranged between 50 stems ha⁻¹ and 750 stems ha⁻¹ (Table 1).

2.2. Sampling strategy used to create a gradient of stand densities

A total of 14, 12, and 6 plots were sampled at Kiwitea, Hautope 1, and 2, respectively (Table 1). The above totals included two open-field areas at each farm site. Field surveys were made in June 1998 at Kiwitea and in February 1999 at Hautope 1 and 2 to identify potentially suitable plots for sampling. A sample plot consisted of four nuclei trees planted in a square pattern surrounded with buffer trees of similar size and spacing. Tape surveys were made to determine the spatial arrangement and stocking rate of trees in the plots. For each site, the tree stocking rate was used to stratify potential sample plots into groups, from within which random selections were taken. The systematic grouping of plots served two main functions: firstly, it provided a base for selecting a wide range of representative stand densities and secondly, it enabled a reasonably even spread of stand densities to be selected to obtain well defined relationships between the independent (stand parameters) and dependent (PAR transmission) variables being studied (Myers, 1990). At Ballantrae, 21 sample plots (including three open-field areas) were non-randomly selected from nine arcs and two spokes of the fan shaped 'Nelder' design (Table 1).

Overall, selected tree stocking rates ranged from 10 stems ha⁻¹ to 750 stems ha⁻¹ and there was considerable overlap in stocking rate between the four sites (Table 1). The range in tree crown top heights of sample plots at Kiwitea, Hautope 1, 2, and Ballantrae were 21–39 m, 19–28 m, 6–9 m, and 10–15 m, respectively (Table 1). For their age, the trees at Hautope 2 were small. This likely reflected the exposed and eroded nature of this site. All sample plots at Kiwitea, Ballantrae, Hautope 1, and 2 were on North, Northeast, Southeast, and Northwest facing aspects, respectively (Table 1).

2.3. Tree measurements

Stem diameter at breast height (DBH), live-crown top height, live-crown base height, and crown diameter were measured on each nuclei tree of a sample plot. DBH was calculated from stem circumference (C) measurements taken at 1.4 m above ground level (upslope). Vertical top and base heights of tree crowns from ground level were measured with a telescopic measuring pole (Senshin Industry Co.) or with a hypsometer (Suunto Precision Instruments). The lowest live branch, ignoring epicormic shoots defined the base of a crown. Crown diameter (CD) vertically projected onto a horizontal plane was calculated from two levelled tape measurements taken at perpendicular angles to each other (Bellow and Nair, 2003).

2.4. Stand inventory parameters calculated from tree measurements

DBH and crown diameter measurements were scaled up to a per hectare basis via the tree stocking rate of the sample plot to give an integrated measure of both tree density and individual crown size (Table 2). Additional stand parameters derived from individual tree measurements and scaled up to a per hectare basis were basal area (BA), green crown length (GCL), vertically projected canopy coverage (VPCC), and crown ellipsoidal volume (CEV). BA was calculated from DBH measurements, using the formula: $BA = \pi DBH^2 / 4$. Foliated crown depth (GCL) was calculated as the difference between live-crown top and base heights ($GCL = top - base\ height$). The horizontal cross-sectional area of tree crowns was derived using the same geometrical formula and assumptions used for determining stem basal area. However, for this calculation maximum CD was limited to within the mean distance between trees for a particular sample plot, based on the assumption that adjacent tree crowns did not overlap (Fig. 1). On a per hectare basis, this parameter gives a simple estimate of VPCC (Schreuder et al., 1993). CEV was calculated from CD and GCL measurements using the formula: $CEV = 4/3\pi R^2 H$, where R is the crown radius and H is half the GCL per stem. A solid vertical ellipse with perfect symmetry was assumed to represent the general shape of individual tree crowns (Karlik and Winer, 1999; Stadt and Loeffers, 2000).

Table 2
Stand inventory parameters measured at each farm site.

Abbreviation	Units	Definition
DBH	m ha ⁻¹	Sum of stem diameters over bark at 1.4 m per hectare
BA	m ² ha ⁻¹	Sum of stem basal areas at 1.4 m per hectare
GCL	m ha ⁻¹	Sum of green crown lengths per hectare
VPCC	%	Vertically projected canopy cover ratio
CEV	'000 m ³ ha ⁻¹	Sum of green crown ellipsoidal volumes per hectare
CC	%	Canopy closure ratio

2.5. Stand inventory parameter based on colour digital images of the poplar canopy

The canopy closure ratio (CC) above each sample plot was estimated from a series of colour photographs taken with a Sony MVC-FD7 digital camera (Sony Corp.). As defined by Jennings et al. (1999), CC is “the proportion of the sky hemisphere obscured by vegetation when viewed from a single point”. Unlike VPCC, CC measurements involve an angle of view of the overstorey canopy and also account for gaps within individual tree-crowns (Korhonen et al., 2006). The standard lens of the camera was used, which produced rectangular non-equidistant images. Lens aperture width and shutter speed were automatically selected by the camera (Englund et al., 2000; Guevara-Escobar et al., 2005). In the field the camera was set to view vertically upwards using a spirit-bubble-level, and was mounted at 0.7 m above ground level (upslope) on a height adjustable tripod. Wherever possible, digital images were taken under calm, uniformly overcast sky conditions to maximise image contrast and minimise interference by direct sunlight (Englund et al., 2000; Frazer et al., 2001). Sampling dates at Kiwitea, Hautope 1 and 2, and Ballantrae were 25/01/1999, 13/02/2000, 14/02/2000, and 2/03/2001, respectively, when trees were fully foliated.

The spacing between the four nuclei trees, used to define a sample plot, created an overstorey canopy that was naturally more open towards the plot centre (Fig. 1). Therefore, estimating the average CC by random sampling was inappropriate, as there was a chance the majority of sampling points could have been concentrated under a dense or open part of the overstorey canopy (Knowles et al., 1999). Instead, to provide complete coverage of the poplar canopy above each sample plot, sampling points were restricted using a systematic star-shaped design developed by Knowles et al. (1999). Seventeen images were taken for each sample plot: at the centre of the plot, and at distances of 6 m and 12 m, radiating outwards along the eight major compass directions from the central point (Fig. 2).

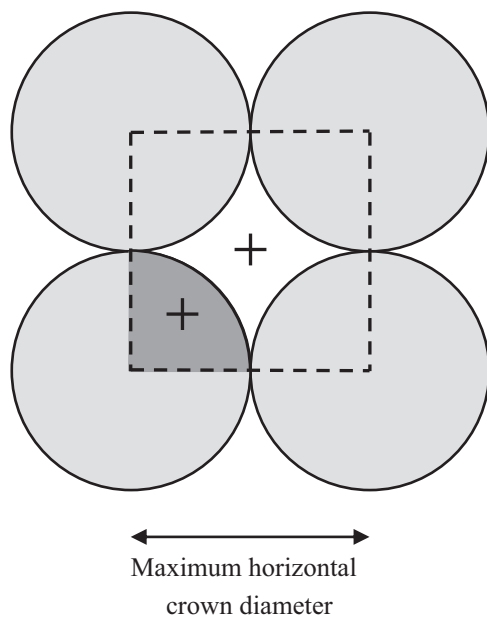


Fig. 1. A schematic aerial view of four ‘nuclei’ trees (grey circles) defining the boundary (dashed lines) of a sample plot. Light measurements were taken directly under the tree crown (dark grey area) and at the centre of a sampling plot.

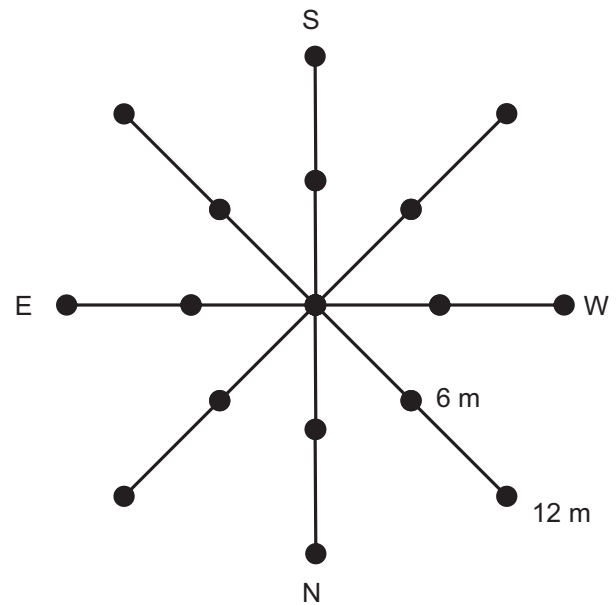


Fig. 2. Sampling grid overlaid and centred on a sample plot to estimate CC. Adapted from Knowles et al. (1999).

Digital image analysis was based on the method of Guevara-Escobar et al. (2005). This analysis followed three stages: firstly, identifying and separating overstorey canopy and background sky areas of an image through their respective colours (segmentation process); secondly, reducing these two colour-defined areas to purely black and white, respectively; and thirdly, counting the total number of pixels within each simplified category to give an estimate of CC.

Sky and canopy pixels of an image were differentiated using a colour filter created in Corel Photo-Paint® (version 9.0 for Windows®, Corel Corp. 1999). An individual filter consisted of a palette of representative sky colours manually selected directly from an image via the software's colour masking function. A threshold value was set for these selected colours so that each would include 20 of their closest neighbours within the available colour spectrum. This reduced the total number of distinctive colours, and thus time, needed for identifying pixels belonging to the sky portion of an image. The variable-zoom function in Corel Photo-Paint® aided in the investigation of finer image detail, but similar to the results of Englund et al. (2000), solely focusing on a small portion of the image often caused inaccuracy in separating other parts of an image. A semitransparent red overlay was added (tagged) to pixels associated with the selected colours to visually check the precision of the segmentation process. Overall, three to ten colours were chosen for separating sky and canopy pixels of an image; depending on the degree of contrast between the two elements and also their respective uniformity of colour. Images captured on completely overcast days were preferred, as this reduced the negative effects of colour halos and the blurring of canopy edges. Once the filter (colour mask) was completed, it was saved as a standard template for the remaining images of a sample plot. Nevertheless, the precision of the standard filter was visually rechecked for each image and the original set of base colours was modified where necessary. Potential bias or non-random variation caused by human error was minimised by having a single person analyse all of the digital images (Gendron et al., 1998; Beaudet and Messier, 2002; Lhotka and Loewenstein, 2006).

The individually tailored filters (colour masks) protected image pixels that were within the colour ranges specified, but could also be inverted so protecting either the sky or overstorey canopy areas of an image. This enabled the entire originally unprotected canopy area to be converted to black, the mask inverted, and the remaining sky area converted to white. These simplified black and white binary images were saved as new files, and the black canopy pixels were identified and counted in SigmaScan® Pro (version 4.0 for Windows®, SPSS Inc. 1998). The counted number of black canopy pixels divided by the total number of pixels within the image matrix (VGA 640 × 480 pixels) represented CC. Overall, CC for an entire sample plot was based on the mean of the 17 images taken in the field.

2.6. PAR measurements

The percentage of above-canopy PAR transmitted through the poplar canopy was estimated from diffuse non-intercepted radiation (DIFN) measurements taken with paired LiCor LAI-2000 Plant Canopy Analysers (LiCor Inc., Lincoln NE, USA). These sensors measure 400–490 nm (blue light) short-wave radiation simultaneously from five integrated concentric annuli of the upward hemisphere, covering in total a 150° field-of-view (Welles and Norman, 1991; Hanan and Bégué, 1995). Under a wide range of canopy structures (or light gradients), several researchers

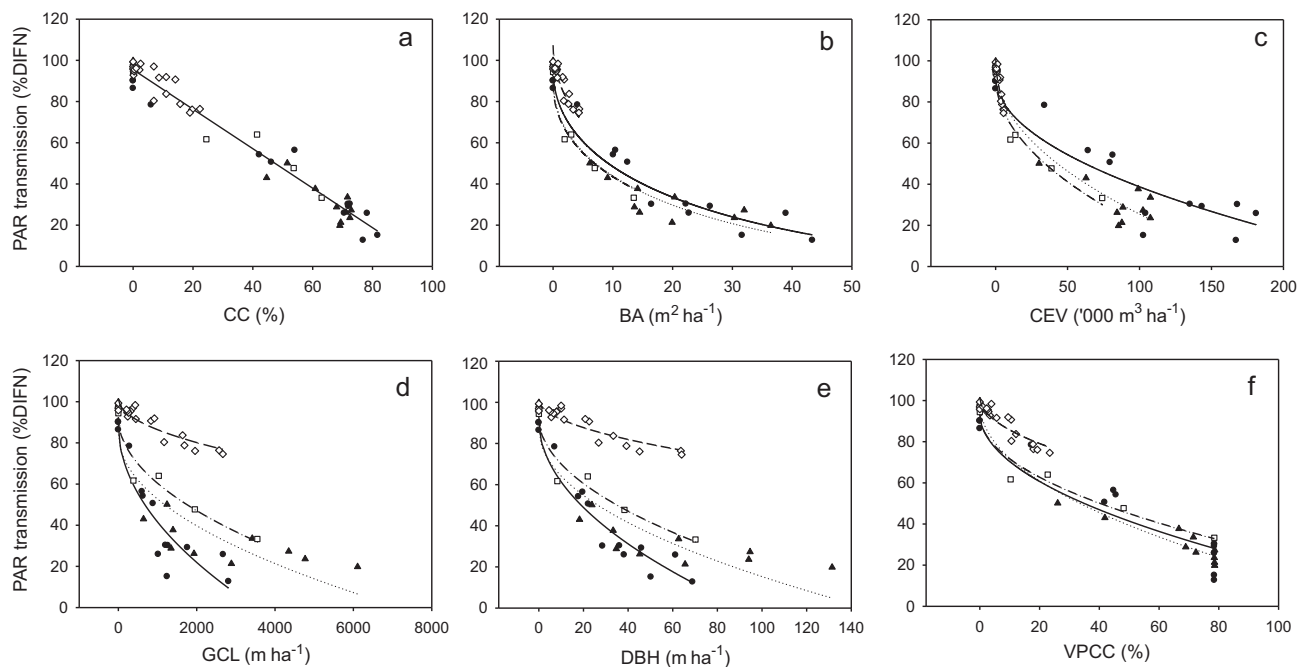


Fig. 3. Estimated percentage of above-canopy PAR (%DIFN) transmitted at the centre of a vertically projected canopy gap (VPG) between fully in-leaf poplars, over a range of (a) canopy closure ratios measured with a standard digital camera (CC), (b) stand basal areas (BA), (c) crown ellipsoidal volumes (CEV), (d) green crown lengths (GCL), (e) stem diameters at breast height (DBH), and (f) vertically projected canopy cover ratios (VPCC). Symbols: (●) Kiwitea, (▲) Hautope 1, (□) Hautope 2, and (◇) Ballantrae site. Regression models are described in Table 3.

have shown that instantaneous readings of understorey DIFN (I_u), relative to simultaneous above-canopy readings (I_o), can be used as a reliable estimate of mean daily or seasonal PAR transmission (Comeau et al., 1998; Gendron et al., 1998; Lieffers et al., 1999; Machado and Reich, 1999):

$$\text{Estimated PAR transmission (\%DIFN)} = \left(\frac{I_u}{I_o} \right) \times 100 (\text{units : \%}) \quad (1)$$

This measurement is conceptually similar to the diffuse site factor obtained from hemispherical (fisheye) canopy photographs or images and also paired quantum sensor readings, taken simultaneously from above and below a canopy on completely overcast days (Messier and Puttonen, 1995; Parent and Messier, 1996; Gendron et al., 1998; Messier et al., 1998; Machado and Reich, 1999). However, an important difference is that the latter method accounts for scattered diffuse (transmitted and down-reflected) radiation from the overstorey, whereas the former two methods treat all overstorey elements (e.g. trunks, branches, leaves) effectively as opaque (Hanan and Bégue, 1995; Gendron et al., 1998; Lieffers et al., 1999).

%DIFN measurements were taken using two synchronised and cross-calibrated LAI-2000 Plant Canopy Analyser (PCA) units; one was moved around the various sampling positions of interest, while the other was positioned permanently in a nearby open field, as an above-canopy reference. Both PCA units had their short-wave radiation sensor fields of view (azimuth) restricted to 180°, and using a compass were orientated to the general aspect of the farm site. The view restriction prevented the PCA sensors from 'seeing' the operator, direct beam radiation, or hill upslope from the trees (Welles and Norman, 1991; Hanan and Bégue, 1995; Comeau et al., 1998; Gendron et al., 1998). At each location eight %DIFN measurements were taken with the portable PCA unit levelled horizontally at one metre above the ground (Welles and Norman, 1991). All %DIFN measurements were obtained within a month of taking the digital canopy images, except for at Ballantrae, which were obtained in the same month but in the year prior (this exception was due to the unavailability of equipment).

%DIFN measurements were taken in two contrasting understorey environments of each sample plot. The first environment was defined as the area directly below the vertical projection of the tree crown on the North-eastern corner of a sample plot (VPC). The second environment was defined as the vertically projected gap between the crowns of the four nuclei trees (VPG, Fig. 1). All light measurements were taken at the centre of each understorey environment. At Ballantrae VPC measurements were taken only under five arcs of the Nelder design.

2.7. Pasture net herbage accumulation measurement

Pasture net herbage accumulation (NHA) was measured at Kiwitea, Hautope 1 and Hautope 2 when the trees were fully foliated (November 1999–February 2000) using a double-trim method (Radcliffe, 1974). In all open field, VPG, and VPC environments, pasture re-growth from 25 mm above ground level within a 0.2 m² quadrat was harvested at monthly intervals from underneath grazing exclusion

cages. The placement of the cages was restricted to a medium hill-slope class of 13–25°. Herbage samples were washed and then dried at 80 °C to a constant weight in a forced-draught oven. Pastures were typical Southern North Island hill pastures dominated by grass species (e.g. *Agrostis capillaris* and *Lolium perenne*) with a low abundance of legumes (Nicholas et al., 1997). The areas were grazed with sheep and cattle.

2.8. Statistical analysis

Analysis of covariance (ANCOVA) was performed, using the REG procedure of SAS® (version 9.1 for Windows®, SAS Institute, Inc. 2002), to predict %DIFN based on stand parameters and site. In each model, %DIFN was the dependent variable and stand parameter and site were independent continuous (metric) and categorical (non-metric) variables, respectively (Brenson et al., 1983; Kleinbaum et al., 1998). Ballantrae was the comparison (reference) group in all models. Separate ANCOVAs were carried out for VPG and VPC environments. The quality of fit of each model was checked through inspection of scatter, residual and normal probability plots, along with more formal test statistics (SAS, 1990). Some independent and dependent variables were square root ($\sqrt{}$) or natural logarithm ($\ln(x+1)$) transformed to improve the fit and underlying assumptions of the models (as indicated in appropriate tables).

ANCOVA was also used to investigate the relationship between %DIFN and pasture NHA across the Kiwitea, Hautope 1 and 2 sites.

3. Results

3.1. %DIFN at the centre of a vertically projected gap (VPG) between fully in-leaf poplars

%DIFN ranged between $94.8 \pm 1.4\%$ (pooled mean \pm standard error, $n = 10$) in open field areas to 12.7%, 19.8%, 33.0%, and 74.6% in the VPG under the highest stand density measured at Kiwitea, Hautope 1, Hautope 2 and Ballantrae, respectively (Fig. 3). In general, VPG %DIFN was inversely related to all of the tested stand parameters (Fig. 3; Table 3). However, there were marked differences in the general form, complexity, and precision of the above relationships (Fig. 3; Table 3).

CC measured with a standard digital camera provided the simplest relationship with VPG %DIFN (Fig. 3a; Table 3). Out of the different stand parameters tested, the assigned simple linear (straight-line) model for CC had the lowest standard error of

Table 3

Models developed for stand parameters to estimate the percentage of above-canopy PAR (%DIFN) transmitted at the centre of a vertically projected canopy gap (VPG) between fully in leaf poplar trees.

Parameter	Model ^a	Adj. R ²	RMSE
CC	$Y = 95.47 (1.1) - X \times 0.96 (0.02)$	0.97	5.39
BA	$\sqrt{Y} = 10.36 (0.11) - \sqrt{X} \times 0.89 (0.04) - \text{Kiwi} \times 0.59 (0.19) - \text{Hautp1} \times 0.92 (0.20) - \text{Hautp2} \times 0.95 (0.21)$	0.95	6.14
VPCC	$Y = 101.68 (2.40) - \sqrt{X} \times 5.04 (0.90) - \text{Kiwi} \times 7.82 (3.99) - \text{Hautp1} \times 3.49 (4.62) - \text{Hautp2} \times 8.51 (4.45) - \sqrt{X} \times \text{Kiwi} \times 2.37 (1.00) - \sqrt{X} \times \text{Hautp1} \times 3.26 (1.04) - \sqrt{X} \times \text{Hautp2} \times 1.76 (1.16)$	0.96	5.89
CEV	$Y = 101.58 (2.92) - \sqrt{X} \times 0.30 (0.06) - \text{Kiwi} \times 9.47 (4.82) - \text{Hautp1} \times 4.92 (5.63) - \text{Hautp2} \times 9.07 (5.36) + \sqrt{X} \times \text{Kiwi} \times 0.13 (0.07) + \sqrt{X} \times \text{Hautp1} \times 0.07 (0.07) + \sqrt{X} \times \text{Hautp2} \times 0.07 (0.07)$	0.94	7.17
DBH	$Y = 101.63 (2.95) - \sqrt{X} \times 3.11 (0.68) - \text{Kiwi} \times 10.09 (4.75) - \text{Hautp1} \times 14.93 (5.24) - \text{Hautp2} \times 8.69 (5.48) - \sqrt{X} \times \text{Kiwi} \times 6.43 (0.98) - \sqrt{X} \times \text{Hautp1} \times 4.02 (0.92) - \sqrt{X} \times \text{Hautp2} \times 4.13 (1.18)$	0.94	7.26
GCL	$Y = 101.54 (3.53) - \sqrt{X} \times 0.48 (0.13) - \text{Kiwi} \times 12.55 (5.66) - \text{Hautp1} \times 17.52 (6.21) - \text{Hautp2} \times 8.96 (6.58) - \sqrt{X} \times \text{Kiwi} \times 1.02 (0.19) - \sqrt{X} \times \text{Hautp1} \times 0.51 (0.16) - \sqrt{X} \times \text{Hautp2} \times 0.54 (0.21)$	0.91	8.79

^a All models were highly significant ($P < 0.0001$, $n = 53$). Standard errors of regression coefficients are given in parentheses. Ballantrae is the reference site in the models. Root mean square error (RMSE) is in natural units. $Y = \text{VPG \%DIFN}$, $X = \text{stand parameter}$.

prediction (RMSE = 5.39) and explained 97% of the variation in VPG %DIFN (Table 3). The slope of the relationship was not different from -1 ($P = 0.0958$) and there were no site differences in the relationship between CC and VPG %DIFN ($P = 0.1248$). Overall, VPG %DIFN decreased at a constant rate from open field levels to 17% under the highest measured CC of 82% (Fig. 3a).

The models developed for all other stand parameters were more complex and contained varying degrees of negative curvature (represented as $\sqrt{\text{one-bend}}$ transformations) (Table 3; Fig. 3b–f). Nevertheless, these models also accounted for a very high proportion of variation in VPG %DIFN with adjusted coefficient of determination (Adj. R^2) values greater than 90% (Table 3). BA had the simplest relationship with VPG %DIFN out of the models with curvature (Fig. 3b; Table 3). The slope of the relationship did not differ across the four farm sites ($P = 0.2034$). However, the small and young trees at Ballantrae consistently intercepted 12–19% less DIFN in the VPG than for all other sites ($P < 0.01$) (Fig. 3b).

In contrast, the slope of relationships using CEV, GCL, DBH, and VPCC, as independent variables, differed across sites ($P = 0.0212$, $P < 0.0001$, $P < 0.0001$, and $P = 0.0237$, respectively) (Fig. 3c–f; Table 3). As CEV increased VPG %DIFN decreased at a 26% lower rate under the large and mature trees at Kiwitea compared to Hautope 1 ($P < 0.05$). The rate of change in VPG %DIFN tended to be less at Kiwitea than Hautope 2 and Ballantrae ($P < 0.07$) (Fig. 3c; Table 3). For GCL and DBH the smallest and greatest rates of change in VPG %DIFN occurred under the small and young trees at Ballantrae and the large and mature trees at Kiwitea, respectively; whereas, Hautope 1 and 2 had intermediate rates of change ($P < 0.05$) (Fig. 3d and e; Table 3). The difference in slope between the large and mature, and small and mature stands at Kiwitea and Hautope 2, respectively, for DBH was significant only at the $P < 0.06$ level. For VPCC, the slope of the relationship was greater for the large and mature trees at Kiwitea and Hautope 1 than for the small and young trees at Ballantrae ($P < 0.05$) (Fig. 3f; Table 3). Otherwise, there were no other significant differences in slope among the sites (Fig. 3f; Table 3). Underneath stands that had reached maximum theoretical VPCC of 78.5%, VPG %DIFN was estimated to range between 25% and 33% (Fig. 3f). Overall, the pooled dataset lacked sampling points under small and young and large and old trees at very high and low tree densities (stems ha^{-1}), respectively (Fig. 3).

3.2. %DIFN directly below the vertical projection of a fully in-leaf poplar crown (VPC)

Between the open field and low poplar stand densities %DIFN decreased at a faster rate directly below the VPC than within the VPG (Fig. 3 vs. Fig. 4). In the fitted models this greater negative curvature was represented by $\ln(x+1)$ or $\sqrt{X \times Y}$ one-bend transformations (Table 4). Thereafter, VPC %DIFN became relatively constant from a low stand density onwards, irrespective

of the actual stand parameter used (Fig. 4). However, the level of VPC %DIFN varied significantly between sites. On average, VPC %DIFN at Kiwitea, Hautope 1, Hautope 2, and Ballantrae was $11 \pm 2\%$ (mean \pm se), $26 \pm 2\%$, $28 \pm 4\%$, $76 \pm 2\%$, respectively. The difference in VPC %DIFN between the large and mature and small and mature trees at Hautope 1 and 2, respectively, was not significant ($P = 0.61$).

All of the fitted models accounted for a high proportion of variation in VPC %DIFN (Adj. $R^2 = 0.74$ – 0.96). BA, VPCC, GCL and CEV had the simplest relationships with VPC %DIFN out of the stand parameters tested (Table 4). The slope of these relationships did not change significantly across the four sites (Fig. 4b–f; Table 4). However, over the range of stand densities measured there were consistent differences in VPC %DIFN between sites ($P < 0.001$, $P < 0.0001$, $P < 0.0001$, and $P = 0.004$, respectively, Fig. 4b–f; Table 4). For BA, VPC %DIFN was greater underneath the large and mature trees at Hautope 1 and small and young trees at Ballantrae in comparison to the large and mature trees at Kiwitea and small and mature trees at Hautope 2 ($P < 0.05$; Fig. 4b). VPCC had similar site differences to BA (Fig. 4b and f). However, the difference between the small and mature trees at Hautope 2 and the large and mature trees at Hautope 1 was only significant at the $P = 0.05$ level. For GCL, VPC %DIFN underneath the large and mature trees at Kiwitea was consistently lower than at all other sites. VPC %DIFN at Kiwitea was predicted to be 41%, 33% and 61% lower than at Hautope 1, Hautope 2, and Ballantrae, respectively ($P < 0.01$; Fig. 4d). For CEV the large and mature trees at Hautope 1 intercepted up to 12% less DIFN than under the large and mature trees at Kiwitea and small and mature trees at Hautope 2 ($P < 0.01$; Fig. 4c).

In contrast to the above stand parameters, the slope of relationships using CC and DBH as independent variables, differed across the sites ($P = 0.0141$ and $P = 0.0043$, respectively; Fig. 4a and e; Table 4). For both CC and DBH the decrease in VPC %DIFN with increasing stand density was lower under the small and young trees at Ballantrae compared to all other sites ($P < 0.05$, $P < 0.01$, respectively; Fig. 4a and e; Table 4). Again, similarly to the VPG, the pooled dataset for underneath the VPC lacked sampling points from small and young and large and old trees at very high and very low tree densities, respectively (Fig. 4).

3.3. Relationship between pasture production and %DIFN

There was a strong straight-line relationship between pasture NHA and %DIFN during the period when the trees were fully foliated (Fig. 5). At the lowest measured %DIFN of 5% understorey pasture NHA was predicted to be 21% of open field production. Thereafter, understorey NHA increased at a constant rate of 8.6% for every 10% increase in %DIFN (Fig. 5). There were no site differences in the relationship between NHA and %DIFN ($P = 0.4816$). Overall, the simple straight-line model accounted for 84% of the variation in pasture NHA. Few data points were present from 60% to 85% DIFN (Fig. 5).

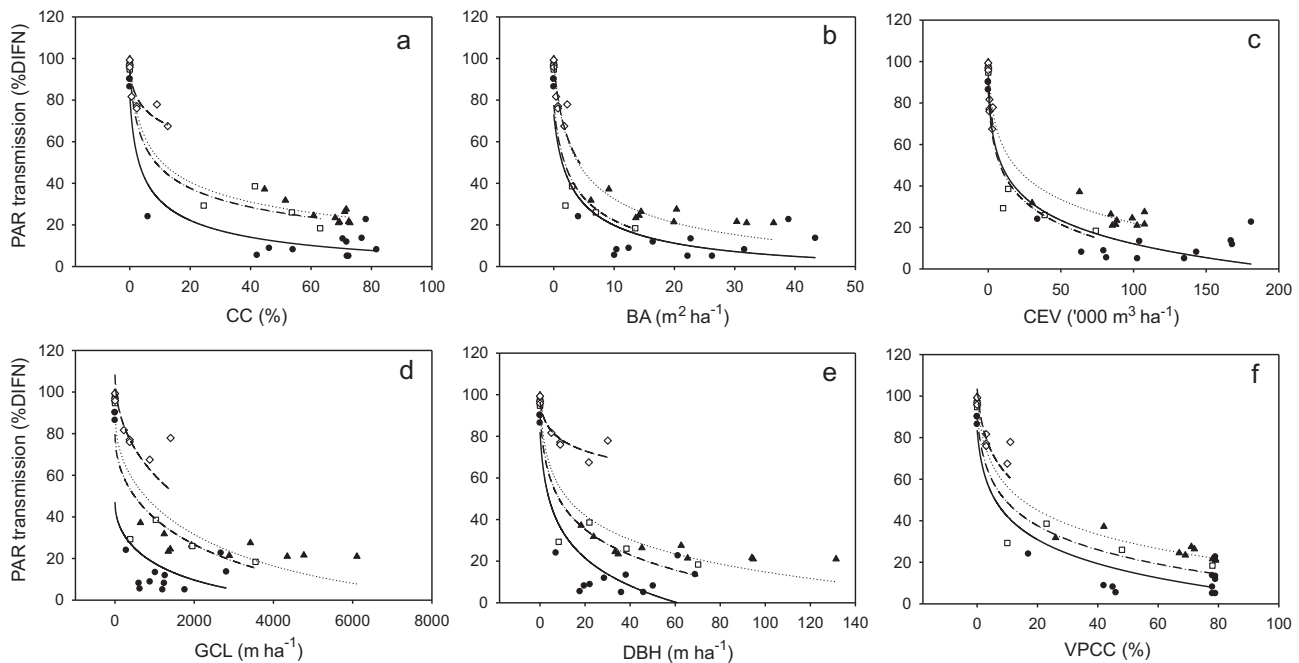


Fig. 4. Estimated percentage of above-canopy PAR (%DIFN) transmitted directly underneath vertically projected crowns (VPC) of fully in-leaf poplars, over a range of (a) canopy closure ratios measured with a standard digital camera (CC), (b) stand basal areas (BA), (c) crown ellipsoidal volumes (CEV), (d) green crown lengths (GCL), (e) stem diameters at breast height (DBH), and (f) vertically projected canopy cover ratios (VPCC). Symbols: (●) Kiwitea, (▲) Hautope 1, (□) Hautope 2, and (◇) Ballantrae site. Regression models are described in Table 4.

Table 4
Models developed for stand parameters to estimate the percentage of above-canopy PAR (%DIFN) transmitted directly underneath vertically projected crowns (VPC) of fully in leaf poplar trees.

Parameter	Model ^a	Adj. R^2	RMSE
CC	$\sqrt{Y} = 9.67 (0.33) - \ln(X+1) \times 0.54 (0.24) - \text{Kiwi} \times 0.60 (0.49) + \text{Hautp1} \times 0.33 (0.57) + \text{Hautp2} \times 0.07 (0.57) - \ln(X+1) \times \text{Kiwi} \times 0.89 (0.26) - \ln(X+1) \times \text{Hautp1} \times 0.64 (0.27) - \ln(X+1) \times \text{Hautp2} \times 0.64 (0.28)$	0.94	5.62
BA	$\sqrt{Y} = 9.90 (0.33) - \ln(X+1) \times 1.71 (0.13) - \text{Kiwi} \times 1.35 (0.48) + \text{Hautp1} \times 0.10 (0.50) - \text{Hautp2} \times 1.09 (0.51)$	0.88	9.13
VPCC	$Y = 103.60 (2.73) - \ln(X+1) \times 17.32 (0.74) - \text{Kiwi} \times 19.94 (3.60) - \text{Hautp1} \times 5.70 (3.77) - \text{Hautp2} \times 13.22 (4.06)$	0.96	7.33
CEV	$Y = 93.31 (2.63) - \ln(X+1) \times 16.58 (0.71) - \text{Kiwi} \times 4.67 (3.94) + \text{Hautp1} \times 5.48 (4.03) - \text{Hautp2} \times 6.64 (4.14)$	0.96	7.36
DBH	$Y = 96.54 (5.42) - \ln(X+1) \times 7.73 (2.58) - \text{Kiwi} \times 14.54 (7.62) - \text{Hautp1} \times 1.98 (8.50) - \text{Hautp2} \times 5.58 (8.54) - \ln(X+1) \times \text{Kiwi} \times 12.14 (3.10) - \ln(X+1) \times \text{Hautp1} \times 9.51 (3.14) - \ln(X+1) \times \text{Hautp2} \times 10.55 (3.50)$	0.92	9.77
GCL	$\sqrt{Y} = 10.41 (0.51) - \sqrt{X} \times 0.08 (0.01) - \text{Kiwi} \times 3.55 (0.62) - \text{Hautp1} \times 1.03 (0.69) - \text{Hautp2} \times 1.48 (0.74)$	0.74	15.79

^a All models were highly significant ($P < 0.0001$, $n = 40$). Standard errors of regression coefficients are given in parentheses. Ballantrae is the reference site in the models. Root mean square error (RMSE) is in natural units. $Y = \text{VPG \%DIFN}$, $X = \text{stand parameter}$.

4. Discussion

The %DIFN underneath the closed canopy of large and mature trees at Kiwitea and Hautope 1 was 15% and 20% of the open field. Chen et al. (1997) and Messier et al. (1998) reported similar PAR transmission levels under *Populus* spp. of equal size and BA. These levels were still at least 5–10% higher compared to other hardwood species (Hughes et al., 1985; Jenkins and Chambers, 1989; Buckley et al., 1999; Beaudet and Messier, 2002; Balandier et al., 2006). Dissimilar VPG and VPC %DIFN measurements for a given stand density under the small and mature and small and young trees at Hautope 2 and Ballantrae, respectively, indicated that the stands sampled at these sites had not reached complete canopy closure (Figs. 3 and 4). Open field %DIFN values of less than 100% were probably caused by the fifth detector ring of the LAI-2000 sensors picking up obstructions (e.g. hills or trees) near the horizon (Figs. 3 and 4) (Hale, 2003; Groot, 2005).

A large number of studies have shown strong relationships exist between measures of forest canopy structure and understorey PAR transmission (Vales and Bunnell, 1988a; Jenkins and Chambers, 1989; Comeau et al., 1998; Buckley et al., 1999; Comeau and Heineman, 2003; Lhotka and Loewenstein, 2006). Similarly to

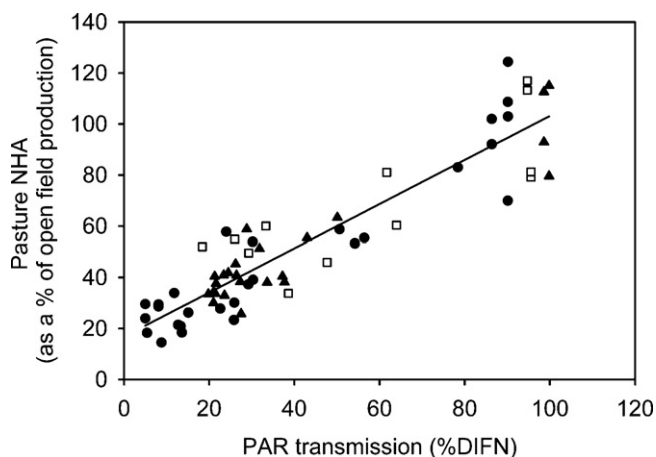


Fig. 5. The relationship between pasture NHA and %DIFN during the period when poplars are fully foliated. Symbols: (●) Kiwitea, (▲) Hautope 1, and (□) Hautope 2. Straight-line equation: $\%NHA = 16.81 (2.48) + \%DIFN \times 0.86 (0.05)$. Standard errors of regression coefficients are given in parentheses, $R^2 = 0.84$, $RMSE = 11.54$, $P < 0.0001$, $n = 64$.

Table 5
Relationships between PAR transmission and CC.

Source	Tree genus	Measurement method	CC	%PAR	Approx. CC range (%)	Equation	R ²	n
Buckley et al. (1999)	<i>Quercus</i>	Spherical densitometer with 60° angle of view. Measured at plot centre.		Ceptometer and quantum sensor. Paired instantaneous measurements taken at multiple points to give a plot mean.	0–90	91.21 – 0.95 × CC	0.99	12
Comeau et al. (1998) ^a	<i>Pinus</i> <i>Betula</i>	Spherical densitometer with 60° angle of view. Measured at multiple points to give a plot mean.		Quantum sensors. Paired continuous measurements taken over a season at multiple points to give a plot mean.	0–90 50–95	98.81 – 1.03 × CC 133.93 – 1.34 × CC	0.98 0.92	12 11
Jenkins and Chambers (1989)	Mixed hardwood spp.	Spherical densitometer with 60° angle of view. Measured at multiple points.		Quantum sensor. Instantaneous measurement repeated over time at multiple points.	55–95	112.91 – 1.16 × CC	0.71	180
Lhotka and Loewenstein (2006)	Mixed hardwood spp.	Spherical densitometer with 60° angle of view. Measured at plot centre.		PAR ceptometer and HOBO PAR sensor. Paired instantaneous measurements at plot centre.	75–95	61.08 – 0.60 × CC	0.68	50
Machado and Reich (1999) ^a	Mixed conifer dominant	Hemispherical photography limited to 60° angle of view. Measured at multiple points		Quantum sensor and gallium arsenide photodiodes. Paired continuous measurements at multiple points.	50–95	79.69 – 0.79 × CC	0.61	60

^a 100 – CC has been substituted for GF or canopy openness in regression equation.

this study, several have also shown marked differences in the general form (e.g. linear or curvilinear), complexity, and precision of the relationships, depending on the stand parameter(s) used as the independent variable (Comeau et al., 1998; Buckley et al., 1999; Lhotka and Loewenstein, 2006).

Of the stand parameters tested for estimating VPG %DIFN, CC measured with a standard digital camera had the simplest relationship with no site differences (Table 3; Fig. 3a). CC also had the highest adjusted coefficient of determination (Adj. R²) and the lowest standard error of prediction (RMSE) out of the indices tested. In particular, the regression statistics for CC suggests that the simple linear (straight-line) model fitted was a very good first approximation of the actual relationship, and that any gain in precision by including other independent (explanatory) variables was likely to be small. The –1:1 slope of the regression line indicated a directly proportional inverse relationship between VPG %DIFN and CC. CC systematically measured with a standard digital camera offers a good surrogate of VPG %DIFN across a wide range of poplar stand densities and sites.

Buckley et al. (1999), using a spherical densitometer to measure CC, found a similar relationship for red oak (*Quercus rubra* L.) and red pine (*Pinus resinosa* Ait.) stands (Table 5). Many other researchers have also reported straight-line relationships between understorey PAR transmission and overstorey CC or gap fraction (Table 5). Gap fraction (GF) or canopy openness is the proportion of sky not occupied by canopy – the opposite of CC (Comeau et al., 1998; Frazer et al., 2001; Bellow and Nair, 2003). However, there is considerable variation in the slope of these reported relationships, as shown in Table 5. Other researchers have also reported strong curvilinear relationships (Vézina and Péché, 1964; Vales and Bunnell, 1988a; Yirdaw and Luukkanen, 2004).

Reasons for differences in the slope and shape of these relationships includes variation between studies in: (i) tree species, (ii) the range of CC or GF measured, and (iii) equipment and sampling methods used to measure PAR transmission and CC or GF (Table 5). Jenkins and Chambers (1989) found the relationship between CC and PAR transmission changed depending on the tree species composition of mixed forest stands. All of the studies in Table 5, apart from Buckley et al. (1999), are restricted to medium to high levels of CC. Extrapolation of these restricted relationships towards lower levels of CC suggests their slopes would become more 1:1 or they would be curvilinear. Most of the studies used paired sensors to measure PAR transmission. However, samples ranged from instantaneous (indirect) to continuous (direct) measures taken over time, and under varying weather conditions. Also, the location of PAR relative to CC or GF measurements varied between studies (Table 5).

Global (direct and diffuse) PAR transmission estimates for a given CC or GF are less likely to be affected by different sampling locations and methods underneath tall fully-closed stands with homogenous small gaps in the overstorey canopy (Bunnell and Vales, 1990; Stadt et al., 1997). However, underneath sparser and more heterogeneous canopies the interaction between sun (solar disc) position, cloud cover, and canopy gaps can have a major impact on global PAR transmission estimates; mainly through the effect on direct-beam radiation transmission (Comeau et al., 1998; Gendron et al., 1998). Comparisons of instantaneous PAR transmission methods show paired measurements taken around midday under clear skies produce the most variable results in predicting global PAR transmission, as this method is highly influenced by sun position relative to cloud cover and canopy gaps at the time of measurement (Messier and Puttonen, 1995; Comeau et al., 1998; Gendron et al., 1998). In contrast, the overcast day or DIFN methods produce more temporally consistent estimates because of the approximately even distribution of diffuse light emanating from the sky in all compass (azimuth) directions during the day (Messier and Puttonen, 1995; Gendron et al., 1998). These two

methods have empirically been shown to be highly correlated to mean daily or seasonal global PAR transmission (Washitani and Tang, 1991; Hanan and Bégué, 1995; Messier and Puttonen, 1995; Parent and Messier, 1996; Comeau et al., 1998; Gendron et al., 1998; Machado and Reich, 1999). However, by not directly accounting for direct-beam radiation, global PAR transmission may be under- or overestimated in some micro-sites, especially in and around large canopy gaps or underneath heterogeneous stands (Stadt et al., 1997; Comeau et al., 1998).

The angle of view sampled for CC or GF can significantly affect estimates. In general, CC increases and stand-level variability decreases with increasing angle of view (Bunnell and Vales, 1990; Fiala et al., 2006; Lhotka and Loewenstein, 2006). However, the effect of view angle is less apparent underneath stands of higher CC (Bunnell and Vales, 1990; Guevara-Escobar et al., 2005). All of the studies in Table 5 used equipment measuring a 60° view angle, thus this is unlikely to be a factor for any observed differences. However, in the current study the angle of view sampled was not determined and by using the digital camera's standard lens (producing rectangular images) it is not equal in all compass (azimuth) directions.

The type of camera and exposure settings (lens aperture width and shutter speed) used for taking photographs or digital-images can affect estimates of CC or GF (Macfarlane et al., 2000; Frazer et al., 2001). Again, the divergence is influenced by the stand densities being measured (Hale and Edwards, 2002; Inoue et al., 2004; Zhang et al., 2005). The subjective nature of manual grey-scale thresholding or colour filtering methods for separating image elements is another potential source of error (Nobis and Hunziker, 2005). Similarly, large observer variation can occur when separating occupied and non-occupied canopy areas on spherical densitometers (Vales and Bunnell, 1988b; Ganey and Block, 1994).

Extensive research, covering a wide variety of tree species, has shown a strong relationship exists between stand BA and PAR transmission (Vales and Bunnell, 1988a; Jenkins and Chambers, 1989; Buckley et al., 1999; Comeau and Heineman, 2003; Hale, 2003; Balandier et al., 2006; Comeau et al., 2006; Lhotka and Loewenstein, 2006). Comeau (2001) measured very similar PAR transmission levels for a given stand BA underneath boreal aspen (*P. tremuloides* Michx.) stands in north-eastern British Columbia (BC), Canada. PAR transmission levels were below 40% and 60% when stand BA exceeded 14 m² ha⁻¹ and 8 m² ha⁻¹, respectively (Comeau, 2001). However, in a later study, Comeau et al. (2006) found the relationship between stand BA and PAR transmission changed significantly between different climatic zones of BC. These differences were attributed to a lower stand LAI for a given BA in drier zones than wetter zones (Messier et al., 1998; Comeau et al., 2006).

Given that the small and young trees at Ballantrae were located in the same climatic zone as the large and mature trees at Kiwitea, it is unlikely that the consistently greater PAR transmission levels at the former site could be attributed to a lower LAI due to soil-moisture stress (Table 3; Fig. 3b). Nevertheless, there are several other factors that could have caused the LAI, for a given BA, to be lower at Ballantrae. For even-aged oak (*Quercus petraea* and *Q. robur*) stands in France, Balandier et al. (2006) reported adding stand age to the relationship markedly improved the amount of variation in PAR transmission that was explained. Non-linear changes in the relationship between LAI and BA occur as a stand ages. The LAI normally increases to a maximum value at a certain tree age and then decreases (Balandier et al., 2006).

Differences in silvicultural management between sites could have been a major contributing factor. While the stands at Kiwitea, Hautope 1, and Hautope 2 were untended, the small and young trees at Ballantrae had been lower-bole pruned. This would markedly reduce the LAI for a given BA. Underneath young evenly-spaced grey alders (*Alnus cordata*), Devkota et al. (2001) increased

%DIFN over 4-fold by increasing the lower-bole pruning height from 2.5 m to 7 m. Also, %DIFN was probably overestimated at Ballantrae because these measurements were taken in the year prior to BA measurements.

On an individual site basis, under trees of similar size and architecture, VPG %DIFN was strongly related to CEV, GCL, DBH, and VPCC. However, the assigned curvilinear relationships varied with farm site (Fig. 3c–f). Similarly to BA, these stand parameters integrate both tree density and a measure of individual crown size into a single value. However, the relative proportion that each component contributes to this single value impacts on the three-dimensional distribution of leaf area within a stand. Also, none of these parameters account for differences in LAI caused by environmental stresses or variation in tree age. These confounding factors make it difficult to determine the cause or causes of the site differences.

Vales and Bunnell (1988a) and Comeau et al. (1998) reported DBH was strongly related to PAR transmission in conifer and paper birch (*Betula papyrifera* Marsh.) stands, respectively. Both studies used an exponential decay type curve to describe this relationship. Comeau et al. (1998) stated that further testing was required to determine if their developed relationship between DBH (*sensu* 'Lorimers competition index') and PAR transmission could be generalised to other sites. Results from this study indicate that the above relationship would change in stands containing trees of markedly different average size for a given DBH ha⁻¹.

In a later study, Comeau and Heineman (2003) developed and compared several alternative multiple-regression models based on easily measured stand parameters for predicting %DIFN in young paper birch stands. Out of the stand parameters tested, tree density in combination with either quadratic mean diameter or height of the tallest tree explained as much variation in %DIFN as any other parameter combination (which included BA). By using these parameters the separate effects of tree density and individual crown size on PAR transmission is partitioned out and is not confounded. Similarly, in investigating the relationship between GCL and understorey pasture production for even-aged *Pinus radiata* (D. Don) stands, Percival et al. (1984) and Percival and Knowles (1988) found mean GCL stem⁻¹ was a useful covariate for combining data taken from a number of sites. This covariate became increasingly important as the range of stand ages increased (Percival et al., 1984). Also, including crown top height and tree density or mean crown depth (GCL stem⁻¹) improved the fit of VPCC based models fitted by Lhotka and Loewenstein (2006) for uneven-aged mixed-hardwood stands.

The relationship between each of the tested stand parameters and VPG %DIFN varied with farm site (Table 4; Fig. 4). This indicates that directly below the poplar crowns some other unaccounted for factor(s) must also be influencing %DIFN. Many of the factors previously discussed for the VPG %DIFN site differences could be involved. Centring CC measurements on the VPG might have caused the actual tree-canopy surrounding the VPG understorey environment to be misrepresented.

Some stand inventory parameters had a number of practical advantages over the others. DBH, BA, and VPCC were the simplest to measure and required minimal equipment. In comparison, GCL and CEV measurements generally took longer, especially under large trees, and required more specialised equipment, in the form of a measuring pole and hypsometer. Taking digital images of the tree canopy was also quick and simple. However, the overcast sky conditions needed limited the flexibility of this technique, especially in remote locations where there was often only a narrow 'window' of opportunity for gathering the data. A faster, cheaper, and less weather dependent alternative for determining CC would be an index based on visual (ocular) estimates (Bellow and Nair, 2003).

With DBH, BA, VPCC, GCL and CEV being partly based on tree stocking rate, they can be used to directly calculate the number of

trees that need thinning to achieve a desired level of PAR transmission. In contrast, while CC can be used for the same purpose, it would require continual measurement during silvicultural operations. An advantage of DBH and BA stand parameters is their direct linkage to forest growth and yield models (McElwee and Knowles, 2000; Comeau, 2001). Connecting such models would allow farmers and extensionists to strategically evaluate how proposed planting and thinning treatments would affect understorey PAR transmission levels over the entire lifetime of a stand (Comeau, 2001). How the relationship between these stand parameters and %DIFN may change over time in response to thinning and pruning treatments requires further investigation.

The strong straight-line relationship between pasture NHA and %DIFN when trees were fully foliated ($r^2 = 0.84$, $P < 0.0001$) in the study could be used by land owners to determine understorey NHA and the value of thinning and pruning to reduce shading. The predicted NHA values from the developed relationship are comparable to other pasture NHA measurements previously taken underneath New Zealand poplar stands. Guevara-Escobar et al. (2007) found directly below mature (30-year-old) poplars transmitting 25% incident PAR pasture NHA was 60% of open field production during late summer/early autumn. In contrast, Douglas et al. (2001) measured 63–71% open field pasture NHA adjacent to young (8–11-year-old) poplars transmitting 62% incident light in autumn. From visual field observations of 40 poplar-stands across the Bay of Plenty and East coast regions of New Zealand, McElwee and Knowles (2000) noted significant understorey pasture biomass occurred underneath stands with up to 88% canopy closure. However, low PAR transmission levels can reduce the forage quality of understorey pastures (Belesky et al., 2006).

5. Conclusion

The directly inverse relationship between CC and VPG %DIFN was the simplest, most accurate and robust, of the parameters investigated. With a good relationship also found between understorey pasture NHA and %DIFN, the direct impact of a poplar stand on understorey biomass production can be quantified and the benefits of thinning or pruning to reduce shading evaluated. Development of a reliable CC index based on visual (ocular) estimates would improve this method's practicality for widespread and routine sampling of a large number of small sized stands.

BA had the simplest relationship with VPG %DIFN and VPC %DIFN of the stand parameters based on individual tree measurements. For each of the understorey environments the slope of the relationship was consistent across all farm sites. This stand parameter is also simple to use in the field and can be directly related to stand growth and yield models. However, alone it cannot account for the effects of intensive silvicultural practices, such as lower bole pruning. All of the other relationships between stand parameters and VPG %DIFN and VPC %DIFN were more complicated and varied, to different extents, with farm site. For DBH, BA, GCL, VPCC, and CEV site differences were likely related to these single independent variables being unable to account for variation in stand leaf area, caused by the combined effects of the tree density, individual tree-crown size (related to tree age and intensive silvicultural management practices), and environmental stresses at each farm site. Further study is required of multiple stand parameters that can account for variation in stand leaf area caused by factors such as thinning and lower bole pruning.

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