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A NON-DESTRUCTIVE METHOD FOR RAPID ESTIMATION OF UNDERSTOREY BIOMASS IN BAUXITE MINE REHABILITATION

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SUMMARY

Estimates of understorey biomass are necessary for a range of applications including predictions of fire behaviour, in nutrient cycling studies and for estimates of vegetation water use. Previous studies have estimated understorey biomass in the jarrah forest of south western Australia and in areas rehabilitated after bauxite mining, however, these used destructive harvesting methods and were site specific. The aim of this study was to develop a non-destructive method that would allow rapid and accurate estimation of understorey biomass across a range of different aged rehabilitated mined areas.

A total of 55 quadrats, 2m x 2m in size, were established across five rehabilitated sites varying in age from 1.5 years to 17.5 years since establishment. Each quadrat was assessed for cover of all understorey species present, together with height of vegetation in the quadrat. All live vegetation was harvested, separated into woody stems > 10mm diameter and leaf and small stem material < 10mm diameter, and dry weights determined.

Total understorey biomass was found to be satisfactorily predicted by the single parameter cover in the log-log model Ln(biomass) = 0.94*ln(cover)-2.73 (R2 = 0.91), with a bias correction factor when back-transforming to arithmetic units of 1.049. The model performed well in validation tests and is suitable for all ages of rehabilitation. However, the study indicated that true cover, and therefore biomass, may be substantially underestimated in cases where the understorey is particularly dense and tall (>120% cover, >3m height). The biomass of leaf and small stem material <10mm diameter was reliably predicted by the log-log model Ln(biomass) = 0.859*ln(cover)-2.62 (R2 = 0.85), with a bias correction factor of 1.061. Height alone was not a good predictor of total biomass (pooled ages, R2 = 0.49), and was even worse for biomass of leaf and stems <10mm (pooled ages, R2 = 0.25). Estimating cover alone therefore provides a reliable and rapid method for estimating understorey biomass in rehabilitated mined areas. The models also allow retrospective estimates of biomass to be made from historical records of understorey cover.

Understorey in rehabilitated areas develops to a peak in biomass and in height at around 10 years after establishment, with declines thereafter related to senescence of the major shrub species. The proportion of woody stem material approached a maximum of approximately 38% after 10 years and remained relatively constant thereafter.

INTRODUCTION

Estimates of understorey biomass are necessary for a range of applications including fuel load estimation in fire research (McCaw, 1991), nutrient cycling studies (Hingston et al., 1981; Ward and Pickersgill, 1985) and vegetation water use studies (eg. Lane and Mackay, 2001). All these applications are relevant to understanding the developing jarrah forest ecosystems established after Alcoa's bauxite mining in south-west Australia, but there is currently no simple and rapid method to estimate understorey biomass in these areas.

Various techniques for estimating biomass are available, including destructive sampling, calibrated visual techniques (eg. Haydock and Shaw, 1975) and 'double sampling' methods (Catchpole and Wheeler, 1992). The latter offer the possibility of accurate estimates of biomass without the need for laborious and time-consuming destructive harvesting. In this approach, one or more easily measured variables are regressed against biomass for a number of test samples, and are subsequently measured on new sites to provide rapid estimates of biomass. The approach assumes that the regression equations are valid for the new sites. The biomass of shrubs and larger understorey species has been estimated using basal stem diameter (Brown, 1976; Harrington, 1979; Hingston et al., 1981). However, measurement is likely to be relatively slow in dense and low-growing vegetation. For multi-stemmed shrub species, Harrington (1979) concluded that height was a better predictor. In dense karri forest understorey, Sneeuwjagt (1971) showed that total live weight was closely related to the product of height and cover. Both these variables may therefore be useful for rehabilitated mined jarrah forest.

Alcoa collects and maintains an extensive botanical monitoring dataset of rehabilitated areas. Standard monitoring plots 20m x 20m in size are established in which the cover and density of all understorey species present within twenty 2m x 2m quadrats are recorded (Koch, 2007). There is therefore the opportunity to estimate biomass for these historical datasets if suitable regressions can be developed using cover alone.

The aims of this study were (i) to determine suitable regression models for the accurate estimation of understorey biomass from one or more non-destructive variables, valid across all rehabilitation areas, and (ii) to determine if cover alone was a reliable predictor of understorey biomass.

METHODS

Study sites

The study was conducted at the Huntly mine, approximately 100km south of Perth near Dwellingup, Western Australia. A total of five sites, each covering an area with an approximate 50m radius, were selected from locations across the Huntly mine (Appendix 1) that had been mined and rehabilitated 1.5 – 17.5 years previously (Table 1). All sites were selected from a primary successional chronosequence, with no disturbance from fire (Appendix 2).

Sites were chosen such that vegetation at the site was representative of the rehabilitation established across the entire area. All sites had been prepared using current rehabilitation procedures aimed at establishing a jarrah-dominant native forest ecosystem.

Table 1. Description of study sites.

Site	**Estab year**	**Age** (yrs)	**Location** (AGD84)	
A	2007	1.5	422820	6395800
B	2006	2.5	422710	6396340
C	2004	4.5	414050	6392900
D*	1998	10.5	413100	6393250
E	1991	17.5	414200	6392840

*Site D was located adjacent to permanent vegetation monitoring plot JK291.

Understorey assessment and processing

At each site, between 10 and 13 quadrats (total 55), 2m x 2m in size, were subjectively chosen to span the range of understorey cover present. Percentage cover of live understorey species in the quadrat was estimated visually. Eucalypts and other canopy species were included if they were too small for a diameter measurement to be taken, but annuals and small ground layer species were ignored as previous work had shown these to contribute little to total cover or biomass. Separate estimation of cover for each species took into account vertical structuring of the understorey, such that it was possible for the sum of all cover estimates to exceed 100%. Cover estimates were recorded independently by two observers, and the same observers were used for all 55 quadrats.

Two measurements of vegetation height were also collected using a height stick. Maximum height was the height of the tallest live shoot within the quadrat; mean top height was subjectively assessed as the maximum height of the majority of the understorey in the quadrat, ignoring taller but only minor stems or branches. Heights were not measured at Site C nor for six quadrats at Site E.

All live understorey vegetation except annuals and groundcover species in each quadrat was harvested to ground level and weighed. Representative sub-samples were oven-dried at 70oC for 3 days and total oven-dry weights calculated for each quadrat. Material from each quadrat was then sorted into two fractions: leaf and stem < 10mm diameter, and woody stem material > 10mm in diameter. Discrepancies between the original dry weights and the summed dry weights of the two components occurred for four quadrat samples, and separate component results for these were discarded. All quadrats were assessed and harvested between December 2008 and February 2009.

Data analysis

Relationships between visual estimates of summed percentage cover (hereafter referred to as ‘cover’) or maximum understorey height, and total biomass or mass of leaf and stem material <10mm diameter, were explored using regression analysis. Ordinary least squares regression was chosen over other approaches since the purpose was to derive an equation to predict biomass from estimates of cover or measurements of height that contain measurement error (Warton et al., 2006). Relationships between biomass and regressor variables were examined for each individual site and regression slopes tested for significant differences between sites using analysis of covariance (ANCOVA). Both regression analyses and ANCOVA were undertaken using Minitab release 15 (Minitab Inc. State College, PA, USA). Tests of whether regression slopes differed significantly from unity were undertaken using RMA regression on the software PAST 1.9 (Hammer et al., 2001).

Maximum height and mean top height were found to be highly correlated (R2 = 0.95). Since maximum height is the least subjective measurement, this variable was selected for all analyses (hereafter referred to as 'height').

RESULTS

Understorey characteristics with rehabilitation age

A total of 35 species were recorded across all sites. Richness averaged 4.6 species/quadrat but there was no clear trend in species richness with rehabilitation age (Table 2). The composition of dominant species varied across sites. Younger rehabilitation sites were characterised by a number of Acacia species (principally A. lateriticola, A. pulchella and A. drummondii) which subsequently declined with rehabilitation age, to be replaced by Bossiaea aquifolium, Hypocalymma angustifolium and Billardiera heterophylla in the older sites (Table 2).

Table 2. Mean species richness per quadrat, and the proportion of total cover (across all quadrats in a site) of selected species or groups of species at each site.

Site	**Age** (yrs)	**Species richness**	**Proportion of total quadrat cover**				
			Acacia spp.	*Bossiaea aquifolium*	*Hypocalymma angustifolium*	*Billardiera heterophylla*	Total of selected species
A	1.5	5.5	0.94	0	0.002	0	0.94
B	2.5	3.5	0.79	0.09	0.06	0	0.94
C	4.5	6.2	0.24	0.38	0.14	0.012	0.78
D	10.5	4.0	0.01	0.70	0	0.20	0.91
E	17.5	4.2	0.07	0.46	0.17	0.24	0.93

The maximum recorded biomass, height and proportion of woody stem material in a quadrat for each site were plotted against rehabilitation age to determine trends over time (Figure 1). Maximum values were used in preference to means given the biased selection of quadrats, however, results are indicative of the maximum expression of each characteristic over time. Fitted equations for both biomass and height showed a quadratic form, peaking at approximately 10 years after establishment and declining to age 17.5 years. The trend in height with age is consistent with maximum heights in rehabilitation reported earlier by Marshall and Chester (1995), and with mean dominant Acacia height reported by Koch and Davies (1993) (Figure 1b). The latter study showed a somewhat earlier decline in height, presumably related to the shorter lifespan of Acacia, described above. The proportion of woody stem material rose exponentially with rehabilitation age, approaching a maximum of 38% by age 10 years (Figure 1c). There was no apparent trend in cover over time, with maxima typically in the range 90-110% even in 1.5 year old rehabilitation.

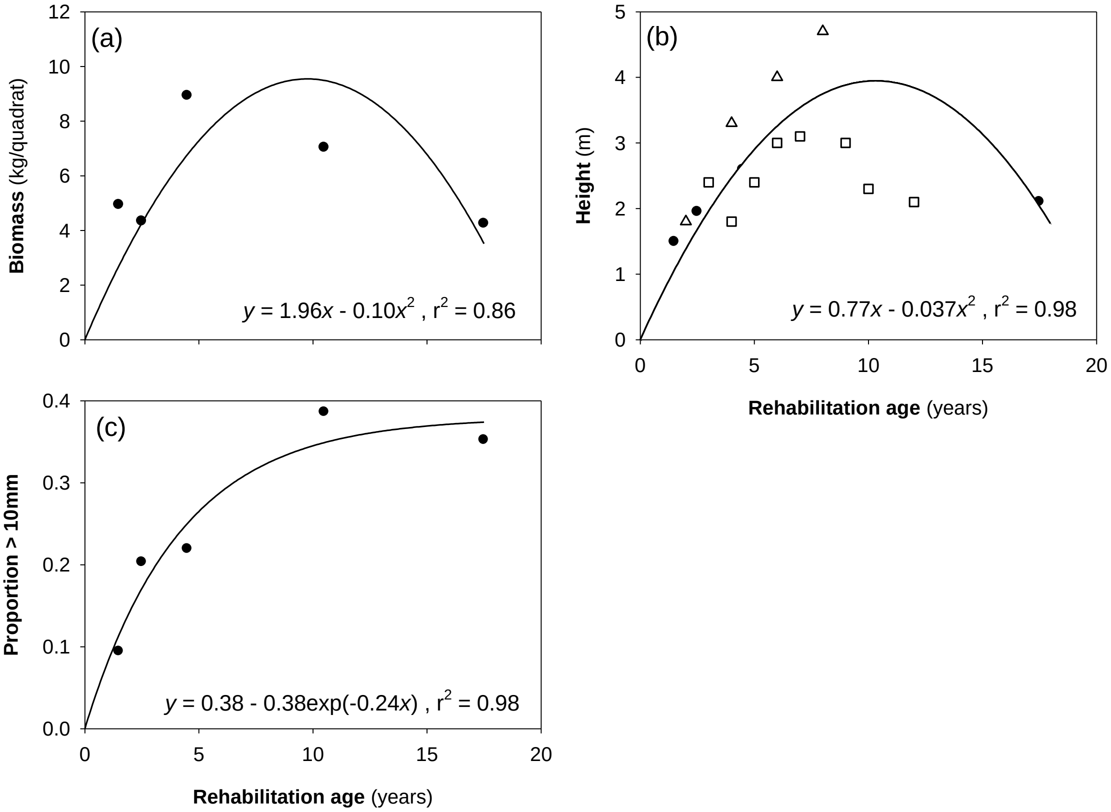

Figure 1. Changes with rehabilitation age in the maximum recorded values at each site of (a) biomass per quadrat, (b) height and (c) the proportion of woody stem material. Also shown in (b) are data from Marshall and Chester (1995) (Δ), and from Koch and Davies (1993) (□), see text for details.

Model development

Total understorey biomass was reasonably well correlated with cover when data from all sites were pooled, particularly where cover was <40% (Figure 2a). Better correlations were obtained for individual sites (Table 3), however, analysis of covariance indicated that, with the exception of Site E, regression slopes for individual sites were not significantly different from eachother. In addition, none of the intercepts were significantly different from zero. Therefore, a single relationship for all sites was assumed, and biomass and cover data from all sites were natural log transformed to more closely satisfy the assumption of homogeneity of variance. A single sample with the smallest biomass was excluded from statistical analyses of the natural log transformed data because of the large influence that it had on these regressions. This sample had a mass of < 0.1 kg with an estimated cover of 8% (averaged between observers). The log-log model resulted in an improved correlation (R2 = 0.90, Table 3, Figure 2b). A bias correction factor is supplied in Table 3, by which the computed biomass should be multiplied when back-converting to arithmetic units. The correction factor is calculated as the antilogarithm of half the residual mean square of the regression (Baskerville, 1972).

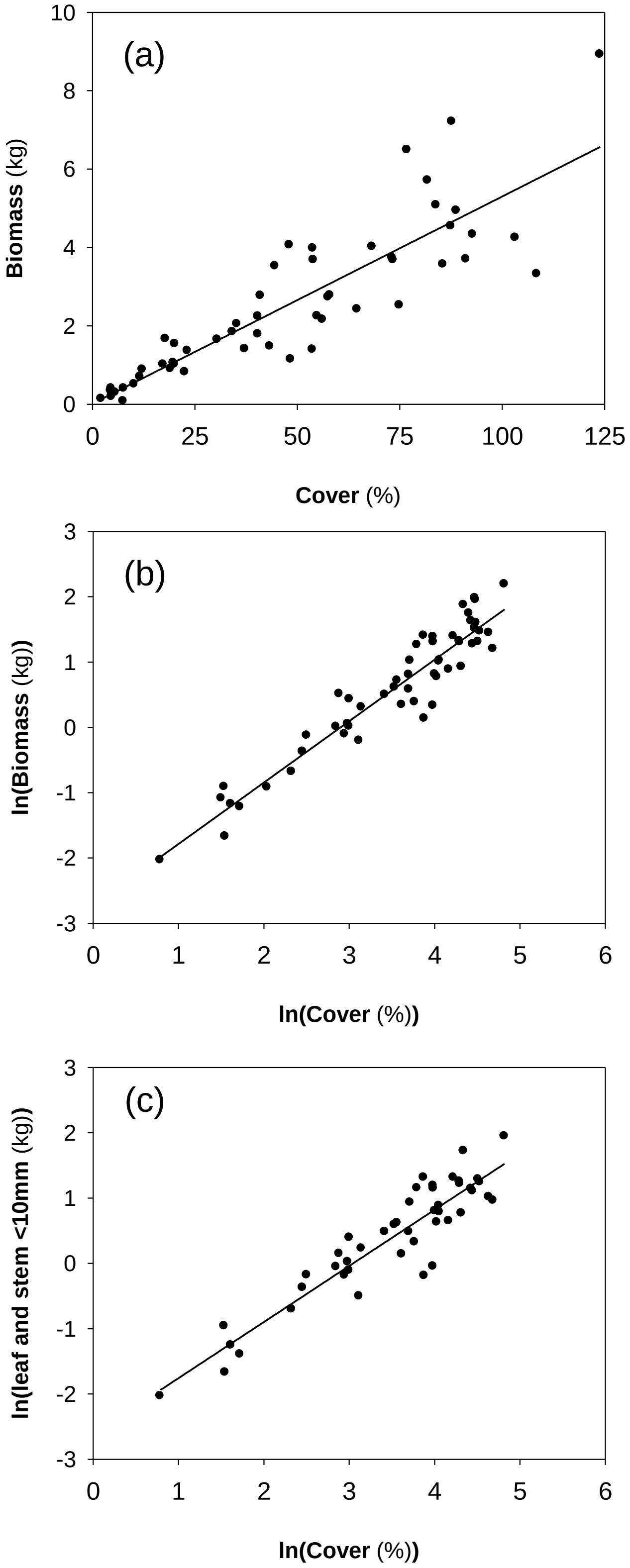

Figure 2. Relationship of total understorey biomass (kg/quadrat) and cover (%) for pooled sites as (a) linear, and (b)log-log, models, and (c) leaf and stem <10mm biomass (kg/quadrat) and cover (%) for pooled sites. Details of regression models are given in Table 3.

The mass of leaf and small stem material (<10mm diameter) formed the majority of total biomass, constituting 75% or more of total biomass in almost 90% of samples. The majority of quadrat samples with higher proportions of woody material were from the oldest Site E. As a consequence, cover was also a good predictor of leaf and small stem biomass (Table 3). The log-log model for pooled data was able to explain 85% of the variation in leaf and small stem biomass (Table 3, Figure 2c).

Table 3. Results of regressions between total understorey biomass or biomass of leaf and stem material <10mm diameter (kg/quadrat) against cover (%), for pooled data and for each individual site. Linear models are of the form y = ax + b, log-log models are of the form ln(y) = a.ln(x) + b. A bias correction factor (BCF) is given for the log-log model regressions (Baskerville, 1972).

Component	**Site**	**Age** (yrs)	**Model form**	**N**	**Slope**	**Intercept**	**R^2**	**BCF**
Total	All	-	Linear	55	0.055	-0.03	0.76	-
	A	1.5	Linear	11	0.052	0.18	0.88	-
	B	2.5	Linear	10	0.048	0.06	0.94	-
	C	4.5	Linear	10	0.069	0.04	0.84	-
	D	10.5	Linear	13	0.063	-0.40	0.79	-
	E	17.5	Linear	11	0.034	0.15	0.83	-
	All	-	Log-log	54	0.940	-2.73	0.90	1.049
Leaf/stem <10mm	All	-	Linear	46	0.038	0.25	0.68	-
	A	1.5	Linear	10	0.048	0.19	0.86	-
	B	2.5	Linear	9	0.040	0.17	0.88	-
	C	4.5	Linear	9	0.052	0.32	0.87	-
	D	10.5	Linear	8	0.033	0.26	0.73	-
	E	17.5	Linear	10	0.024	0.25	0.76	-
	All	-	Log-log	46	0.859	-2.62	0.85	1.061

Height alone was not as good a predictor as cover for total biomass, and was even worse for biomass of leaf and stems <10mm, for both pooled and individual sites (Table 4). There was no association at all for the oldest Site E. There were predictable changes in slope and intercept for site-specific regressions with rehabilitation age (Table 4), suggesting that age could be used to improve predictions. However, there was no significant improvement (total biomass R2 = 0.64, data not shown).

The combination of height and cover were also investigated as predictors of biomass, firstly as a stepwise linear regression and secondly as a linear regression of the product of the two variables (log transformed). Both cases were confounded by reduced sample sizes (n=36 for total biomass, n=25 for biomass of leaf and stem <10mm) owing to lack of height measurements for some quadrats. Correlations were never better than those for cover alone, and the stepwise regression for leaf and small stem biomass failed to include height at all. Examination of scatter plots suggested that where correlations comparable to cover alone were observed, this may have been due in part to a reduced number of datapoints with high cover values, which showed the greatest variation in biomass (Figure 2a).

Table 4. Regression results between understorey biomass (kg/quadrat) and height (m) for pooled data and for each individual site. Height was not measured for Site C. Equations are of the form y = ax + b. NS indicates regression was not significant.

Component	**Site**	**Age** (yrs)	**N**	**Slope**	**Intercept**	**R^2**
Total	All	-	36	1.88	-0.31	0.49
	A	1.5	11	5.26	-3.79	0.48
	B	2.5	10	3.29	-1.82	0.54
	C	4.5	-	-	-	-
	D	10.5	10	2.52	-2.15	0.65
	E	17.5	5	1.00	0.84	NS
Leaf/stem <10mm	All	-	30	1.18	0.29	0.25
	A	1.5	10	4.40	-3.14	0.54
	B	2.5	9	2.40	-0.94	0.41
	C	4.5	-	-	-	-
	D	10.5	6	1.18	-0.07	0.30
	E	17.5	5	0.92	0.37	NS

Model validation

Predicted total biomass using the log-log model of cover only was compared with observed total biomass (Table 5). The result was influenced by the small sample size of quadrats with higher biomass (> 6kg/quadrat, Figure 3a), which were underestimated by the model and caused the slope to differ significantly from 1. If the four samples with observed biomass > 6kg/quadrat were omitted, the resultant regression had a slope not significantly different from 1 and a correlation coefficient of almost 0.8 (Table 5).

The model was also tested against two independent datasets containing total biomass and cover collected using identical techniques to the present study. The study by Jones (unpublished) investigated understorey in 20 year old rehabilitation that had been either burnt or thinned and burnt seven years previously. Observed cover ranged from 7-98%. The study by Standish and Morald (unpublished) was carried out at a single site in unburnt 5.5 year old rehabilitation. Cover ranged from 4-175%. For the study by Jones, predicted biomass when all data were considered was heavily influenced by two samples with biomass >6kg/quadrat (Figure 3b). When these were ignored, the regression slope was not significantly different from unity (Table 5). For the study of Standish and Morald, the model showed a good fit with observed results (Table 5, Figure 3c).

Table 5. RMA regressions of predicted total biomass vs observed in this study and two unpublished datasets (see text). Only P-values for slopes are reported.

Study		**n**	**Slope**	**Intercept**	**P**	**R^2**
This study	All samples	55	0.82	0.44	0.002	0.76
	Only samples <6kg	51	1.02	0.12	0.76	0.79
Jones (unpub.)	All samples	18	0.51	1.06	<0.0001	0.58
	Only samples <6kg	16	0.94	0.24	0.64	0.76
Standish and Morald (unpub.)	All samples	28	0.94	0.38	0.37	0.87

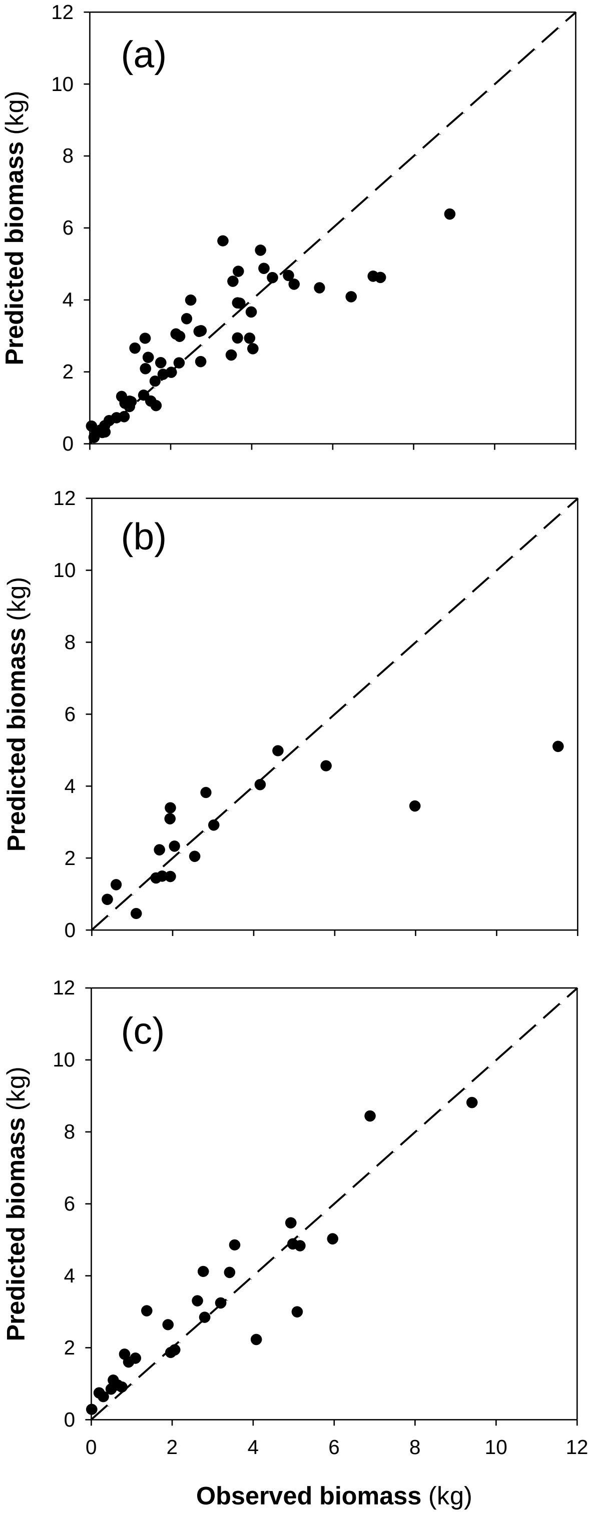

Figure 3. Predicted total biomass using the log-log model for pooled cover data (Table 3) in relation to observed total biomass for (a) this study, (b) a study by Jones (unpub.), and (c) a study by Standish and Morald (unpub.). Dotted lines in all cases refer to the 1:1 line.

DISCUSSION

Summed percentage cover was the best predictor of understorey biomass, accounting for 80-95% of the variation in total biomass, and 73-88% of variation in leaf and stem material <10mm, in each age of rehabilitation (Table 3). The log-log model provided the best fit for pooled sites, with correlation coefficients of 0.9 and 0.85 for total and non-woody components respectively (Table 3). The good performance of the log-log model for total biomass against two independent datasets from rehabilitation of different ages and fire history lends further confidence in the wide applicability of the method. This is a successful result, permitting rapid and non-destructive estimation of understorey biomass across the range of rehabilitation ages with satisfactory accuracy. The result also opens the way for estimates of biomass to be made from historical records of understorey cover collected as part of Alcoa's long-term botanical monitoring program.

Visual assessment of cover is likely to be heavily weighted towards the presence of foliage and in the quadrats sampled, leaf and small stem material was almost always >70% of total biomass (Figure 1c). Visual assessment appeared to be particularly accurate in predicting biomass when summed cover in the quadrat was less than 40% (Figure 1a). Conversely, when samples exceeded a total biomass of 6kg/quadrat, equivalent to approximately 120% summed cover, the model appeared to underestimate observed biomass (Figures 3a, b). This might arise due to a higher proportion of heavier woody material in the sample, but this was not the case in either this study or the study by Jones. The most likely cause is the increasing difficulty in accurately assessing cover in dense vegetation, and dense tall vegetation in particular. All quadrats with underestimated biomass in Figures 3a and 3b contained vegetation with a maximum height in the range 3.3-4.1m, and were in sites 4.5-10.5 years since establishment or fire when expression of understorey biomass and height is peaking (Figure 1a, b). Conversely in the study by Standish and Morald, which showed good fit with the model predictions (Figure 3c), samples with >6 kg/quadrat were assessed with cover exceeding 160%. We conclude that the model is applicable over a wide range of understorey density but that true cover may be substantially underestimated in the field where understorey is particularly dense and tall (>120% cover, >3m height).

Understorey height was not a useful predictor of total biomass or the biomass of leaf and small stems in this study. Correlation coefficients were lower than for cover alone at each site, and regression slopes were age-dependent. Even with age included as a second variable, height only explained 64% of the variation in biomass for pooled data. While the product of height and cover has been shown to be a useful predictor of biomass (Sneeuwjagt, 1971; Porté et al., 2009), this appeared not to be the case here. However, it is conceivable that including height in a model could compensate in part for inaccuracies in estimates of cover in taller understorey vegetation, and consequently perform better in rehabilitation stands 4-10 years in age.

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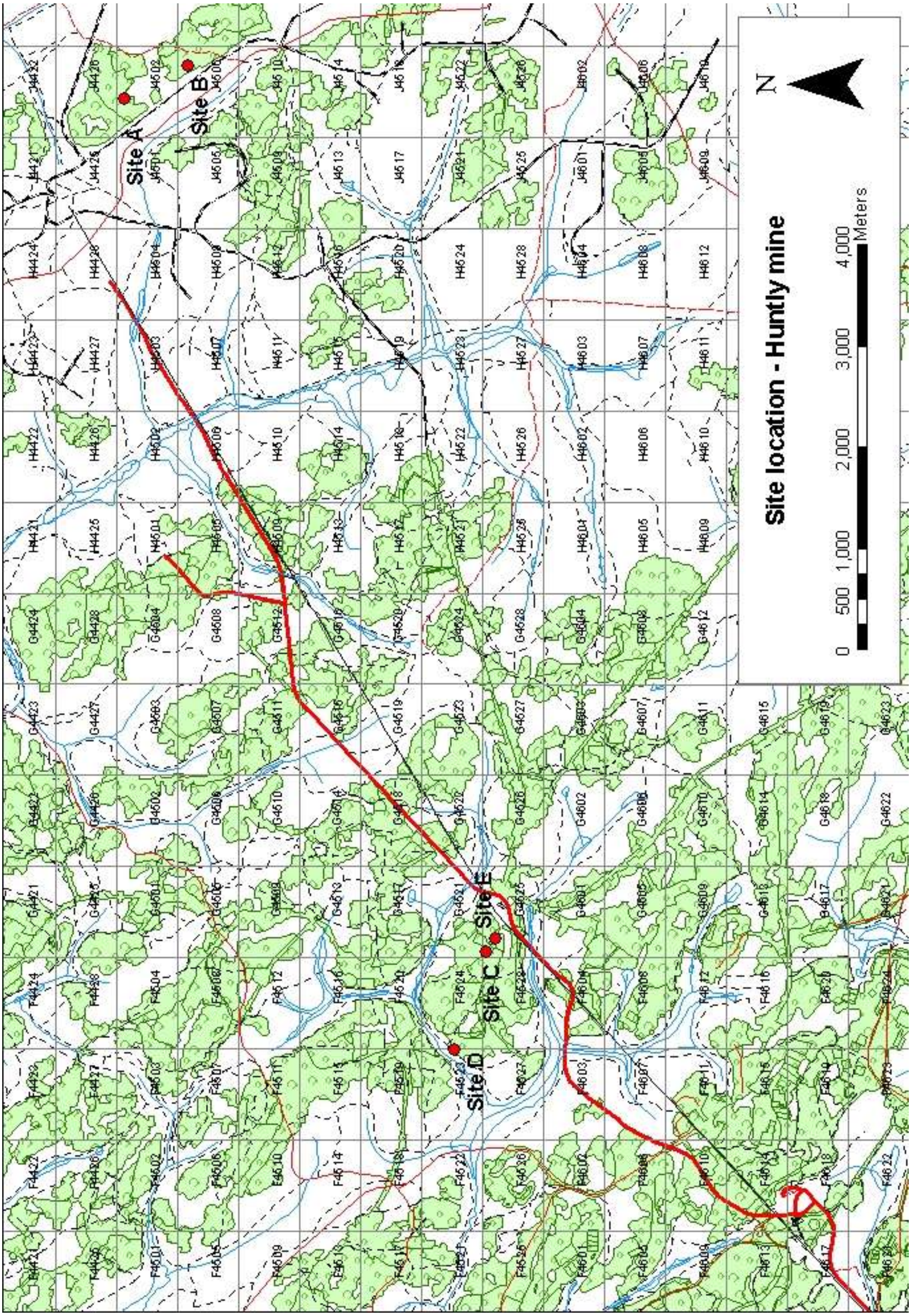
APPENDIX 1. LOCATION OF STUDY SITES



APPENDIX 2. PHOTOS OF STUDY SITES

Site A, 1.5 years since establishment.

Site B, 2.5 years since establishment.

Site C, 4.5 years since establishment.

Site D, 10.5 years since establishment.

Site E, 17.5 years since establishment.