Using visual obstruction to estimate heathland fuel load and structure

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Brief summary: Fuel structure and loading plays an important role in determining fire behaviour. We present a simple technique for assessing critical aspects of vegetation structure. The method is tested for *Calluna vulgaris* dominated heathlands but could rapidly be calibrated for use in other habitats.

Abstract. A robust, non-destructive field technique for estimating fuel characteristics is described. Visual obstruction of a banded measurement stick placed vertically through a stand of vegetation is governed by a combination of the height of the vegetation and its density. The method is tested in a *Calluna vulgaris* (L.) Hull heathland. The vertical distribution of visual obstruction is calibrated to give estimates of total fuel loading, the loading of separate size categories and the vertical distribution and horizontal heterogeneity of fuels. This paper provides a quick and simple method for estimating total biomass and structure that may be useful not just in studies of fire behaviour but where non-destructive assessment of biomass, vegetation density or canopy structure is needed. Calibration equations can be rapidly created for use in other vegetation/fuel types.

Introduction

Fuel structure describes the overall arrangement of fuel particles and layers including such factors as dead to live ratio, bulk density, height, fuel load and the loading of individual fuel components or size classes. For any given fire the nature of the fuel plays a key role in determining its behaviour, and an understanding of fuel structure is a prerequisite for any investigation of fire behaviour. Numerous studies demonstrate the linkages between fuel structure and rate of spread (Fernandes 2001), fireline intensity (Hobbs & Gimingham 1984), peak temperatures and their residence times (Molina & Llinares 2001, Gimeno-García *et al.* 2004) and flame lengths (Bradstock & Gill 1993). While higher fuel loadings can lead to hotter, faster-spreading fires, fuel architecture (distribution and structure) is also known to be critical (Fernandes & Rego 1998, Chaffey & Grant 2000).

The density, homogeneity and size distribution of fuel elements are important in determining the rate of spread of fire. Bulk density (the amount of combustible material per unit volume of the fuel bed) is an important parameter in fire modelling (e.g. Thomas 1971, Rothermel 1972, Drysdale 1998, Andrews *et al*. 2005). In very sparse vegetation, increased density will, up to a point, allow more rapid fire spread but Thomas (1971) and Rothermel (1972) have shown that in continuous fuels, bulk density is inversely related to rate of fire spread a relationship that was observed for *Calluna* fires by Davies *et al*. (2006). Significant breaks or gaps in vegetation cover will however break up fire-fronts and disrupt fire spread (Van Wilgen *et al.* 1985, De Luis *et al.* 2004).

Fine fuels ignite much more readily than larger fuel elements as their greater surface area-to-volume ratio means they dry out quickly and their lower thermal inertia allows them to reach combustion temperatures more rapidly. For the same fuel loading, a larger proportion of fine fuels will allow faster combustion, increased rate of production of radiative energy and more complete combustion by both flaming and smouldering combustion (Anderson 1970).

Many techniques have been developed to assess various aspects of the fuel environment (see Catchpole and Wheeler 1992; Stewart *et al.* 2001). These include simple allometric techniques based on measurement of plant basal diameter, height and cover (Brown 1976, Halpern *et al.* 1996, Hamilton 2000, Hierro *et al.* 2000). However, not all of the methods provide structural information. Three-dimensional destructive sampling of fuel complexes (Cohen *et al*. 2003) or three-dimensional point quadrats (Hartley 1997) remain options but are laborious and time consuming. On the other hand, quicker methods, such as simple (Anderson 1982) or calibrated (e.g. Ottmar *et al*. 2001) photographic guides, or simplified intercept methods (Egan *et al.* 2000), do not provide the level of accuracy or detail required. As part of a developing programme of fire research, a need was identified for simple techniques capable of describing those fuel attributes likely to be important to fire behaviour: bulk density, canopy density, loadings of different fuel size classes, canopy heterogeneity, surface-area to volume ratio and the relative proportions of dead and live fuels.

Many fire behaviour models require fuel structure data, such as bulk density and fuel size-class partitioning as inputs (e.g. Rothermel 1972, Andrews *et al.* 2005) whilst for other important fire danger rating systems (e.g. Forestry Canada 1992) and understanding of the nature of fuel, especially in non-standard fuel types, is important for implementing the system effectively. The FuelRule method, described in detail below, allows rapid and robust estimation of standing biomass, fine and coarse fuel and moss/litter layer biomass, bulk density and indices of canopy density and stand heterogeneity. It combines elements of widely used methods such as weight estimation (Catchpole & Wheeler 1992), line intercept (Van Wagner 1968) and 'Levy pole' (Chaffey & Grant 2000, Egan *et al*. 2000) techniques, but primarily relies on the use of visual obstruction readings (Robel *et al.* 1970, Benkobi *et al.*2000) from a measuring stick painted with a set of evenly spaced bands. The method is tested in *Calluna vulgaris* (L.) Hull (hereafter referred to as *Calluna*) dominated dwarf shrub heath in the Scottish Highlands (Fig. 1).

In large areas of upland Britain *Calluna* forms a dense, often continuous, canopy which, in older stands, is lifted above the ground by thick woody stems. *Calluna* has been seen to follow an identifiable progression of life phases (Watt 1947, Gimingham 1988):

- **Pioneer**: the period of establishment and early growth. After roughly 2 years the leading shoot looses its identity and basal branches equal it in height. The plants reach up to15cm in height. Flowering is sparse. There are many small open patches between individual plants and grasses, sedges and other plants may be common. Depending on circumstances usually the first 3-5 years of growth.
- **Building**: Maximum cover and density of the canopy. Plants reach a maximum of 30-60cm high with thick shoot growth. Flowering is vigorous and the ground stratum below the *Calluna* is reduced to a minimum. Usually aged 7-15 years.
- **Mature**: Short shoots are more clustered, abundant flowering. A gap may begin to form in the canopy allowing increased light and rising numbers of other plant species particularly bryophytes. Aged roughly 14-25 years.
- **Degenerate**: A well-defined gap forms as the central branches die back. Peripheral branches become flattened. New long shoots are sparse. Rapid increase in other plant species. In theory seedlings of *Calluna* begin to grow in the gap and structurally varied, uneven aged stands form.

Considerable structural differences may also exist due to, amongst other things, varying productivity (Miller 1979), wind pruning, grazing pressure and habit (MacDonald *et al.* 1995). Previous studies have identified links between shrub biomass and height (e.g. Brown *et al.* 1982, Russell & Tompkins 2005), and the FuelRule method seeks to utilise allometric relationships while also taking into account the effects of vegetation density. This paper presents an overview of the technique and theoretical considerations before going on to describe a test of the method.

Materials and Methods

The FuelRule in theory

The FuelRule is a 2 m stick measuring 150 cm long and 2.5 cm wide painted with alternating white and yellow bands (Fig. 1). One face has bands 10 cm wide whilst the reverse has two bandwidths of 2 and 5 cm starting at opposite ends and running half its length. Each set of bands is labelled alphabetically. The bandwidth used for survey is chosen according to the height of the vegetation in order to ensure that during each monitoring campaign an average of at least five bands is obscured to some degree. Having at least five band-width readings for each sampling location ensures a relatively robust logit regression curve can be fitted to the data as discussed below.

In order to take a reading the stick is placed vertically into a stand and pressed down through the moss/litter layer (*Calluna* heathland in the British uplands is typically underlain by a deep mat of pleurocarpous mosses) until it reaches the more compacted F-horizon (fermentation layer) below. The following information is then recorded: moss/litter depth, the highest point of contact of each species touching the stick and the highest point of each species within 5 cm of the stick (Table 1). The user then stands at arm's length to the stick and makes a visual estimate of the percentage of each band obscured by vegetation. The total percentage cover of *Calluna* in a 0.5 m × 0.5 m area centred around the stick is also visually estimated.

The logit (see http://en.wikipedia.org/wiki/Logistic_function) of percent obscured is regressed on mid-band height (Fig 2). A logit regression is used as the shape of the resulting curve (Fig 2a and 2b) best reflects experimental observations of the attenuation of light, and thus visibility, through a tree/shrub canopy (e.g. Grace & Woolhouse 1973, Shropshire *et al.* 2001). When percent obscured is logit transformed the slope of the now straight-line regression (Fig 2c and 2d) reflects how rapidly the amount of each band visible declines the deeper one looks into the vegetation. This measure is here referred to as the Canopy Density Index (*CDI*). The regression can also be used to estimate the height in the canopy at which 50% of the stick will be obscured (referred to as *50%h*). The area beneath the line when plotted on untransformed axes (Fig. 2a and 2c) is a function of the height of the stand and its density and relates to the total biomass. This measure is referred to here as the Biomass Measure (*BM*). These calculations can be performed by a computer program, PObscured, available either from http://firebeaters.org.uk or from the corresponding author.

When the FuelRule is placed in a stand of vegetation gradually more of it will be obscured the deeper into the vegetation one attempts to look. If the FuelRule is placed in a stand with a particularly dense canopy all but the top few bandwidths will be totally obscured leading to a relatively steep regression (high *CDI*) (Figs. 2a and 2c). In sparse stands however, it is possible to see deeper into the canopy giving a lower regression coefficient (low *CDI*) (Figs. 2b and 2d).

Mid-band height is normally measured relative to the surface of the moss/litter layer; this enables the prediction of canopy fuel load excluding ground fuels and any stems buried within them. The deep layer of pleurocarpous mosses found beneath many *Calluna* stands frequently has an exceedingly high moisture content (Hobbs & Gimingham 1984, Davies 2005), does not often constitute 'available' fuel and is rarely consumed by normal management fires except following periods of drought (Davies 2005). The fuel load of this layer can be estimated separately.

Study area

Study sites (Table 2) were located on the northern and western flanks of the Cairngorm Mountains of North-East Scotland. Sixty five calibration quadrats, 0.5 m x 0.5 m, were sampled on a number of sites selected to represent a range of *Calluna* dominated fuel types in burnable vegetation. Twenty eight quadrats were on Ralia moor, 26 at a fire research site on Crubenmore Estate, six on South Drumochter Estate and five in Abernethy Forest RSPB reserve. The first three sites are actively managed grouse moors containing a mixture of *Calluna* stand types while at the latter site quadrats were located in exceptionally tall *Calluna* with a relatively sparse and open canopy both within *Pinus sylvestris* forest and at the forest edge.

Calibration sampling

Nine equally-spaced sticks were recorded in each quadrat after a preliminary visual estimation of species cover values. The observer held the stick at arms length. Vegetation in the quadrat was then harvested down to the top of the moss layer. The moss/litter layer and the stems within it were collected separately. At each location the following were recorded: TopEx (an estimate of topographical exposure, Chapman 2000), altitude, slope, aspect and grazing intensity estimated from the evidence of the presence of grazing animals, the general structure of the *Calluna* canopy and the proportion of shoots that showed signs of grazing.

In the laboratory, harvested material was first sorted by species. A sub-sample of half the *Calluna* plants by volume was clipped and sorted into the following fuel classes: live stems with foliage (all < 2 mm in diameter), dead stems with foliage (all < 2 mm in diameter), live stems < 2 mm in diameter without foliage, live stems 2-5 mm, live stems > 5 mm and bare dead stems. These samples, together with the moss and litter, and stems buried within the moss layer were dried in an oven at 80°C for 48 hours before being weighed.

The relationships between mean quadrat FuelRule values (Table 1) and their standard deviations, and total quadrat biomass above the moss layer, fine fuel (defined here as live and dead stems < 2 mm in diameter and all foliage) biomass and the mass of the moss/litter layer were investigated using best-subsets and polynomial regression analysis in Minitab 14 (Minitab Inc. 2003). We also examined age-related changes in vegetation structure and fuel class partitioning.

Stand-level application

To provide an independent assessment of the results we tested the predictive ability of the equations developed during the calibration by comparing the results of destructive and FueRule surveying of fourteen 15 × 20-m experimental fire plots (Davies 2005). The plots were surveyed using three parallel 15-m transects with nine FuelRule stick measurements on each transect. A single quadrat was located in a visually representative area of each plot and destructively harvested and processed as described earlier. The total monitoring effort, in terms of field and lab/computer time, was comparable.

Between observer error

Several authors (e.g. Hatton *et al.* 1986, Kercher *et al.* 2003) have attested that subjective assessments of cover lead to significant errors between observers. We examined the differences in FuelRule readings between seven different observers in a single quadrat in each of a high, medium, and low fuel loading stand. Of the observers three had previously used the FuelRule whilst four were complete novices. Before testing began, observers were briefly trained on the stick technique and likely sources of bias, and given practice estimating cover values using shaded squares published by the Ontario Institute of Pedology (1985). Results were analysed in Mintab 14 (Minitab Inc. 2003) using a General Linear Model.

Results

Regression equations were created for the prediction of total biomass above the moss layer, moss and litter biomass, and the biomass of fine fuels (Table 3). All equations are for, and all figures show, fuel loading expressed as grams per metre square.

Total biomass above the moss layer

BM (Table 1, Fig. 2d) on its own provided relatively good predictions of total above-moss biomass (Table 3) although a number of outliers were present. The addition of *Mean h* to the regression marginally improved the R^2 (adj) but had little effect on the presence of three of the outliers (Fig. 3).

Moss and litter biomass

Analysis revealed that *Mean M/L* (Table 1) is an excellent predictor of both moss biomass (R^2 (adj) 0.80) and moss biomass and buried stems combined (R^2 (adj) 0.82) (Table 3). The addition of second predictors did not significantly improve these equations. Both these equations suggest the presence of some moss or litter even when the depth reading is zero.

Biomass of fine fuels

Total fine fuels less than 2 mm in diameter including live and dead stems with and without foliage were best predicted by a combination of *BM*, *50%h* and % Cover. Log transformation was used to remove the problem of the prediction of negative amounts of fuel in stands with low *BM* and only sparse cover (Equation 5, Table 3). A number of outliers have a significant effect on the equation (Fig. 4).

Bulk density

Bulk density (g m^{-3}) is defined by Pyne *et al.* (1996) as fuel loading divided by the mean height of the fuel bed. If we define *canopy density* as Fine Fuel Biomass/*Mean h* (g m^{-3}) we can regress this value against *CDI*:

$$\text{Canopy Density} = 3.30 - 8.94 \times \text{CDI} \qquad (7)$$

The regression has an R^2 (adj) of 0.59. The fitted line plot for the regression shows several outliers (Fig. 5).

Stand-scale testing of equations

In general there was a fairly good relationship between the results of experimental plot surveys and destructively sampled fuel quadrats (Fig. 6). For roughly half the plots, mean estimated plot biomass lies within one standard deviation of the line of perfect agreement.

Age-related changes in fuel bed structure

With no definitive measure of stand age where measurements were taken we used *Mean h* (Table 1) as a proxy for age. It can be noted than whilst the mass of fine fuels demonstrates an asymptotic relationship with height (Fig. 7a, Miller 1979), coarse stems appear to increase in mass exponentially within the range of stands we surveyed (Fig. 7b).

The standard deviations of FuelRule measures are proposed as indicators of canopy heterogeneity. Analysis of changes in the variability of *CDI* and *BM* with increasing height and *Calluna* phase reveals a number of points. Pioneer stands have the most variable *CDI* values with a gradual reduction in standard deviations from the building to mature phase (Fig. 8a). There is a general reduction in variability with the average height of the stand. For *BM* variability increases with age and the highest standard deviations are found in tall mature and degenerate *Calluna* stands (Fig. 8b).

Between observer error

Variation between observers, fuel loadings and individual FuelRule readings within each quadrat was examined with GLM for all predictors (Table 4). While there were significant differences between observers for *Mean M/L*, *50%h* and *BM*, the between-observer mean square was very small compared with the between-fuel loading mean square. This means that although observers do record statistically significantly different results the variation between observers is small in comparison to the difference between the quadrats. There was also a significant difference between individual sticks within a quadrat for all predictors demonstrating multiple scales of heterogeneity in *Calluna* fuel structural characteristics.

Discussion

The results of the regression analyses show that the FuelRule can provide relatively robust estimates of fuel load and structure across a wide range of heathland fuel structures. The calibrations presented here are more suitable for use in relatively homogenous building and mature stands with relatively few quadrats having been studied in either pioneer or degenerate *Calluna*.

As we suspected adjusted R^2 values show that fine fuel biomass is better predicted than total biomass above the moss layer. For our purposes this is not of great concern as 'available', fine fuel biomass drives fire behaviour. The differences in predictive ability for fine and total fuel loading can be explained by the fact that in most stands the majority of visual obscurity is caused by the dense *Calluna* canopy of fine stem and foliage whilst the larger, thicker stems below simply raise the canopy above the ground without contributing much to obscurity readings (Fig. 7). Changes in fire behaviour in building to degenerate stands will be driven by structural changes rather than increases in fuel loading *per se*, as coarse stems do not generally constitute "available" fuel for management fires (Davies 2005). A greater number of quadrats in mature and degenerate stands with more open canopies may change these simple relationships as gaps open in the canopy through stems falling over (Gimingham 1988). This may lead to a net loss of fine fuel, a decrease in mean canopy height but an increase in the quantity of coarse stems.

Bulk density is an important parameter in fire modelling describing the compactness of a fuel bed. It is used in several fire behaviour models including the classic Rothermel model (Rothermel 1972). Examining Fig. 5, and considering the working of the stick, it would seem fair to assume that *CDI* provides a robust index of *Calluna* canopy density. We use the term 'canopy density' as opposed to simply bulk density as the majority of the obstruction of the stick is caused by the fine fuels and foliage of the *Calluna* canopy rather than the stems below it. Larger stems below the canopy are, despite their greater diameter, likely to have little additional effect on the visibility of a stick which is already mostly obscured by the vigorously branching fine stems and foliage. Even in older, more open stands the low density of large *Calluna* stems means that on average they may also contribute relatively little to visual obstruction.

For stand-scale surveys, poor agreement between the cut quadrats and the FuelRule survey reflects inaccuracies in both methodologies. Mean predicted biomass and its variation within and between transects may reflect the FuelRule transects picking up real spatial variation in structure that cannot be detected from the single selected 'representative' quadrat.

Standard deviations of all FuelRule variables provide measures of structural heterogeneity and it is interesting that variability in *BM* increases with stand age whilst *CDI* shows the opposite relationship. This suggests that *BM* detects variability in the height of the canopy where quadrats have relatively similar *CDI* values (i.e. a canopy of uniform density, and constant slope of regression line) but the height at which this material is found varies changing the area beneath the line. The standard deviation of *CDI* is generally higher in pioneer and young building stands but it is noticeable that there is considerable overlap between the *Calluna* phases. This suggests *CDI* detects the presence of significant open patches where much of the stick is visible. These could either occur in young stands where individual bushes have not yet grown sufficiently large that their canopies merge to form continuous cover; or in older stands where the collapse and opening of the canopy causes gaps to appear. Structural differences within and between different stands of vegetation and the presence of canopy gaps as evidenced by the standard deviation of *CDI* has been shown to be important in determining fire behaviour (Davies 2005).

Outliers

A proportion of the variance can be explained by the presence of a small number of outliers (see Figs. 3 to 5). All of these can be confidently ascribed to the unusual site conditions of the area in which these quadrats were located.

In Fig. 3, the outlier Q43 was located in sparse vegetation but had unexpectedly high *BM* values due to its height; Q27 and Q50 were in stands with high TopEx values (sheltered) and particularly dense canopies which held large amounts of dead foliage that would normally have been lost as litter. In Fig. 4, for fine fuel biomass, Q25, while predicted to be at the top end of the range of fine fuel loadings, had an even greater biomass than expected due to an unusually large amount of suspended dead foliage.

A number of outliers were also obvious in the analysis of *CDI*. These were located either in very dense stands containing high fine fuel loads or in very heterogeneous quadrats with significant canopy gaps. It would appear that when dead foliage loadings are above a certain level and the canopy is already particularly dense further increases in dead fuel loading are possible under certain site conditions such as low TopEx but do not cause additional change in the amount of the FuelRule obscured.

The technique could be improved by the analysis of further quadrats and their separation into a number of fuel types (*sensu* Scott & Burgan 2005). Those sites appearing as outliers in the calibrations should be investigated further in particular. The inclusion of a measure of canopy depth might also help to provide a more accurate measure of canopy density.

Between observer error

The existence of significant differences between observers for *BM* is not surprising (Table 4), though the fact these existed even after instruction in the assessment of percent cover using the charts created by the Ontario Institute of Pedology (1985) suggests that where the technique is to be used by multiple observers some group training is desirable. A number of factors including viewing angle and indeed observer height and arm length will all have an impact on variation between observers and it would be wise for individuals to calibrate their readings before using the technique. However, it is clear that the variation between observers is very small compared to the variation between samples and between fuel types.

The large amount of variation between observers with regards to *Mean M/L* (Table 4) is partly due to the variability in moss depth across a quadrat, as shown by the significant differences between sticks within a quadrat. This means that variation may exist due to differences in stick placement. Alternatively, there may have been progressive compression of the moss by the blunt end of the stick as successive observers worked on the same quadrat. This may explain why Equations 3 and 4 predict some moss and litter biomass even where the depth was recorded as zero.

The fact that, for all stick measures, significant differences existed between individual readings within a quadrat, as well as between fuel loading groups, suggests that there are several scales of variation in canopy structure and that these are significant even over small areas (within a 0.25 m^2 quadrat). This has important implications for the design of surveys and the relevant scale of fuel bed assessment with respect to fire behaviour. Controlled burning experiments have demonstrated that fire rate of spread is reduced in stands with increased density as estimated by *CDI*, and where stands are more gappy as evidenced by increased standard deviations of *CDI* (Davies 2005).

Future developments

Variation in the ratio of dead-to-live fuels can be of importance to fuel flammability and fire behaviour (Schwilk 2003, De Luis *et al*. 2004). It is however difficult to assess accurately for *Calluna* due to its growth form with small imbricate leaves that are difficult to separate from the stem. Simple field methods to determine this are urgently required and a number of possible techniques are currently under development.

The FuelRule method provides a potential method for ground-truthing remote-sensing data (Egan *et al*. 2000) allowing estimation of vegetation structure and biomass directly as well as indices of structure that have been shown to be directly related to fire behaviour (Davies 2005, Davies *et al*. 2006). The FuelRule also provides a quick survey technique for detecting the effects of other impacts such as grazing, climate change and nitrogen deposition (Cannell *et al*. 1997, Milne & Hartley 2001, Wessel *et al*. 2004). Attempts at remote sensing *Calluna* dominated vegetation have already begun with the work of Egan *et al.* (2000) and Wright *et al*. (1997) but require further development. Producing tools such as fuel maps and simple guides to fuel load and potential fire behaviour (e.g. Ottmar *et al*. 2001) will allow land-managers and agencies to recognise areas of high fire hazard enabling targeted use of fire that minimises risk of escape, maximises the ecological value of prescribed burning and allows fire to be used safely for hazard reduction.

The FuelRule has been presented here in the context for which it was first developed: fuel estimation for fire research. The technique should however be of interest across a wide range of ecological research areas where an assessment of vegetation production and canopy density is required, for example studies of grazing impact, habitat condition and for the assessment of the condition of *Calluna* moorland (Bardgett *et al*. 1995). Calibrations can be developed quickly an easily and the method is recommended for testing in shrub and grasslands up to one metre tall.

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Table 1: Definition of FuelRule values used in the text and equations. Mean values and standard deviations for all sticks in a quadrat (n = 9) were used in regression analysis against biomass.

Name of Value	Observed/Calculated	Description
Mean M/L	Observed	Mean depth of the moss or litter layer
Mean h	Observed	Maximum height at which vegetation makes contact with the stick
50%h	Calculated	Height at which 50% of the stick is obscured
BM	Calculated	Biomass Measure. Area beneath the regression line of logit percent obscured on height (Fig. 1).
CDI	Calculated	Canopy Density Index. Slope of the logit regression line of % obscured on measurement height (Fig. 1)

Table 2: FuelRule quadrat locations and vegetation descriptions. Grid references identify an Ordnance Survey grid square roughly within the centre of each monitoring location, the range of altitudes surveyed is also given. Plant communities are a list of NVC (Rodwell 1991a & 1991b) communities covered by the survey. Grazing level is a subjective assessment for the entire monitoring area. Ranges of key fuel vegetation and fuel load descriptors are also shown, where ‘Range of Loadings’ is total fuel load above the moss/litter layer. *CDI* = Canopy Density Index, *Mean h* = mean height of vegetation.

Location	**Latitude & Longitude**	**Altitudinal range (m a.s.l.)**	**Vegetation communities**	**Grazing level**	**Range of *Mean h* (cm)**	**Range of *CDI***	**Range of *Calluna* cover (%)**	**Range of loadings (t ha^{-1})**
Ralia Estate	57° 1’43” N 4° 6’33” W	290 – 480	H9, H10, H12, H16, H18, M15	High	5.1 – 46.1	-0.34 – -0.17	55 – 99	4.4 – 14.2
Crubenmore Estate	56° 58’53” N 4° 14’17” W	450 – 515	H10, H12, H16, M15	Medium	9.4 – 50.3	-1.01 – -0.15	75 – 99	5.5 – 23.2
South Drumochter Estate	56° 54’2” N 4 ° 14’0” W	450 – 750	H12, H22, M15	Medium	18.4 – 35.6	-0.75 – -0.41	90 – 99	7.4 – 25.0
Abernethy Forest	57° 13’28” N 3° 37’24” W	270 – 310	W18	Low	36.6 – 59.3	-0.34 – -0.17	50 – 99	3.8 – 19.4

Table 3: Regression equations developed for three fuel types (top) and the standard errors of the constant and predictors (bottom). Predictors used in the equations are described in Table 1. Units are g m^{-2}.

Equation number	Fuel property	Equation	R^2 (adj)
1	Biomass above Moss	$220 + 74.5 \times BM$	0.64
2	Biomass above Moss	$143 + 61.5 \times BM + 7.8 \times \text{Mean h}$	0.67
3	Moss Biomass	$302 + 124.5 \times \text{Mean M/L}$	0.80
4	Moss and Buried Stem Biomass	$407 + 170.8 \times \text{Mean M/L}$	0.82
5	Fine Fuel Biomass	$-292 - 42.7 \times 50\%h + 7.2 \times \%Cover + 80.9 \times BM$	0.70
6	Ln (Fine Fuel Biomass)	$4.36 - 0.595 \times Ln(50\%h) + 0.0126 \times \%Cover + 1.08 \times Ln(BM)$	0.69

Equation number	Constant SE	Predictor 1 Name	Predictor 1 SE	Predictor 2 Name	Predictor 2 SE	Predictor 3 Name	Predictor 3 SE
1	82	BM	7.0				
2	85	BM	8.4	Mean h	3.1		
3	56	Mean M/L	7.7				
4	72	Mean M/L	9.9				
5	142	50%h	17.5	%Cover	1.6	BM	19.0
6	0.22	Ln (50%h)	0.26	%Cover	0.002	Ln (BM)	0.28

Table 4: Results of Observer Error GLM: P-values are given along with the degrees of freedom (d.f.), adjusted mean squares (MS) and F-ratio (F) for the variance between fuel loadings, individual sticks within a quadrat and different observers on Biomass Measure (*BM*), Canopy Density Index (*CDI*), *Mean h*, *50%h* and *Mean M/L* readings.

Variable	**Fuel Loading**				**Sticks**				**Observer**			
	d.f.	MS	F	P	d.f.	MS	F	P	d.f.	MS	F	P
BM	2	734.96	30.85	< 0.001	24	131.91	5.54	< 0.001	6	53.63	2.25	0.042
CDI	2	5.19	32.57	< 0.001	24	0.27	1.72	0.028	6	0.29	1.81	0.101
Mean h	2	16167.21	297.88	< 0.001	24	137.00	2.52	< 0.001	6	23.95	0.44	0.850
50% h	2	841.35	27.73	< 0.001	24	140.75	4.64	< 0.001	6	88.98	2.93	0.010
Mean M/L	2	1420.26	471.58	< 0.001	24	10.27	3.41	< 0.001	6	39.48	13.11	< 0.001

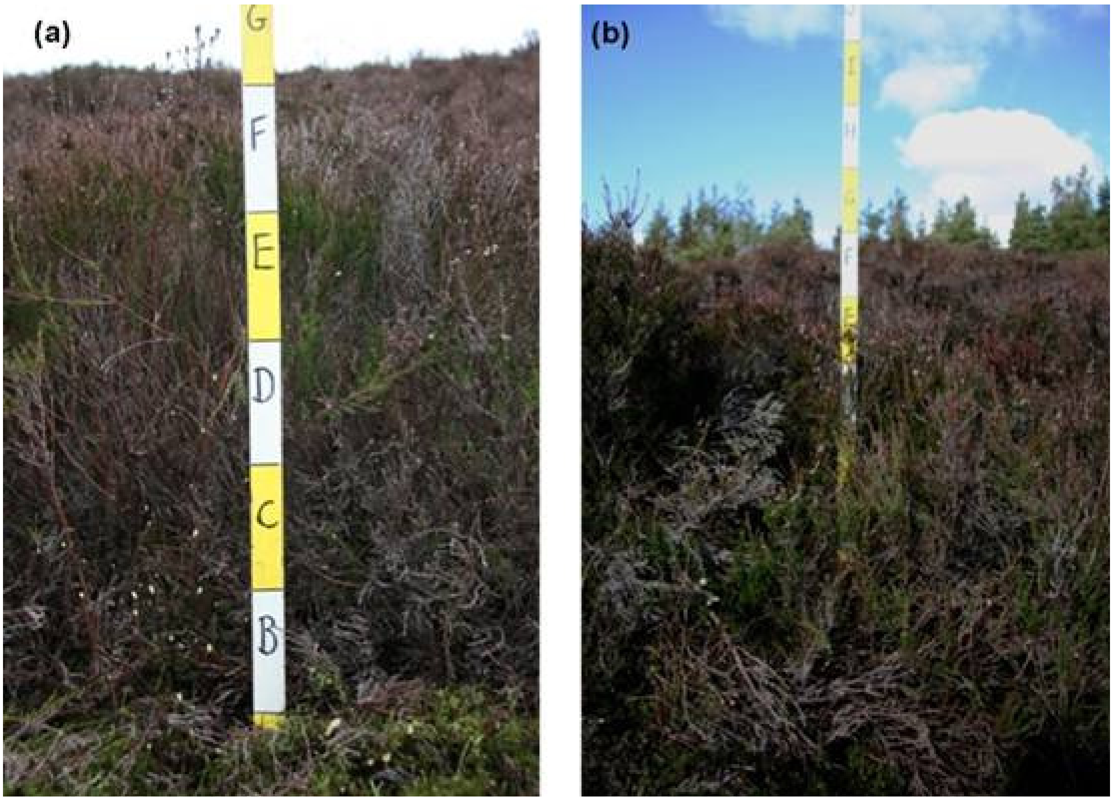

Fig. 1: An illustration of the FuelRule with (a) the heather canopy cut away to show the vertical structure of the fuel and (b) placed within an intact stand of heather. The bandwidths shown are 10 cm.

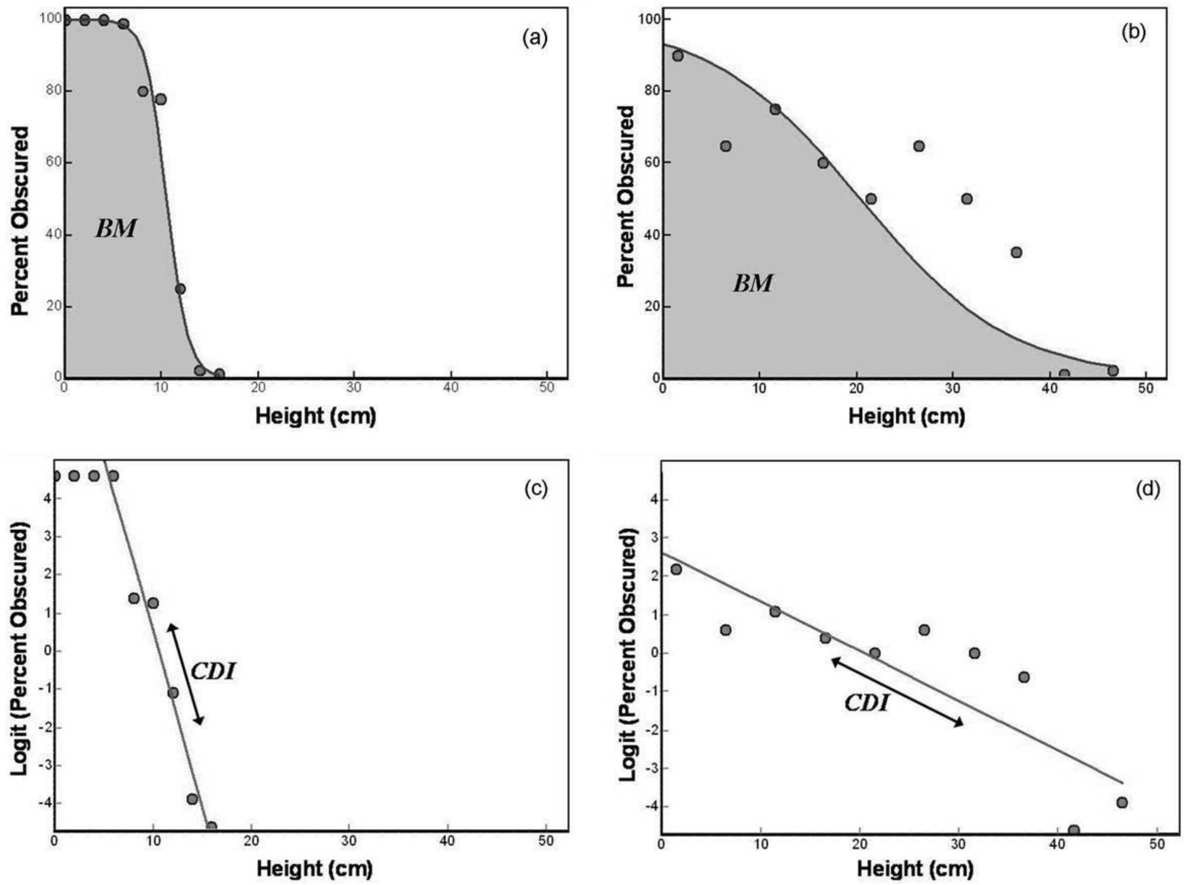

Fig. 2: Example graphs produced by PObscured for two *Calluna* stand**s**: (a) a young, dense stand, (b) an old, sparse stand and the same data using Logit percent obscured (c) and (d). Canopy Density Index (*CDI*) is defined as the slope of the logit regression line whilst *BM* corresponds to the area beneath the regression on linear axes (shaded).

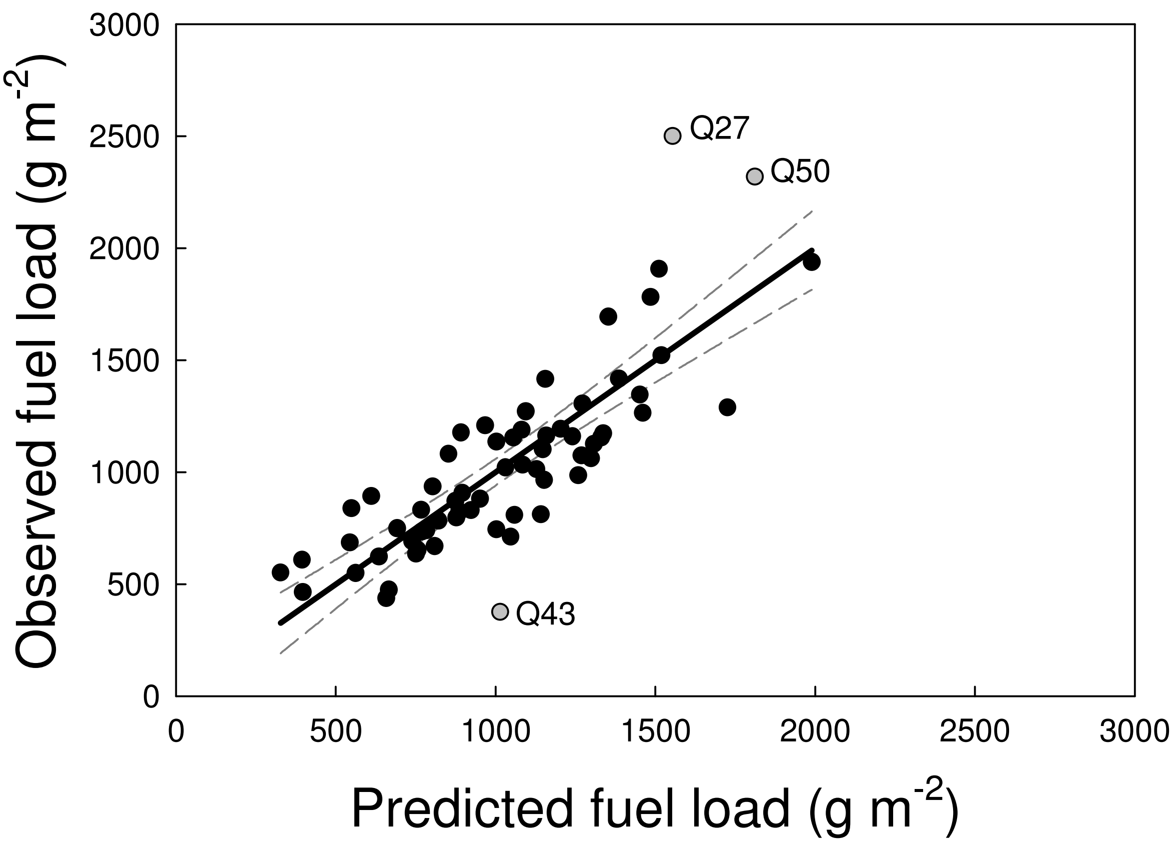

Fig. 3: Predicted versus observed values for the regression of biomass above moss on *BM* and *Mean h* (Equation 2). Quadrats Q27, Q43 and Q50 are outliers. Error bands are 95% confidence intervals.

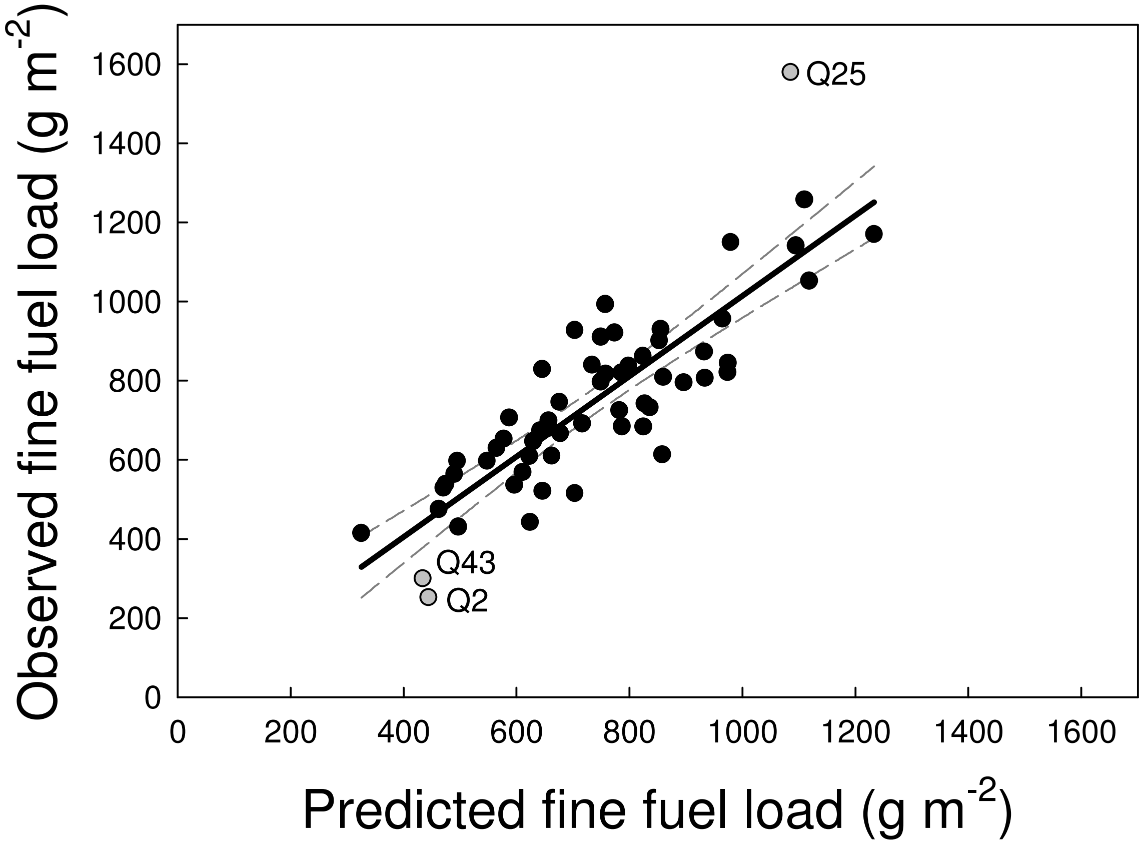

Fig. 4: Predicted versus the fitted biomass for the regression of fine fuels on Ln (*50%h*) %Cover and Ln (*BM*) (Equation 6). Three outliers are highlighted and these are discussed in the text.

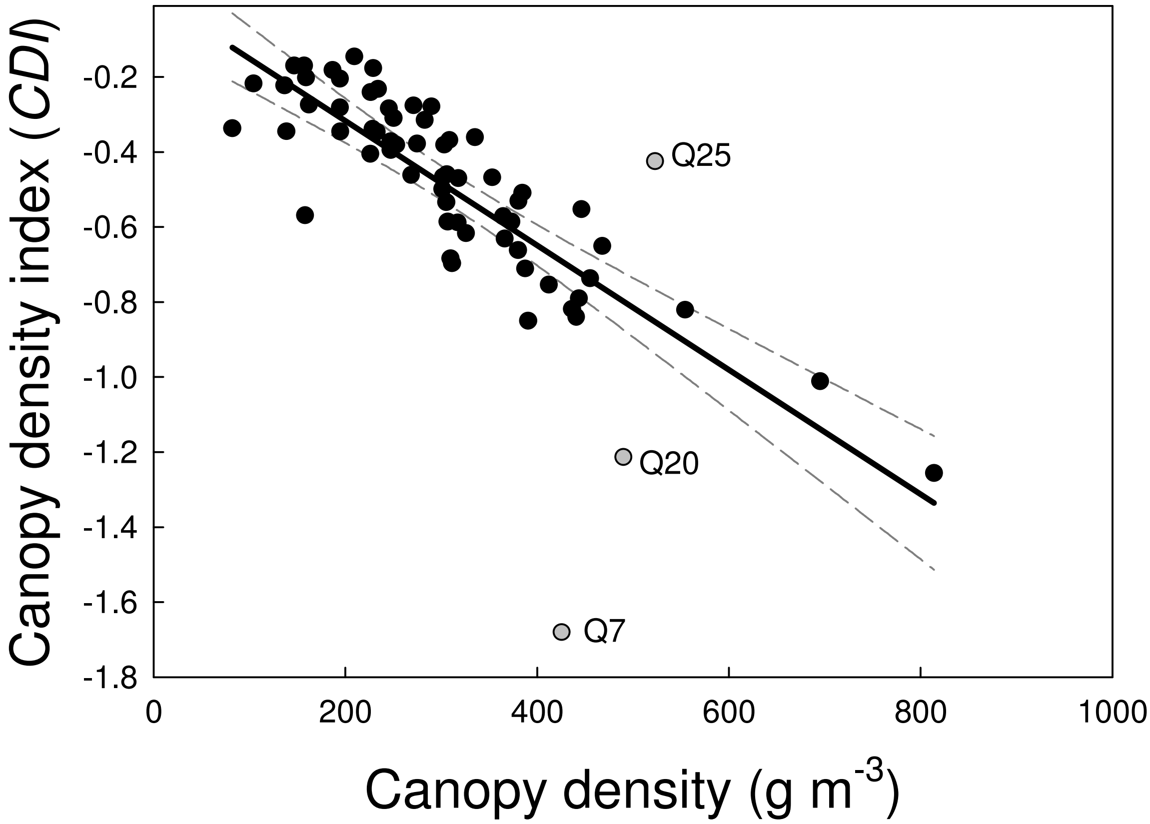

Fig. 5: Fitted line plot for the regression of canopy density on *CDI*. Bands are 95 % confidence intervals and prediction limits. Outliers highlighted are discussed in the text.

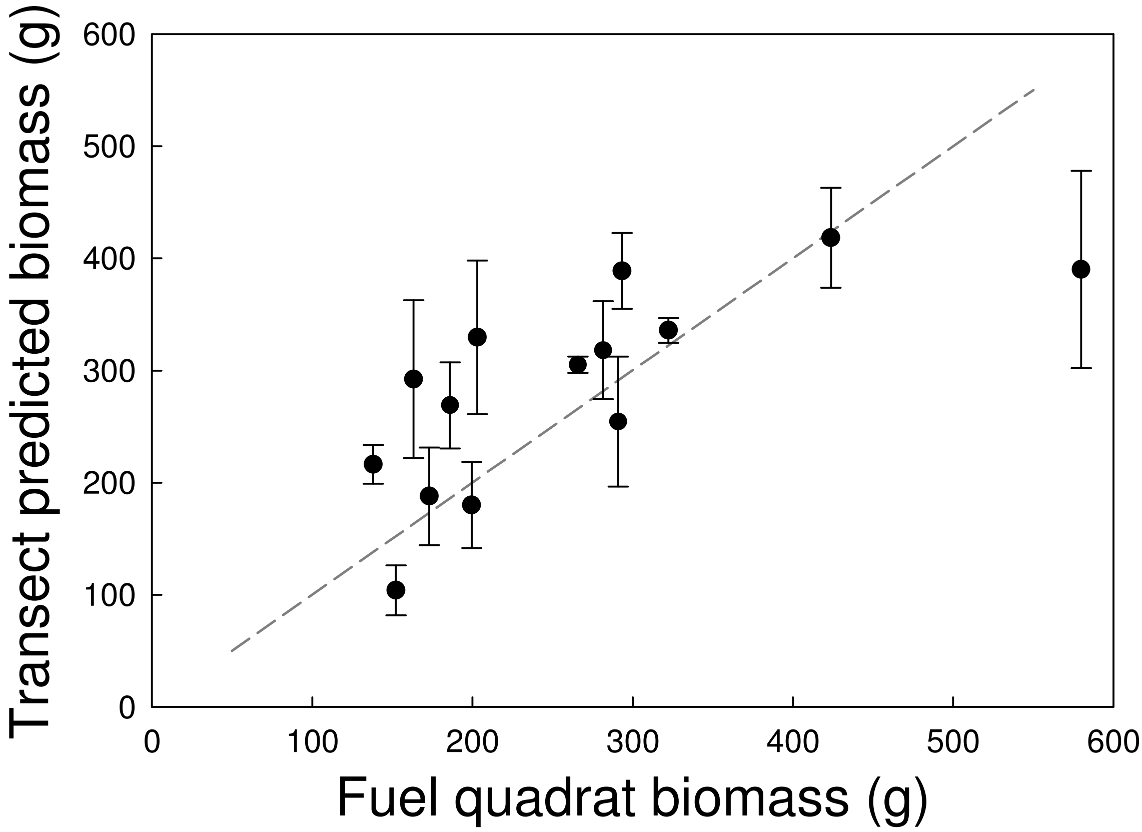

Fig. 6: Mean FuelRule transect biomass estimates plotted against fuel loading from destructively harvested fuel assessment quadrats for fourteen 15 m x 20 m experimental fire plots. The X-axis shows the biomass of a single destructively harvested quadrat located in a representative area of each plot. The Y-axis shows the mean fuel load estimated from three FuelRule transects. Error bars are ± 1 standard deviation.

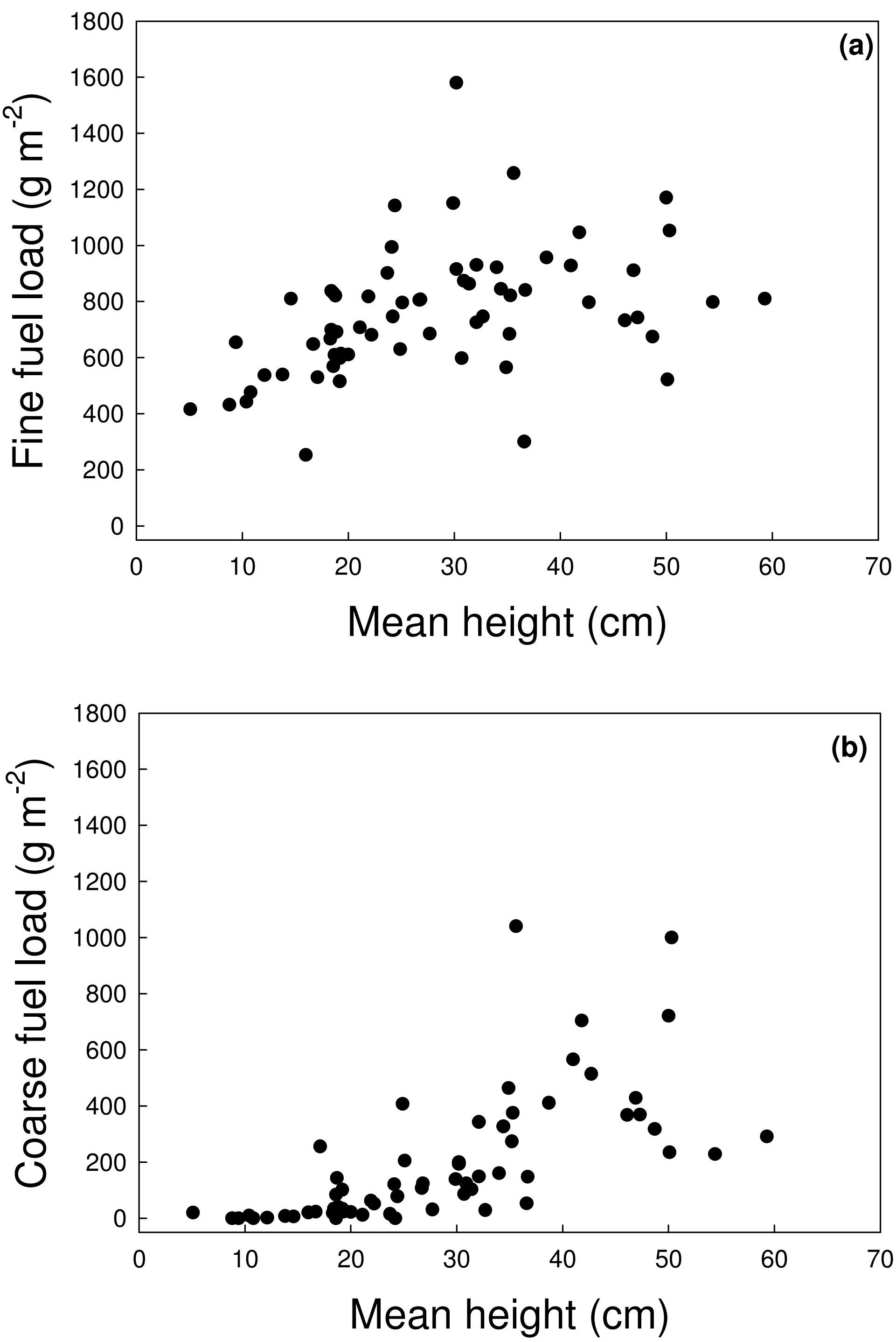

Fig. 7: Change in the loading of fine (canopy) and coarse (stem) fuels with increasing average stand height. In older stands the canopy is lifted off the ground by the growth of thick stems increasing total fuel load whilst fine load remains relatively constant.

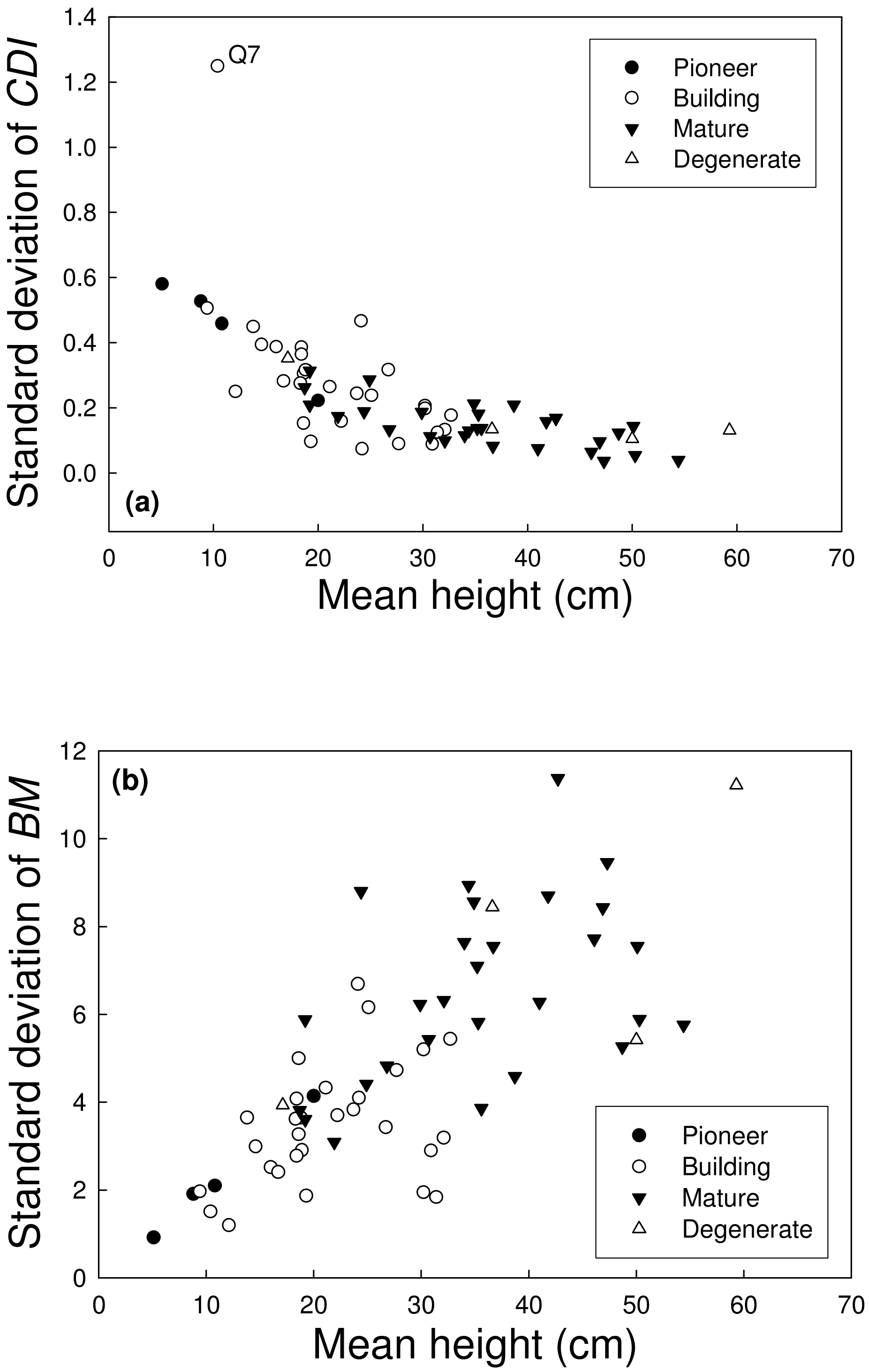

Fig. 8: Change in the variability of FuelRule measures BM and CDI with increasing mean stand height (a proxy for age). Q7 was located in an extremely heavily grazed stand with *Calluna* showing a “drumstick” growth form and on average an extremely dense canopy.