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Assessing the effectiveness of scrub management at the landscape scale using rapid field assessment and remote sensing

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ABSTRACT

Controlling scrub encroachment is a major challenge for conservation management on chalk grasslands. However, direct comparisons of scrub removal methods have seldom been investigated, particularly at the landscape scale. Effective monitoring of grassland scrub is problematic as it requires simultaneous information on large scale patterns in scrub cover and fine-scale changes in the grassland community. This study addressed this by combining analysis of aerial imagery with rapid field surveys in order to compare the effectiveness of four scrub management strategies on Defence Training Estate Salisbury Plain, UK.

Study plots were sited within areas undergoing management and in unmanaged controls. Controls showed dramatic increases in scrub cover, with encroachment of a mean 1096 m^2 per hectare over ten years. Whilst all management strategies were effective in reducing scrub encroachment, they differed in their ability to influence regeneration of scrub and grassland quality. There was a general trend, evident in both the floral community and scrub levels, of increased effectiveness with increasing management intensity. The dual methodology proved highly effective, allowing rapid collection of data over a range of variables and spatial scales unavailable to each method individually. The methodology thus demonstrates potential for a useful monitoring tool.

1. Introduction

Unchecked succession to scrub and woodland poses a serious threat to the conservation of open grassland habitats across the globe (Crofts and Jefferson, 1999; Eldridge et al., 2011). The calcareous grasslands of Western Europe are a habitat of high conservation value, due to their high biodiversity and large number of rare or threatened species (Bossuyt et al., 2006; WallisDeVries et al., 2002). Originally limited to steep slopes and outcrops, many calcareous grasslands developed after forest clearance beginning in Neolithic times, and were maintained by grazing, hay mowing and removal of woodland regrowth for firewood (Poschlod and WallisDeVries, 2002). In the twentieth century, fertilization and ploughing for agriculture led to rapid declines in calcareous grasslands across Europe (Hirst et al., 2000), whilst abandonment of traditional grazing and hay cutting made the remaining fragments vulnerable to degradation by scrub encroachment (Poschlod and WallisDeVries, 2002). Invasion of scrub on grasslands reduces floral diversity by creating shade and enriching the underlying soil with organic debris, encouraging shade-tolerant and competitive species (Butaye et al., 2005; Bossuyt et al., 2006).

In temperate grasslands scrub is naturally managed by browsing and grazing (WallisDeVries et al., 2002; Woodcock et al., 2005) and by fire (Morris, 1975). Conservation management typically involves scrub removal by mechanical means (cutting or flail mowing), herbicide application or controlled burning (Crofts and Jefferson, 1999). These approaches may be employed singly or in combination. The effects of scrub encroachment have been studied at local, ecosystem (Van Auken, 2009) and, recently, global scales (Eldridge et al., 2011) and there is an extensive literature demonstrating the effects of individual management techniques. However, comparisons between techniques are considerably rarer. Often such studies are limited to small areas and rarely use a standardised methodology (Menges and Gordon, 2010), making it difficult to disentangle the effects of scrub management actions from other site factors. As a result, most practical guidelines for selecting scrub management methods are based on anecdotal observations rather than long-term experimentation (Bacon, 2003). If this problem is to be addressed it is necessary to overcome the practical difficulties in

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monitoring accurately both the primary effects on problem species, and the secondary effects on grassland quality (i.e. floral community and vegetation structure in relation to species and values which typify well-maintained examples of the habitat). Achieving these simultaneously is a particular challenge at the large spatial scales encountered in many grassland habitats.

Remote sensing, in particular aerial imagery, has long been used to gather data over large areas in a consistent and repeatable way (Hoffer and Johannsen, 1969). Image analysis procedures involving classification of land cover types on the basis of their spectral and spatial characteristics has enabled the use of aerial imagery as a staple for provision of data on the extent, pattern and distinctness of landscape features (Franklin, 2001; Jensen, 2005). In some respects, grassland habitats are well suited to this approach as many features of interest to conservation (e.g. scrub, bare ground, water bodies) are readily distinguished, and previous studies have employed remote sensing in order to detect scrub encroachment over large areas (Laliberte et al., 2004; Mitchard et al., 2009). However, remote sensing is not always able to quantify accurately changes in floristic composition, particularly at fine spatial scales. In many situations, detecting such detailed changes is of great importance to informing conservation practice (Feilhauer et al., 2010). Grassland floristic communities in particular seldom have obvious real-world boundaries and are often spectrally very similar, particularly in high summer (Peterson and Aunap, 1998). Enhancing the ability of remote sensing techniques to detect change in floristic composition is currently an active area of research (Schmidtlein et al., 2007; Feilhauer et al., 2010) but the methods involved require investment in specialist remote sensed datasets. Where scrub encroachment is concerned, the problem is also likely to be compounded by the fact that the same factor that threatens the floral community also masks it from aerial imagery.

In contrast to remote sensing, ground survey is less consistent and repeatable in mapping land cover, but is effective in measuring change in plant community composition and structure (Sutherland, 2006). Comprehensive ground survey is costly and requires a high level of taxonomic expertise, restricting its use to small areas. A compromise approach is to undertake a partial ground survey focussing on a limited sub-set of or indicator species and attributes that are easy to identify. So-called 'rapid assessment methods' have been successfully developed and deployed for lowland grasslands (Robertson and Jefferson, 2000).

Combining image analysis with rapid ground survey thus offers a complementary approach for monitoring both detailed changes in the plant community and wider landscape patterns, over a large area, at relatively low cost. This study undertook a quantitative assessment of the effectiveness of four scrub management strategies at the landscape scale using a combination of analysis of readily available aerial photographic images with a rapid ground survey method. The scrub management strategies assessed form a spectrum of management intensity; from single treatments using herbicide or mechanical management, through single applications of both types, culminating in multiple instances of both methods. The study also evaluated the monitoring methodology as a means of rapid and accurate assessment of scrub management on chalk grasslands, and potentially other habitats, in North West Europe and beyond.

2. Methods

2.1. Study site

This study was carried out on Defence Training Estate Salisbury Plain (DTE SP), UK (Fig. 1). This area contains 50% of remaining UK

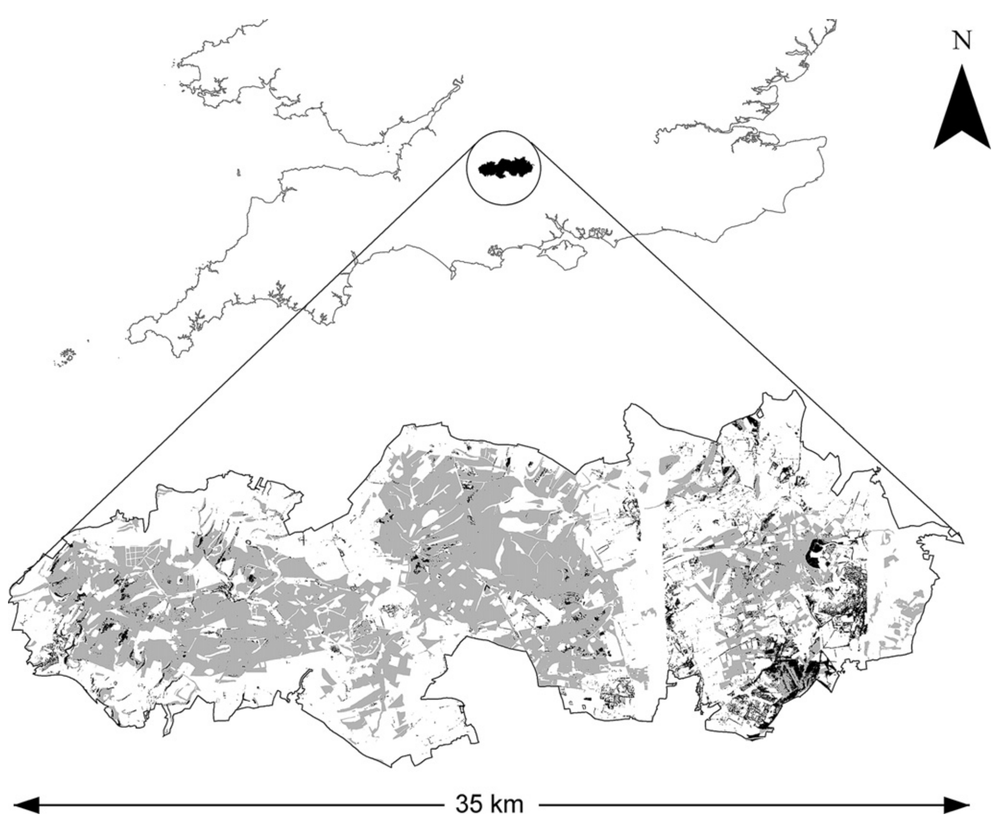

Fig. 1. Map of Southern UK showing the location of Defence Training Estate Salisbury Plain. Unimproved calcareous grassland is shaded grey (Walker and Pywell, 2000), scrub is shaded black.

chalk grassland, and forms the largest continuous area of this habitat in Western Europe (Walker and Pywell, 2000). Military ownership since the late 19th century has resulted in the protection of DTE SP from damage and fragmentation by agricultural intensification. However, until recent years, military training restricted grazing management so that extensive areas were invaded by scrub, particularly hawthorn *Crataegus monogyna* and gorse *Ulex europaeus* (Walker and Pywell, 2000), threatening the conservation value of the calcareous grassland (Iliffe et al., 2000). To counter this threat a campaign of scrub removal and grazing has been undertaken over the last 11 years, with around 30 km^2 undergoing active scrub removal.

2.2. Scrub management regimes

Using annual maps of scrub management (spring 1994 to summer 2010), we identified areas of species rich chalk grassland (see Walker and Pywell, 2000) which had undergone management between 2004 and 2007, giving the grassland time to recover whilst keeping a low probability of total scrub regeneration (Bobbink and Willems, 1993). We selected four management treatments for survey on the basis of their wide scale application to all temperate grasslands: 1) herbicide spray (foliar spray of scrub < 1.5 m high with glyphosate, 360 g L^{-1} applied as 2.5% solution), 2) cut (chainsaw cutting of scrub > 0.5 m high, followed by stump treatment with glyphosate, 360 g L^{-1} applied as 20% solution), 3) cut and spray (single applications of both cutting and spraying) and 4) 'intensive' management (multiple applications of both cutting and spraying). The commencement of management activities was contemporaneous with the reintroduction of grazing to managed areas and adjacent controls. Grazing was restricted to 10–14 days annually in temporary pennings, with no more than 50% of each penning grazed in consecutive years. For further details of the grazing regime see Woodcock et al. (2005).

Monitoring took place within 1 ha (10,000 m^2) survey plots identified as having minimum 5% scrub cover before management began. This threshold has been previously identified as indicative of significant threat to grassland quality (Robertson and Jefferson, 2000). Paired control plots were allocated in order to control for spatial heterogeneity (Chapman, 1999) with a control located within 750 m of each managed plot, in an area which had not undergone any scrub management between 1994 and 2010, and with similar levels of scrub cover to the managed plot, prior to management. Seven managed-control pairs for each management type (56 plots total) were located in geographically separate areas. All spatial data for selecting survey plots were handled using ArcMAP (v 9.3.1 ©ESRI 2009).

2.3. Quantifying scrub cover using aerial imagery

High spatial resolution (0.25 m × 0.25 m pixels) aerial photographic imagery (i.e. true colour; red, green and blue bands) were obtained for 1999 and 2010, representing the situation before and after all scrub management activities on the survey plots. All images were taken in late summer and, in the case of 2010, were contemporaneous with the field survey (30th August 2010). We applied a pixel-based supervised maximum likelihood classification to assign basic land cover classes (bare chalk, scrub, grassland, deep shade). The image layers fed into the classification were 1) the first principal component from principal components analysis (PCA) of the red, green and blue bands; 2) the red band alone; 3) Haralick mean texture of the red band (Haralick et al., 1973). PCA reduces variability in the data by transformation into a number of uncorrelated variables ('principal components') providing, in this case, a metric of overall 'darkness' or 'lightness'. The red band was employed for the latter two layers as green vegetation shows strong absorbance in the red end of the spectrum (Franklin, 2001). Textural analyses have been shown to greatly enhance separability among cover classes with similar spectral qualities (Franklin et al., 2000; Morgan et al., 2010). In this case, mean texture was chosen as it showed the greatest difference between land cover classes. Mean texture was extracted from a grey-level co-occurrence matrix generated using a 9 × 9 pixel moving window. Three metrics of scrub cover were then obtained for all survey plots for both years: total scrub cover area, scrub patch number and average scrub patch size. Classification procedures were carried out in ENVI (v 4.4 ©ITT VIS 2007).

2.4. Quantifying effects of scrub management using rapid field survey

Surveys were conducted from 16th to 27th August 2010, using a variant of Natural England's rapid assessment method for tall calcareous grasslands (Robertson and Jefferson, 2000). The method consisted of a visual assessment, followed by a W-shaped transect across the survey plot, recording presence of 22 positive and 6 negative indicator species within a 1 m × 1 m quadrat at ten intervals on the transect. We supplemented the indicator species list with 12 positive indicators of particular importance or prevalence on DTE SP (Walker and Pywell, 2000), 10 scrub species and 12 shade-tolerant species (see Supplementary Material S1 and S2 for details).

2.5. Statistical analysis

Comparisons between managed and control sites employed paired *T*-tests whilst comparisons between management types were performed by conversion of data to difference from controls followed by *T*-tests or one-way ANOVA. In order to meet statistical assumptions continuous data were $\log_{10}$ transformed prior to analysis, percentage data angular transformed and intra-pair difference data transformed by taking the square-root of the absolute value, then multiplying by ± 1 depending on the sign of the difference.

Euclidean distances were calculated within managed-control pairs to analyse differences in the total indicator species community. Euclidean distance is defined as:

$$ED_{jk} = \sqrt{\sum (X_{ij} - X_{ik})^2}$$

where ED_{jk} = Euclidean distance between samples j and k; X_{ij} = number of individuals of species i in sample j; X_{ik} = number of individuals of species i in sample k (Krebs, 1999).

3. Results

3.1. Image analysis

Scrub cover showed no significant difference between managed and control plots in 1999, due to the deliberate selection of plot pairs with similar levels of scrub prior to management ($T = 0.142$, $p = 0.888$). In 2010 managed plots showed significantly lower total scrub area and average area of scrub patches than their controls (paired *T*-tests, $N = 27$ in both cases; $T = 5.37$, $p < 0.001$; $T = 4.10$, $p < 0.001$ respectively). Significant scrub encroachment took place on control plots between years (mean scrub cover 1999 = 5.14%, SE = 1.74%; 2010 = 16.11%, SE = 2.58%, see Supplementary Material S3) with a mean increase of 1096 m^2 of scrub per hectare (SE = 272 m^2). Not only was there an increase in the total area of scrub, but the number and average area of scrub patches also increased (paired *T*-tests, $N = 27$ in all cases; $T = 5.94$, $p < 0.001$; $T = 2.62$, $p = 0.011$; $T = 5.94$, $p < 0.001$ respectively).

When analysed independently (Fig. 2) all management types except spraying significantly reduced total scrub area relative to their controls between 1999 and 2010 (*T*-tests, spray; $N = 7$, $T = 2.34$, $p = 0.058$, cut; $N = 7$, $T = 5.05$, $p = 0.002$, cut–spray; $N = 6$, $T = 3.56$, $p = 0.016$, intensive; $N = 7$, $T = 4.97$, $p = 0.003$). The decrease for sprayed plots was near significant and the difference of sprayed plots from controls was significantly non-zero in 2010 (one sample *T*-test, $T = 2.80$, $p = 0.031$). No management type showed a significant difference in the number of scrub patches between years. However, when the count of patches was limited to those over 1 m^2 in area, both cut and intensive plots showed a significant reduction between years (*T*-tests, $N = 7$ in both cases, $T = 3.12$, $p = 0.021$; $T = 2.68$ $p = 0.036$ respectively). Average patch size also decreased significantly from 1999 to 2010 for intensive plots (*T*-test, $N = 7$, $T = 3.74$, $p = 0.010$), but not for other management types.

The quality of the classification was indicated by a significant correlation with the percentage scrub cover estimates derived from the field surveys (Pearson correlation, $N = 53$, $r = 0.75$, $p < 0.001$). This relationship remained significant when data for managed and control plots were analysed separately.

3.2. Rapid field survey

Estimated percentage scrub was significantly lower in managed areas than controls, as was average sward height, whilst the total number of positive indicator species was significantly higher (paired *T*-tests, $N = 27$ in all cases; $T = 4.80$, $p < 0.001$; $T = 2.12$, $p = 0.044$; $T = -3.23$, $p = 0.003$ respectively). Managed areas had significantly fewer scrub species (paired *T*-test, $N = 27$, $T = 2.67$, $p = 0.013$), a difference amplified when scrub seedlings (<15 cm high) were removed from the dataset (paired *T*-test, $N = 27$, $T = 5.12$, $p < 0.001$).

Independent comparisons between management types and paired controls (Table 1) revealed several differences, although all showed significantly lower percentage scrub. Only intensive management significantly reduced average sward height, whilst both cut and intensive managements showed significantly higher total occurrence of positive indicator species (Table 1). Weighting positive indicator species by rarity increased significance for intensive plots whilst decreasing that for cut plots (Table 1). Total scrub species occurrence was not significantly different between any individual management type and its controls but when seedlings were excluded, a significantly lower occurrence of adult scrub species was apparent on cut–spray and intensive managements.

Analysis of Euclidean distances showed a clear trend of increased difference in the plant community with increasing intensity of management (Fig. 3; one-way ANOVA, $F = 3.44$, $p = 0.034$). Tukey *post hoc* tests showed that the significance of this trend is largely attributable to the difference between spray and intensive managements ($F = 3.17$, $p = 0.021$).

4. Discussion

4.1. Effectiveness of scrub management

The results confirm that scrub encroachment is a serious threat to the high conservation value of grassland on DTE SP, covering an additional 10.96% land area over ten years on control plots. Controls showed associated degradation of the underlying grassland, being poorer in species indicative of well-maintained chalk grassland and having a taller grass sward (Robertson and Jefferson, 2000). The

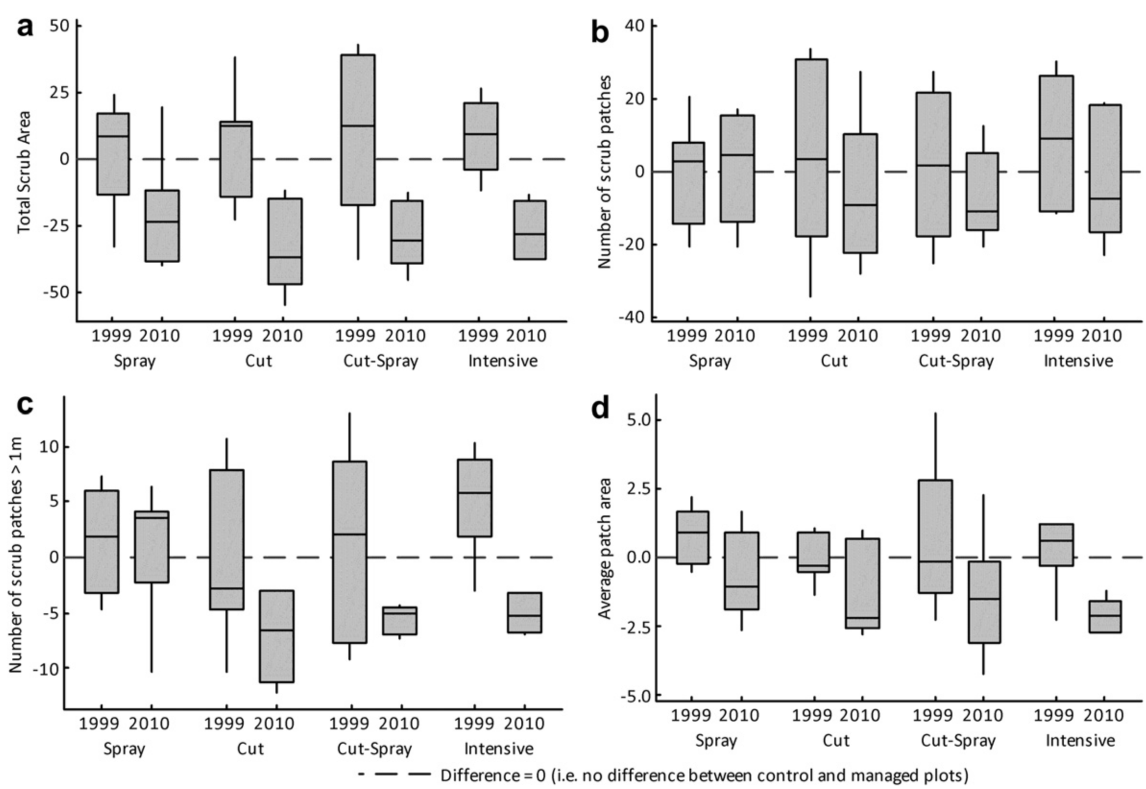

Fig. 2. Difference between managed and control plots for scrub metrics obtained from analysis of aerial imagery, in the years before and after management. (a) Total scrub area; (b) number of scrub patches; (c) number of scrub patches over 1 m^2 in area; (d) average area of scrub patches. Data are categorised by management type (increasing in intensity along the *X* axis). Negative values indicate that managed plots showed a lesser value than controls, positive values *vice versa*.

Table 1
Results of independent paired *T*-tests between management types and their controls, for the six variables from field survey which showed an overall significant difference between managed and control plots.

Management type		Percentage scrub cover	Average sward height (cm)	Total positive indicators	Weighted positive indicators[b]	Total scrub species	Adult scrub species
Spray	N	7	7	7	7	7	7
	T	3.82	2.00	0.10	0.03	1.53	2.16
	p[a]	0.009**	0.092	0.921	0.977	0.178	0.074
Cut	N	7	7	7	7	7	7
	T	3.78	2.14	3.13	2.80	1.41	2.13
	p[a]	0.009**	0.231	0.020*	0.031*	0.208	0.077
Cut–Spray	N	6	6	6	6	6	6
	T	4.13	1.33	0.90	1.40	1.46	4.13
	p[a]	0.006**	0.076	0.403	0.210	0.195	0.006**
Intensive	N	6	6	6	6	6	6
	T	2.51	3.12	2.56	5.43	2.28	5.55
	p[a]	0.046*	0.021*	0.043*	0.002**	0.063	0.001**

[a] * Denotes significance at $p < 0.05$ level, ** denotes significance at $p < 0.01$ level.
[b] Weightings 1–5 applied to species occurring in >80%, 60–79%, 40–59%,20–39%,1–19% of quadrats, respectively.

results also show that all scrub managements are, to some extent, effective in reducing the rapid rate of scrub encroachment seen on controls. However, since invasive scrub species are typified by high seed set, high germination rates and produce multiple shoots and suckers in response to cutting, scrub regeneration is rapid (Bacon, 2003). Some plots approached pre-managed scrub levels 3–6 years after treatment, a rate comparable to previous studies (e.g. Dzwonko and Loster, 2007; Maccherini et al., 2007). The speed of regeneration and the resultant formation of small scrub patches comprised of seedlings and shoots is probably behind the observation that no management type showed a reduction in the total number of scrub patches, and the changes in significance seen when seedlings are excluded from the dataset.

A trend of increased efficacy in both the removal of scrub and the restoration of grassland quality was evident with increasing management intensity (Figs. 2 and 3, Supplementary Material S3). The least intensive management, single application spraying, showed only slight evidence of a difference in total scrub area, evidencing almost complete scrub regeneration. A single spray of large scrub bushes is often not enough to kill them (Bacon, 2003) due to the resilience of scrub species and the variability in the effect of foliar herbicides imparted by the timing of application and individual plant condition (Harrington and Miller, 2005). The use of contact herbicides, such as Glyphosate, which rapidly lose phytotoxicity on contact with the soil and so limit damage to non-target plants, results in unimpaired regeneration from surviving adult scrub plants and from the seed bank (Hurst and John, 1999). Even where no part of the adult plant survives, sprayed 'skeletons' are left standing (evident to field surveyors 3–6 years after management) and may limit the ability of spraying to improve the quality of the underlying grassland by providing continued (albeit decreased) shade, increasing nutrient levels *via* decay, and restricting access for grazers. Although skeletal bushes could also potentially inflate the metrics of scrub cover by misclassification as living scrub in the image analysis, scrub cover derived from aerial images was not significantly higher on spray plots than the estimate from the field survey (which discounted dead bushes). Since significant grassland recovery is often cited to take 3–5 years following scrub removal (Bobbink and Willems, 1993; Zobel et al., 1996; Barbaro et al., 2001) it is unsurprising that near-complete scrub regeneration within the same time period, combined with persistent negative effects from scrub remnants, should swamp any beneficial effects of spraying on grassland quality. These considerations suggest caution in using foliar spraying alone, especially where cutting is a viable alternative.

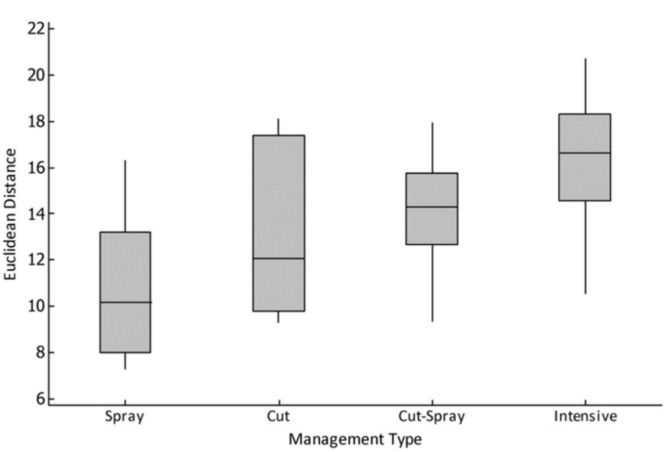

Fig. 3. Boxplot of Euclidean distance in the indicator species community from controls. Based on 40 indicator species: positive, negative and shade tolerant. A greater distance indicates a greater difference in the composition and abundance of plant species of managed sites from controls. Increased distance is evident with increased intensity of management.

Where time and access constraints dictate a single treatment, cutting is likely to be the preferred option. By removing adult scrub entirely, cutting ensures that there is neither continued shading from dead scrub nor survival of adult bushes, thus increasing the likelihood of a beneficial effect on the grassland community. This was evidenced in the study by the observed higher numbers of positive indicator species. Cutting has been the management of choice for studies combining grazing with active scrub removal, and grassland species abundance and richness have previously been shown to increase rapidly after cutting of even dense scrub cover (Zobel et al., 1996; Barbaro et al., 2001; Maccherini et al., 2007). Cutting has also been stated to be generally sufficient in preventing the local extinction of many grassland indicators, although not in maintaining a completely healthy sward structure and composition (Gibson, 1986). A single cut does not affect the scrub seed bank, so seedlings are quick to return (Maccherini et al., 2007) and cut stumps regenerate very rapidly (Bacon, 2003). However, when compared to intact bushes or branches, seedlings and shoots are more accessible and palatable to both domestic and wild grazing animals. Thus even though regeneration begins rapidly, cut scrub is slower to achieve pre-treatment levels.

The reduction in adult scrub species observed on cut–spray plots was not present on cut or sprayed plots, so it is probable that combining managements significantly slows the regeneration of some scrub species (Bacon, 2003). Aside from this effect, cut–spray management was not consistently more effective than cutting alone. It is likely that a single subsequent spray adds little to what is achieved by cutting for similar reasons as on sprayed-only plots, exacerbated by a reduced surface area for herbicide uptake after cutting.

Several studies have shown that long-term benefits of scrub clearance appear only after combined or repeated treatments (Zobel et al., 1996; Barbaro et al., 2001; Menges and Gordon, 2010). In this study, intensive management was most effective in both removing scrub cover and improving the quality of the underlying grassland. The greater effect than cut–spray management suggests that this is due to the frequency of intervention rather than the mere combination of management types. Many invasive scrub species of European calcareous grasslands (e.g. hawthorn, blackthorn *Prunus spinosa*, privet *Ligustrum vulgare*) cannot persist long in the seed bank (Davies and Waite, 1998), so repeated removal of adults, seedlings and regenerating shoots depletes local sources of scrub, forcing slower recolonisation from outside the managed area (Bossuyt et al., 2006). This longer term removal of scrub is likely to drive the improvements in grassland quality (Bacon, 2003). Species which are highly intolerant of scrub encroachment, or slow to establish after scrub removal, will occur only where scrub levels have remained consistently low (Zobel et al., 1996). Thus the success of intensive management in both removing scrub and slowing its regeneration leads to suitable conditions not only for positive indicators in general, but for rarer species less frequently encountered on the survey.

Further research is required into the effectiveness of grazing and other low-level managements, such as weed wiping with selective herbicides, in preventing the regeneration of scrub once the initial managements investigated in this study have taken place. Few studies have investigated the changes in management type and frequency of intervention required to prolong the initial benefits seen when simply comparing managed versus unmanaged areas. However, there is some evidence that subsequent grazing is sufficient to prolong the benefits of initially effective scrub removal (Pywell et al., 2010).

4.2. Methodological considerations

The dual methodologies allowed insight into a wide range of effects of scrub management after comparatively rapid and low cost data collection. Image analysis allowed rapid extraction of detailed measures of scrub cover which would be impossible on the ground whilst field surveys collected data on grassland community and structure invisible to the imagery employed. Since photographic aerial images cannot provide the same basis for detailed distinctions between land cover classes as more specialist hyperspectral sensors, the field survey also provides a useful check for assessing the veracity of the image analysis (Morgan et al., 2010). For example, field data was used in manual deletion of Juniper *Juniperus communis*, a priority species for UK calcareous grasslands and not managed as other scrub (Robertson and Jefferson, 2000). Recent studies attempting to devise methods by which remote sensing can be used to gain accurate measures of the floral community have taken this approach, using field surveys in order to train or test classification procedures (Schmidtlein et al., 2007; Feilhauer et al., 2010).

Although the classification output was limited to readily distinguished land cover types, the resultant metrics are informative and easily interpreted. Distinct land cover features, like scrub bushes, are well suited to classification as they do not require the imposition of arbitrary boundaries between land cover types which are at best an approximation in the continuum structure of grassland floral stands, particularly where changes of interest are comparatively small (Laliberte et al., 2004; Schmidtlein et al., 2007). Although the use of continuous measures of compositional variation can be employed to avoid imposing such distinctions, they are difficult to interpret and cannot be derived from simple photographic images. When compared to specialist remote sensing datasets, aerial photographic images are both easier to handle and cheaper to obtain (Hirst et al., 2000; Morgan et al., 2010) and, unlike most other remote sensing datasets, possess a historic record reaching back at least 60 years in the UK (Fuller, 1983). Given the existence of such a record, this work would be enhanced by a full annual time series of field data and aerial imagery, extending from immediately prior to management to several years after. Such data would allow detailed rates of scrub encroachment to be ascertained which, in conjunction with monitoring the establishment and persistence of effects on the grassland community (Kahmen et al., 2002), would allow investigation into the exact frequency and type of intervention required to make intensive management effective. Whilst the pixel-based classification employed in this study has the benefit of simplicity, there is also scope to investigate the potential advantages of employing object-based classification of the aerial images, since such procedures have the potential to enhance the accuracy of classification and have been used effectively to map scrub encroachment from time-series aerial imagery (Hudak and Wessman, 1998; Laliberte et al., 2004).

4.3. Conclusions

This study has shown that all four scrub managements significantly alter the fate of calcareous grassland from otherwise rapid scrub colonisation. There is, however, a clear trend of increased efficacy with increased intensity of management – in removing scrub, retarding recolonisation and promoting grassland quality. Thus, where possible, an intensive campaign of varied treatments over several consecutive years may be of greater long-term benefit than applying repeat treatments only after scrub has regenerated to problem levels.

This study has also demonstrated the advantages of combining aerial photographic imagery with rapid field assessments in order to perform rapid and efficient surveys over a large spatial scale. Simple analysis of a readily available remotely sensed resource has provided data on large scale scrub cover, whilst rapid field survey has given information on the floral community of sufficient detail to detect differences as a result of management. If the suitability of management methods is to be extrapolated beyond a single site or landscape, it is of prime importance to study both of these responses, particularly in the light of recent suggestions that the effect of scrub encroachment and removal varies considerably with local conditions and the scrub species concerned (Eldridge et al., 2011). The two methods are thus complementary and together provide potential for an extremely useful, rapid and low-cost monitoring tool for scrub on grassland and for other open habitats.

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Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jenvman.2011.12.005.

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