Title of project: How does deer grazing affect the diversity, composition and cover of ground flora in an ancient lowland woodland in East Anglia?

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ABSTRACT

Deer populations are expanding globally and can damage woodland ecosystems. The impact of deer grazing on woodland ground flora is uncertain and more research is required to inform decisions on how to best manage deer populations. Differences in ground flora diversity, composition and vegetation cover were recorded in exclosure plots and control plots at Bradfield Woods, Suffolk, where populations of three species of deer have been increasing. There was a higher mean species diversity in control plots because deer grazing prevented the dominance of palatable species such as bramble and honeysuckle. Control plots had greater abundance of unpalatable species such as grasses and sedges and surprisingly, a higher abundance of Dog's Mercury. There was no significant difference in browsing zone and ground level vegetation cover between exclosure and control plots, probably due limitations of the method used. Overall, it may be beneficial to maintain current deer densities at Bradfield Woods to help conserve ground flora. However, in making deer management decisions, the conservation value of the current species composition must be considered along with how other trophic levels are affected by deer.

1. Introduction

Deer (Cervidae) populations are expanding and becoming homogeneous globally. In England, increasing numbers of deer have been accompanied by an increasing number of species establishing. For example, since 1980, three exotic deer species from Asia (Reeves' Muntjac (*Muntiacus reevesi*), Chinese Water deer (*Hydropotes inermis*) and Sika deer (*Cervus Nippon*)) have become prevalent in addition to the native Red (*Cervus elaphus*), Fallow (*Dama dama*) and Roe (*Capreolus capreolus*) deer species. Muntjac are now likely to be the most common deer species in England (Rackham, 2003). It is difficult, however, to estimate deer density in a particular habitat as in addition to being elusive, most deer constantly move between different environments. This is especially true in England's highly fragmented landscape.

This proliferation in deer is caused by a combination of factors. With the removal of large predators and stricter controls on deer hunting over the last 100-150 years in the UK, deer numbers are not well controlled. Moreover, sowing of winter crops and a higher frequency of milder winters increase annual survival rate (Fuller and Gill, 2001).

Deer affect many ecosystems but the most damaging impacts can be seen in woodlands. Woodlands cover a relatively small proportion of the UK - less than 15%, only a third of which is classified as native woodland (Atkinson and Townsend, 2011). Yet, current deer densities pose a serious threat to this habitat. Crucially, deer alter the woodland vegetation structure - shrub density typically declines and coppiced stools/ felled areas of woodland take longer to regenerate with deer browsing. Stalled regeneration leads to canopy gaps being open for longer which influences the ground flora species composition. Moreover, deer alter the nutrient cycle through eating and defecating in different areas and preferentially browsing fast-growing trees so that the slow-growing trees, which produce less leaf litter, dominate. The ground flora are also affected directly- the palatable species are grazed out completely or to low densities whilst the unpalatable species proliferate (Kirby, 2001, Stewart, 2001, Watkinson et al., 2001). Through these changes deer also affect other trophic levelsnamely invertebrates (Stewart, 2001), birds (Fuller, 2001) and small mammals (Flowerdew and Ellwood, 2001).

Despite this, deer grazing can prevent succession of vegetation, potentially promoting biodiversity (Newman et al., 2013). Working out how best to manage deer populations to maintain biodiversity is a critical and complex task and further research is needed examining how different taxa respond to deer.

It is key to measure changes in the diversity and structure of ground flora in response to deer grazing because this layer is basal to other trophic levels. In addition, unlike for trees and shrubs, it is relatively easy to separate (and hence account for) the influences of topography, soil and coppice management on ground level species composition and diversity (Watkinson et al., 2001, Rackham, 2003).

Responses to deer grazing have been examined using exclosure experiments whereby species are sampled within a fenced exclosure and either compared to a spatial (adjacent) control or temporal (pre-fencing) control. Such experiments have been criticized as a crude tool which doesn't test the dynamic nature of deer grazing (e.g. density of deer and seasonality of grazing) (Watkinson et al., 2001). Whilst these limitations are valid, exclosure experiments are still useful for gathering baseline research. Exclosures are the most practical way of measuring responses to deer and the major responses are highlighted such that associated subtler effects can be investigated in further studies.

Ground flora responses to deer grazing in previous exclosure studies are conflicting. In terms of diversity, responses vary from there being a higher diversity or no significant difference in diversity of ground flora in exclosures compared to controls (e.g. McShea and Rappole, 2000, Pellerin et al., 2010 respectively) to long-term declines in diversity in exclosures compared to controls (e.g. Perrin et al., 2011). Despite this, ground flora composition changes can be generalized, e.g. woody/tall palatable species such as Bramble *(Rubus fruticosus)* become more abundant in exclosures, suppressing growth of woodland herbs relative to control plots (e.g. Perrin et al., 2011, Newman et al., 2013).

It is pertinent to look at the impacts of deer grazing in ancient woodlands, which have been present in the UK since at least 1600 (1750 in Scotland). These woodlands now only cover roughly 1% of land area in the UK (Atkinson and Townsend, 2011). Grazing may be the main threat to these woodlands (Rackham, 1993), and yet Barkham (1992) suggested that the ground flora typical of ancient woodlands may in fact be the result of hundreds of years of 'intensive' selective grazing.

Bradfield Woods National Nature Reserve is an ancient lowland woodland in East Anglia. It is an ideal study site with rich biodiversity (e.g. up to 370 species of vascular plants) and traditional coppice management which has remained largely unchanged since 1252 (Rackham, 2003). Due to increasing Roe deer and Muntjac populations, deer exclosures were put up in the 2000s, with paired control areas, to examine the impact of deer grazing in the woodland.

In early autumn, I studied how the ground level vascular plant diversity and composition, and ground and browsing zone vegetation cover varied between exclosure and control plots.

2. Materials and Methods

2.1 Study Site

Bradfield Woods is an actively coppiced 64ha ancient woodland in Suffolk (53^{0}11'N, 0^{0}48'E) (Holt et al., 2011). Coppicing is the regular removal of woody vegetation from multi-stemmed stumps which subsequently regenerate (Rackham, 2003). Currently the woodland is coppiced on a 25-year cycle, different sections being cut each year to create a mosaic of different aged stands (Vaughan, 2009). The topography of the site is fairly simple – slopes do not exceed 2.5^0 (Rackham, 2003) - but the soil complexity at the site adds additional heterogeneity. The soils vary widely in type and texture; the basal chalky boulder-clay is mixed to different extents with loess and sand and soils range from pH 3.1 to 7.4 (Vaughan, 2009).

Such variation in the dominant vegetation structure and soils gives rise to the rich biodiversity recorded at Bradfield Woods. Most of the sub-communities of the National Vegetation Classification W8 Ash (*Fraxinus excelsior*)-Field maple (*Acer campestre*)-Dog's Mercury (*Mercurialis perennis*) are represented and W10 Pedunculate Oak (*Quercus robur*)- Bracken (*Pteridium aquilinium*)- Bramble (*Rubus fruticosus*) woodland is found in sandier areas. These plant communities are not distinct and merge into each other throughout the woodland (Vaughan, 2009). Common Hazel (*Corylus avellana*), European Alder (*Alnus glutinosa)* and Birch (*Betula*) spp. are also dominant tree species (Holt et al., 2013).

Since the 1980s the native Roe deer and invasive Reeves' Muntjac have expanded rapidly in number in Bradfield Woods (Holt et al., 2010) and Fallow deer (*Dama dama)* colonized the wood in the 2000s (Holt et al., 2013). The browsing intensity is estimated to be 'low to moderate…typical of the wider landscape' (Holt et al., 2011). To examine the impact of deer, the management put in eight deer exclosures (areas encompassed by 1.8m steel fences) with adjacent control areas of similar size and with similar density of mature trees in a split-plot design (Hinsley et al., 2009, Holt et al., 2011). The exclosure areas are 0.42 ± 0.13 ha and control areas 0.55 ± 0.21 ha (mean $\pm$ SD). The exclosures were put in place over 5 years from 1999 to 2003 directly following coppicing of each area the previous winter (Holt et al., 2013). Initially, deer were also partially excluded by a brushwood fence in the control areas. This was breached by the deer within 1-2 years and the controls have been regularly grazed ever since (Holt et al., 2010).

2.2 Fieldwork

In September 2013, the ground-level (under 1m) vascular plant species (<1cm diameter) in exclosures and control plots were sampled in Bradfield Woods with comparable methodology and sampling effort to other exclosure studies (Morecroft et al., 2001, Pellerin et al., 2010). Plots were studied by restricted random sampling; fifteen 1m x 1m quadrats were distributed in each plot according to randomized GPS co-ordinates. A buffer of 2-3m was left at the edge of the plots, however, to avoid edge effects. Quadrats were dropped from a height of 1m and the percentage cover of each species within each quadrat was estimated. Standing at one of the edges, a photo of each quadrat was taken and used for calculations of ground-level vascular vegetation cover and for reference.

Browsing zone vegetation cover (up to 2m above ground) was also recorded by photograph. An umbrella was held upside-down at 2m above each quadrat, creating a bright screen against which the vegetation below it could be distinguished. A photo was taken facing skywards from the centre of each quadrat capturing this darker vegetation against the lighter umbrella. This fieldwork was carried out before any significant leaf-fall had occurred.

2.3 Data analysis

Average species diversity (as mean Shannon-Weaver indices) were calculated for each of the sixteen plots. Exclosure plots were then compared with their adjacent control plots for this measure with a scattergraph and a two-tailed T-test for matched pairs.

Species composition was analysed with a non-metric multidimensional scaling (NMDS) ordination using average species abundance (mean percentage cover) data for each plot. This method visualizes where exclosure and control plots lie in relation to different species so that one can gauge species composition similarity. Centroids and 95% confidence areas were plotted on the ordination. In addition, to identify the key species differing between exclosures and control plots, two composite bar charts were created- one based on the mean abundances of species in each plot (see Appendix 1) and one on the mean abundances of species in exclosure and control plot types. For both charts only the dominant species (with on average >5% cover) were plotted. To support findings from the composite bar charts, the mean $\pm$ standard deviation of species richness was calculated for exclosure and control plot types.

Initially, there were reservations in using mean percentage cover as a proxy for abundance; species with high abundance in small areas cannot be distinguished from species that are widespread at low density. However, with a strong positive correlation between mean percentage cover and 'species occurrence' (the number of quadrats that a species was present in across a plot) (Spearman's Rank Correlation, $r_s(6) = 0.98$, $P<0.01$), mean percentage cover was deemed a good proxy for abundance.

Both photos taken facing skywards from the ground (for browsing zone vegetation cover) and photos taken looking down at the quadrats (for ground level vegetation cover) were analysed using ImageJ software. For the former, manipulation of the photos in ImageJ allowed the area of the darker leaves to be measured against the total area of the lighter umbrella; data which was used to calculate the percentage cover of vegetation in the browsing zone (from the ground to 2m high). Likewise, the percentage cover of ground-level vascular vegetation was calculated for each quadrat from the area of vegetation (as opposed to bare ground)/m^2. For both browsing zone vegetation cover and ground level vegetation cover, average percentage cover for each plot were again compared in paired exclosures and controls in two-tailed matched pairs T-tests. Boxplots were plotted showing the medians and distributions of exclosure and control plot results.

All statistical analyses, the NMDS ordination and boxplots were made using the statistical program 'R'. The scattergraph and composite bar charts were produced using Excel. Matched pairs T-tests were more appropriate than one-way ANOVAs for the above measures as there was considerable variation between the 8 plot-pairs (stemming from the large diversity of soils across the site). Null hypotheses were rejected at the $P<0.05$ level.

Soil variation was examined as an alternate explanatory variable for the variation in species diversity across the site. GPS co-ordinates of quadrat positions and a map of Bradfield Woods showing soil pH bands (Vaughan, 2009) were loaded as different GIS layers on Google Earth and the pH band that each quadrat was within was recorded. The relationship between plant species diversity in each quadrat and the local soil pH was then examined by plotting a histogram (on Excel) summarizing each soil pH band with a value of mean diversity (mean Shannon-Weaver index) and a one-way ANOVA was carried out. The same map of soil pH was labeled with exclosure and control plots and analysed visually alongside mean species diversity results for each plot.

3. Results

3.1 Vascular Plant Species Diversity

In total, 43 different vascular plant species were identified across all eight plot-pairs. Across the plots, there was significantly higher mean vascular plant species diversity (in terms of Shannon-Weaver indices) in controls compared to exclosures (Paired T-Test, $t_7 = 4.79$, $P < 0.01$). The Shannon-Weaver indices were consistently higher in the control plots (Figure 1.)

The extent to which a paired exclosure and control plot differed in the diversity was variable, with Plot 4 exclosure and control having a difference in mean Shannon-Weaver indices six times larger than the difference within Plot 6. There was also clear variability in species diversity between the eight different plot-pairs.

3.2 Vascular Plant Species Composition

In an NMDS ordination there was clear separation of exclosures and controls by species composition, with a little overlap as would be expected (Figure 2).

In a composite bar chart the key differences in species composition in exclosures and controls were summarized (Figure. 3). Given the variation between different plot-pairs, differences were also analysed for each exclosure-control pair (Appendix 1). Bramble (*Rubus fruticosus agg.)* was consistently more abundant in exclosures and Honeysuckle (*Lonicera periclymenum)* was more abundant in 7 out of the 8 exclosures, compared to the controls. Grasses and sedges (e.g. Pendulous Sedge (*Carex pendula*), Wood-Sedge (*Carex sylvatica*), Tufted Hair-Grass (*Deschampsia cespitosa*) and Yorkshire-Fog (*Holcus lanatus*)) were generally more abundant in control plots though this was very variable between plot-pairs. Violet (*Viola)* spp. were also generally found in greater numbers in control plots (higher abundance in 5 out of 8 plot pairs). Notably, Dog's Mercury (*Mercurialis perennis*) was more abundant in 6 out of 8 control plots compared to exclosure plots.

More species were found in the control plots (16.1 ± 2.5 (mean ± SD) compared to the exclosure plots (13.0 ± 4.2). It appears that the exclosure plots had fewer, more dominant species.

Focusing on nationally important species, there was no significant difference in abundance of the Oxlip (*Primula elatior*), between exclosures and controls (Paired T-test, $t_7 = 0.12$, $P = 0.91$, NS).

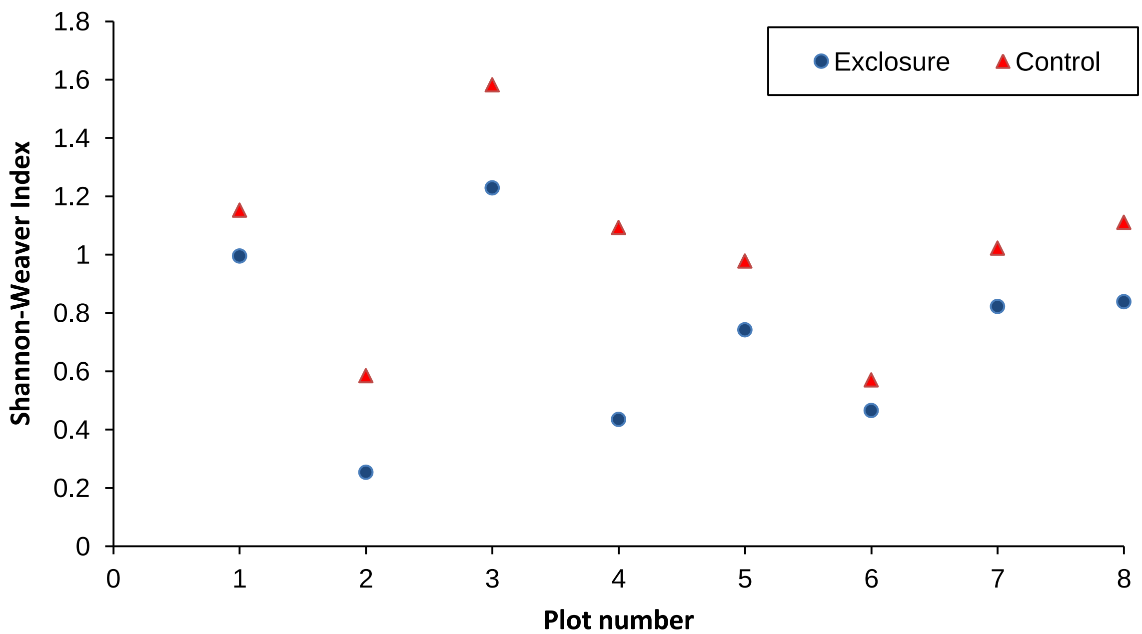

Figure 1. Scattergraph showing the mean vascular plant species diversity (as Shannon-Weaver indices) in exclosure and control plots of each split-plot pairing. Blue circles represent exclosure plots and red triangles represent control plots.

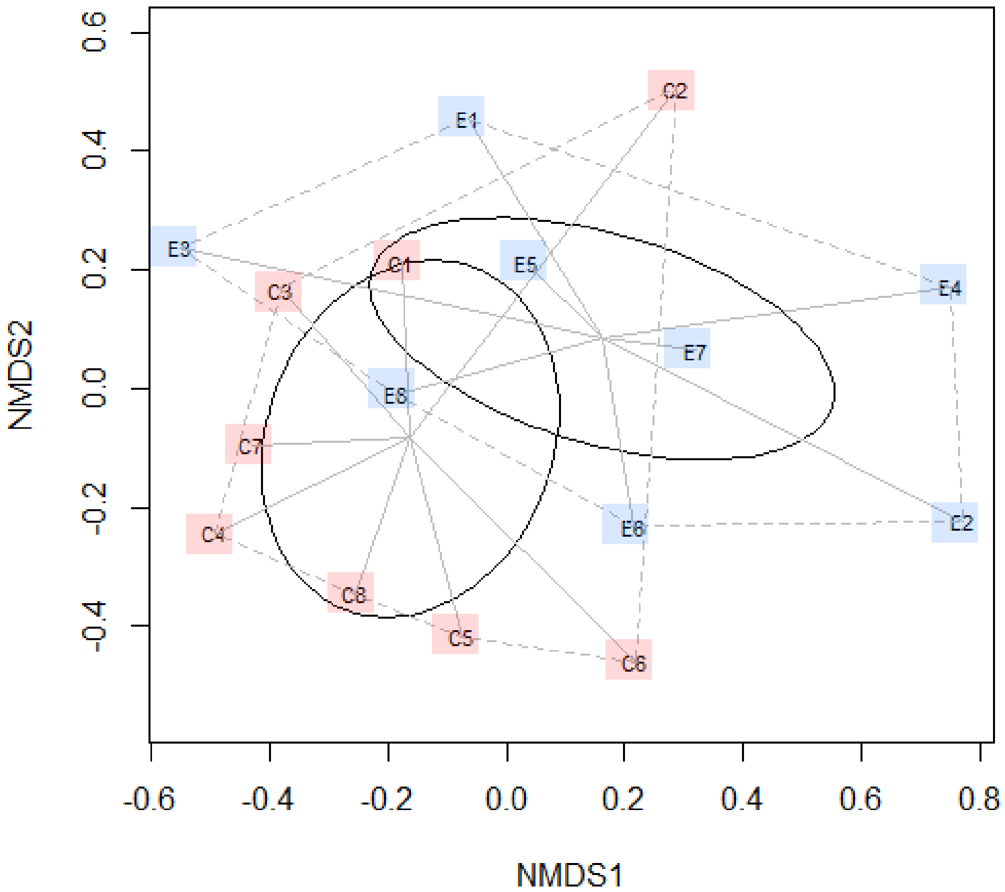

Figure 2. NMDS ordination showing the separation of exclosure and control plots by mean abundances (percentage cover) of different plant species. Plot type centroids and ellipses containing 95% confidence areas are shown. E/C refer to the plot type (exclosure or control) and numbers 1-8 refer to the plot number. Exclosure plots are highlighted in blue and control plots in red.

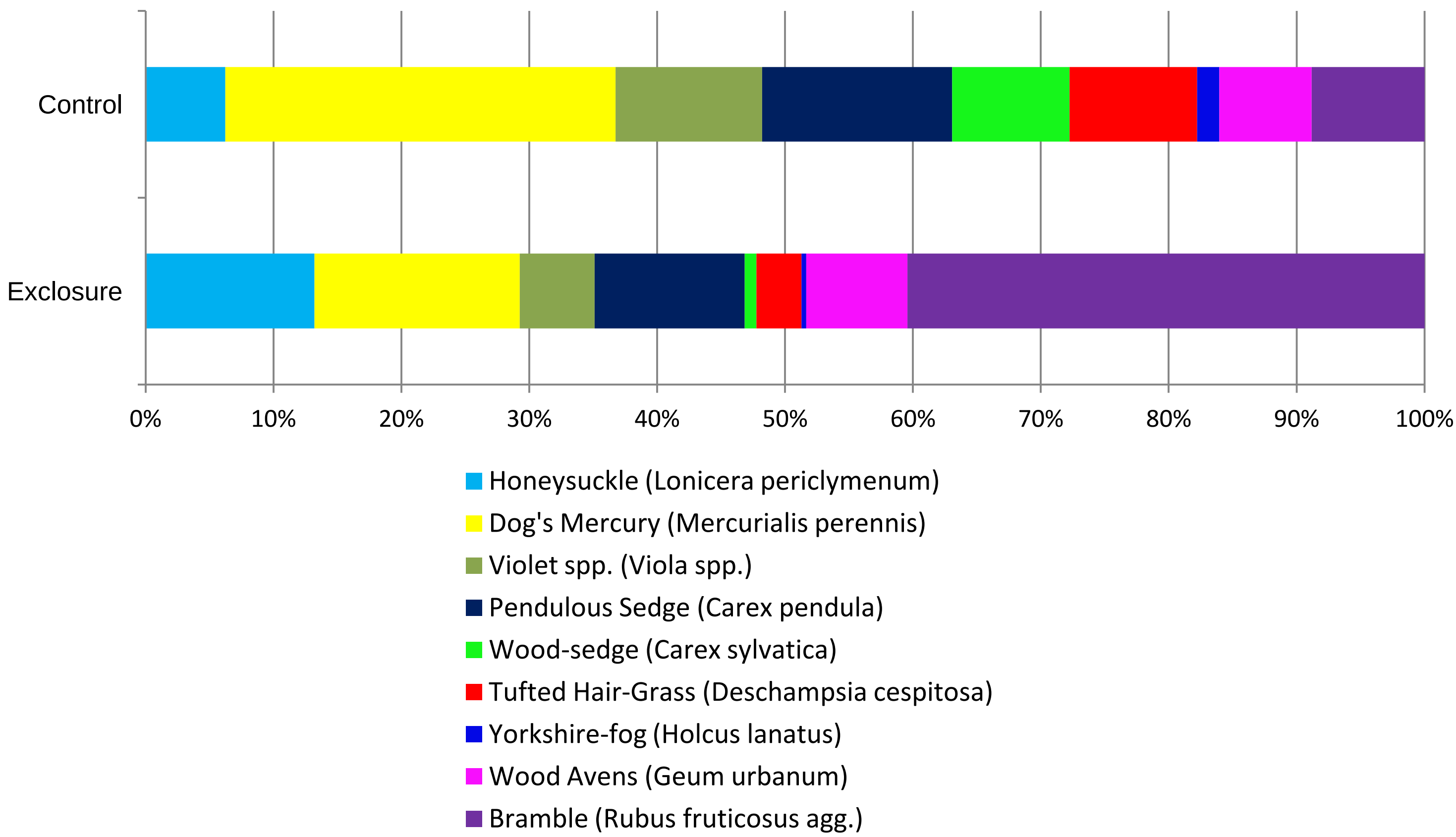

Figure 3. Composite bar chart showing the relative differences in mean abundance of ground level vascular plant species in exclosure and control plots. Only the most dominant plant species (species of >5% cover) are shown.

Notably, three species frequently cited as dominant woodland plants in exclosures (Perrin et al., 2011, Kirby, 2001, Newman et al., 2013) are rare across the whole site of Bradfield Woods – Ivy (*Hedera helix*) was found in only 3 plots at low percentage cover and the Great Wood-rush (*Luzula sylvatica*) and the Bilberry (*Vaccinium myrtillus*) were not found at all.

3.3 Browsing zone and Ground-level vegetation cover

Both mean browsing zone vegetation cover and mean ground level vascular vegetation cover were not significantly different between exclosure plots and control plots (Paired T-test, $t_7 = 0.06$, $P = 0.95$, NS and Paired T-test, $t_7 = 0.68$, $P = 0.52$, NS, respectively). There was large variation in these measures within exclosure and control plots, and the two plot types had similar medians for both measures (Figure 4).

3.4 Alternative Explanatory Variables: Soil Variation

There was a statistically significant relationship of increasing species diversity with increasing soil pH across the site (Figure 5; one-way ANOVA, $F_{3, 221} = 18.61$, $P < 0.001$) suggesting that soil variation explains some of the differences in ground flora diversity across exclosure and control plots at Bradfield Woods.

A site map of soil pH, labeled with exclosures and controls (Figure 6), shows that variation in soil pH is more likely to affect the difference in diversity between different plot pairs than the diversity differences between the exclosure and control of a certain plot pair. For example, plot 5 had the largest difference in soil pH but a relatively small difference in species diversity between its exclosure and control.

In contrast, plot 3 had the same soil pH band but a relatively large difference in diversity in its exclosure and control. Looking between different plot pairs however, diversity differences followed the pattern of increasing diversity with increasing pH (e.g. plot 3 had the most calcareous soils and the highest diversity whilst plot 2 had the most acidic soils and the lowest diversity).

4. Discussion

4.1 The impact of deer grazing on ground level vascular plant species diversity and composition

Control plots had higher ground-level vascular plant species diversity compared to exclosure plots, a finding that is supported by other exclosure experiments. A summary table of key recent exclosure experiments in woodlands (Appendix 2) shows that studies with long-term exclosures (e.g. Putman et al., 1989, Perrin et al., 2011, Newman et al., 2013) had lower and often declining diversity in exclosures over time relative to control plots. Younger studies (e.g. Morecroft et al., 2001, Pellerin et al., 2010) did not show a significant difference between the two plot types. Bradfield Woods has had exclosures in place for 11-15 years and so as with other long-term studies there has been enough time for a significant difference to arise between the different treatments.

At Bradfield Woods we can be confident that deer presence/absence is the chief cause of a difference in diversity. Key alternate factors affecting ground flora diversity in woodlands are topography, coppice age and soil type (Watkinson et al. 2001, Rackham, 2003). There is very little variation in topography across Bradfield Woods. The age of coppice changes dramatically across the site

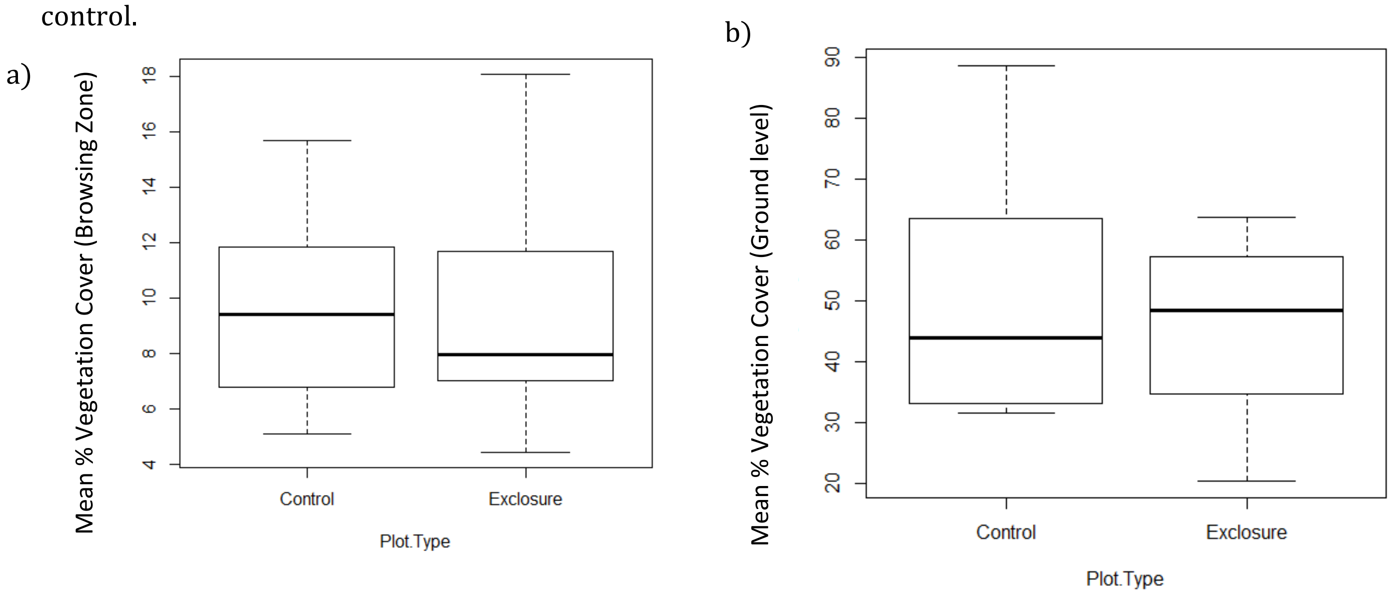

Figure 4. Boxplots showing how a) the Browsing zone vegetation cover and b) the Ground-level vascular vegetation cover vary between control and exclosure plots. The median and distribution of mean vegetation cover (calculated as mean percentage cover for each plot) is shown.

as does soil pH but control and exclosure plots were compared in pairs- for each plot pair coppice age is the same and soil pH does not vary greatly enough between the exclosure and control of a pair to have a clear link with diversity.

As in other long-term exclosure studies, exposure to deer grazing in Bradfield Woods has been great enough to cause a difference in ground flora species composition between exclosure and control plots, which drives the difference in diversity.

Critically, palatable species such as bramble and honeysuckle were found in higher abundance in exclosures and exclosures had fewer (indicated by a lower species richness) but more dominant species compared to control plots. Other studies support these observations. In the first few years after an exclosure is erected, studies have found a peak in diversity in exclosures, as many species can thrive from the removal of direct grazing pressure. However, in the long term palatable species such as bramble and honeysuckle come to dominate exclosures, outcompeting entirely or reducing woodland herbs and ferns to low densities (Putman et al., 1989, Perrin et al., 2011, Newman et al., 2013). Bramble, for example, is known for spreading rapidly and shading out herbaceous species (Watkinson et al., 2001). A shift from woodland specialist species to woodland generalist species in exclosures has also been noted (Perrin et al., 2011).

In control plots, grasses and sedges and violet spp. were generally more abundant than in exclosure plots. This increase in unpalatable species

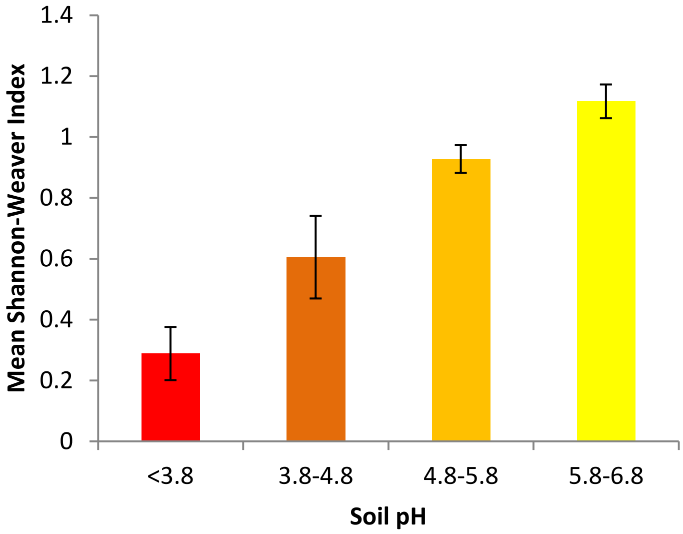

Figure 5. Histogram showing how mean vascular plant species diversity varies with soil pH. The mean diversity value of each pH band was calculated from a dataset of all quadrat samples except those from the plot 4 exclosure for which there is no soil pH data. Error bars represent Standard Error.

has also been observed in other studies. Many grasses can tolerate grazed habitats due to having basal meristems and high levels of silica in leaves (Pellerin et al., 2010, Morecroft et al., 2001, Kirby, 2001). Tufted Hair-Grass and Yorkshire-Fog especially, are noted for thriving in grazed conditions (Kirby, 2001). Short herbs such as violet spp. thrive (Putman et al., 1989), no longer being suppressed by taller plant species such as bramble (Kirby, 2001, Watkinson et al., 2001).

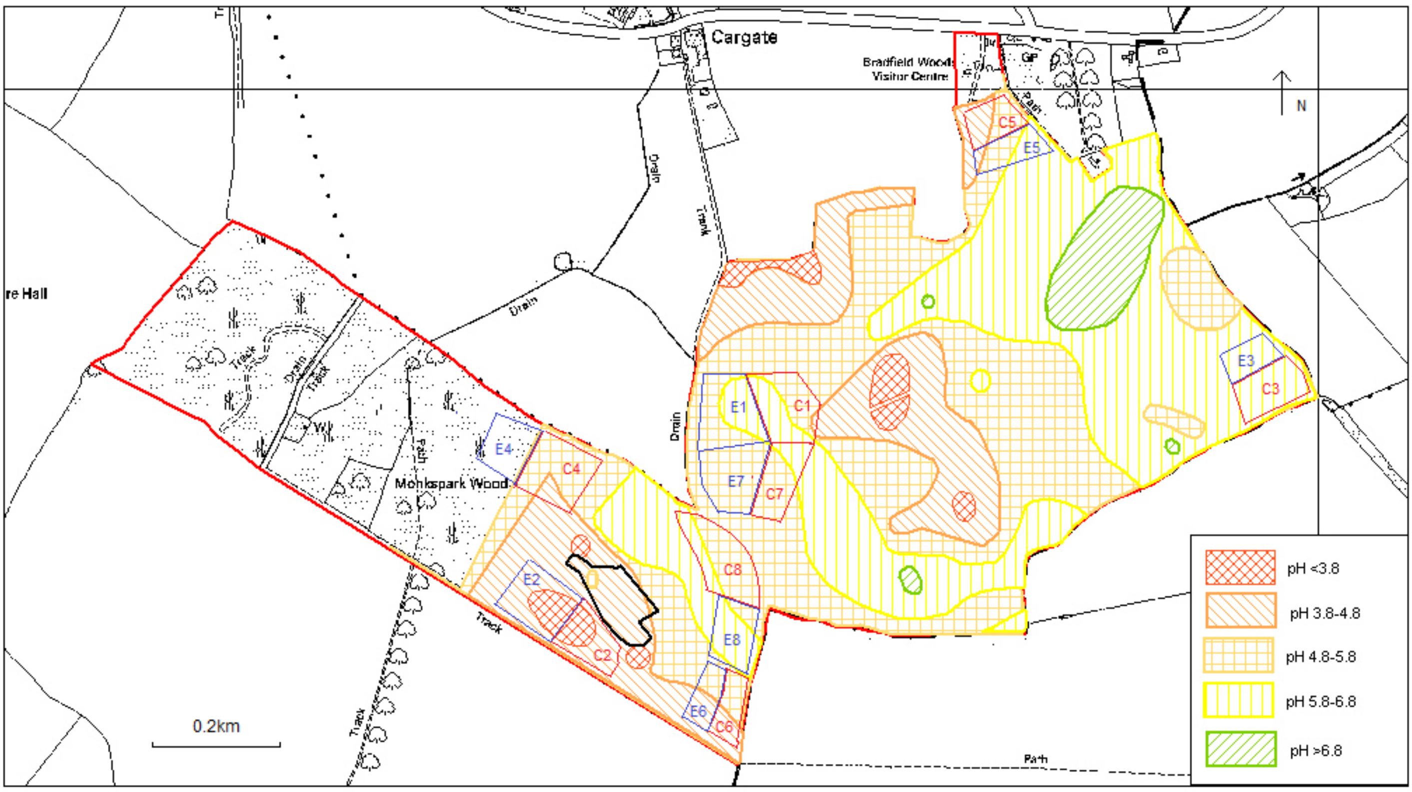

Figure 6. Map of soil pH at Bradfield Woods with plots (Exclosures and Controls) marked on. Exclosures are outlined in blue and labeled 'E', controls are outlined in red and labeled 'C'. The numbers refer to the plot number. The basal soil pH map is taken from Vaughan, 2009.

Dog's Mercury is well reported to be heavily grazed by deer- particularly by Muntjac, which are the most abundant deer species at Bradfield Woods (Putman et al., 1989, Vaughan, 2009) and exclosure studies have found decreases in Dog's Mercury and other woodland forbs in control plots (Morecroft et al., 2001, Cooke and Farrell, 2001). Hence, it is surprising that Dog's Mercury was notably more abundant in control plots compared to exclosure plots at Bradfield Woods. There are suggestions that forbs such as Dog's Mercury can take advantage of a more open canopy in grazed habitats, but Fuller and Henderson (1992) found that the canopy cover closed within 6 years of being coppiced at Bradfield Woods. Hence, there is no clear reason for the greater abundance of Dog's Mercury in control plots, though there is evidence suggesting that this species can survive herbivory, experiencing stunted growth rather than being killed by it (Kirby, 2001).

The higher species diversity in control plots, then, is caused by the current deer grazing pressure preventing succession and hence, the dominance of a few plant species. We have seen however, that much of the diversity in the control plots is composed of grass and sedge species. In Putman et al.'s 1989 study, in the control 60% of species found were classified as grassland, marsh and ruderal species. In the exclosure, there were fewer species but only 50% were of this classification. Hence, in general, deer grazing is beneficial for the conservation of ground flora, maintaining a higher diversity of species than in the absence of deer, but the true conservation value of deer grazing is dependent on the types of species that the management sets out to conserve.

Given this, it was pertinent to compare results for the oxlip, a species of national conservation interest. No significant difference in abundance was found between exclosure and control plots. This is likely to be due to the season of sampling. Lower abundance in control plots may be expected as Muntjac and Fallow deer are known to graze on oxlips. However, in the autumn oxlips are only likely to experience light grazing- Muntjac usually eat only the flowers and Fallow deer eat the leaves but are still relatively low in number in the woodland (Kirby, 2001). Hence, oxlip abundance should be studied again in the spring.

Naturally, a change in ground flora species composition will lead to species changes in other trophic levels. Many invertebrates depend on ground vegetation for shelter, food and breeding, the lifecycle of some species closely connected to just a few or even one plant species (Putman et al. 1989). For example, Pollard et al. (1998) found that 4 out of 18 butterfly species at Monks Wood, Cambridgeshire, have increased since the 1970s, alongside increases in deer populations. All 4 species were found to have grass-feeding larvae. Moreover, grass-feeding moth species increased to a greater extent than did species in other moth groups. In contrast, the white admiral butterfly (*Ladoga Camilla*), a woodland butterfly species, has been shown to lay its eggs on honeysuckle and deer grazing causes a loss of egg-laying sites (Pollard and Cooke, 1994). Likewise, small mammals have also been shown to have distinct ground-level habitat structure preferences and communities change with deer grazing (Putman et al. 1989).

Changes in ground flora in response to deer grazing have less of an impact on bird species however. For birds, the overall vertical vegetation density is more important (Fuller, 2001). It is believed that in particular, shrub density declines have contributed strongly to declines in songbirds in the UK and reduced Common Nightingale (*Luscinia megarhynchos*) and Blackcap (*Sylvia atricapilla*) populations in Bradfield Woods have been linked to deer browsing (Holt et al., 2010, Holt et al., 2013)

4.2 The impact of deer grazing on browsing zone and ground level vegetation cover

Given that the current deer grazing intensity at Bradfield Woods is high enough to impact the composition and diversity of ground flora species, it is surprising that no significant difference was found in both browsing zone vegetation cover and ground level vegetation cover between exclosure and control plots.

It is possible that the extent of deer browsing ('low to moderate' (Holt et al., 2011)) at Bradfield Woods may not be great enough to cause a significant difference in browsing zone and ground level vegetation cover. However, given the high number of studies reporting changes in browsing level vegetation structure (Kirby, 2001, Fuller, 2001), it is more likely that the methodology used incurs a high amount of error, leading to the high variation in results shown in the boxplots. Variation may have arisen from differences in perspective in the photos i.e. vegetation at different distances from the camera obscure the umbrella/ground by different amounts. Obvious outliers were removed from mean calculations but more subtle variation in distance to the camera could not be corrected for.

A three-dimensional measure may be required, such as the use of a pinframe whereby vegetation 'hits' are recorded for each 10cm height up to 2m (see Putman et al., 1989), measuring both ground level and browsing zone vegetation. However, even the use of this measure in Putman et al.'s study did not give a significant difference between exclosure and control plots despite obvious visual differences. Hence, the sensitivity of the technique may need to be increased by having shorter distance intervals to record vegetation 'hits'. In addition, though measurements were made before any significant leaf fall, it would be more appropriate to make measurements in the late spring/summer when maximum vegetation cover can be observed.

5. Conclusions

Acknowledging that coppice ages 0-10 years and 16-25 years and the most calcareous soils (>pH 6.8) were not sampled at Bradfield Woods in this study, we can still draw conclusions that can be applied to the general management of the woodland. Fuller and Henderson (1992) showed that most key woodland characteristics at Bradfield Woods did not change significantly beyond 14 years after coppicing. Additionally, though soil pH has a strong effect on species diversity it does not appear to directly influence the impact of deer grazing.

As a National Nature Reserve, maintaining and enhancing biodiversity is a key priority at Bradfield Woods (Vaughan, 2009). We can say with confidence that complete deer exclusion from the site would be undesirable (and very difficult to maintain). Instead, maintaining current densities may be the most beneficial management option for conservation of ground flora diversity at the site. As previously mentioned, however, species composition is equally as important as species diversity in the woodland and further research is required into how species composition in control plots changes with variation in deer density. A more desirable species composition (e.g. more woodland specialist species) may be achieved with lower or even higher deer densities and maintaining current densities of deer may not be best decision for conserving ground flora.

Unsurprisingly, experimentally varying deer densities is very difficult to practically achieve, though experiments have been conducted with large exclosures containing a known density of deer (Putman et al., 1989). Insights would ideally come from natural gradients of deer density in woodlands, but such situations are rarely observed.

Moreover, further research is needed into how different trophic levels interact in response to deer grazing. The intensity of current deer grazing at Bradfield Woods may have a beneficial impact on ground flora composition but species composition changes in other trophic levels may be undesirable. For example, it has been suggested that dormice populations, which use ground flora for nesting and foraging, decline in response to deer grazing (Flowerdew and Ellwood, 2001), and indeed in the 1990s dormice disappeared from Bradfield Woods. An understanding of species interactions will help find the optimum deer density that benefits the most taxa at Bradfield Woods.

However, to be able to draw upon exclosure studies on a regional or even national scale for informing management decisions, a greater geographical range of studies are required, particularly for ancient woodlands. It is striking that three well reported grazing-sensitive species, Ivy, the Great Wood-rush and the Bilberry are at a very low density/absent from Bradfield Woods despite the great vascular plant diversity of the site. The Great Wood-rush was last recorded in 1969 and the Bilberry has never been recorded at the site. This demonstrates that every woodland is distinct (Watkinson et al., 2001) and generalizations from exclosure studies, particularly concerning composition changes, should be made with care until a greater range of studies is undertaken.

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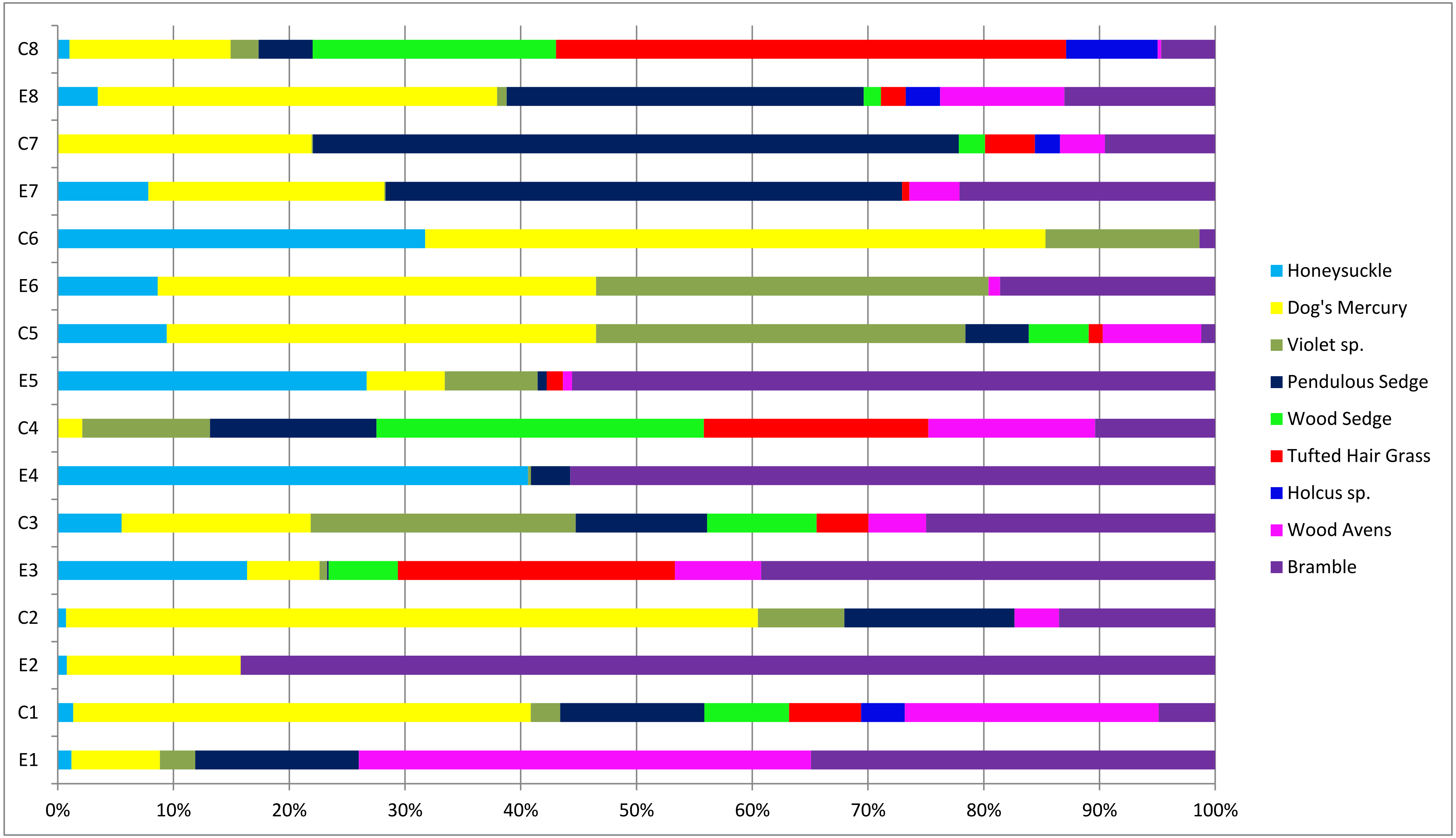
Appendices



Appendix 1 Composite bar chart showing the relative differences in mean abundance of ground level vascular plant species in each plot. Only the most dominant plant species (species of >5% cover) are shown. E/C refer to the plot type (exclosure or control) and numbers 1-8 refer to the plot number.

Appendix 2 A table summarizing recent key exclosure studies in woodlands in Western Europe, mainly in the UK. Main variables of the study site/ study methods are detailed alongside the diversity results of the study. Spatial control refers to a grazed control adjacent to the exclosure and temporal control refers to a pre-fencing grazed state of the exclosure as a control.

Author(s), year	Species/ Group	Area of study	Type of woodland	Length of study	Mean exclosure size (ha)	Spatial or Temporal control?	Density of deer/ intensity of deer grazing	Season sampling took place in	Ground flora diversity in Exclosure compared to Control
Perrin, Mitchell & Kelly, 2011	Sika Deer	Southwest Ireland	Yew-wood Oak-wood	Surveyed at intervals over 32 years	0.07	Spatial	Average 1970- 1996 = 0.43/ha ‘Heavy’	-	Indications of a long-term decline in biodiversity.
Newman, Mitchell & Kelly, 2013	Large herbivores	Ireland	Oak-wood	Surveyed at intervals over 41 years	0.45	Temporal	-	-	Homogenisation of species diversity over time. Species richness and Simpson’s diversity Index peaked after 10 years and downwards trend thereafter, eventually diversity values lower than pre-fencing control.
Putman, Edwards, Mann & Hill, 1989	Fallow deer	New Forest, Hampshire	Deciduous woodland	Surveyed 6, 14 and 22 years after exclosure erected	5.6	Spatial	1/ha ‘heavily grazed’	Summer	Lower Shannon-Weaver diversity index after 14 and 22 years.
Pellerin, Said, Richard, Hamann, Dubois-Coli & Hum, 2010	RoeDeer Red Deer	Eastern France	Beech-wood	Surveyed over 3 years after exclosure erected	1	Spatial	Average 2005-2008 = Roe deer 0.53/km* Red deer 0.80/km* *no. of deer seen per km of road. ‘Medium’	Spring	Declined in 1st year but no significant difference after 3 years
Morecroft, Taylor, Ellwood & Quinn, 2001	Roe deer Muntjac	Wytham Woods, Oxford	Ancient abandoned coppice woodland	Surveyed for one season, 2 years after exclosure erected.	0.3	Spatial	-	Summer	Too early to detect significant difference.