

# The long-term development of temperate woodland creation sites: from tree saplings to mature woodlands

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Tree planting is at the forefront of the current environmental agenda to mitigate climate change and tackle the biodiversity crisis. In the United Kingdom (UK), tree planting has been a priority for more than a century and has helped increase woodland cover from a historic low of 5 per cent at the beginning of the 20th century to a current figure of 13 per cent. However, we still know relatively little about the long-term development of woodland creation sites (particularly of native woodlands) over ecologically realistic timescales. We surveyed a chronosequence of 133 temperate woodland patches encompassing 106 woodland creation sites (10–160 years old) and 27 mature 'ancient' woodlands (>250 years old), using a combination of field surveys and remote sensing techniques to quantify vegetation structural changes associated with woodland development. Woodland creation sites displayed similar vegetation development patterns to those described for other woodland systems, i.e. a gradual transition as woodlands undergo 'stand initiation', 'stem exclusion' and 'understorey re-initiation' stages, and became more similar to 'ancient' woodlands over time. Structural heterogeneity, average tree size and tree density were the attributes that varied the most among woodland developmental stages. In general, structural heterogeneity and average tree size increased with woodland age, whilst tree density decreased as would be expected. Younger sites in stand initiation were strongly dominated by short vegetation, stem exclusion sites by taller trees and older sites had a more even vegetation height distribution. There was a large degree of overlap between the vegetation characteristics of woodlands in understorey re-initiation stages and older ancient woodlands (partly driven by a lack of regeneration in the understorey); these results suggest that it takes between 80 and 160 years for woodland creation sites to develop certain vegetation attributes similar to those of mature ancient woodlands included in this study. Woodland management practices to create canopy gaps and reducing grazing/browsing pressure to promote natural regeneration are likely to accelerate this transition, increase the structural heterogeneity and biodiversity value of woodland creation sites and enable adaptation and resilience to climate change.

## Introduction

Long-term, large-scale deforestation has reduced global forest cover by 50 per cent over the last three centuries (Ramankutty and Foley, 1999) resulting in drastic biodiversity declines and impaired ecosystem functioning (IPBES, 2019). Forest area continues to decline at alarming rates in many parts of the world (e.g. Africa and South America), with an estimated 420 million ha of forest lost globally since 1990 (FAO, 2020). However, increasing recognition of the paramount importance of forests for biodiversity and human wellbeing has led to a gradual slowing of net forest loss over recent decades, particularly in temperate regions of Europe and Asia. These trends have been largely driven by tree planting schemes leading to a global increase of 123 million ha of planted forest since 1990, although nearly half of this (45 per cent) consists of commercial production forests

(FAO, 2020). Tree planting is increasingly regarded as a key part of the solution to mitigate climate change and tackle the biodiversity crisis (e.g. Holl and Brancalion, 2020), and as such has made its way to the forefront of the environmental agenda. International commitments, such as the Bonn Challenge (aiming to restore 350 million ha of forest by 2030) and the UN's upcoming Decade on Ecosystem Restoration 2021–2030, are expected to accelerate and further mobilise action and resources to scale up reforestation efforts globally (IUCN, 2019).

In the UK, tree planting has been a priority for more than a century (Harmer *et al.*, 2015) and has contributed to increasing woodland cover from a historic low of 5 per cent at the beginning of the 20th century (down from a post-glacial of *ca.* 70 per cent) to the current figure of 13 per cent (Watts, 2006; Forestry Commission, 2020a). Tree planting is expected to continue at

an accelerated rate, driven partly by the current environmental policy agenda that includes ambitious woodland expansion targets to mitigate climate change and tackle the biodiversity crisis. For instance, the UK Government has pledged to plant 180 000 ha of trees in England over a 25-year period (2018–2042; Defra, 2018) and the Scottish Government has a current target of planting 12 000 ha of trees per year, increasing to 15 000 ha from 2024 (Scottish Government, 2018). Whilst within the last 100 years the majority of woodland creation in the UK has been dominated by non-native coniferous plantations (primarily for timber production), there has been a gradual shift towards planting more native woodlands with multiple objectives, recognizing the wider environmental, visual and cultural benefits provided by native woodlands (Harmer *et al.*, 2015); for instance, 42 per cent of the 10 860 ha of new woodland planted in Scotland during 2019–2020 was classed as native (Forestry Commission, 2020a). The majority of these (relatively small) native woodland patches have been planted on former agricultural land (Ferris-Kaan, 1995; WEAG, 2012). Recently, there has also been increased recognition of the importance of increasing quality as well as quantity of new woodland cover (Woodland Trust, 2020) and of enhancing woodland adaptability and resilience (Scottish Government, 2019).

Despite decades of tree planting initiatives, we know relatively little about how woodland creation sites (particularly native woodlands) develop over time, how they function and the impacts they have on biodiversity and ecosystem service provision (Fuentes-Montemayor *et al.*, 2015; Harmer *et al.*, 2015; Burton *et al.*, 2018). Whilst successional processes in natural forests and vegetation development in forestry production systems have been well studied (e.g. Peterken, 1996; Kimmins, 2004), many of the ecological processes of native woodland creation sites remain poorly understood or quantified (Ferris-Kaan, 1995; but see Harmer *et al.*, 2001). These might differ from ‘natural’ successional processes because of land-use legacies arising from abrupt changes in land-use (e.g. from agriculture to woodland), which can have long-lasting effects on woodland development; for instance, tree growth rates and drought vulnerability are higher in former agricultural areas with highly fertile soils (Alfaro-Sánchez *et al.*, 2019). Legacy effects often depend on previous land-use intensity, for instance with less severe impacts expected by planting on former pasture than on arable land (Holmes and Matlack, 2018). Additionally, initial planting conditions such as tree spacing and species composition are also likely to be major determinants of the future trajectory of woodland creation sites, as they will influence tree growth, mortality and survival processes that govern vegetation dynamics (Peterken, 1996). Planting methods used for establishing new native woodlands often mimic modern forestry practices, which can result in simple homogeneous vegetation structures (e.g. of even-aged species-poor plantations) unlike those of most natural systems, which tend to be more species-diverse and spatially heterogeneous (Ferris-Kaan, 1995).

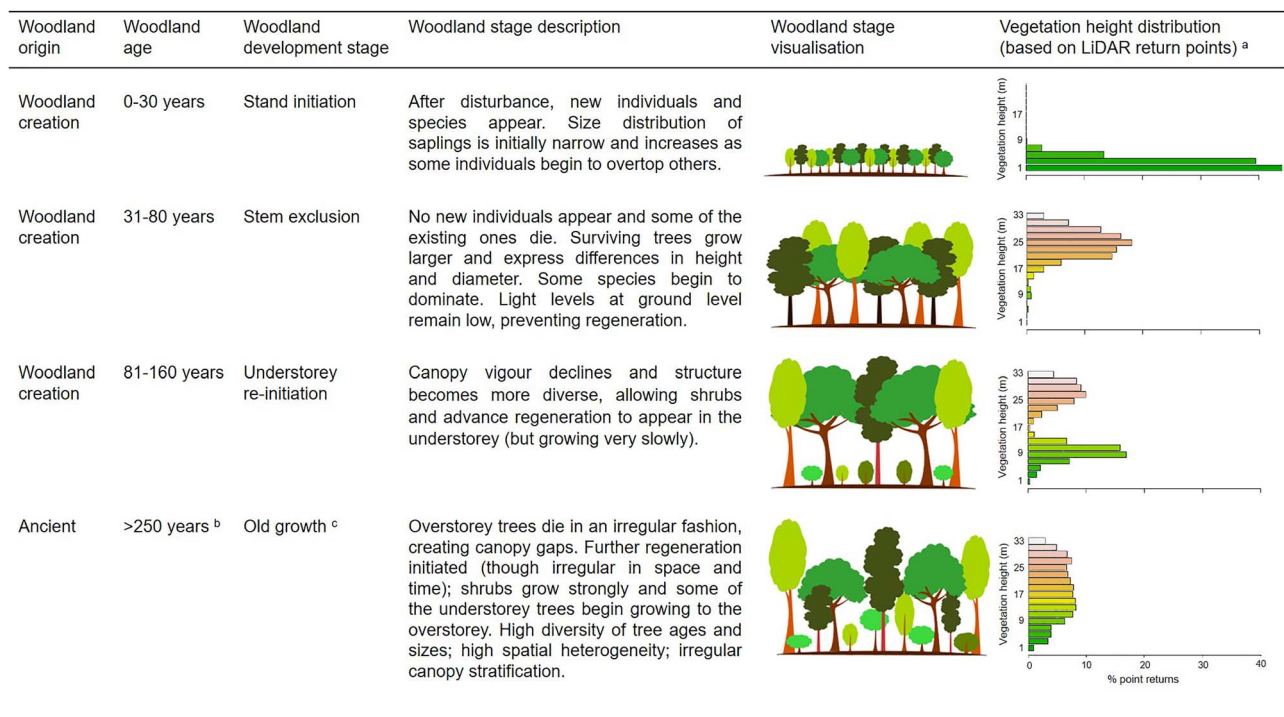
The mechanisms driving woodland dynamics change in importance over time. For instance, younger stands (<20 years) tend to be more strongly affected by environmental stress than by other factors (Peterken, 1996). Grazing and/or browsing pressure can also be disproportionately important drivers of woodland dynamics during these early stages, when young trees have not yet reached a sufficient height to escape ungulate

herbivory damage that might increase tree mortality rates (Rhodes *et al.*, 2017, 2018). Herbivory pressure can continue to be a major determinant of vegetation composition and structure in later development stages when natural regeneration is expected to take place. Interspecific competition usually becomes a more important driver of vegetation dynamics after canopy closure, and natural disturbances such as windthrow become dominant factors in old-growth forests (>200 years; Peterken, 1996). The dynamics of woodland creation sites are also likely to be influenced by either a lack of natural disturbance events (e.g. gap formation due to large tree mortality in older and larger sites) or disturbance from forestry practices (e.g. thinning, successive regeneration felling). All these drivers of tree demography dynamics are likely to be reflected in the vegetation structure of a woodland, which in turn will influence woodland biodiversity; for example, variation in tree size (likely to be partly determined by herbivory pressure and management practices) has been identified as one of the main drivers influencing the species richness and abundance of many taxa in woodland creation sites (e.g. Fuentes-Montemayor *et al.*, 2017, 2020; Fuller *et al.*, 2018).

Vegetation structural changes are unlikely to be evident in the short term, particularly in temperate woodlands where successional rates and habitat development are slow. This makes it not only imperative, but also challenging, to study woodland ecosystems over sufficiently long temporal scales (from decades to centuries) to detect meaningful structural changes (Harmer *et al.*, 2001). The Woodland Creation and Ecological Networks project (WrEN; [www.wren-project.com](http://www.wren-project.com)) is a large-scale ‘natural experiment’ designed to study the long-term effects (up to 160 years) of woodland creation on biodiversity and ecosystem functioning (Watts *et al.*, 2016). WrEN also provides a unique opportunity to quantify long-term vegetation structural changes in woodland creation sites. Here, we surveyed a chronosequence of 133 temperate woodland patches encompassing secondary (woodland created on former agricultural land between 10 and 160 years ago; part of the WrEN project) and mature ‘ancient’ woodlands (continuously wooded for at least 250 years) across England and Scotland. Our overall aim was to assess how the vegetation structure of woodland creation sites develops over time, and how it compares with that of mature ancient woodlands (likely to display structural features more similar to old-growth stages and usually regarded as higher quality habitats for many taxa than woodlands in earlier successional stages; Spencer and Kirby, 1992). Specifically, we addressed the following questions:

1. Which are the key vegetation attributes driving differences between woodlands of different ages?
2. Does the vegetation structure of woodland creation sites resemble that of mature ancient woodlands? And if so, how long does it take for this to happen (as an indication of ‘waiting times’ from planting trees to delivering woodlands with a more natural, complex structure and potentially higher biodiversity value)?

We expected woodland creation sites within a 10–160 year timespan to display similar development patterns and structures to those described for other woodland systems following major disturbances, i.e. undergoing ‘stand initiation’, ‘stem exclusion’



**Figure 1** Outline of woodland development stages (descriptions adapted from [Oliver and Larson, 1996](#) and [Peterken, 1996](#)). <sup>a</sup>Conceptual changes in the height distribution of vegetation points as woodlands develop over time. Recreated using simulated data based on the study by [van Ewijk et al., 2011](#). Colours correspond with height (m) and are for aesthetics only. Strata are shown in 3 m groups for visualization. <sup>b</sup>>250 years in Scotland and > 400 years in England, but likely to be much older; see Methods for details). <sup>c</sup>Whilst ancient woodlands included in this study are likely to display structural features and contain important components of ‘old-growth’ stages, we do not expect them to be an exact representation of this woodland development stage due to past and present anthropogenic impacts.

and ‘understorey re-initiation’ stages ([Oliver and Larson, 1996](#)). We expected mature ancient woodlands to contain important components of ‘old-growth’ stages, e.g. a more complex vegetation structure and larger amounts of deadwood (see [Figure 1](#) for a description of each woodland development stage).

## Methods

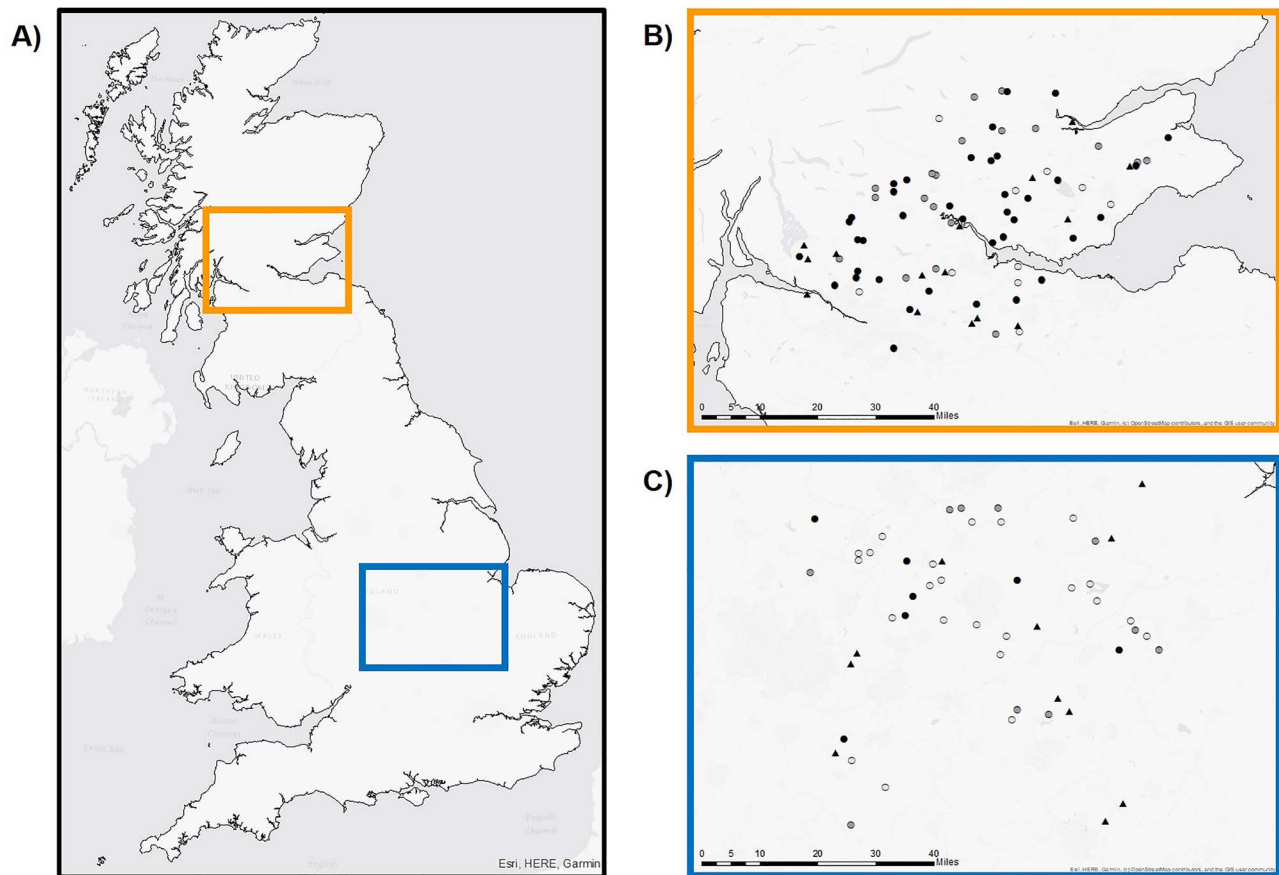
### Study area and site selection

Our study sites were in two regions of the UK (central Scotland and central England) dominated (>70 per cent) by agricultural land and representing fairly typical lowland landscapes in these countries. We used a systematic site selection protocol to minimize variation in topography, climate and soil types across sites (e.g. Land Capability for Agriculture restricted to lowland arable to improved grassland), and the National Forest Inventory ([Forestry Commission, 2012](#)) to identify 106 broadleaved woodland patches created over the past 160 years on former agricultural land (see [Watts et al., 2016](#) for further details on site selection). We used the Ordnance Survey historic maps collection ([EDINA, 2013](#)) to determine the approximate date when each woodland was created (i.e. the time period when each woodland patch ‘appeared’ in maps). Woodland creation sites ranged in size (0.5–30 ha) and approximate age (10–160 years). In addition, we used the Ancient Woodland Inventory (a spatial dataset of sites which have been continuously wooded since at least 1750 in Scotland and 1600

in England; [Spencer and Kirby, 1992](#); [Forestry Commission, 2011](#)) to select mature woodlands with longer ecological continuity. Ancient woodlands were selected with similar characteristics (e.g. patch size, degree of connectivity and amount of surrounding woodland) and located in the same landscapes as the woodland creation sites ([Figure 2](#)). The age gradient of woodland creation sites selected for this study is likely to represent well-recognized developmental stages for temperate woodland habitats (see [Figure 1](#); [Oliver and Larson, 1996](#); [Peterken, 1996](#)): Stand initiation (0–30 years since planting;  $n = 33$ ), stem exclusion (31–80 years since planting;  $n = 29$ ) and understorey re-initiation (81–160 years since planting;  $n = 44$ ); ancient woodlands (continuously wooded for >250 years, but likely to be much older;  $n = 27$ ) are likely to display structural features more similar to old-growth stages. However, we acknowledge that many ancient woodlands have a long and complex history of management (e.g. coppicing) and may display characteristics of different development stages despite their long continuity of woodland cover.

### Vegetation surveys

We conducted field surveys to characterize the vegetation structure of all woodland sites. Vegetation surveys were conducted using the point-centred quarter method along an edge-to-interior transect, with points established every 15 m along each transect ([Ferris-Kaan and Patterson, 1992](#)). At each point, a cross of two perpendicular lines (one of them following the direction



**Figure 2** Map of Great Britain (A) showing the study areas in Scotland (B, top orange box) and England (C, bottom blue box). Woodland creation sites (circles) are shown according to their development stage: stand initiation (light grey), stem exclusion (dark grey) and understorey re-initiation (black). Ancient woodlands are shown as black triangles.

of the transect) was established to divide the surrounding area into four quarters; within each quarter, we measured the distance from the centre point to the nearest tree (used to subsequently calculate tree density), identified its species and measured its diameter at breast height (DBH; only trees  $\geq 7$  cm DBH were included). Each point also served as the corner of a  $10 \times 10$  m quadrat used to visually assess understorey cover (% using Domin scale), and a  $2 \times 2$  m quadrat to visually assess woody debris on the ground (index ranged from 1 to 3; 1 = leaf litter and small twigs  $\leq 1$  cm in diameter; 2 = larger branches  $\leq 10$  cm; 3 = coarse woody debris  $> 10$  cm diameter, including fallen trees). Canopy cover (%) was assessed using a sighting tube with an internal crosshair (Ferris-Kaan and Patterson, 1992); if the crosshair intersected canopy vegetation, the presence of canopy was recorded; this was repeated 10 times at 1 m intervals perpendicular to each of the transect points.

### LiDAR surveys

We used open-access LiDAR data to characterize the three-dimensional structure of a subset of woodland sites ( $n=40$  sites encompassing all four woodland development stages). LiDAR point cloud data were obtained from the Environment

Agency and the Scottish Environmental Protection Agency (see [Supplementary data 1](#) for further details on data acquisition and processing). Point cloud data were used to create vegetation height distribution plots for individual woodland sites to graphically evaluate the effects of woodland age on vegetation structure. We used the 'Vertical Complexity Index' (VCI) function from the lidR package (Rousset and Auty, 2018) on the point cloud data to calculate a vegetation VCI (a variant of Foliage Height Diversity based on Shannon's index; van Ewijk *et al.*, 2011) for each site. We then ran a Pearson correlation test to assess how VCI related to our field-based structural heterogeneity metric (variation in tree DBH). Because of limitations in data availability and the resulting smaller sample size, we did not conduct any further statistical analyses on the LiDAR data; instead, these results are presented for illustrative purposes only (i.e. to complement and support our field data analyses and to exemplify the utility of this method for characterizing woodland structure).

### Statistical analyses

We used Linear Discriminant Analysis (LDA) to explore differences in vegetation characteristics among woodland development stages. We selected LDA over other multivariate analysis

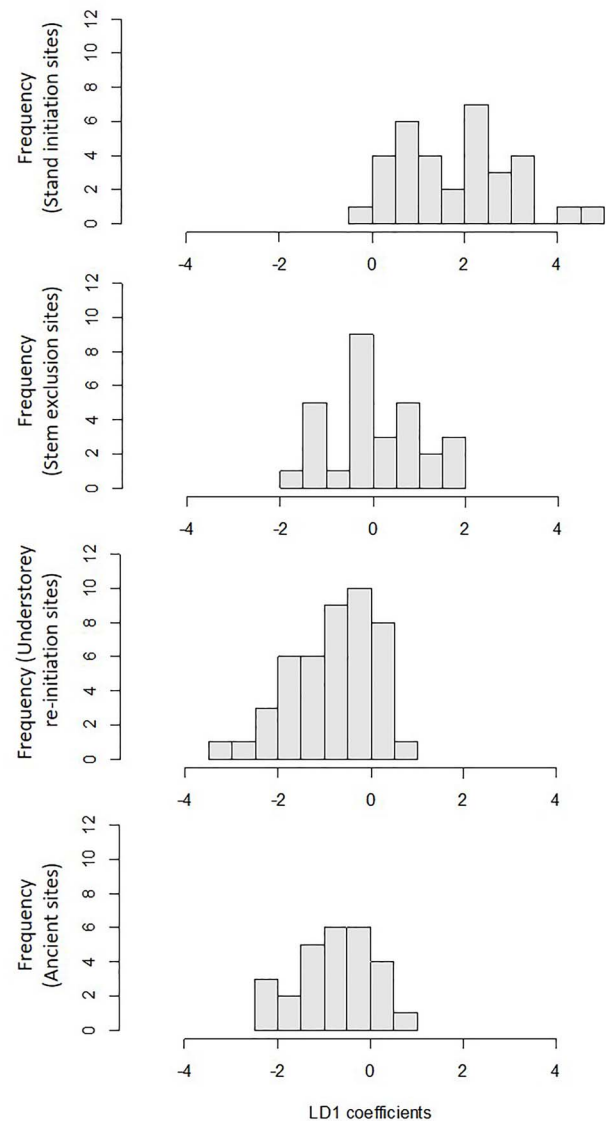
methods because it is a form of discriminant analysis, i.e. it looks for linear combinations of variables ('vegetation attributes' in this case) to produce discriminant functions that maximize the separation of objects ('woodland sites' in this case) among different classes known *a priori* ('woodland development stages' in this case; Leps and Smilauer, 2003). Additionally, LDA produces coefficients to quantify the relative contribution of each of the explanatory variables to the observed separation of objects along each discriminant function; this can provide biological insights into the determinants of the dissimilarity among object classes (e.g. identifying vegetation attributes that are most influential in driving differences between woodland stage categories). All vegetation attributes described in the 'Vegetation surveys' section were included in the LDA; for tree DBH, we included mean (as a metric of tree size) and standard deviation (SD, as a metric of structural heterogeneity) values. In addition, we used linear regressions to quantify differences in individual vegetation variables between woodland development stages (as a categorical factor); significance values were adjusted for multiple comparisons using the Bonferroni correction. Exploratory plots of vegetation attributes and preliminary LDAs indicated that results for the two study regions were broadly similar (Supplementary data 2); we therefore pooled data across the two study regions for further analyses and we present those results for simplicity. Tree species richness, tree density, understorey cover and tree DBH mean and SD were log<sub>10</sub>-transformed to improve data distribution prior to analyses. LDAs conducted for each study area separately and linear regressions for individual vegetation attributes using 'age' as a continuous (rather than categorical) predictor are presented in Supplementary data 2 and 3.

## Results

The vegetation structure of the woodlands included in this study was highly variable. Tree density ranged from 67 to 4063 trees per ha (with an average of 759.7), mean tree DBH from 8.1 to 90.2 cm (average = 29.6), structural heterogeneity (i.e. tree DHB SD) from 1.3 to 43.4 cm (average = 13.7), tree species richness from 1 to 13 (average = 4.8) and canopy cover from 18 to 100 per cent (average = 70.7). Most of these vegetation attributes varied to some degree according to woodland development stage (Figures 3 and 4); most notably, average tree size and structural heterogeneity (i.e. variation in tree sizes) increased with woodland age, whilst tree density decreased.

The first Linear Discriminant Function (LD1) of the LDA showed that there was a 53.6 per cent separation between sites in different woodland development stages, in terms of their vegetation characteristics. The degree of separation explained by LDs 2 and 3 was much lower (11.4 per cent and 1.2 per cent respectively) and is not discussed further. There was a gradual transition in LD1 coefficients from younger to older woodlands, particularly between stand initiation, stem exclusion and understorey re-initiation stages, whilst there was a large degree of overlap between sites in understorey re-initiation stage and ancient woodlands (Figure 3).

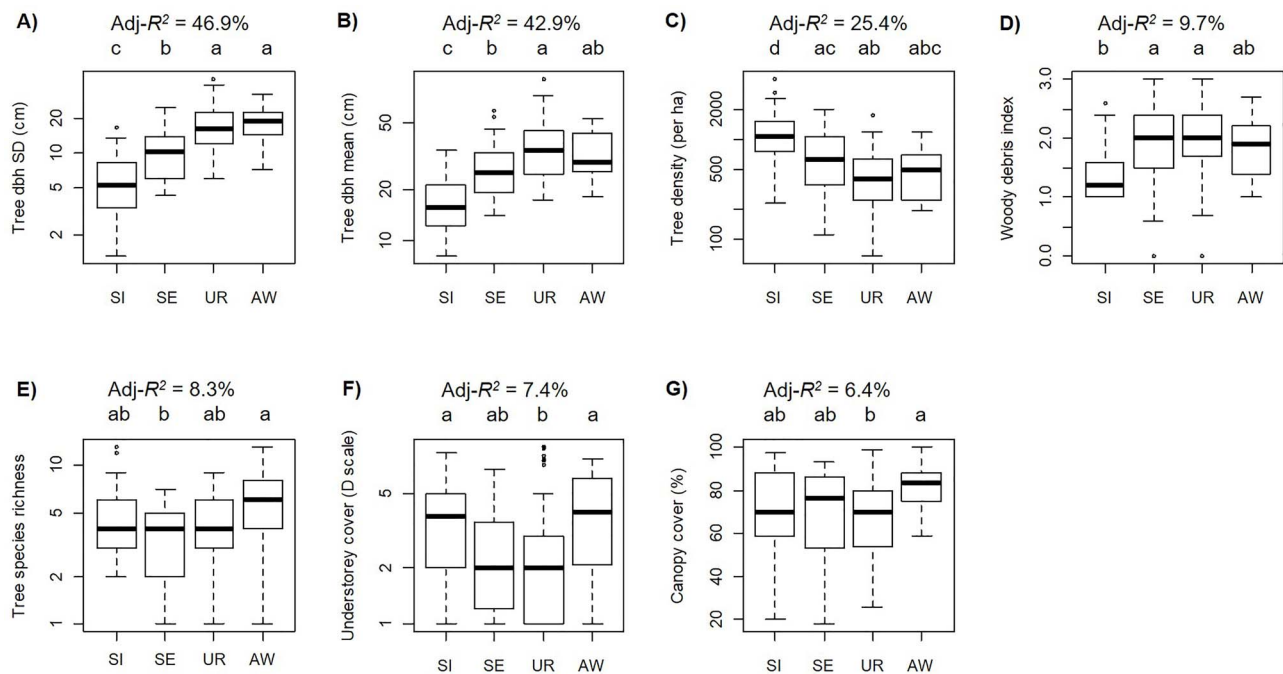
The most influential variable (based on its relatively large LD1 coefficient and  $R^2$  value) driving differences between woodland stage categories was variation in tree size (i.e. tree DBH SD), with older woodlands having significantly higher structural



**Figure 3** Histograms of the first Linear Discriminant function (LD1) coefficients of woodlands in different development stages.

heterogeneity (in terms of tree sizes; Figure 4a). As would be expected, differences in average tree size (bigger in older woodlands) and tree density (lower in older woodlands) also explained a relatively high degree of variability among woodland development stages (i.e. had high  $R^2$  values; Figure 4b,c). There were smaller differences in amount of woody debris, tree species richness, understorey cover % and canopy cover % among woodlands in different development stages (Figure 4d–g).

Variation in tree size (our field-based structural heterogeneity metric) was positively correlated with the LiDAR-derived vegetation VCI (Pearson correlation coefficient = 0.59;  $P < 0.001$ ). In general, the vegetation height distribution of individual woodland sites was in accordance with conceptual expectations based on their developmental stage (Figure 1); i.e. younger sites in stand initiation were strongly dominated by short vegetation, stem exclusion sites were (less-markedly) dominated by taller trees



**Figure 4** Boxplots of vegetation attributes of woodlands in different development stages. Different letters represent statistically significant differences between groups ( $P < 0.05$  with values corrected for multiple comparisons). Y-axes in (A–C) and (E–F) have been back-transformed from  $\log_{10}$  used in linear models. SI = Stand initiation; SE = Stem exclusion; UR = Understorey re-initiation; AW = Ancient woodland. In (E) outliers in stand initiation phase reflect shifts in woodland planting patterns over time (i.e. woodlands created more recently have been planted with a larger number of tree species).

and ancient woodlands had a more even vegetation height distribution. In accordance with our field data analysis, sites in understorey re-initiation phase appeared very similar to ancient sites and did not clearly display the two-layer vegetation structure expected as a consequence of natural regeneration (i.e. there appeared to be limited regeneration in the understorey; Figure 5).

## Discussion

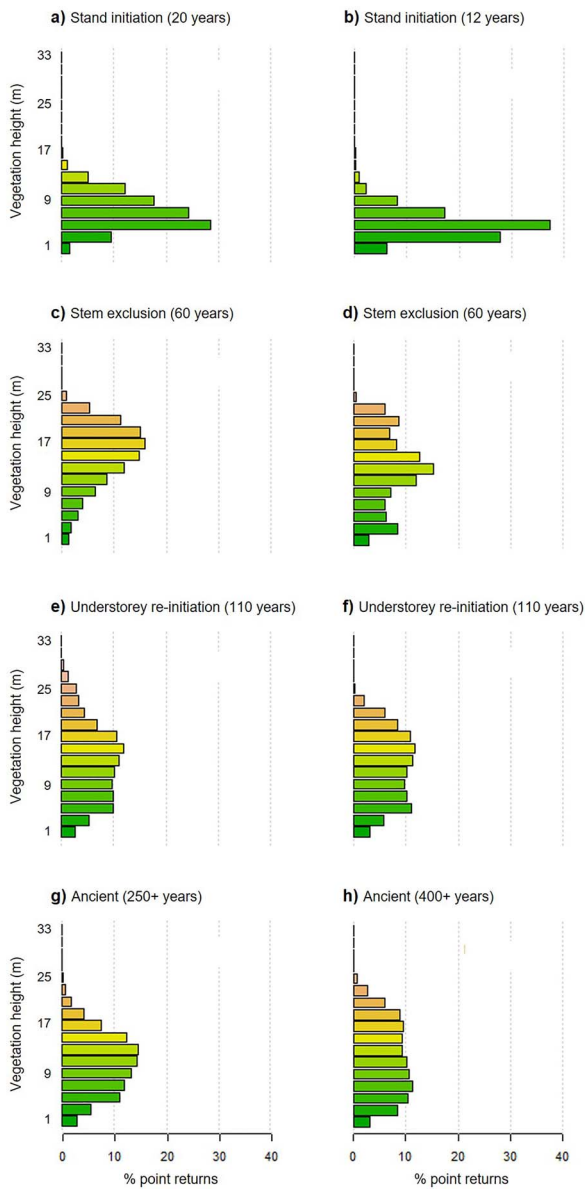
In this study, we quantified vegetation structural changes occurring in temperate woodland creation sites over a 160-year period after planting on former agricultural land. Our findings show that woodland creation sites display similar development patterns to those described for other woodland systems following major disturbances (i.e. undergoing stand initiation, stem exclusion and understorey re-initiation stages; Oliver and Larson, 1996). We also compared the vegetation attributes of woodland creation sites with those of mature ancient woodlands with longer ecological continuity.

### Development of woodland creation sites and similarities with mature ancient woodlands

There was a moderate degree of separation between sites in different woodland development stages, driven by vegetation characteristics. As expected, there was a gradual transition in the vegetation attributes of younger to older woodlands, with sites in stand initiation stages progressing towards more

advanced stages. Interestingly, there was a large degree of overlap between woodlands in understorey re-initiation stages and ancient woodlands, suggesting that some vegetation attributes of woodlands 80–160 years are fairly similar to those of much older woodlands (>250 years old). This was supported by similarities in individual vegetation attributes between these two late developmental stages. There was also considerable variation within age classes (Supplementary data 3) suggesting other factors may be promoting (e.g. gap creation due to natural disturbances) or hindering (e.g. herbivore browsing) the development of woodland structures, rather than being driven by age alone. Climatic, topographic and edaphic factors (e.g. soil quality determined by nutrient and moisture regimes; Pyatt *et al.*, 2001) can also play important roles on tree growth rates and consequently on woodland development. As part of our initial site selection process, we attempted to control environmental variation by selecting woodland sites within fairly homogeneous lowland agricultural landscapes (see Methods section and Watts *et al.*, 2016 for details). Still, it is possible that some variation persists, but this is unlikely to affect the general patterns observed here. In addition, factors such as degree of land degradation prior to woodland creation (e.g. intensive arable vs. unimproved grassland) and proximity to existing woodland (as a source of propagules) are also likely to strongly influence the structure, function and complexity of woodland creation sites (ongoing work by the authors and others).

Structural heterogeneity (i.e. variation in tree size), average tree size and tree density were the attributes that varied the most among woodland developmental stages. Specifically, structural



**Figure 5** Height distribution of vegetation points (from LiDAR data) of woodlands in four development stages: stand initiation (a and b), stem exclusion (c and d), understorey re-initiation (e and f) and ancient woodlands (g and h). Examples of Scottish (left column) and English sites (right column) are presented. Colours correspond with height (m) and are for aesthetics only. Strata are shown in 3 m groups for visualization.

heterogeneity and average tree size increased with woodland age, whilst tree density decreased. However, there was little difference in these attributes between woodlands in understorey re-initiation stages and ancient woodlands, suggesting a levelling-off at this point. Whilst young woodlands inevitably have relatively low variation in tree sizes (because not enough time has passed for trees to grow large), the opposite is not necessarily true; i.e. older woodlands that would be expected to have younger smaller naturally regenerating trees to increase size variability could have this inhibited, for example by high browsing pressure or

shading. A slight (non-significant) decrease in average tree DBH and increase in tree density from understorey re-initiation to ancient woodlands suggests a degree of natural regeneration in the latter that is missing in the younger stage of woodland development. The distribution of vegetation height (LiDAR-derived metric) also indicated differences between most woodland stages, but similarities between understorey re-initiation and ancient sites; these similarities appear to result from a lack of regeneration, probably driven by excessive herbivory pressure affecting the understorey layer. However, we did not directly quantify the degree of natural regeneration in our sites, and we can only infer it from other vegetation characteristics. Other vegetation attributes that displayed smaller differences among woodland development stages could be more strongly influenced by a combination of herbivory and management factors; for instance, it was surprising that older woodlands did not consistently have higher amounts of woody debris or understorey cover than woodlands in earlier successional stages.

Additionally, the significant, positive correlation between our field-based and LiDAR-derived vegetation structural heterogeneity metrics (variation in tree size and vertical complexity index, respectively) corroborates the potential value of using remote sensing data to characterize woodland structure over large spatial scales (e.g. van Ewijk *et al.*, 2011).

### Importance of woodland management

Woodland management can greatly alter vegetation structure. For instance, understorey cover (partly driven by natural regeneration) is significantly reduced by the presence of grazing stock in woodland patches (Fuentes-Montemayor *et al.*, 2020) and by deer browsing (e.g. Eichhorn *et al.*, 2017). In Great Britain, 40 per cent of woodland habitat is in unfavourable condition due to herbivore damage (Forestry Commission, 2020b); in Scotland, over a third (33 per cent) of native woodlands have such high levels of herbivory (mainly by deer) as to prevent successful regeneration of most tree and shrub species, and 13 per cent have no regeneration at all (Forestry Commission, 2014; Forestry Commission, 2020b). In addition, only 35 per cent of Great Britain's native woodlands have a 'complex' vertical structure (i.e. are composed of >5 storeys or multiple heights of trees) and 45 per cent have a negligible deadwood component (Forestry Commission, 2020b). Whilst we have no direct information on past management in our study sites, there are no signs of recent management interventions (apart from the presence of grazing stock in some sites), and we consider intensive past management unlikely given the nature (e.g. small size and agricultural setting) of these woodlands. The sites studied here are fairly small patches (all <30 ha, most <5 ha) immersed in an agricultural matrix, some of them heavily overgrazed (particularly sites in Scotland). They are characteristic of British woodlands (including ancient semi-natural woodlands of which ca. 70 per cent are <5 ha; Reid *et al.* 2021). The similarities we found between older woodland creation and ancient woodland sites should not necessarily be interpreted as an indication that they both represent top-quality habitats. Mature ancient woodlands in the UK have a long history of disturbance and management (e.g. coppicing, felling and removal of deadwood); whilst some disturbance and

management regimes positively affect (and are an integral part of) woodland ecosystems, others can have negative impacts on their vegetation structure that persist for centuries (Rackham, 1980; Peterken, 1996). Larger ancient woodlands managed for conservation purposes are likely to be more structurally complex and of higher biodiversity value than the sites we studied here.

Woodland management practices can also play an important role in improving woodland quality by accelerating woodland development. During stem exclusion stages, trees begin to compete with each other for space and light; natural thinning processes take place (i.e. some outcompeted individual trees die, allowing surviving trees to grow larger and resulting in differences in sizes) and structural heterogeneity within the woodland increases. But when all saplings grow at similar rates (i.e. no individuals grow faster to shade neighbours), self-thinning is slow and a dense stand of slow-growing trees can persist for a long time (Peterken, 1996). This is the case of many unmanaged Woodland Grant Scheme sites planted in the early 1990s in Scotland (Fuentes-Montemayor *et al.*, 2015), where a lack of management has led to densely closed canopies with no gaps or light for regeneration to occur. Management activities aimed at promoting natural regeneration on such sites (e.g. through a combination of opening canopy gaps and reducing herbivore pressure) could fast-track woodland development and improve habitat conditions for a range of taxonomic groups (e.g. woodland plants; Harmer *et al.*, 2001; Kerr, 1999). Excluding (or minimizing) in-site grazing and browsing (e.g. by installing deer-proof fencing) might be particularly important in very young woodlands undergoing stand initiation, and also during understorey re-initiation and ancient stages when canopy conditions would naturally allow seedlings/saplings to develop into new tree cohorts. Tree regeneration is likely to increase structural diversity (in terms of tree age and size distributions) and three-dimensional heterogeneity. In addition, managing woodlands to promote natural regeneration is likely to enable adaptation through natural selection and enhance woodland resilience to climate change (Whittet *et al.*, 2019).

### Biodiversity value of woodland creation sites

Woodland creation sites provide valuable habitat and resources for a wide range of taxonomic groups including invertebrates, birds, bats and small terrestrial mammals (e.g. Fuentes-Montemayor *et al.*, 2017, 2020; Fuller *et al.*, 2018; Whytock *et al.*, 2018). Vegetation attributes associated with woodland development (e.g. average tree size and variation in tree size) are among the main drivers influencing the species richness and abundance of many taxa, and there is evidence that woodlands become gradually better over time for some species (e.g. bats and small terrestrial mammals; Fuentes-Montemayor *et al.*, 2017, 2020). Our results suggest that there is a 'waiting time' of between 80 and 160 years from woodland planting to achieving a more natural, complex vegetation structure of potentially higher biodiversity value (although some younger sites had relatively high structural complexity levels, suggesting woodland age is not the only driving factor; Supplementary data 3). This value can both be enhanced (e.g. by promoting structural heterogeneity; Kerr, 1999) or undermined (e.g. by livestock grazing; Lindenmayer *et al.*, 2018) through management activities.

### Alternative woodland creation strategies

Tree planting has been the most common woodland expansion strategy for over a century in countries like the UK (Harmer *et al.*, 1995), where overabundant deer populations resulting from a lack of natural predators and control currently put on increased herbivory pressure on woodland vegetation and limit natural regeneration (Gill and Fuller, 2007). Planting seedlings/saplings is generally a quicker and more reliable method for establishing woodland than allowing an area to regenerate or to be colonized naturally (Harmer *et al.*, 1995; Harmer *et al.*, 2001). But recently in the UK there have been calls for 'natural colonization' (i.e. allowing trees to colonize new areas naturally) to be incorporated more widely as a woodland expansion strategy (Woodland Trust, 2020). Natural colonization is perceived to lead to more heterogeneous and complex woodlands of higher natural value (Harmer and Gill, 2000) and also maintain local tree genotypes likely to enable local adaptation to climate change (Harmer *et al.*, 2015; Woodland Trust, 2020). The overall similarities between patterns observed here in vegetation development of woodland creation sites and those described for other woodland systems suggest that past land-use legacy effects and initial planting conditions do not preclude the natural development of woodland creation sites over time. Planted sites are also likely to subsequently experience some natural colonization from nearby woodlands, which will influence the development of these sites through time. These planting sites seem to follow 'initial floristics' patterns whereby all tree species establish at approximately the same time after a disturbance (but assert dominance at different times; Egler, 1954) and eventually develop into woodlands with some vegetation characteristics similar to those of mature ancient woodlands. However, even if woodland planting sites ultimately resemble semi-natural systems, our results cannot provide information on how they compare with natural colonization sites (e.g. do the latter reach higher structural complexity more quickly than planting sites?). We suggest that future research should address this knowledge gap. In practice, we advocate that tree planting and natural colonization should have complementary roles in woodland cover expansion.

### Conclusion

Woodland expansion is widely regarded as a key part of the solution to counteract climate change and tackle the biodiversity crisis. Ambitious environmental policy targets (e.g. to increase woodland cover from 13 to 17 per cent by 2050 in the UK; Committee on Climate Change, 2020) often fail to acknowledge the time lags between habitat creation and its conservation outcomes (Watts *et al.*, 2020). Our results suggest that it may take 80–160 years for tree planting sites to develop into woodlands with a vegetation structure similar to that of mature, ancient semi-natural woodlands, likely to be of higher biodiversity value than woodlands in earlier successional stages (e.g. Fuentes-Montemayor *et al.*, 2015, 2017, 2020). Woodland management practices to promote natural regeneration and reducing grazing/browsing pressure are likely to accelerate this transition, increase the structural heterogeneity and biodiversity value of woodland creation sites and enhance woodland adaptability and resilience to climate change. Tree planting is likely to continue to be an integral part of woodland expansion targets in temperate



regions; natural colonization could play a complementary role, but its outcomes are likely to be achieved over longer timescales and be context dependent.

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## Data availability

Data associated with this paper will be deposited in the University of Stirling's Online Repository for Research Data (DataSTORRE).

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## Supplementary data

Supplementary data are available at *Forestry* online.

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## Conflict of interest statement

None declared.

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