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Short Communication

Tree species selection for ecosystem services and resilience in agroforestry systems

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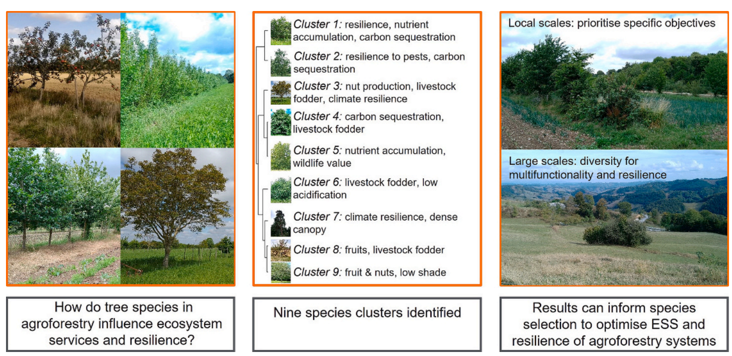
HIGHLIGHTS

- We review ecosystem service and resilience attributes in agroforestry tree species
- All species had benefits and risks in terms of these attributes
- Species selection should be guided by locally relevant attributes at the farm level
- At larger scales, species diversity is needed for multifunctional resilient systems
- Further research needed to understand species selection for soil-related factors

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Agroforestry systems have generated significant interest from research, policy and practice for their potential to deliver multiple ecosystem services alongside food production. However, information on tree species selection to maximise benefits and minimise risks is highly fragmented.
Objective: This study evaluates how tree species in agroforestry systems influence ecosystem services and resilience to climate change and biotic threats, focussing on a UK context.
Methods: A rapid literature review assessed 33 tree species and 17 attributes related to ecosystem services and resilience, selected with input from 28 stakeholders. We analysed correlations among attributes of tree species relating to ecosystem services and resilience and identified synergies and trade-offs. We used cluster analysis to define functional groups of tree species.
Results and conclusions: Nine species clusters were identified, each with distinct benefits and risks in terms of ecosystem services and resilience attributes. Taxonomically similar species tended to have similar ecosystem service and resilience attributes. Correlation analysis identified trade-offs between the value of tree species to wildlife and projected future range. We identify further research needs to understand and communicate the role of tree species selection for agroforestry systems, particularly with regard to soil-related factors such as acidification, nutrient and organic matter accumulation, and pollution mitigation.

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Significance: Species selection at farm and local levels should be guided by local ecosystem service and resilience priorities alongside management objectives. At regional and national levels, we advocate for a taxonomically diverse range of species to support multifunctional, resilient agroforestry systems.

1. Introduction

Agroforestry systems, where functional trees and shrubs are integrated into agricultural systems, are of increasing interest for sustainable land management, as recognised by policies in England (Defra, 2024) and elsewhere (e.g. EU Regulation 2021/2115; United States Department of Agriculture, 2019). Interest in agroforestry systems is gaining momentum because of their potential to provide multiple ecosystem services. These include provisioning services such as food, timber, and fuel; supporting services such as nutrient cycling; and regulating services such as pollination, erosion protection, and climate regulation via carbon sequestration (Dmuchowski et al., 2024; Sollen-Norrlin et al., 2020; Torralba et al., 2016). These benefits are balanced against a number of potential risks. For example, given that tree planting is a long-term investment, resilience to climate change is an important consideration (Yu et al., 2021). Other relevant considerations in agroforestry systems include tree-crop competition for water and light (Cannell et al., 1996) and the risk of increased pest and disease problems (Pumariño et al., 2015). The balance of benefits versus risks will largely depend on appropriate system design, of which tree species choice is likely to be a key factor (Jose et al., 2004; Kletty et al., 2023).

Although species selection in agroforestry systems is of importance for ecosystem service provision, scientific literature as to the relative benefits and risks is scarce in temperate regions (but see Gosme et al., 2025). This is despite early research into modern agroforestry systems emphasising the importance of species choice to minimise tree-crop competition and maximise nutrient cycling (e.g. Anderson and Sinclair, 1993; Schroth, 1995). More recently, interest in the reintegration of woody species into livestock feeding strategies has seen some species-specific comparisons of their nutritional value (Kendall et al., 2021; Mahieu et al., 2021). Furthermore, research into the climate resilience of tree species, although largely focussed on forestry (e.g. Koch et al., 2022), is broadly applicable to agroforestry systems. However, at present there is a lack of understanding regarding tree species selection for ecosystem service provision in agroforestry systems, their resilience to climate change, the trade-offs and synergies between these attributes, and whether species can be categorised into functional groups for their delivery (Mitchell et al., 2021). Such an understanding would help to guide tree species selection for agroforestry systems at both local levels (e.g. land management and farm-level agroforestry system design) and national levels (e.g. policies to target specific ecosystem services such as carbon sequestration).

The aim of this study is therefore to evaluate the current state of evidence regarding the influence of tree species in agroforestry systems on ecosystem services and resilience to climate change and biotic threats, focussing on a UK context. More specifically, we address two objectives: 1) to explore correlations among attributes of tree species relating to ecosystem services and resilience to indicate synergies and trade-offs, and 2) to define functional groups of tree species according to their attribute profiles to assist in species choice.

2. Methods

2.1. Species selection

This study formed part of a wider task to develop a guide for tree species selection in UK agroforestry systems (Staton et al., 2024). The first step was to identify a list of tree and shrub species to investigate. This was undertaken as a collaborative exercise with a network of 28 UK-based stakeholders with expertise in agroforestry systems from government agencies, charities, and academic institutions. Four online meetings were held with the stakeholder group in 2023, to discuss the process of species selection, attribute selection, and attribute evaluation. Attendees were encouraged to provide feedback via verbal communication, the ‘chat’ function in the online meeting application, and through follow-up emails. Where appropriate, attendees were separated into virtual breakout rooms to facilitate discussion.

To guide species selection, stakeholders were initially invited to select up to six priority species each to include in the study. Six responses were received, which identified a total of 21 species based on stakeholders' experience of advising on agroforestry systems and aspirations for the future. An additional 12 species were then selected through a combination of stakeholder verbal feedback in meetings and a review of relevant literature such as the Agroforestry Handbook (Raskin and Osborn, 2019). A mix of native and introduced species were included, for a variety of productive functions including food production (e.g. fruit / nuts), timber, short-rotation coppice, and livestock fodder. The majority of species are commonly planted in the UK, although some relatively novel species of emerging interest in the UK were selected (e.g. *Alnus rubra*, *Quercus rubra*). For simplicity, we use the term ‘tree species’, although one species (*Corylus avellana*) is technically a shrub (Stace, 2019).

2.2. Attribute selection for ecosystem services and resilience

Stakeholders were also engaged in selecting attributes relevant to ecosystem services and resilience. The co-authors led the selection of attributes, which was guided by informal feedback from stakeholders during meetings (described above). Initially, a total of 20 attributes were included. Following a review process with relevant experts (including those outside of the stakeholder group, where additional expertise was required), this was reduced to 17 attributes (see Table 1). Three attributes were therefore excluded from the study, namely water consumption, landscape pollution mitigation, and spray-drift reduction. Water consumption was excluded because of the apparently limited role of species compared with site-specific factors such as climate and soil type (Nisbet, 2005), while the latter two attributes were excluded because of limited species-specific information.

After the species and attributes had been selected, the next stage was to assign a score for each attribute for each species via a rapid literature review (Table 1). For most attributes, a ‘traffic light’ system was applied whereby each species was ranked as low, moderate or high, although this was flexible with ranges used where appropriate (e.g. low to moderate), and a ‘very high’ and/or ‘negligible’ category used for some attributes, where this was judged appropriate. Where information could not be found, an ‘unknown’ category was used.

A confidence level was assigned to each relevant attribute value, with mean scores calculated for each attribute (Table 1). The scoring system was as follows:

- High confidence (score = 3): well-replicated evidence or information from reputable sources, for the species in question.
- Moderate confidence (score = 2): evidence for the species available but less reliable, e.g. limited expert opinion or a limited number of studies / limited replication.
- Low confidence (score = 1): no (or very limited) direct evidence for the species, assessment primarily inferred from other tree characteristics or similar species.
- Attribute unknown (score = 0): no evidence or inference available.

Table 1
Attribute scoring system for ecosystem services and resilience. Higher scores represent a high benefit or low disbenefit. For more information, including literature sources, see Supplementary Material 1. Scores were scaled prior to analysis.

Attribute	Scoring system	Summary of evaluation process (see Supplementary Material 1 for details)	Mean confidence level (scale 0–3)
Ecosystem services			
Food products	0 = negligible; 0.5 = minor use; 1 = mainstream production	Assigned '1' if commonly cultivated for food products e.g. fruits, nuts.	N/A
Wood & biomass products	Maximum yield class (log-transformed)	Maximum potential yield class as described in Ecological Site Classification documentation (Forest Research, 2024), or inferred based on similar species.	N/A
Nutrient and organic matter accumulation	0 = low; 0.5 = moderate; 1 = high	Predicted based on canopy area and root depth.	1.15
Acidification (inverse)	0 = high; 0.5 = moderate; 1 = low	Literature review, benchmarked against commonly-studied species.	1.12
Livestock fodder benefits	0 = potentially toxic; 0.33 = low; 0.66 = moderate; 1 = high	Literature review, considering crude protein, condensed tannins, micronutrient levels, other nutritional value, and palatability.	1.64
Carbon sequestration (20, 40 and 60 years)	Average $tCO_2e/ha/year$ for trees at 3 m spacing, assuming maximum potential yield class	Above ground biomass only, estimated using UK Woodland Carbon Code (2021).	1.73
Native status	0 = neophyte survivor; 0.2 = neophyte naturalised; 0.6 = Archaeophyte; 0.8 = native to one region; 1 = native	Based on Stace (2019).	3
Value to wildlife	Average value between 1 (low) and 5 (high) across taxonomic groups	Synthesised from Alexander et al. (2006)	1.67
Resilience attributes			
Disease susceptibility (inverse)	0 = high; 0.5 = moderate; 1 = low	Categorised based on frequency of diseases and their damage level.	3
Invertebrate pest susceptibility (inverse)	0 = high; 0.5 = moderate; 1 = low	As disease susceptibility.	3
Vertebrate pest susceptibility (inverse)	0 = high; 0.5 = moderate; 1 = low	As disease susceptibility.	2.79
Projected future range	0 = net range contraction; 0.5 = very minor net range change; 1 = net range expansion	Categorised based on predicted range change in the UK.	2.09
Drought tolerance	0 = sensitive; 0.33 = moderately sensitive; 0.67 = moderately tolerant; 1 = tolerant	Reported tolerance to drought conditions	3
High temperature tolerance	0 = sensitive; 0.33 = moderately sensitive; 0.67 = moderately tolerant; 1 = tolerant	Reported tolerance to high temperature conditions	3
Shade			
Shade area	0 = low; 0.5 = moderate; 1 = high	Based on canopy height, width and shape.	N/A
Canopy density	0 = open; 0.5 = moderate; 1 = dense	Based on density / openness of canopy.	N/A
Leaf emergence	0 = evergreen; 0.5 = early; 1 = late	Based on Stroh et al. (2023)	N/A

2.3. Analysis

All analysis was undertaken in R version 4.0.2 (R Core Team, 2020). Attributes were scaled so that their minimum and maximum values were 0 and 1, where 1 represents a high benefit or low risk/disbenefit (see Table 1).

Correlations between attributes were explored using scaled data and non-parametric methods, because of the non-normal data structure, using the 'cor' function. The Kendal and Spearman methods gave identical significance results, and Spearman was selected because of its better ability to handle ties (Puth et al., 2015). The 'pairwise.complete.obs' function was used to handle missing values. Correlations were visualised using the 'corrplot' package (Wei and Simko, 2021).

Species clusters were visualised by producing a heatmap in the 'pheatmap' package (Kolde, 2019). The package uses hierarchical clustering to group similar rows (tree species in our analysis) and/or columns (ecosystem service and resilience attributes) in a dendrogram. The default Euclidean distance method was used. The optimal number of species clusters was determined to be nine, based on a comparison of 30 indices using the NbClust package (Charrad et al., 2014). For this optimal cluster analysis, missing data for 15 values across four attributes were imputed using mean attribute values. A visual inspection of the results also supported nine clusters as optimal, representing the highest number of clusters before individual species were separated. Column (attribute) clustering was not applied, although an alternative version with column clustering is presented in Supplementary Material 2.

The attributes 'wood and biomass products' and the three carbon sequestration timescale values were highly correlated because they were all calculated using maximum potential yield class. Therefore, of these four attributes, only carbon sequestration over 20 years was included in the cluster analysis, based on its high policy relevance. In addition, native status was not included in the cluster analysis, given that this was intended to serve as a proxy for biodiversity value which was represented by the 'value to wildlife' attribute.

3. Results

3.1. Correlations between attributes

Many of the correlations between attributes (see Fig. 1) are to be expected based on similar methods of evaluation (e.g. carbon

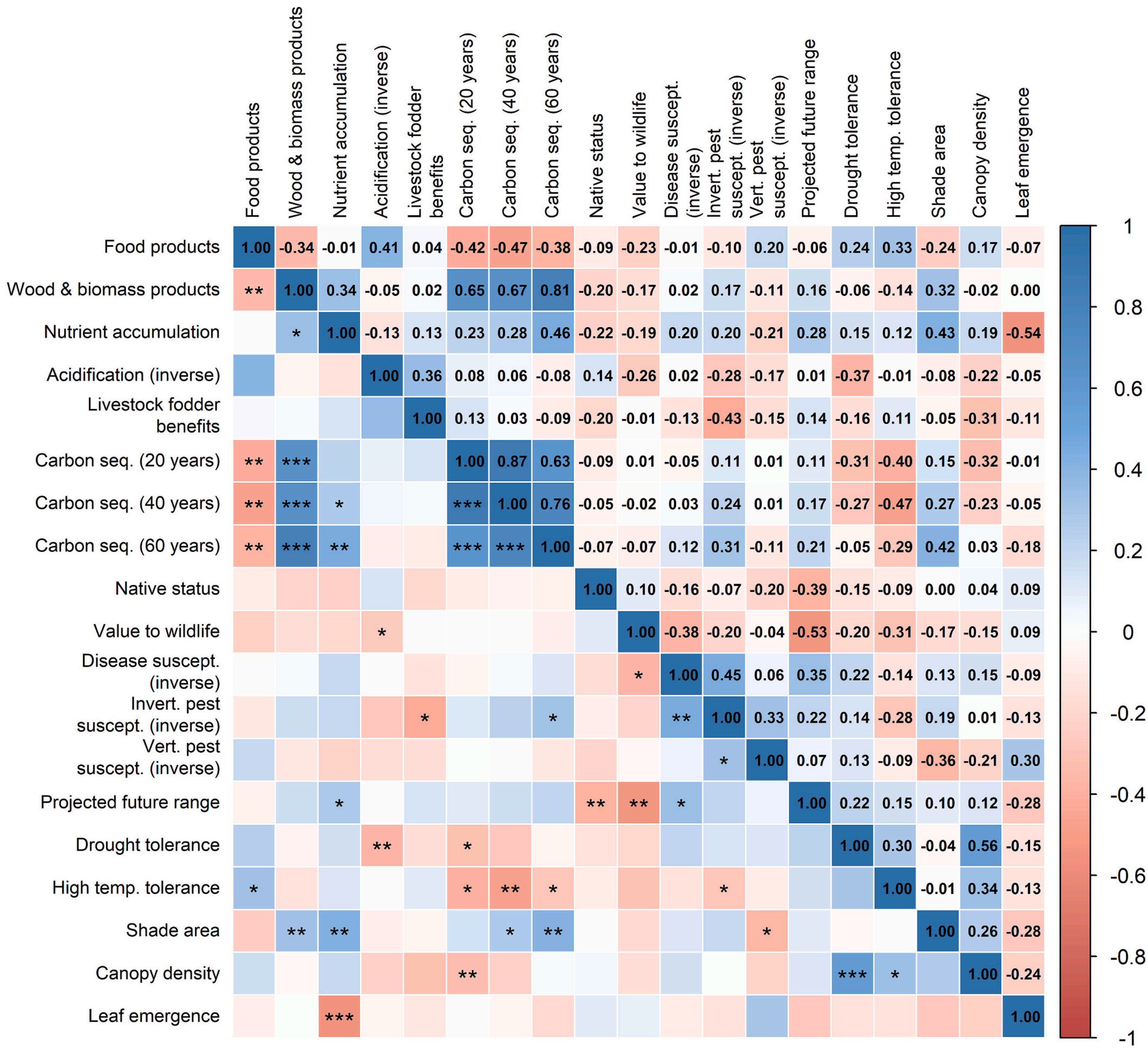

Fig. 1. Correlation matrix between attributes, where 1 (blue) represents a positive correlation, 0 (white) no correlation, and − 1 (red) a negative correlation. Attributes with the suffix 'inverse' are disbenefits, where a positive correlation denotes a lower disbenefit (hence, positive correlations are always beneficial). Shade attributes (the final three rows / columns) could be benefits or disbenefits, depending on farm objectives. Values in the upper-right triangle represent correlation coefficients, asterisks in the lower-left triangle denote *p*-value significance where * < 0.05, ** < 0.01, *** < 0.0001. For full attribute names, see Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sequestration, wood and biomass products, nutrient accumulation). Other correlations, which could not be explained by their similarity of evaluation methods, included negative correlations between projected future range and both value to wildlife and native status, as well as between high temperature tolerance and carbon sequestration. Tree species with earlier leaf emergence time (which could be a benefit or disbenefit, depending on the farm's objectives) were associated with higher nutrient accumulation levels, while canopy density (again either a benefit or disbenefit) was positively correlated with drought tolerance.

3.2. Species functional clusters

Species were grouped into the following nine functional clusters based on their attributes (Fig. 2):

1. Non-native *Alnus* species, associated with high resilience attributes together with high nutrient and organic matter accumulation and carbon sequestration.
2. *Betula*, native *Alnus*, and *Eucalyptus*, associated with high resilience to pests and generally high carbon sequestration with low shade effects.
3. Nut-producing species with high nutrient and organic matter accumulation, low acidification disbenefits, high livestock fodder benefits, projected range expansions and high temperature tolerance.
4. A group of high carbon sequestering species, with high nutrient and organic matter accumulation, and moderate to high livestock fodder benefits.

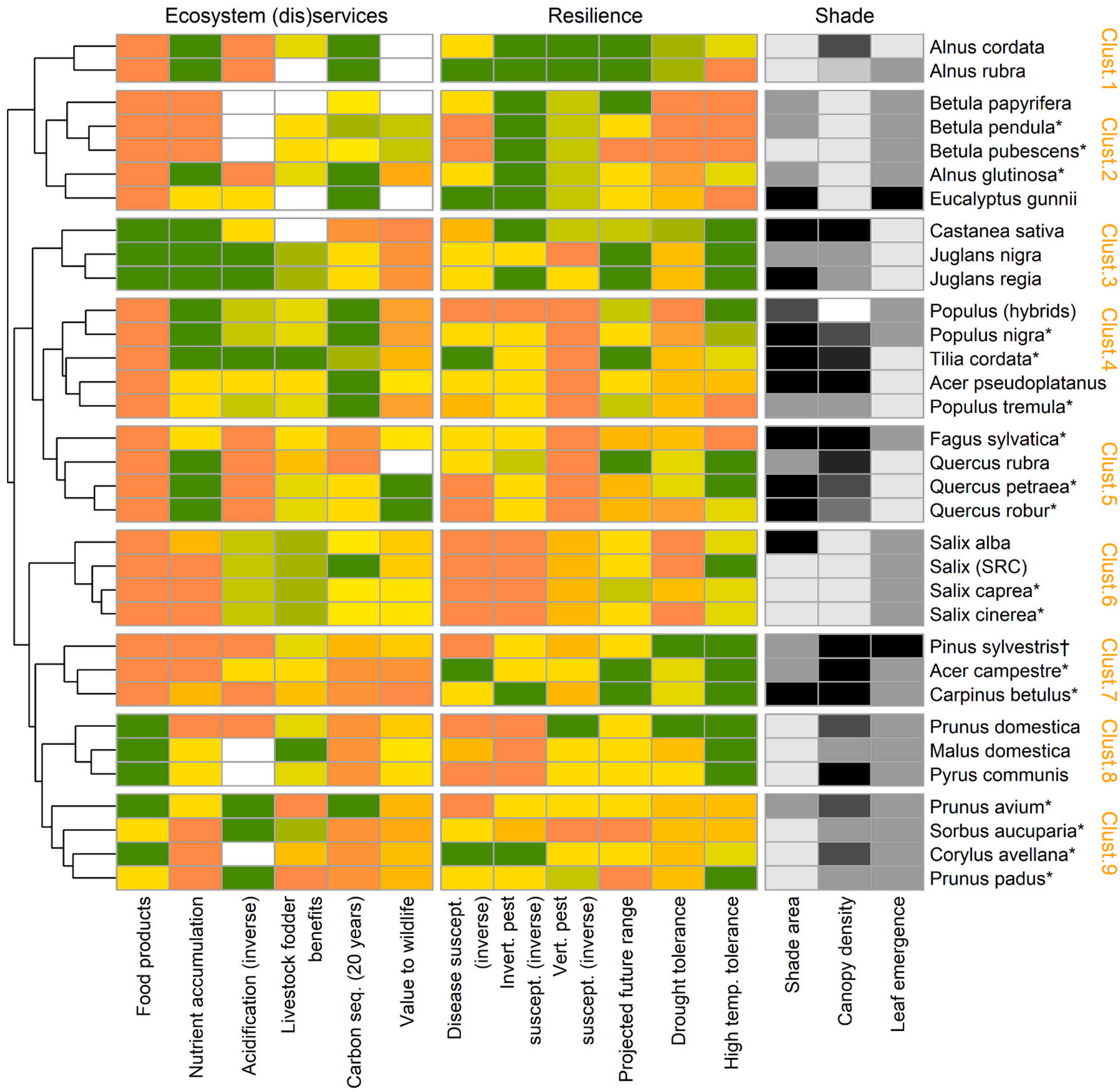

Fig. 2. Heatmap for attributes in tree species. Colour scheme: green = high benefit or low risk/disbenefit (acidification and susceptibility to disease and pests); red = low benefit or high risk/disbenefit; yellow = intermediate, white = no data. A separate colour scheme is applied for shade attributes, because these could be a benefit or disbenefit depending on the system, where darker colours indicate higher shade area, higher canopy density, and longer leafing period. Asterisks (*) denote native species and dagger (†) a species native to part of the UK. A version with column clustering is presented at Supplementary Material 2. For full attribute names, see Table 1. Other abbreviations: Clust. = Cluster, SRC = Short Rotation Coppice. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. *Fagus* and *Quercus* species, associated with high nutrient and organic matter accumulation, moderate to high value to wildlife, and high shade effects.
6. *Salix* species, with low acidification disbenefits, high livestock fodder benefits and low shade.
7. A group of climate resilient species native to at least part of the UK, with dense canopies and high climate resilience.
8. Fruit producing species with livestock fodder benefits and moderate wildlife value.
9. Fruit and nut producing species with low acidification effects and low shade.

4. Discussion

Our analysis revealed varying levels of evidence for ecosystem service and resilience attributes across the 33 tree species. The correlation analysis revealed synergies and trade-offs between these attributes. Functional clusters of tree species according to ecosystem service and resilience attributes corresponded closely to their taxonomic classification, with each cluster having a distinct set of ecosystem service and resilience benefits.

Of particular policy relevance was the negative correlation between projected future range and both value to wildlife and native status. It is likely that non-native species are introduced at least in part for their potential for future range expansion. This pattern highlights a trade-off between climate resilience and biodiversity value, a pattern that has also been observed in agroforestry systems in North America (Jovanelly et al., 2025). Indeed, value to wildlife had negative correlations with all but one (native status) of the ecosystem service and resilience attributes, although this is caveated by the relative scarcity of evidence for non-native species (Mitchell et al., 2017). Resilience attributes tended to be positively correlated with each other, albeit our evaluation of susceptibility to pests and disease did not take their range changes into account.

Our cluster and heat mapping analysis indicated that species belonging to the same genus were associated with similar attributes for ecosystem services and resilience, supporting ecological theory and evidence linking phylogeny with ecosystem functioning and services (e.g. Oka et al., 2019; Srivastava et al., 2012). In particular, congeneric species were consistently clustered into the same or neighbouring cluster with only one exception (*Acer campestre* and *pseudoplatanus*). To some extent, this could be an artefact of the methodology, e.g. attributes values were sometimes inferred from congeneric species where species-specific evidence was lacking (see Supplementary Material 1). Nevertheless, the consistently strong correspondence to taxonomy indicates that the benefits and risks of other similar species could be inferred based on our findings.

Each cluster exhibited unique strengths in terms of their ecosystem service and resilience attributes. Therefore, to maximise a desirable attribute, such as carbon sequestration, wildlife value, or drought tolerance, this analysis could inform the selection of a suitable species or species cluster for specific objectives at the farm or local level. However, to deliver multiple ecosystem services and resilience benefits at a regional or national scale, our findings suggest that a diversity of species across each of the clusters is needed. Similar recommendations have been made for tree planting in forestry and urban settings (Messier et al., 2022; Schuler et al., 2017; Wood and Dupras, 2021).

The identified clusters can support initial decision-making when combined with site suitability assessments (Gosme et al., 2025). For example, in situations where carbon sequestration and nutrient accumulation are key goals, species from Clusters 1 and 4 may be appropriate. In this case, the analysis also highlights the susceptibility of Cluster 4 species to vertebrate pest damage, which may necessitate robust tree protection measures. Alternatively, in landscapes where biodiversity enhancement is a priority, species from Clusters 5, 6 and 8 may be favoured for their moderate to high value to wildlife, particularly when combined to deliver a diversity of tree species that supports a wider range of fauna. However, localised advice and site suitability assessment remain essential to refine species selection.

Our study also provided insight into future research priorities for tree species selection in agroforestry systems. Two attributes, landscape pollution mitigation and spray-drift reduction, were originally included in the scope of this study but were ultimately withdrawn due to a lack of species-specific evidence. Landscape pollution mitigation is a particularly challenging research topic given the need for data across large spatial scales with sufficient replication. Initial research on spray-drift reduction by tree species has demonstrated the potential importance of traits such as timing of leaf emergence and morphology (Bentrup et al., 2019; Wenneker and Van de Zande, 2008), which requires further research.

Of the attributes which could be included in this study, acidification and nutrient and organic matter accumulation had the lowest confidence levels (Table 1). Limited species information was found for acidification, largely from forestry contexts (De Schrijver et al., 2012; Hagen-Thorn et al., 2004). Nutrient and organic matter accumulation could only be inferred based on root depth and canopy volume (Isaac and Borden, 2019; Pardon et al., 2017), despite evidence indicating that this is a major potential benefit of agroforestry systems (Sollen-Norrlin et al., 2020; Torralba et al., 2016). Among attributes with moderate levels of evidence, the value of trees for livestock fodder is an emerging research area. Some species groups, such as *Salix*, are relatively well studied (e.g. Kendall et al., 2021; Mahieu et al., 2021), whereas others such as *Alnus rubra* and *Populus nigra* remain largely unknown in this regard. Carbon sequestration is relatively well documented for woodland contexts (UK Woodland Carbon Code, 2021), but in agroforestry systems is complicated by the wide diversity of tree species planted and unique management operations, such as stem density, planting arrangements, pruning, and fruit harvesting (Soil Association, 2023). Wildlife value and projected future range were inferred based on generalised evidence from other systems, and more evidence specific to agroforestry contexts is needed. Finally, four attributes had relatively high confidence levels, namely susceptibility to disease, invertebrate and vertebrate pests, and native status, because they were generalised from a broader knowledge base beyond agroforestry research. However, tree species in agroforestry systems may have reduced susceptibility to pests and diseases than in monocultures. From the perspective of species, non-native species of higher novelty in the UK were relatively poorly documented.

All the tree species studied have benefits and risks associated with ecosystem service delivery for agroforestry systems, with none scoring highly across all attributes. To support site-specific and multi-criteria selection of tree species, key information from the database (see Data Availability), including environmental tolerances, have been integrated into the AgroforesTreeAdvice decision support tool (https://agroforestreeadvice.sk8.inrae.fr/, Gosme et al., 2025). This platform integrates tree species selection tools for agroforestry systems across Europe. There would be benefit in further developing tools to assist farmers and land managers with farm-level planning to optimise benefits and minimise risks, including integration with the Ecological Site Classification (Forest Research, 2024).

In conclusion, our study reveals that the delivery of ecosystem services and resilience attributes by tree species in agroforestry systems largely reflects their taxonomy. Nine distinct clusters of tree species were identified, each associated with a unique set of benefits. Therefore, at the farm or local level, where the number of tree species is often constrained for practical reasons, species choice should prioritise specific ecosystem services and resilience attributes based on farm management objectives. At regional and national levels, we advocate for a taxonomically diverse range of species to deliver multifunctional, resilient agroforestry systems. Priorities for further research of ecosystem services in agroforestry systems should include the effects of tree species on acidification, nutrient and organic matter accumulation, nutritional value for livestock, and carbon sequestration, while more research on the potential benefits of climate resilient non-native species in agroforestry systems is needed.

CRediT authorship contribution statement

Tom Staton: Writing – review and editing, Writing – original draft, Visualisation, Investigation, Formal analysis. **Kate Beauchamp**: Writing – review and editing, Project Administration, Investigation. **Alice Broome:** Writing – review and editing, Project Administration, Investigation. **Laurence Smith**: Writing – review and editing. **Tom Breeze:** Writing – review and editing, Project Administration, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104476.

Data availability

Data is available at https://doi.org/10.6084/m9.figshare.28506500. The guide for tree species selection, which is based on the same data in a user-friendly format for practical uses, is available for free download at https://www.forestresearch.gov.uk/research/expanding-agroforestry-a-tree-species-guide-for-agroforestry-in-the-uk/.

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