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Research Paper

Modelling the production impacts of scaling up agroforestry systems in England and Wales

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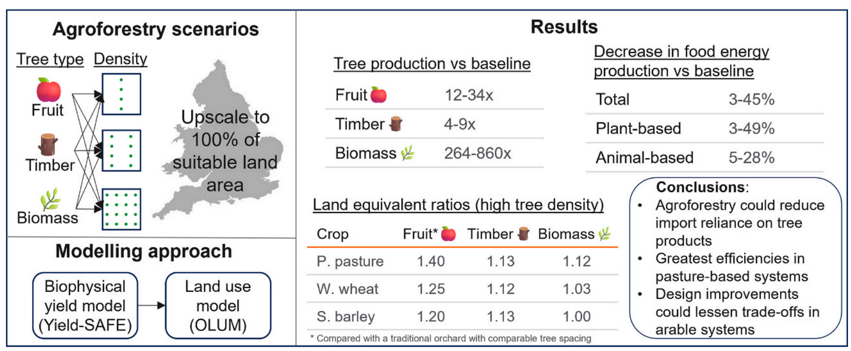
HIGHLIGHTS

- Agroforestry can improve domestic tree product supply, reducing import reliance.
- Food energy output drops by 3–45% under varying forms of agroforestry adoption.
- Arable crop output declines the most while ruminant livestock are least affected.
- Timber and apple agroforestry more productive than low-intensity monocultures.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Land managers and governments face the challenge of using finite land, labour, and financial resources to achieve multiple objectives. Agroforestry, the integration of trees with farming, is promoted as a strategy for achieving multiple policy objectives relating to productivity, climate change and biodiversity. However, regional and national-scale studies validating its effectiveness remain limited.
OBJECTIVE: Our study aimed to model the impacts of scaling up agroforestry on food and fibre production in England and Wales. We developed nine agroforestry scenarios combining three tree types (apple, poplar, and short rotation coppice (SRC) willow) at three planting densities. Each scenario scaled agroforestry to all suitable agricultural land (representing 79% of total agricultural land) as a simple modelling objective, rather than a realistic target.
METHODS: We used the well-established Yield-SAFE model to simulate tree-crop/grass interactions at low, medium, and high tree densities, and inputted the resulting yields into the Optimal Land Use Model (OLUM), a linear programming model with the objective of maximising food energy production under defined constraints. The OLUM was validated using baseline data.
RESULTS AND CONCLUSIONS: Scaling up agroforestry increased domestic supply of tree products, for which the UK is heavily import-dependent. However, this came at the expense of the calorific value of food production, which decreased by 3% to 45%, depending on tree type and density. The largest reductions were observed in

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arable and vegetable crops, due to reduced area and yields. Ruminant livestock outputs were least affected, supported by increases in grassland area. Timber and apple agroforestry systems were predicted to be more land-efficient than equivalent monocultures (for apples, traditional orchards), based on land equivalent ratios.
SIGNIFICANCE: Upscaling agroforestry could reduce import reliance on tree products while contributing to environmental objectives. To minimise reductions in domestic food supply, policymakers should prioritise agroforestry in pasture-based systems and support wider food system changes. Design improvements could lessen trade-offs associated with tree planting in arable systems. Future research should investigate how scaling up agroforestry systems affects greenhouse gas emissions, biodiversity, soil, water, and the general resilience of the farmed landscape.

1. Introduction

Land managers and governments have to balance economic objectives such as food and fibre production with environmental targets, such as restoring biodiversity and mitigating climate change, and social goals, such as improving health and well-being. These challenges have intensified in the wake of recent geopolitical events, the Covid-19 pandemic, and extreme weather events (Abay et al., 2023; Molotoks et al., 2021), all of which have exposed vulnerabilities in global supply chains and renewed policy attention to the resilience of domestic food systems (Burgess et al., 2021; Defra, 2024; European Commission, 2025). In densely populated countries such as the UK, where pressure on land use is high, navigating these intersecting priorities is particularly complex. In response, policy is placing renewed focus on food security alongside environmental and social sustainability, as reflected in England's Land Use Framework consultation (Defra, 2025) and the EU's Vision for Agriculture and Food (European Commission, 2025).

Agroforestry, which integrates trees/shrubs with crop or livestock systems, is increasingly recognised as one solution to address this challenge. By combining food, fibre, and biomass production with ecosystem services such as carbon sequestration and biodiversity conservation, agroforestry offers a multifunctional approach to land management (Kletty et al., 2023; Mayer et al., 2022a; Smith et al., 2013; Sollen-Norrlin et al., 2020; Veldkamp et al., 2023). Given that England produces only 16% of its consumed fresh fruit (Defra, 2023), and the UK just 22% of its consumed wood products and 4% of wood pellets (Forest Research, 2024), expanding agroforestry could help strengthen national supply chains while delivering environmental benefits. However, as with many sustainable farming systems which often involve trade-offs in productivity (Jones et al., 2023; Mayer et al., 2022b), the production impacts of agroforestry depend heavily on design factors, including tree attributes and planting density (Keesman et al., 2007). Nevertheless, the potential to meet multiple land use objectives has driven recent policy support for agroforestry. Emerging or adopted policies in England, Wales, and the EU include measures aimed at encouraging the establishment and maintenance of agroforestry systems (Defra, 2024b; Mosquera-Losada et al., 2023; Welsh Government, 2024). Alongside these top-down incentives, the integration of agroforestry systems is gaining momentum through the farmer-led regenerative agriculture movement (Beacham et al., 2023; Newton et al., 2020).

Despite this momentum, there remains a critical gap in national-scale studies assessing the productivity impacts of agroforestry. While small-scale studies have demonstrated the production efficiencies of temperate agroforestry systems, with land equivalent ratios often indicating higher productivity than equivalent monocultures (Sollen-Norrlin et al., 2020), there is limited evidence on how large-scale upscaling would affect food and fibre production at regional or national scales (Castle et al., 2022). Addressing this knowledge gap is essential to inform evidence-based strategies that seek to balance food security with economic, social, and environmental sustainability.

To address this knowledge gap, this study aims to model the potential impacts of scaling up agroforestry on food and fibre production in England and Wales. We hypothesised that upscaling agroforestry would reduce national food energy output but improve land-use efficiency relative to monocultures, and that these trade-offs would differ by tree type and density, with forage-based livestock systems being less negatively affected than arable cropping (Giannitsopoulos et al., 2025). To test this hypothesis, we developed nine agroforestry scenarios combining three tree types (apple, poplar for timber, and willow for biomass) at three densities, and evaluated their impacts using a novel combination of biophysical and land-use modelling approaches. This combined approach enabled us to quantify trade-offs between food and tree products at a national scale, offering new insights into how agroforestry could reduce import dependence on tree products whilst balancing food security and environmental objectives. We modelled the impacts of upscaling agroforestry to 100% of suitable agricultural land, not as a realistic target, but as a simplified modelling approach to provide clear insights into potential system-wide impacts.

2. Methods

We adapted two existing models to evaluate the impacts of scaling up agroforestry systems on food and fibre production (see Fig. 1 for summary workflow). We modelled a hypothetical future year where agroforestry systems had been implemented on all suitable agricultural land in England and Wales with an equal distribution of tree ages. Firstly, we developed nine different agroforestry scenarios varying in tree products and densities. Next, we calibrated the well-established Yield-SAFE model (Burgess et al., 2023; van der Werf et al., 2007) and used this to model field-scale tree-crop interactions in each agroforestry scenario. The resultant yields were used as inputs into the national-scale Optimal Land Use Model (OLUM ((Smith et al., 2018)), a linear programming model based in GAMS (General Algebraic Modelling System, http://www.gams.com/). The OLUM was used to evaluate national food and fibre production under each scenario compared against the baseline. This choice of models allowed us to integrate results from field-scale biophysical tree-crop interactions into a national land use model.

2.1. Agroforestry scenarios

Nine agroforestry scenarios were modelled (Table 1), focusing on three contrasting tree species selected based on their economic relevance in England and Wales (Newman, 2019): (1) apples, which have emerged as a popular choice in innovative agroforestry systems as well as having historic use in traditional orchard systems (Smith et al., 2016), (2) hybrid poplars (Beaupré) for timber production, which have been relatively well studied in the UK because of their potential for rapid growth (García de Jalón et al., 2018b; Newman et al., 2018), and (3) willow for biomass production, which is recommended for short rotation coppice (SRC), although its use remains limited (Defra, 2024c; Smith, 2016). Apple trees were modelled using MM106 rootstocks, due to their increasing popularity in agroforestry systems (Forestry Commission, 2024; Staton et al., 2022a). For each species, three tree densities were applied based on commonly modelled tree row spacings (Burgess and Graves, 2022) This resulted in nine agroforestry scenarios (Table 1) in addition to a baseline scenario (i.e. business as usual, S0).

Within each agroforestry scenario, trees were planted on all suitable agricultural land. This amounted to 79.1% of total agricultural land, with substantial regional variation, from 60.7% in Wales to 92.4% in south-east England (see Supplementary Material 1, Table SM1.4 for full regional breakdown). Suitable agricultural land was defined by excluding the following land-types:

(i) Rough grazing (one of the pasture types in OLUM), which typically occurs on unproductive soils and thus is of poor suitability for the modelled tree species.
(ii) Humose soils, which include peaty soils that are not recommended for tree planting (Forestry Commission, Natural England, 2023).
(iii) Orchards, on the basis that they already comprise high tree cover.
(iv) Protected cropping on the basis that these high value systems will not change.
(v) Priority Habitats identified in national policy, which are typically not recommended for new tree planting because of their existing nature conservation value. Their extent was estimated at 12.4% of permanent pasture based on published data (Chaplin et al., 2017), after accounting for Priority Habitats already excluded under the previous criteria.

2.2. *Agroforestry modelling using Yield-SAFE*

To model the agroforestry scenarios, we first simulated tree-crop interactions for each of the nine scenarios to generate yield inputs for the national-scale OLUM. This was undertaken using the Yield-SAFE model (YIeld Estimator for Long term Design of Silvoarable AgroForestry in Europe (Burgess et al., 2023; van der Werf et al., 2007)). Yield-SAFE is a process-based biophysical model which predicts tree and crop yields in agroforestry systems based on temperature, light and water availability, according to specified tree and crop species, tree density and management, soil texture, temperature, solar radiation, and rainfall, and has been widely used in previous agroforestry modelling studies (Crous-Duran et al., 2019; Giannitsopoulos et al., 2020; Graves et al., 2010; Graves et al., 2007).

Yield-SAFE was used to simulate 11 representative crop and pasture types, including cereals, legumes, roots, and grasslands (full list in Supplementary Material 2, Table SM2.2). In-built Yield-SAFE parameters were used where appropriate, although additional parameterisation was needed for grassland (Supplementary Material 2). For OLUM crops not included in Yield-SAFE, yields were modelled based on a similar crop (Supplementary Material 2). For example, changes in vegetable yields under tree cover were adjusted proportionally according to predicted changes to potato yields. Each of the three tree functions (see Table 1) was also modelled based on existing Yield-SAFE parameters, with some additional parameterisation for apple (Supplementary Material 2). Each tree and crop type was calibrated as a monoculture against the baseline OLUM yields (see Section 2.3 with details of the calibration process in Supplementary Material 2).

Yield-SAFE was then used to model agroforestry tree and crop yields for each of the 16 combinations of soil and rainfall classes included in OLUM (see Section 2.3), for each agroforestry scenario (Table 1). The resulting tree and crop yield outputs from Yield-SAFE were used as inputs in OLUM for each agroforestry scenario. Several other important assumptions were made in modelling the agroforestry scenarios in Yield-SAFE:

Table 1
Overview of agroforestry scenarios which formed the basis of the analysis.

Tree function	Food	Timber	Biomass
Tree species	Apple on MM106 rootstock	Hybrid poplar (Beaupré)	Hybrid willow
Tree management	Annual pruning	30-year rotation, annual pruning, no thinning (except where stated)	3-year short rotation coppice (SRC) cycle
Tree spacing within rows	3 m	6.4 m	1.2 m, 2 lines in each tree row
Low density: 4 m wide tree rows, 48 m wide crop alleys	Scenario 1 64 trees / ha	Scenario 4 30 trees / ha	Scenario 7 320 stems / ha
Moderate density: 3 m wide tree rows, 24 m wide crop alleys	Scenario 2 123 trees / ha	Scenario 5 58 trees / ha	Scenario 8 617 stems / ha
High density: 3 m wide tree rows 10 m wide crop alleys	Scenario 3 256 trees / ha	Scenario 6 120 trees / ha	Scenario 9 1282 stems / ha
Tree only monoculture (for land equivalent ratio (LER) calculations)	617 trees / ha, traditional orchard (The Tree Council, 2023)	1089 trees / ha, thinned to 133 trees / ha (Christie, 1994)	6600 stems / ha (Biomass Connect, 2023)

- Agroforestry rotations were assumed to be 30 years, which are typical of poplar rotations (García de Jalón et al., 2018b) and commercial lifespans of MM106 apple trees and SRC willow (Forest Research, 2024b; Redman, 2019). Because OLUM simulates one year, we calculated mean annualised yields over 30-year rotations, for both trees and crops.
- Where arable crop yields fell below a threshold expected to generate a positive gross margin (according to Redman (2019), see Supplementary Material 2), the cropped component was assumed to revert to temporary grassland (Burgess and Graves, 2022; Kaske et al., 2021). Although this threshold does not account for labour costs, a minimum gross margin of £0 was considered appropriate given that crop prices would likely increase in response to national underproduction of the relevant crop.
- All agroforestry was based on an alley cropping configuration, with no crops in the tree rows, except for permanent pasture, where the 'cropped area' was 99%.

2.3. *The optimal land use model (OLUM)*

The Optimal Land Use Model (OLUM) was originally developed to predict the production impacts of 100% conversion to organic farming in England and Wales (Smith et al., 2018). The objective function is to

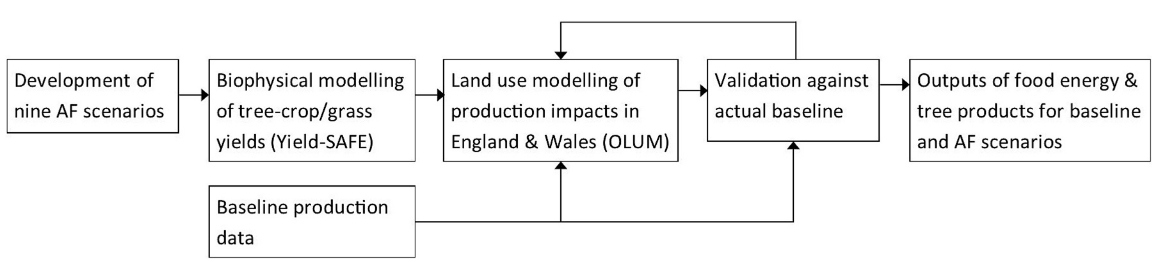

Fig. 1. Schematic of the modelling workflow to assess production impacts of scaling up agroforestry. AF = agroforestry.

maximise food production, expressed as metabolisable energy (ME), as outlined in Eq. (1):

$$Z = \sum_{ij=0}^{n} C_{ij} \bullet x_{ij} \text{ subject to } Rx_{ij} \leq \mathbf{b}, x_{ij} \geq 0, \tag{1}$$

Where Z is the objective function to be maximised, C_{ij} is the ME output per year of agricultural product i on soil x and rainfall class j, x_{ij} is a scalar for the agricultural activity (crop area or livestock number, with livestock stocking rates constrained), Rx_{ij} is a factor for the input and resource requirement associated with the activity, and **b** is a vector for resource endowment and input availability.

Within the model, all agricultural land in England and Wales is classified at a 5 km × 5 km grid resolution based on its Robust Farm Type (e.g. cereal, horticulture, dairy, lowland grazing, for full list see Supplementary Material 1), soil type (heavy, medium, light, humose), and rainfall class (dry, average, wet, very wet). Each of these categories is associated with crop and livestock production data (e.g. crop yields, crop rotations, stocking rates, proportions of different livestock types, livestock feed requirements, livestock yields), which are inputs and constraints in the model. The model fixes land areas by Robust Farm Type, assuming that these are constrained by existing infrastructure and local conditions. The model operates on a one-year timeframe.

2.4. Adaptation of the OLUM for the baseline scenario

Since OLUM was originally developed for organic farming systems (Smith et al., 2018), the first step was to update the model for conventional systems, using more recent data, to serve as the baseline scenario (S0). Where possible, data were sourced from a three-year average from 2017/2018 to 2019/2020 to avoid potential anomalies during the Covid-19 pandemic. Updated data for the baseline scenario included the following, which represented constraints in OLUM (see Supplementary Material 1 for further details and data sources):

- *Areas of Robust Farm Types for each soil and rainfall class*. These are fixed constraints in OLUM. Soil types and rainfall classes were retained from the original OLUM.
- *Yields and energy content for each crop and pasture type*. Proportions of yields across soil and rainfall classes were retained from the original OLUM, with mean average, maximum and minimum yields adjusted according to data in the John Nix Pocketbook (Redman, 2019) or Defra (2023) data.
- *Percentage areas allocated to different crop types for each farm type*. Main groups of crops / land uses, such as winter cereal, spring cereal, break crops, temporary grassland, and permanent grassland, were set as fixed constraints in the model. Within each main group, the area of each specific crop could increase by up to 20%, except break crops whose area was unconstrained. No limits were set for crop area reductions. However, maximum national production of break crops and cereals was capped at 5% above the baseline level. This allowed some rotation flexibility while avoiding overproduction. Geographic restrictions were applied to sugar beet production, as in the original OLUM.
- *Maximum livestock stocking rates in each farm type*. Maximum stocking rates for each farm type were set at current levels, with minimum stocking rates set as the minimum across three performance bands across three years. No minimum stocking rates were specified for crop-based farm types.
- *Livestock feed constituents*. Livestock feed constituents, such as beans and peas, cereals, residue, and soya, were fixed for each farm type. In addition, the proportion of forage consumed by ruminant livestock was a fixed constraint. A minimum constraint was applied to the proportion of cereals, beans and peas allocated to livestock feed versus human consumption, according to the baseline scenario.
- *Livestock attributes for each livestock type*. Livestock attributes included Livestock Units, liveweight, killing out percentage, energy output per year, yields of eggs and milk, and feed requirements.
- *Proportions of different livestock types*. The proportions of livestock types (including age categories) were fixed in each farm type.

Nitrogen constraints in the original OLUM were removed to reflect the availability of synthetic fertilisers in conventional systems. However, nitrogen requirements were predicted to be less than Nitrate Vulnerable Zone N-max limits (Defra, 2024c) for all main crop types apart from sugar beet. Other minor updates were made to OLUM to accommodate the new data formats.

The OLUM outputs of land use, cropping areas and livestock populations under the baseline scenario (S0) were validated against published data for England and Wales for the same years. The outputs compared similarly, with all values within 10% of the published values (see Supplementary Material 3).

2.5. Modelling the agroforestry scenarios using OLUM

Ten iterations of OLUM were run, corresponding to the nine scenarios in Table 1 (using Yield-SAFE outputs) plus the baseline scenario (S0). The OLUM outputs included calorific value of food, volume of timber, and mass of biomass production. In addition, land equivalent ratios (LERs) were calculated for each combination of crop type and scenario, to determine whether the agroforestry systems were more productive than equivalent monocultures (Mead and Willey, 1980) (see Eq. (2)). Although the application of LER in agroforestry studies is problematic (Newman et al., 2018), in this case we compared yields between equivalent areas of agroforestry and monoculture systems, with yields averaged across the 30-year rotation (see Table 1). Where crops were replaced with temporary grassland during the agroforestry rotation (see previous assumptions), this was accounted for within the LER calculations. LERs were calculated for each soil and rainfall class (see Supplementary Material 4), with mean average LERs presented in the Results.

$$\text{LER} = a\left(\frac{Ycrop_{AF}}{Ycrop_{MC}}\right) + (1-a)\left(\frac{Ytg_{AF}}{Ytg_{MC}}\right) + \left(\frac{Ytree_{AF}}{Ytree_{MC}}\right) \tag{2}$$

Where Y = average annual yield across the 30-year rotation (accounting for uncultivated tree rows), *crop* = crop / pasture type, *tg* = temporary grassland (substituted for crops where predicted gross margin < £0), *tree* = tree type, *AF* = hectare of agroforestry, *MC* = hectare of equivalent monoculture, and a is the proportion of the 30-year tree rotation with the ‘crop’ (rather than replacement temporary grassland).

Stakeholder feedback on preliminary results was gathered through an online seminar held on 31 January 2025, attended by 16 UK agroforestry experts from policy, academic institutions, and charities. Additional feedback was also sought through internal seminars at the University of Reading.

3. Results

3.1. Area of crops

The changes in the cropped areas determined from the OLUM is shown in Fig. 2. In general, the relative areas of arable crops in the apple agroforestry scenarios (S1 to S3) were broadly similar to the baseline scenario (S0), with decreases in oilseed rape, peas and beans in favour of sugar beet at higher tree densities. By contrast, the timber agroforestry scenarios (S4 to S6) were predicted to result in substantially reduced areas of oilseed rape, potatoes, and beans and peas, with stronger increases in sugar beet area. The SRC agroforestry scenarios (S7 to S9) resulted in higher areas of oilseed rape but much lower areas of potatoes.

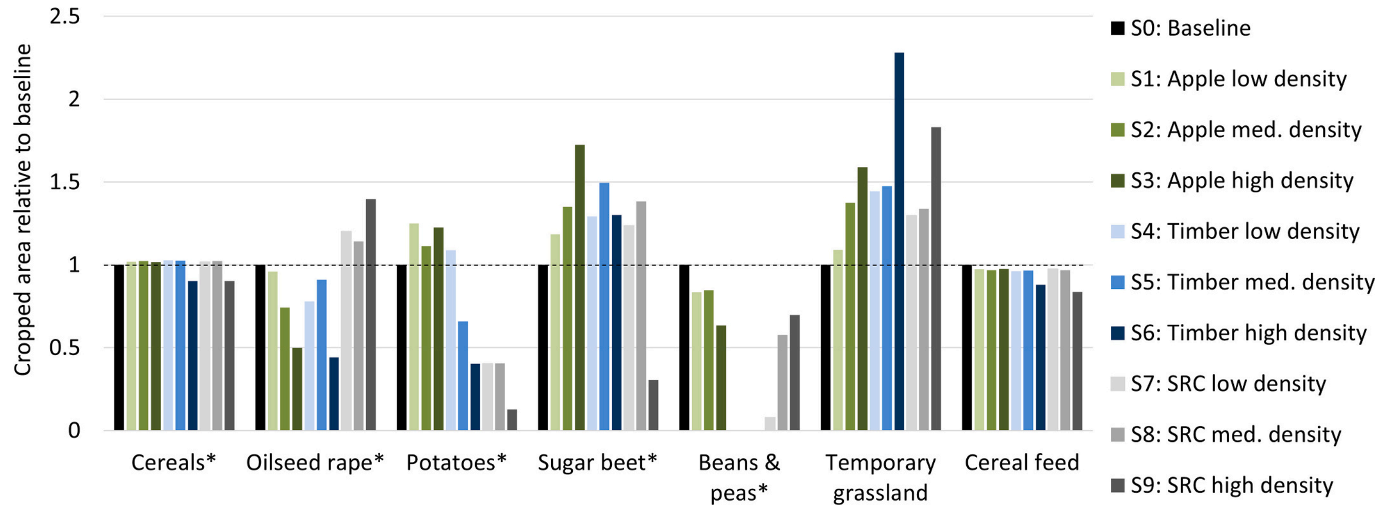

Fig. 2. Area of arable crops and temporary grass under agroforestry scenarios (see Table 1) in England and Wales, assuming an even spread of agroforestry in each year of the 30-year rotation. Dashed line represents the baseline area for each crop group. * denotes for human consumption only. Changes in cropped areas account for flexibility in break crop selection and replacement of unprofitable crops (gross margin < £0) with temporary grassland.

The temporary grassland area increased across all agroforestry scenarios, particularly at higher tree densities, because this replaced crops where yields were projected to be unprofitable.

3.2. *Yields per hectare*

Mean yields per hectare of cropped area across the agroforestry rotation, which account for years where unprofitable crops were not cultivated, varied substantially across agroforestry scenarios and crop types (Fig. 3). Yield reductions were most pronounced in high-density tree systems, reflecting increased competition for light and water. Among all crops, potatoes were most sensitive to tree competition, with yield reductions exceeding 40% compared to baseline. Sugar beet yields also declined markedly at higher tree densities. These reductions were partly caused by replacement with temporary grassland where the crop was projected to be unprofitable. Cereal crop yields were moderately

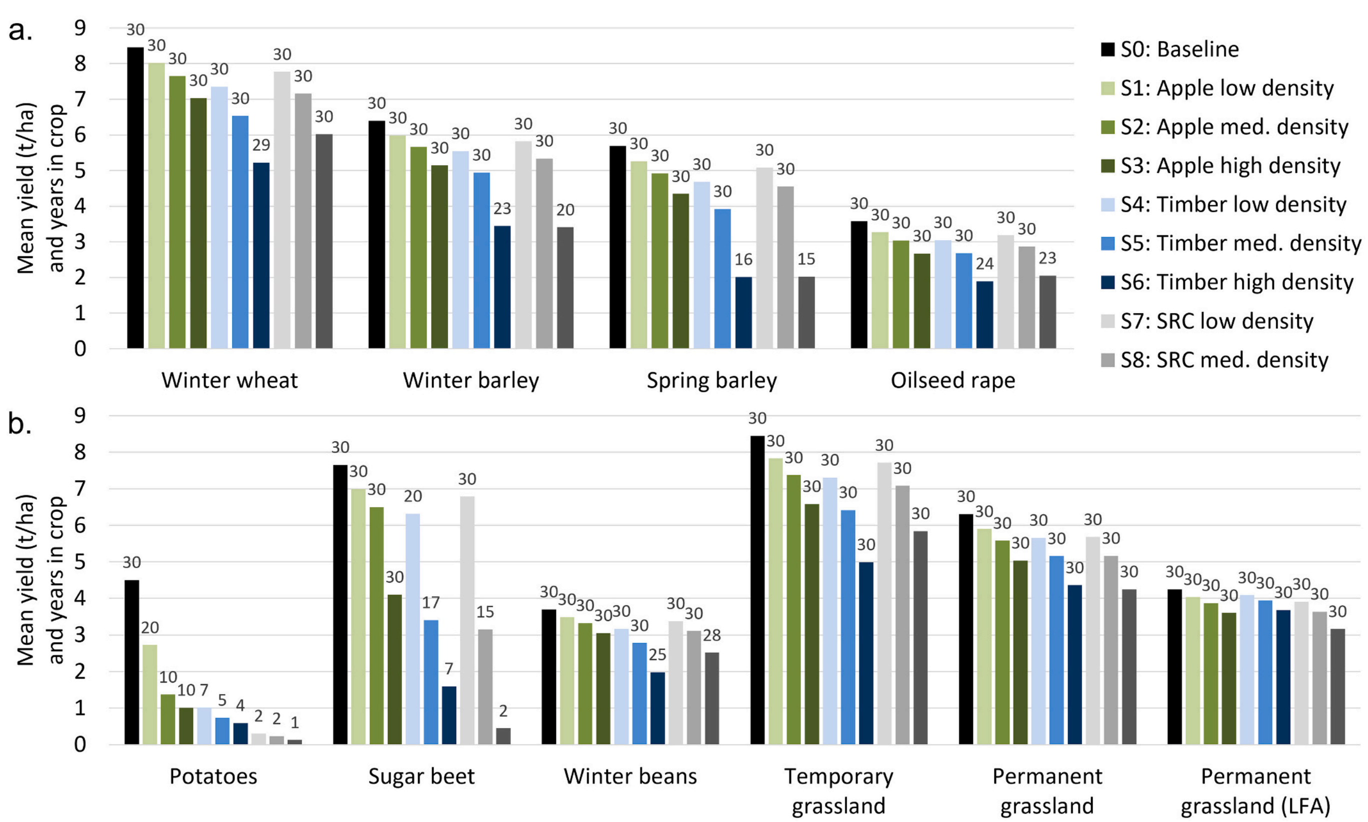

Fig. 3. Mean yields over the 30-year agroforestry rotation (bars), with 'years in crop' (number annotations) indicating the number of years each crop type remained in production before being replaced by temporary grassland due to unprofitability. Mean yields include 'zero-yield' years following crop replacement with temporary grassland. Yields are in tonnes of fresh matter, except for grassland which are dry matter. 'Per hectare' refers to cropped area only, and therefore excludes uncultivated tree rows.

reduced, typically ranging from 5% to 18% at low tree densities, with greater reductions in spring versus winter crops, while oilseed rape and beans showed similar trends. Grassland yields showed similar trends, but were less severely affected by high tree densities. These yield dynamics underpin trade-offs observed in total food energy production.

3.3. Total production

The net effect of the changes in areas of crops/grassland and yields per unit area was to reduce the total production of food energy by 3% to 45%, depending on tree type and density (Fig. 4). Plant-based food energy decreased by up to 49%, and animal products by up to 28%. Cereal energy production decreased by up to 50% under the agroforestry scenarios, both for human consumption and animal feed (Fig. 5), primarily because of reductions in yield rather than area. Sugar beet output was maintained in all but two scenarios, because yield losses were offset by increased area. Production of other break crops decreased substantially because of reductions in both area and yield.

Of the animal-based foods, the most substantial decreases were observed in monogastric production, particularly chicken meat which decreased by up to 63%, largely as a result of reduced grain feed availability (Fig. 5). Milk production remained within 3% of baseline levels, because the model prioritised its high energy conversion efficiency, supported by the increased area of temporary grassland that replaced unprofitable crops. The increase in grassland area also limited impacts on beef and lamb production to a maximum 37% reduction by energy value.

Balanced against these food energy reductions was substantial increases in the domestic production of apple, timber, and biomass (Fig. 4). Apple production was projected to increase by 12–34 times, timber by 4.3–9.3 times, and by SRC biomass 264–860 times compared with current levels, depending on tree density (Fig. 4). The large SRC increase reflects its low baseline production. Timber and SRC outputs were especially high in southern counties (Supplementary Material 5). Table 2 compares tree outputs under the lowest density scenarios to comparable UK-wide imports, highlighting the potential of agroforestry to contribute to national resource supply.

3.4. Comparison with monocultures: land equivalent ratios

The calculation of the mean land equivalent ratio (LER) is partly determined by the nature of the default tree-only system used for comparison. Mean LERs exceeded 1.0 for all of the apple and timber agroforestry scenarios (when apples were compared to traditional orchards), indicating higher predicted productivity than equivalent monocultures (Table 3, see Supplementary Material 4 for breakdown by soil and rainfall class). However, LERs for apple-agroforestry were below 1.0 when compared with intensive monocultures of apples rather than the lower intensity production typical of agroforestry systems (MM106 rootstocks at 3 m spacing). LERs of SRC agroforestry systems were close to 1, indicating comparable productivity to equivalent monocultures. The highest LERs were associated with permanent pasture, where there was no reduction in area, in contrast to the uncropped tree rows modelled in cropland and temporary grassland.

4. Discussion

Our study of the impacts of scaling up agroforestry provides novel insights into national-scale production impacts and trade-offs, going beyond previous site-level studies by integrating the results from a biophysical tree–crop model (Yield-SAFE) with a national land-use optimisation model (OLUM). The impacts of scaling up agroforestry are determined by tree-crop and tree-grass interactions, which in turn impact cropping areas in land use models. These biophysical relationships are central to understanding the trade-offs observed in our results. Scaling up agroforestry increased the domestic supply of apples, timber, and biomass, with outputs in many cases approaching or exceeding current import levels. However, this was accompanied by reductions in food energy production, particularly for arable and vegetable crops. Animal-based foods were less affected, reflecting the stability of grassland areas and the model's prioritisation of efficient livestock systems. Our results also indicate high land use efficiency of agroforestry systems, particularly for apple (when compared to traditional orchards) and timber, according to land equivalent ratios (LERs).

4.1. Production benefits of agroforestry: fruits, fibre and biomass

Agroforestry systems have the potential to contribute substantially to

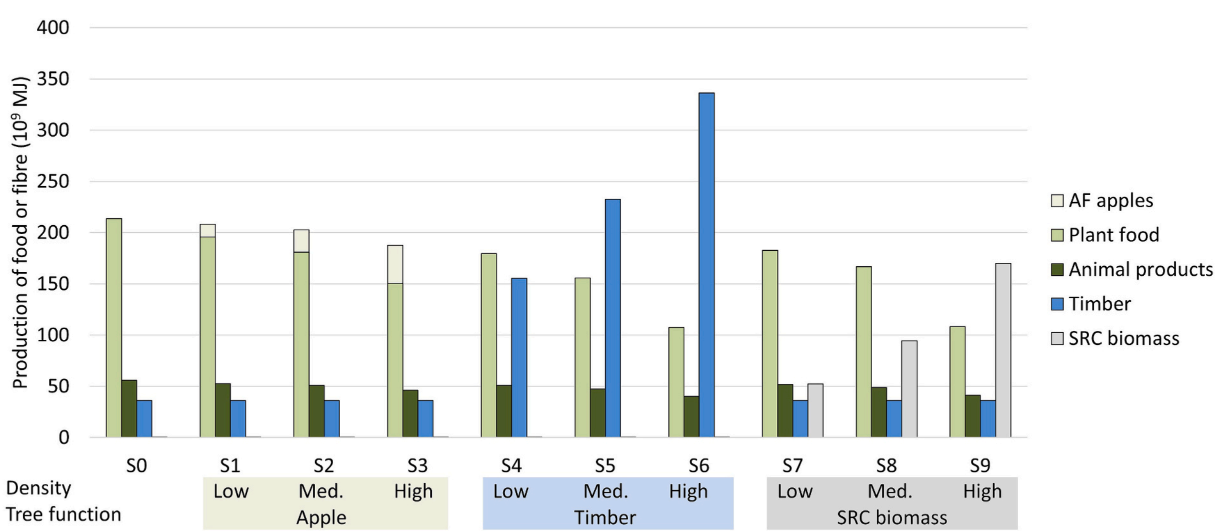

Fig. 4. Impact of agroforestry scenarios (S1-S9, see Table 1) on the total production of food (green), timber (blue) and SRC biomass (grey) in England and Wales, versus the baseline scenario (S0). Plant food only includes crops produced for human consumption. Baseline production levels for timber are based on annual mean 2017–2019 (Forest Research, 2024c), and for SRC, annual mean in England during 2018–2020 (Defra, 2024f), with the Wales contribution estimated by assuming the same percentage of arable land used for SRC. Conversion of timber and SRC production into MJ was calculated using Forest Research (2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

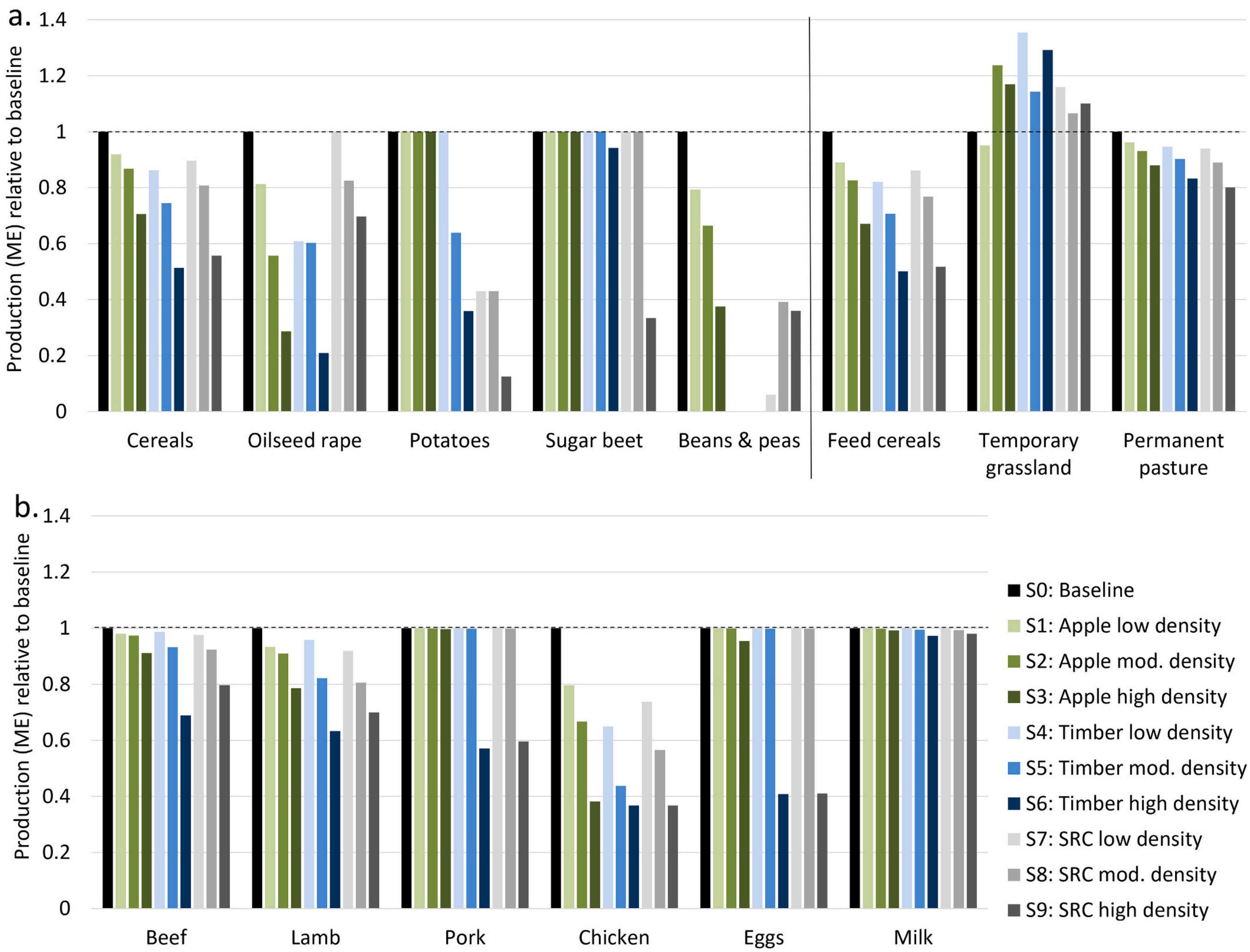

Fig. 5. Production of metabolisable energy (ME) relative to the baseline (dashed line) under nine agroforestry scenarios (see Table 1) in England and Wales: (a) arable crops for human consumption and livestock feed, and (b) livestock production. Permanent pasture includes rough grazing and less favoured area (LFA) pasture. Maximum and minimum stocking rates were constrained for each farm type, with the same constraint applied across all scenarios. Low impacts on milk production arise from the model objective function and the high efficiency of milk production.

Table 2
Comparison of modelled outputs from low-density agroforestry scenarios in England and Wales versus average annual UK imports for tree products. Modelled outputs assume full conversion of suitable agricultural land to agroforestry.

Tree type (with units)	Agroforestry production in England and Wales (low density scenario)	Current UK imports, (annual average 2017–2019)	Low-density production vs imports
Apple (million tonnes)	7.4	0.412 (0.708 for all orchard fruit) (Defra, 2024d)	18.0× import volume (10.5× for all orchard fruit)
Poplar (timber, million m^3)	24.7	49.3 (Forest Research, 2024)	0.50× import volume
Biomass (willow SRC, million oven dried tonnes (ODT))	7.3	7.9 (wood pellets) (Forest Research, 2024)	0.92× import volume

domestic production of tree-based products, including top fruit, timber, and biomass, for which the UK relies heavily on imports (Table 2). By modelling these outputs at a national scale, our study highlights the potential magnitude of import substitution under large-scale upscaling of agroforestry systems, complementing existing farm- and field-level evidence. In our scenarios, apple agroforestry systems produced considerably more fruit than current import volumes, suggesting a meaningful role in improving self-sufficiency of fresh fruit, which currently has the lowest domestic production-to-supply ratio of any major food group (Defra, 2024e). These systems also showed favourable land-use efficiency compared with equivalent low-input monocultures, as reflected in land equivalent ratios (LERs) above one (Table 3). However, when compared with intensive orchard systems, apple agroforestry had LERs below one, indicating lower productivity per unit area. This reflects the typical design of agroforestry as lower-input, regenerative systems, typically based on wider spacings, reduced fertilisation, and minimal pesticide use compared with conventional orchards (Smith et al., 2016). Timber agroforestry systems were also land-efficient, with LERs exceeding one, while biomass systems were of similar productivity to equivalent monocultures.

Our LER findings are consistent with previous field-scale research in temperate systems (García de Jalón et al., 2018b; Graß et al., 2020), although production efficiencies (LER > 1) have been calculated for a biomass system in England (Westaway et al., 2021). By extending LER analysis to the national scale, our study provides additional insights into how productivity trade-offs might play out across different soil and

Table 3
Land equivalent ratios (LERs) of the main modelled crop types in the nine agroforestry scenarios. An LER greater than 1 indicates higher productivity than equivalent monocultures, which are shown in Table 1. An asterisk denotes where temporary grassland was substituted due to the crop's gross margin falling below £0 (which is accounted for in the LERs). LERs for medium tree densities lie between the low and high values.

Agroforestry system	Apple agroforestry				Poplar timber agroforestry		SRC biomass agroforestry	
Comparator system	Traditional orchard		Intensive orchard[1]		High density poplar		SRC plantation	
Tree density	Low	High	Low	High	Low	High	Low	High
Permanent pasture	1.14	1.40	0.96	0.88	1.05	1.13	1.04	1.12
Permanent pasture, LFA	1.11	1.29	0.97	0.91	1.02	1.04	1.02	1.07
Winter wheat	1.08	1.25	0.90	0.73	1.06	1.12*	0.99	1.03
Winter beans	1.07	1.24	0.90	0.72	1.07	1.14*	0.99	1.03*
Temporary grassland	1.06	1.21	0.88	0.68	1.13	1.18	0.99	1.02
Winter barley	1.07	1.23	0.89	0.70	1.07	1.17*	0.99	1.03*
Sugar beet	1.05	1.20*	0.87	0.67*	1.09	1.18*	0.96	1.02*
Potatoes	1.02*	1.20*	0.84*	0.68*	1.12*	1.18*	0.98*	1.01*
Winter oilseed rape	1.04	1.18	0.87	0.66	1.08	1.16*	0.97	1.00*
Spring barley	1.06	1.20	0.88	0.67	1.02	1.13*	0.97	1.00*

[1] The comparator yield of intensive orchard was derived from Defra (2020).

rainfall contexts. Our approach also highlights the sensitivity of LER values to the choice of comparator (i.e. monoculture system), as illustrated for apple-agroforestry LERs (Table 3). Overall, these findings suggest that while agroforestry systems may not match intensive systems in yield per hectare, they can contribute significantly to domestic production as part of a more diverse and multifunctional land use strategy which delivers well-documented environmental benefits.

4.2. Production costs of agroforestry: food energy trade-offs

In this novel national-scale quantification of food production trade-offs under agroforestry, total food energy production decreased under all agroforestry scenarios (Fig. 4), due to a combination of reductions in cropped area from tree planting and yield reductions arising from tree-crop competition for light and water. Potato yields were particularly low, especially in systems with SRC willow or high-density timber (Fig. 3, Supplementary Material 7). This aligns with previous field-scale evidence that tree rows have a greater negative impact on potato than cereal yields, likely due to the large overlap in the growing season of potatoes with the period that trees are in leaf, coupled with sensitivity to water and light limitations (Pardon et al., 2025; Pardon et al., 2018).

Upscaling agroforestry generally had less severe impacts on the livestock sector than on arable cropping (Figs. 4 and 5), for several reasons. First, we assumed that pasture was not removed to plant trees, as is typical of wood-pasture systems, allowing vertical layering and sustainable productivity, indicated by the high LERs for permanent pasture (Table 3). This is consistent with previous evidence on silvopasture yields (Pent, 2020). Second, crops with negative predicted gross margins were replaced with temporary grassland, thus increasing grassland area under agroforestry scenarios (Fig. 2). Third, feed from imports and manufacturing by-products was assumed to remain constant. Fourth, a large proportion of permanent pasture and rough grazing was excluded from tree planting to account for Priority Habitats and upland areas (see Methods). However, grain production declines did affect monogastric livestock production, particularly under higher density scenarios (Fig. 5).

Despite the production efficiencies of food-based agroforestry systems (i.e. apples, S1-S3), as indicated by LERs (Table 3), total food energy output still decreased by 3.1 to 13.3% compared with the baseline. Several factors contributed to this:

1) The apple agroforestry scenarios were modelled on low-intensity systems (see Table 1) typical of regenerative approaches that emphasise environmental benefits. These typically use semi-vigorous rootstocks at, for example, 3 m spacing, with minimal inputs, and yield less than intensive orchards that use dwarfing rootstocks at higher densities, regular fertilisation, irrigation, and pesticides (Redman, 2019).
2) Apple crops, even under intensive production, have lower food energy content than common arable crops such as wheat or potatoes (Supplementary Material 6).
3) The crops with the largest yield penalties in agroforestry systems were typically those with higher food energy outputs, such as sugar beet and potatoes (Supplementary Materials 6 and 7).

Prioritising agroforestry system design for food energy production could increase energy output beyond the scenarios modelled here, particularly considering the high land use efficiency of these systems as indicated by LERs.

4.3. Policy relevance

Policy frameworks for land use and agricultural transition increasingly emphasise the need for multi-functional landscapes that deliver food, climate, and biodiversity outcomes. Agroforestry is widely promoted as one such system, and interest in its role within sustainable land use planning is growing. Applying tree and crop models at landscape scales can help identify key synergies and trade-offs, providing useful insights for policymakers (Burgess et al., 2012). However, there are real constraints on what is achievable, particularly if import levels remain high and productivity gains per hectare are not realised (Burgess et al., 2021).

Government policy support for agroforestry systems in England, Wales, and the EU is largely based on scientific evidence demonstrating its benefits for ecosystem services, resilient food production, and animal welfare (Smith et al., 2022; Sollen-Norrlin et al., 2020; Veldkamp et al., 2023). Agroforestry systems could play a particularly important role in meeting net zero objectives. For example, Burgess and Graves (2022) predicted that planting high-stem agroforestry trees on 20% of arable land or 30% of grassland could offset current direct greenhouse gas emissions from UK agriculture during the tree rotations, assuming no other mitigation measures. At the farm level, once other mitigation options such as reducing fertiliser-related emissions have been implemented, integrating trees and hedgerows is one of the main ways a farm could demonstrate progress toward net zero.

Our study adds to this evidence on environmental benefits by providing a system-wide perspective on how different agroforestry configurations could enhance domestic supply of tree products, including fruit, timber, and wood pellets, all of which are predominantly supplied through imports in the UK. Upscaling top fruit agroforestry systems may also support policy goals to maintain domestic food production by value, given their potential to boost long-term farm income, although this is also highly sensitive to yields and costs (Staton et al., 2022a). In relation to UK food security targets however, our results suggest that large-scale upscaling of agroforestry with non-food trees would lower domestic calorie supply, especially in arable systems. Agroforestry designs that prioritise pasture-based systems and integrate fruit trees rather than timber or biomass may therefore align better with food security objectives. Nevertheless, maintaining domestic food energy production at current levels under an upscaled agroforestry future would require efficiencies elsewhere in the food system, such as dietary shifts and reductions in food waste (Burgess et al., 2021; Mayer et al., 2022a; Wood et al., 2019).

Although we predicted agroforestry systems to be more productive than equivalent monocultures in most cases, their development in the UK is still in early stages, with few long-established sites having accurate yield data. Scaling up effective and regionally adapted systems will require further research into optimal design and management (Majaura et al., 2024). Enhancing the productivity of agroforestry systems could also help reframe perceptions of agroforestry, making it more compatible with prevailing notions of what is a 'good farmer' (Felton et al., 2023).

Our results suggest that agroforestry may be more compatible with grassland than arable systems to optimise food energy production. This aligns with traditional agroforestry systems, such as wood-pasture and traditional orchards in the UK, and similar systems elsewhere in Europe, including the Dehesa and Montado systems still prevalent in Spain and Portugal (den Herder et al., 2017). Grass appears more resilient to tree competition than arable crops, and trees can provide added value to livestock systems through shade, shelter and fodder. Although this suggests a greater focus on grazing systems, recent research suggests that livestock are increasingly being housed indoors (Rubio-Delgado et al., 2023). By contrast, uptake of agroforestry could align with regenerative agriculture approaches that favour increased integration of livestock (Newton et al., 2020).

Realising the benefits of tree production identified in this study will also require targeted investment in infrastructure and markets (Low et al., 2023; Morris and Day, 2023). Although agroforestry can be a financially viable option for farmers (Staton et al., 2022a), this depends on policy support, knowledge of agroforestry management, and prices of tree products (Staton et al., 2022a; Thiesmeier and Zander, 2023). For example, demand for poplar has declined due to the contraction of markets for domestically produced matches and veneers (Savill, 2013). Scaling up domestic fruit and biomass production would require improved storage, processing, and distribution capacity, as well as addressing the economic challenges recently faced by the top fruit industry, particularly the high cost of production relative to imported products (British Apples and Pears, 2023). In addition, farmers would need to acquire new skills and adapt to unfamiliar management practices, such as transitioning between crops and forage. Policy support for training, advisory services, and supply chain development will be essential to enable this shift.

4.4. Limitations and future developments

Our integrated use of Yield-SAFE and OLUM represents a novel framework for exploring system-wide impacts of agroforestry upscaling, which could be adapted for other regions or policy scenarios. As with any large-scale modelling study however, our results should be interpreted in the context of assumptions and limitations. Specific assumptions for modelling the agroforestry scenarios in the OLUM are set out in the Methods. One important caveat is that food output was assessed solely in terms of metabolisable energy. Future research could extend this analysis to include nutritional quality or financial value. The latter aligns with the UK government's target to produce 60% of food by value.

Another key limitation is that climate change effects were not included. Recent modelling in Northern Ireland suggests that in areas with adequate future rainfall, elevated CO_2 would offset temperature and drought impacts on agroforestry productivity (Giannitsopoulos et al., 2025). However, outcomes may differ in drier regions such as Eastern England, and the study did not account for increased frequency of extreme weather events. That study also suggests that the LER benefits of agroforestry are likely to persist under climate change, although there was tendency for tree growth to be favoured over grass and crops. Further research could explore how climate change scenarios influence tree-crop interactions (Gidey et al., 2020; Jägermeyr et al., 2021).

Our study also did not account for agroforestry co-benefits or costs beyond production. Future research could quantify benefits such as enhanced natural pest control (Staton et al., 2021), pollination (Staton et al., 2022b; Varah et al., 2020), soil protection (Torralba et al., 2016; Veldkamp et al., 2023), yield stability (Rosa-Schleich et al., 2019), and livestock benefits including shelter, shade, and tree fodder (Jordon et al., 2020; Kendall et al., 2021). Costs could include additional management and administration (García de Jalón et al., 2018a).

The OLUM could be further developed by adjusting crop productivity estimates to account for regional temperature variations, rather than solely soil and rainfall classes. In addition, our application of OLUM assumed relatively static farm enterprises, largely maintaining existing crop rotations, livestock proportions, and farm types under agroforestry scenarios. Future modelling could incorporate more flexibility to account for transformative shifts in enterprise and rotation strategies that could accompany national transitions toward agroforestry practices.

Yield-SAFE is a frequently used model which is undergoing continual improvements. The limited choice of crops in Yield-SAFE required crop grouping, with all vegetables modelled using potato parameters. This likely underestimated yields for winter vegetables, though these represent a small proportion of national production. Given that the model was originally designed for timber-based silvoarable systems (van der Werf et al., 2007), Yield-SAFE could benefit from improved parameterisation for grassland, and fruit trees under various rootstocks. In addition, Yield-SAFE models tree-crop interactions based on tree density rather than alley width or orientation (van der Werf et al., 2007), making it more accurate at higher densities where tree-crop competition is more uniform. Future developments could enhance modelling accuracy at lower tree densities. In addition, nut-based agroforestry systems, such as those incorporating hazel or walnut, were not modelled here but may offer long-term benefits for climate resilience and are worthy of further research and model development.

Finally, our results suggest that scaling up agroforestry, particularly fruit or timber systems, would reduce imports of these products, but may increase reliance on imported arable and vegetable products. This raises broader questions regarding global environmental trade-offs of widespread agroforestry uptake, including emissions, carbon sequestration, and land use displacement. Consequential life cycle assessment could help explore these dynamics in future work (Schaubroeck et al., 2021; Searchinger et al., 2018; Webb et al., 2025).

4.5. Conclusions

This study shows that upscaling agroforestry systems in England and Wales could significantly increase domestic production of fruit, timber, and biomass, for which the UK currently relies heavily on imports, while also delivering previously documented environmental and animal welfare benefits. However, these benefits come with trade-offs, particularly reductions in food energy output, highlighting the importance of continued improvements in agroforestry system design and broader food system efficiency.

This novel approach integrates the results from a biophysical tree–-crop model (Yield-SAFE) with a national land use optimisation model (OLUM). Scaling up agroforestry to 100% of suitable agricultural land, as a simple modelling objective rather than a realistic target, provides the first national-scale quantification of production impacts in England and Wales. This national-scale approach reveals how trade-offs between tree products and food energy vary across farming systems and agroforestry configurations. Key findings and implications include the following:

- Agroforestry can significantly reduce the UK's heavy reliance on imported tree products.
- Food energy production declined by 3–45%, with the largest impacts on arable and vegetable crops.
- Forage-based livestock systems were least negatively affected by integration of agroforestry systems.
- Land equivalent ratios indicated that timber and apple agroforestry systems outperformed equivalent monocultures (for apple, traditional orchards) in land-use efficiency.
- Design improvements, such as higher-yielding tree varieties and more optimised spatial layouts, could help reduce food production trade-offs.
- Maintaining food energy security alongside agroforestry expansion may require complementary changes across the food system, including dietary shifts and reduced food waste.

Agroforestry systems are a viable solution toward a more multifunctional land use, supporting multiple environmental and import-reduction policy targets. However, the optimal extent and configuration of agroforestry will depend on regional contexts, land suitability, and broader food system dynamics. These results provide novel, national-level evidence to guide policymakers on where and how agroforestry uptake could best contribute to multifunctional land use. Further research is needed to evaluate the greenhouse gas implications of upscaling agroforestry systems.

CRediT authorship contribution statement

Tom Staton: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Paul J. Burgess:** Writing – review & editing. **Anil R. Graves:** Writing – review & editing. **Laurence G. Smith:** Writing – review & editing, Project administration, Investigation, Conceptualization.

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.2026.104651.

Data availability

Data will be made available on request.

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